Global Tipping Points

Report 2023

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Thank you all.

The Global Tipping Points Team

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Foreword

Global Tipping Points Report Foreword by Dr. Andrew Steer, President & CEO at Bezos Earth Fund

Here's a puzzle. Ask a group of the world leading experts on climate change where they stand on the pessimistic/optimistic spectrum, and you will get answers at both ends. Many will say "We are heading for disaster at a scale that we are only beginning to understand", while others will say "We are seeing potential progress at a rate and scale that shocks even the optimists. Just look at those cost curves!"

They can't both be right. Or can they?

This remarkable Global Tipping Points Report 2023 shows that both are indeed correct. And it is only by holding these seemingly inconsistent positions continually in view that we will be able to act with the inspiration and courage necessary to prevent catastrophe.

Things really are bad. Devastating climate events and nature loss are here today. We are no longer talking about tomorrow's problem. This is with average warming of 1.2 degrees Celsius. Under current policies we are on a trajectory of warming beyond 2°C, which will have an impact exponentially greater than what we face today.

But it is worse than this. As warming approaches and surpasses 2 degrees Celsius this may cause critical Earth system tipping points, once considered low-likelihood, to rapidly become much higher-likelihood events. These harmful discontinuities pose some of the gravest threats faced by humanity. Consider for example the runaway collapse of the Greenland and Antarctic ice sheets, which will redefine coastlines worldwide. Or the possibility of the dieback of the Amazon forest, causing it to tip into a savannah-like ecosystem. Already at 1.2 degrees Celsius of warming, warm-water coral reef ecosystems at risk of unravelling. Passing 1.5°C and certainly 2°C risks tipping several other systems, locking in change for centuries to come.

The scientific community has warned of the possibility of runaway climate change for some years, but never before have we had such a comprehensive assessment of the "negative tipping points" as is presented in the following pages.

The good news is that it is not too late. The Global Tipping Points Report shows us that, just as there are dangerous negative tipping points, so too there are very significant positive tipping points in our near-term future if only we have the courage and ambition to seize them. These provide the possibility of changing course much more rapidly than is commonly understood. Electric vehicles, for example, illustrate a growth in market share much more rapidly than anticipated. Potential for exponential change also exists in food systems, holding tremendous promise in meeting climate, biodiversity and development goals, including alternatives to livestock products and green ammonia production for fertilizer.

These positive tipping points will not be reached without effort. They require financial investments, policy support, courageous leadership, behavioural change, technological innovation, and social action, which create the enabling conditions to alter the balance so tipping can occur. And equity and justice must be at the heart of change.

This year we are presented with one of the most important moments in this decisive decade: the Global Stocktake under the Paris Agreement. We have the knowledge, resources, and capability to implement the solutions at speed and scale. But we must act now and in unison. Together, we can ensure positive change is unstoppable, irresistible, undefeatable.

The decisions we make in the next few years will affect the future of humanity for the next thousand.

It's not too late. But later is too late!

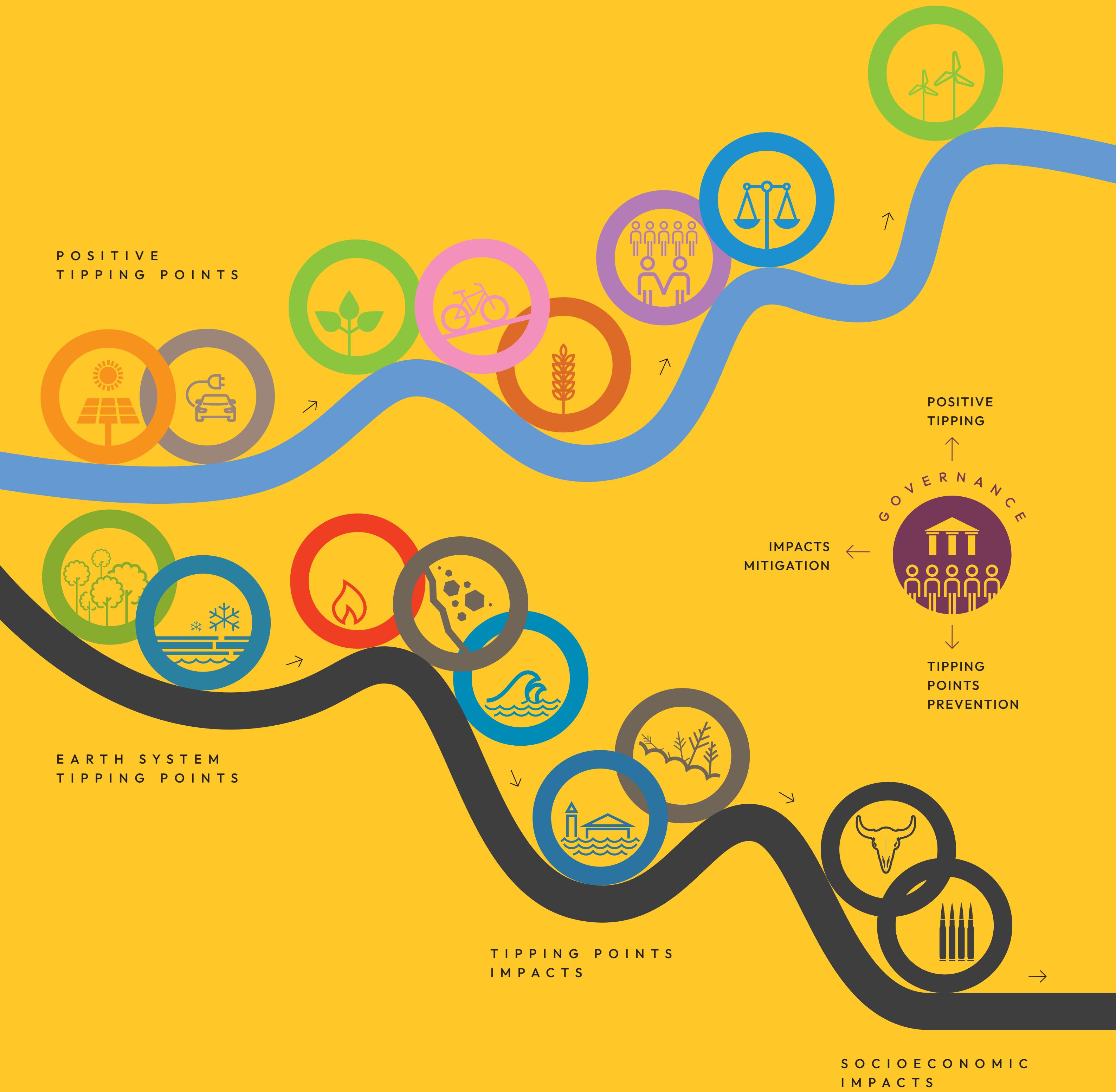
What the experts say

Kingsmill Bond, Senior Principal at the Rocky Mountain Institute (RMI):

"Exeter has written a brilliant analysis of the key issue of our time – how to trigger positive renewable tipping points before we are overwhelmed by negative climate tipping points. Time is short, focus is vital, but there is hope and there are solutions."

Nigel Topping, UN Climate Change High-Level Champion for the UK and Business Champion for the UK Climate Change Committee:

"The Global Tipping Points Report is essential reading for businesses, governments and any organisation who wants to be competitive and capture global markets in the transition to a net zero economy. Low-carbon technologies are growing exponentially, and understanding positive tipping points will enable countries and boardrooms to stay ahead of the curve. In sector after sector, change is happening faster than many realise and will be unstoppable. To understand tipping points is to understand the threats and opportunities ahead and the expert team behind this report have done an exceptional job of providing the information and tools decision makers need in the critical decade ahead.


POSITIVE TIPPING POINTS
POSITIVE TIPPING
GOVERNANCE
IMPACTS MITIGATION
TIPPING POINTS PREVENTION
EARTH SYSTEM TIPPING POINTS
TIPPING POINTS IMPACTS
SOCIOECONOMIC IMPACTS

Narrative summary

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Harmful tipping points in the natural world pose some of the gravest threats faced by humanity. Their triggering will severely damage our planet's life-support systems and threaten the stability of our societies.

For example, the collapse of the Atlantic Ocean's great overturning circulation combined with global warming could cause half of the global area for growing wheat and maize to be lost. Five major tipping points are already at risk of being crossed due to warming right now and three more are threatened in the 2030s as the world exceeds 1.5°C global warming.

The full damage caused by negative tipping points will be far greater than their initial impact. The effects will cascade through globalised social and economic systems, and could exceed the ability of some countries to adapt. Negative tipping points show that the threat posed by the climate and ecological crisis is far more severe than is commonly understood and is of a magnitude never before faced by humanity.

Currently, there is no adequate global governance at the scale of the threats posed by negative tipping points. The world is on a disastrous trajectory. Crossing one harmful tipping point could trigger others, causing a domino effect of accelerating and unmanageable change to our life-support systems. Preventing this – and doing so equitably – should become the core goal and logic of a new global governance framework. Prevention is only possible if societies and economic systems are transformed to rapidly reduce emissions and restore nature.

The current approach of linear incremental change favoured by many decision makers is no longer an option. Existing governance institutions and decision-making approaches need to adapt to facilitate transformational change.

Crucial to achieving this transformational change are positive tipping point opportunities, where desirable changes in society become self-propelling. Concerted actions can create the enabling conditions for triggering rapid and large-scale transformation. Human history is flush with examples of abrupt social and technological change. Recent examples include the exponential increases in renewable electricity, the global reach of environmental justice movements, and the accelerating rollout of electric vehicles. Negative tipping point threats could be mitigated if there was a vast effort to trigger other positive tipping point opportunities.

Unfortunately, in the time lag during which appropriate governance and action might be realised, negative tipping points could still be triggered. This means that societies must urgently be made more resilient to minimise the vast and unequal harms. Critically, more resilient societies are also needed to ensure that collective focus on triggering positive tipping point opportunities can be sustained even through a negative tipping event. This resiliency can be achieved with 'no regrets' actions that anyway make societies more sustainable, equitable and prosperous.

The existence of tipping points means that 'business as usual' is now over. Rapid changes to nature and society are occurring, and more are coming. If we don't revise our governance approach, these changes could overwhelm societies as the natural world rapidly comes apart. Alternatively, with emergency global action and appropriate governance, collective interventions could harness the power of positive tipping point opportunities, helping navigate toward a thriving sustainable future.

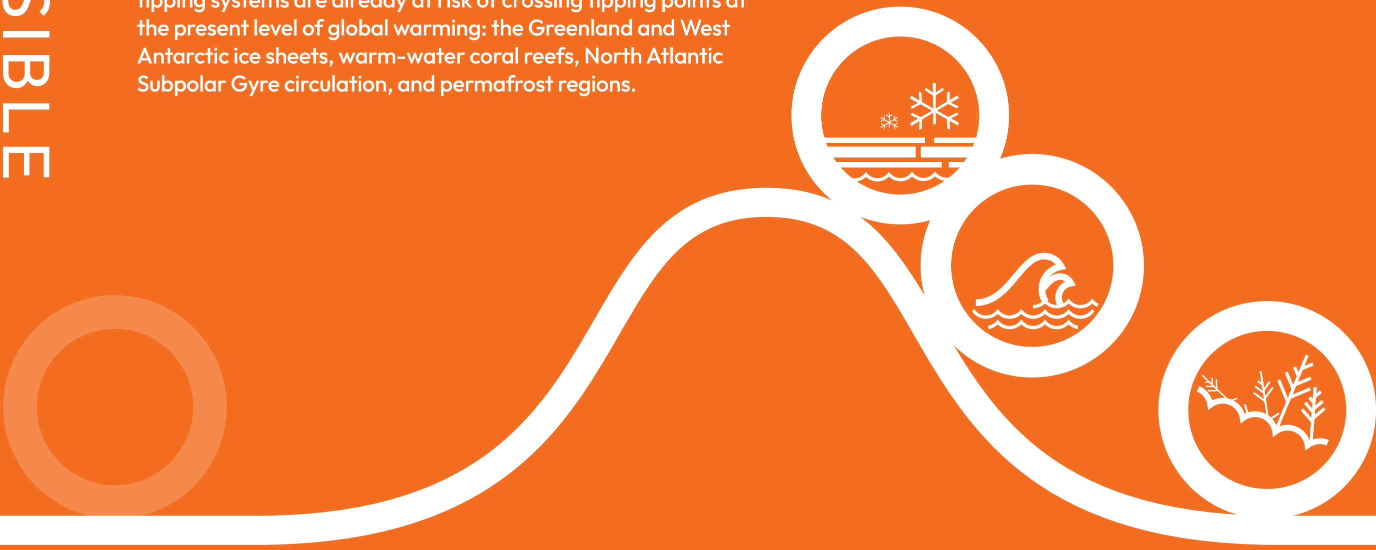
Key messages

IRREVERSIBLE CHANGE

KEY MESSAGE 01

CLIMATE CHANGE AND NATURE LOSS COULD SOON CAUSE ‘TIPPING POINTS’ IN THE NATURAL WORLD

Environmental stresses could become so severe that large parts of the natural world are unable to maintain their current state, leading to abrupt and/or irreversible changes. These moments are called Earth system ‘tipping points’. Five major tipping systems are already at risk of crossing tipping points at the present level of global warming: the Greenland and West Antarctic ice sheets, warm-water coral reefs, North Atlantic Subpolar Gyre circulation, and permafrost regions.



POSING THREATS

KEY MESSAGE 02

THESE TIPPING POINTS POSE THREATS OF A MAGNITUDE NEVER BEFORE FACED BY HUMANITY

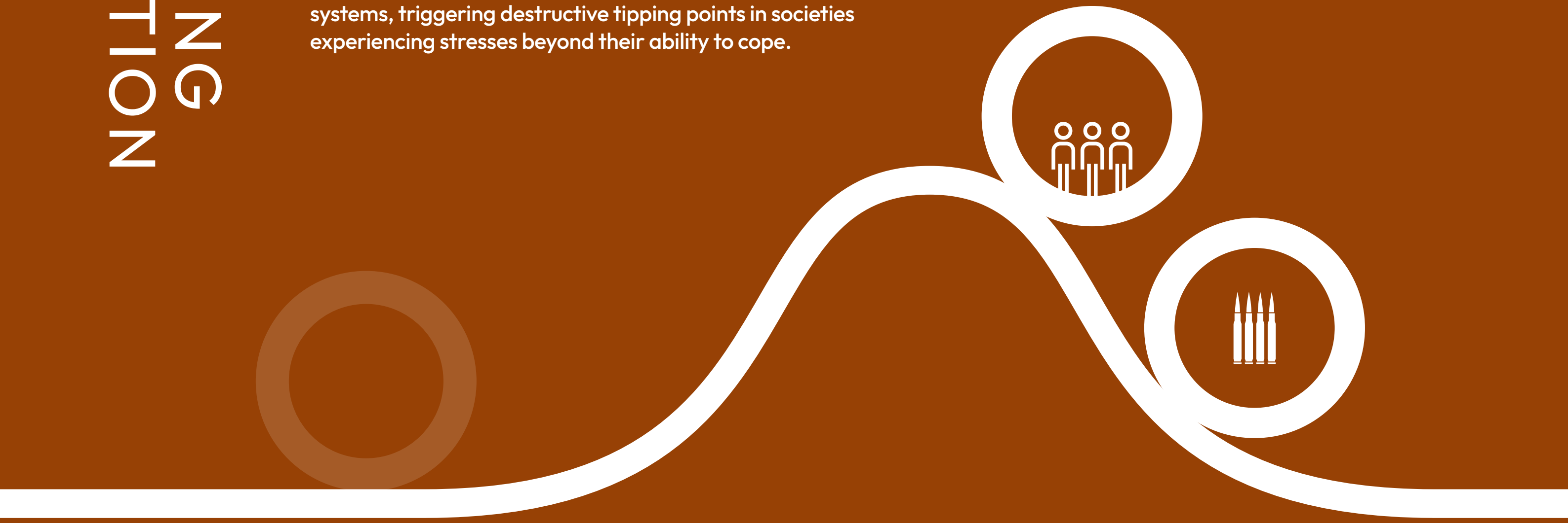
These threats could materialise in the coming decades, and at lower levels of global warming than previously thought. They could be catastrophic, including global-scale loss of capacity to grow major staple crops. Triggering one Earth system tipping point could trigger another, causing a domino effect of accelerating and unmanageable damage. Tipping points show that the overall threat posed by the climate and ecological crisis is far more severe than is commonly understood.

TRIGGERING DESTRUCTION

KEY MESSAGE 03

THE EFFECTS OF TIPPING POINTS WILL BE TRANSMITTED AND AMPLIFIED THROUGHOUT OUR GLOBALISED WORLD

This will multiply crises in the same way that the COVID-19 pandemic caused cascading stress to societies and economic systems globally, with unequal and unjust consequences. These impacts could escalate to threaten the breakdown of economic, social and political systems, triggering destructive tipping points in societies experiencing stresses beyond their ability to cope.

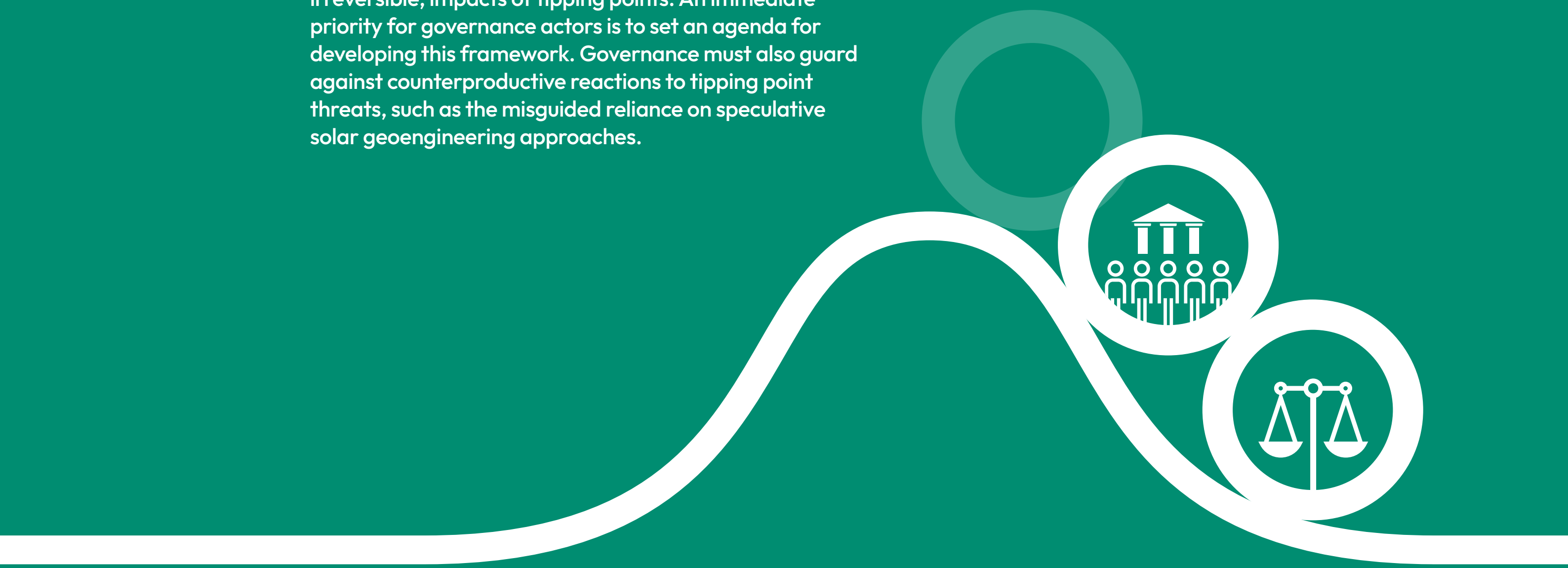


URGENT ACTION

KEY MESSAGE 04

STOPPING THESE THREATS IS POSSIBLE BUT REQUIRES URGENT GLOBAL ACTION

Global governance is currently inadequate to minimise tipping point threats and to do so equitably. Governance is needed across multiple scales to address the different drivers, potentially rapid changes, and diverse, often irreversible, impacts of tipping points. An immediate priority for governance actors is to set an agenda for developing this framework. Governance must also guard against counterproductive reactions to tipping point threats, such as the misguided reliance on speculative solar geoengineering approaches.



VICIOUS CYCLES

KEY MESSAGE 05

EVEN WITH URGENT GLOBAL ACTION, SOME EARTH SYSTEM TIPPING POINTS MAY BE UNAVOIDABLE

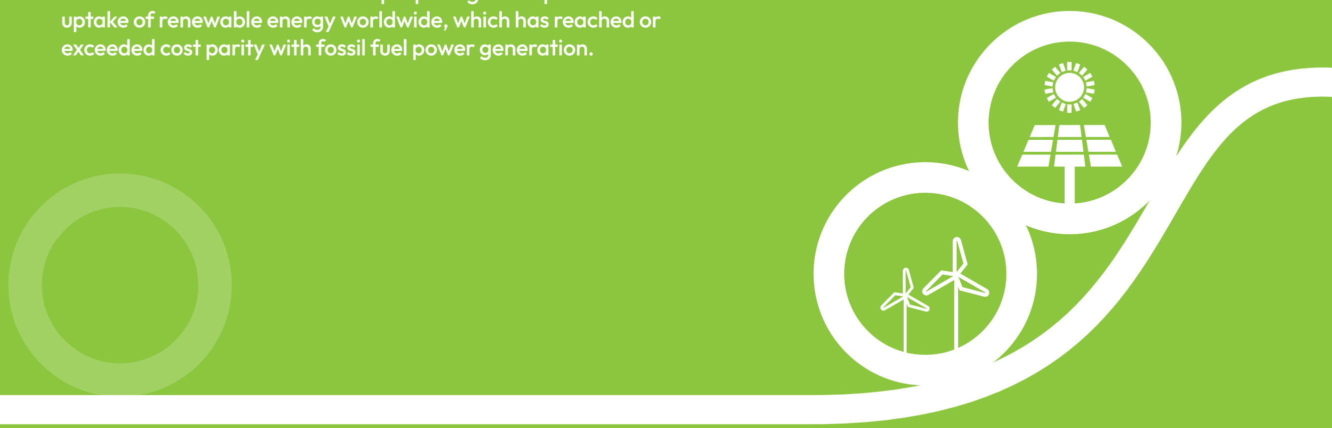
Some Earth system tipping points may still be triggered in the time it takes us to undertake global emergency action. Mitigating risk is still possible by reducing vulnerability, and becomes ever more urgent, because each manifestation of a tipping point threat diverts attention and resources to disaster response, eroding away some of our agency to tackle the underlying drivers. This increases the risk of triggering more Earth system tipping points, creating a vicious cycle.

ACCELERATING TRANSFORMATIONS

KEY MESSAGE 06

'POSITIVE TIPPING POINTS' CAN ACCELERATE A TRANSFORMATION TOWARDS SUSTAINABILITY

A scale and pace of action necessary to mitigate tipping point threats can be achieved, partly because similar tipping dynamics exist in societies, and can work in our favour. These positive tipping point opportunities can be exploited, whereby coordinated strategic interventions can lead to disproportionately large and rapid benefits that accelerate the transition of societies toward sustainability. This is already happening in some cases. For example, targeted actions by innovators, governments, investors and companies have created economies of scale that are now propelling the exponential uptake of renewable energy worldwide, which has reached or exceeded cost parity with fossil fuel power generation.



POSITIVE CHANGE

KEY MESSAGE 07

ONE POSITIVE TIPPING POINT CAN TRIGGER OTHERS, CREATING A DOMINO EFFECT OF CHANGE

For example, as electric vehicles pass a positive tipping point towards becoming a dominant form of transport, this reduces the costs of battery technology. Lower-cost batteries in turn provide essential storage capacity to reinforce the positive tipping point to renewable power, which can trigger another tipping point in producing green ammonia for fertilisers, shipping, and so on.

COORDINATED ACTION

KEY MESSAGE 08

TRIGGERING POSITIVE TIPPING POINTS REQUIRES COORDINATED ACTION THAT CONSIDERS EQUITY AND JUSTICE

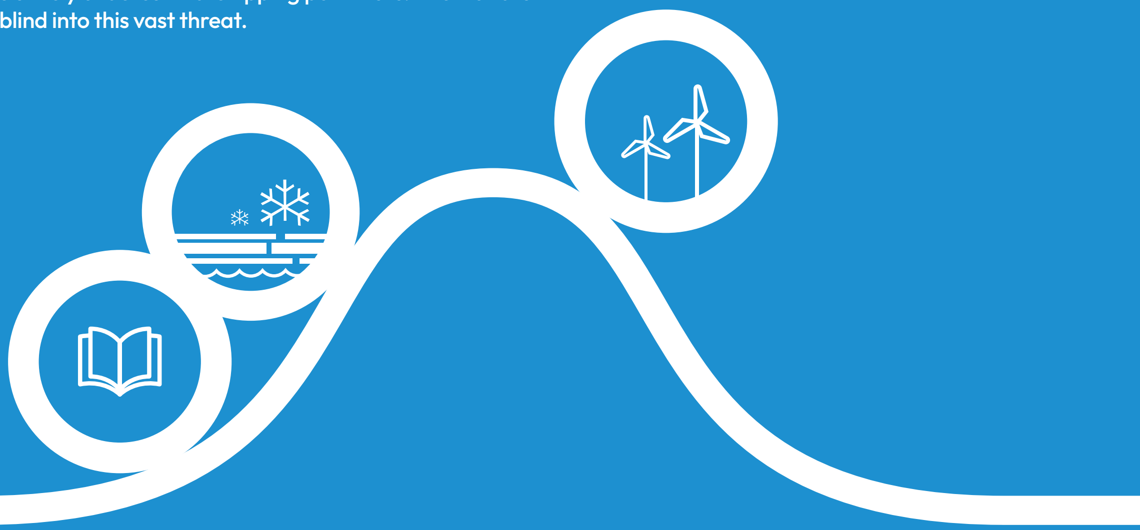
Many areas of society have the potential to be 'tipped', including politics, social norms and mindsets. But these opportunities are not realised on their own. Concerted and coordinated action is usually needed to create the enabling conditions for triggering positive tipping points. Once near a tipping point, it may even be triggered by relatively small groups with targeted action. Appropriate governance can enable this process and is required to equitably manage its knock-on effects, so that all parts of society can engage with and benefit from tipping point opportunities.

KEY MESSAGE 09

A DEEPER UNDERSTANDING

WE NEED A DEEPER UNDERSTANDING OF TIPPING POINTS – BUT WITHOUT DELAYING ACTION

Improving understanding of tipping point threats and opportunities in both nature and societies is an urgent priority to support governance and decision making, with the aim to limit harm and support transformations to sustainability. But this quest for knowledge must not delay or slow action. We know enough to identify that the threat of Earth system tipping points demands an urgent response. Indeed, our best models likely underestimate tipping point risks. The world is largely flying blind into this vast threat.



KEY MESSAGE 10

A POWERFUL COUNTER EFFECT

POSITIVE TIPPING POINTS CAN CREATE A POWERFUL COUNTER EFFECT TO THE RISK OF EARTH SYSTEM TIPPING POINTS CASCADING OUT OF CONTROL

The ultimate risk presented by Earth system tipping points is that they cascade, creating a growing momentum that undermines our collective ability to deal with the vicious cycle of escalating consequences. But both protecting and enhancing our collective ability to realise positive tipping point opportunities – even as damaging events escalate – can create a powerful counter effect, avoiding spiralling disaster. Doing so means urgently making our societies more resilient to this new era of rapid change and implementing equitable global governance.

Key recommendations

1 PHASE OUT FOSSIL FUELS AND LAND USE EMISSIONS NOW

The scale of threat posed by Earth system tipping points underlines the critical importance of the 1.5˚C temperature goal and means that global mitigation should now assume an emergency footing. Fossil fuel emissions should be phased out worldwide before 2050. A rapid end to land use change emissions and shift to worldwide ecological restoration are also needed. Countries should reassess their highest possible ambitions accordingly, particularly wealthy, high-emitting nations.

2 STRENGTHEN ADAPTATION AND LOSS-AND-DAMAGE GOVERNANCE

Some Earth system tipping points are now likely to be triggered, causing severe and spatially uneven impacts on societies and interconnected ecological, social and economic systems. Tipping point impacts will be felt worst by the most vulnerable communities within and between nations, with knock-on impacts for global inequality, the stability of the world economy, and geopolitics. This provides an urgent impetus to strengthen adaptation and loss-and -damage governance in the UNFCCC, adjusting existing frameworks and increasing resources to account for tipping point threats.

3 INCLUDE TIPPING POINTS IN NDCS AND THE GLOBAL STOCKTAKE

Considerations of Earth system tipping point risks, corresponding action, and positive tipping point opportunities should be included in the Global Stocktake (GST), future revisions of Nationally Determined Contributions (NDCs), and in associated national and sub-national policy measures. Future GSTs should assess collective progress towards preventing Earth system tipping points, addressing potential impacts and fostering positive tipping points. All future NDCs should include national-scale systemic assessments of exposure to tipping point risks, measures that contribute to the prevention of tipping points, plans for managing potential impacts and strategies for fostering positive tipping points

4 COORDINATE POLICY EFFORTS TO TRIGGER POSITIVE TIPPING POINTS

Coordinated action by coalitions of state and non-state actors across governance, business and civil society can bring forward positive tipping points in politics, economies, technology, culture, and behaviour. A focus on 'super-leverage points' – for example policy mandates in high-emitting sectors such as power, road transport, green hydrogen/ ammonia and food – could create a cascade of positive changes.

5 CONVENE A GLOBAL SUMMIT ON TIPPING POINTS

The UN Secretary General should convene a global summit on the governance agenda for managing Earth system tipping point risks and maximising coordination on triggering positive tipping point opportunities to speed up mitigation and resilience. It should provide a forum for government, industry and civil society. As a matter of urgency, tipping point threats should also feature on the agenda of key international fora, including the 2024 meeting of the G20 in Brazil.

6 DEEPEN KNOWLEDGE OF TIPPING POINTS AND ITS TRANSLATION INTO ACTION

The above efforts should be supported by investment in improved scientific knowledge and monitoring of negative and positive tipping points, and a much improved science-policy engagement process to more effectively and rapidly convert knowledge into action. To help stimulate this process, we support calls for an IPCC Special Report on Tipping Points in the current assessment cycle.

Section 1

Earth system tipping points

Current state of knowledge

A.1. More than 25 Earth system tipping points have been identified from evidence of past changes, observational records and computer models. (Chapters 1.2, 1.3, 1.4)

A.1.1. In the cryosphere, six Earth system tipping points are identified, including large-scale tipping points for the Greenland and Antarctic ice sheets. Localised tipping points likely exist for glaciers and permafrost thaw. Evidence for large-scale tipping dynamics in sea ice and permafrost is limited. (Chapter 1.2.2)

A.1.2. In the biosphere, 16 Earth system tipping points are identified, including forest dieback (e.g. in the Amazon), savanna and dryland degradation, lake eutrophication, die-off of coral reefs, mangroves, and seagrass meadows, and fishery collapse. (Chapter 1.3.2)

A.1.3. In ocean and atmosphere circulations, four Earth system tipping points are identified, in the Atlantic Meridional Overturning Circulation (AMOC), the North Atlantic Subpolar Gyre (SPG), the Southern Ocean Overturning Circulation and the West African monsoon. (Chapter 1.4.2)

A.2. Some Earth system tipping points are no longer high-impact, low-likelihood events, they are rapidly becoming high-impact, high-likelihood events. (Chapters 1.2, 1.3, 1.4)

A.2.1. Multiple drivers are destabilising tipping systems, including climate change for most as well as habitat loss (e.g. deforestation), nutrient pollution and air pollution for some. Multiple drivers, interactions and feedback loops can make tipping thresholds difficult to assess. (Chapters 1.2.2, 1.3.2, 1.4.2)

A.2.2. Already, at today's 1.2°C global warming, tipping of warm-water coral reefs is likely and we cannot rule out that four other systems may pass tipping points: the ice sheets of Greenland and West Antarctica, the North Atlantics Subpolar Gyre circulation, and parts of the permafrost subject to abrupt thaw. (Chapters 1.2.2, 1.3.2, 1.4.2)

A.2.3. Passing 1.5°C global warming, widespread mortality in warm-water coral reefs becomes very likely, and another three potential tipping systems start to become vulnerable: boreal forest, mangroves and seagrass meadows. (Chapter 1.3.2)

A.2.4. At 2°C global warming and beyond, several more systems could tip, including the Amazon rainforest and subglacial basins in East Antarctica, and irreversible collapse of the Greenland and West Antarctic ice sheets is likely to become locked in. (Chapters 1.2.2, 1.3.2)

A.2.5. Some systems can cross tipping points due to other drivers, or have their warming thresholds reduced by other human pressures, with for example Amazon dieback possible at lower warming if deforestation continues. (Chapters 1.3.2, 1.4.2)

A.3. Earth's tipping systems can interact in ways that destabilise one another, making tipping 'cascades' possible. (Chapter 1.5)

A.3.1. Tipping systems in the climate are closely coupled together. Hence a tipping point in one system can have significant implications for other systems. (Chapter 1.5.1)

A.3.2. Most interactions between climate tipping systems are destabilising, tending to destabilise the Earth system beyond the effects of climate change on individual systems. (Chapter 1.5.2)

A.3.3. Global warming is rapidly approaching levels that could trigger individual tipping points in systems that can interact with and destabilise other tipping systems. (Chapters 1.2.2, 1.3.2, 1.4.2, 1.5.2)

A.3.4. Tipping 'cascades', where tipping one system causes another tipping point to be passed, and so on, are possible but currently highly uncertain. (Chapters 1.5.3, 1.5.4)

A.4. Early warning signals have been detected that are consistent with the Greenland Ice Sheet, AMOC, and Amazon rainforest heading towards tipping points. (Chapter 1.6)

A.4.1. Loss of resilience (the ability to recover from perturbations) is expected before reaching a tipping point, but does not directly reveal how close a tipping point is. (Chapters 1.3.1, 1.6.1)

A.4.2. Loss of resilience can occur in systems without tipping points, hence independent evidence that a system is prone to tipping is needed before interpreting loss of resilience as a tipping point early warning signal. (Chapters 1.6.1, 1.6.3)

A.4.3. The central western Greenland ice sheet, AMOC, and Amazon rainforest all have independent evidence of being prone to tipping and show observational evidence of loss of resilience consistent with moving towards tipping points. (Chapter 1.6.2)

A.5. The risks of crossing Earth system tipping points can be minimised through rapidly reducing anthropogenic drivers of global change. (Chapters 1.2, 1.3, 1.4)

A.5.1. Urgently and ambitiously reducing greenhouse gas emissions can limit the risks of crossing tipping points in the cryosphere, biosphere, ocean and atmosphere circulation. (Chapters 1.2.2, 1.3.2, 1.4.2)

A.5.2. Rapidly reducing other climate forcing agents, such as black carbon for the cryosphere, and aerosols for the monsoons, can further limit the risk of crossing specific tipping points. (Chapters 1.2.2, 1.4.2.3)

A.5.3. The risk of crossing biosphere tipping points can be minimised through a combined approach of rapidly reducing climate forcing and other interacting drivers such as deforestation, habitat loss and pollution, together with ecological restoration, inclusive conservation, and supporting sustainable livelihoods. (Chapter 1.3.2)

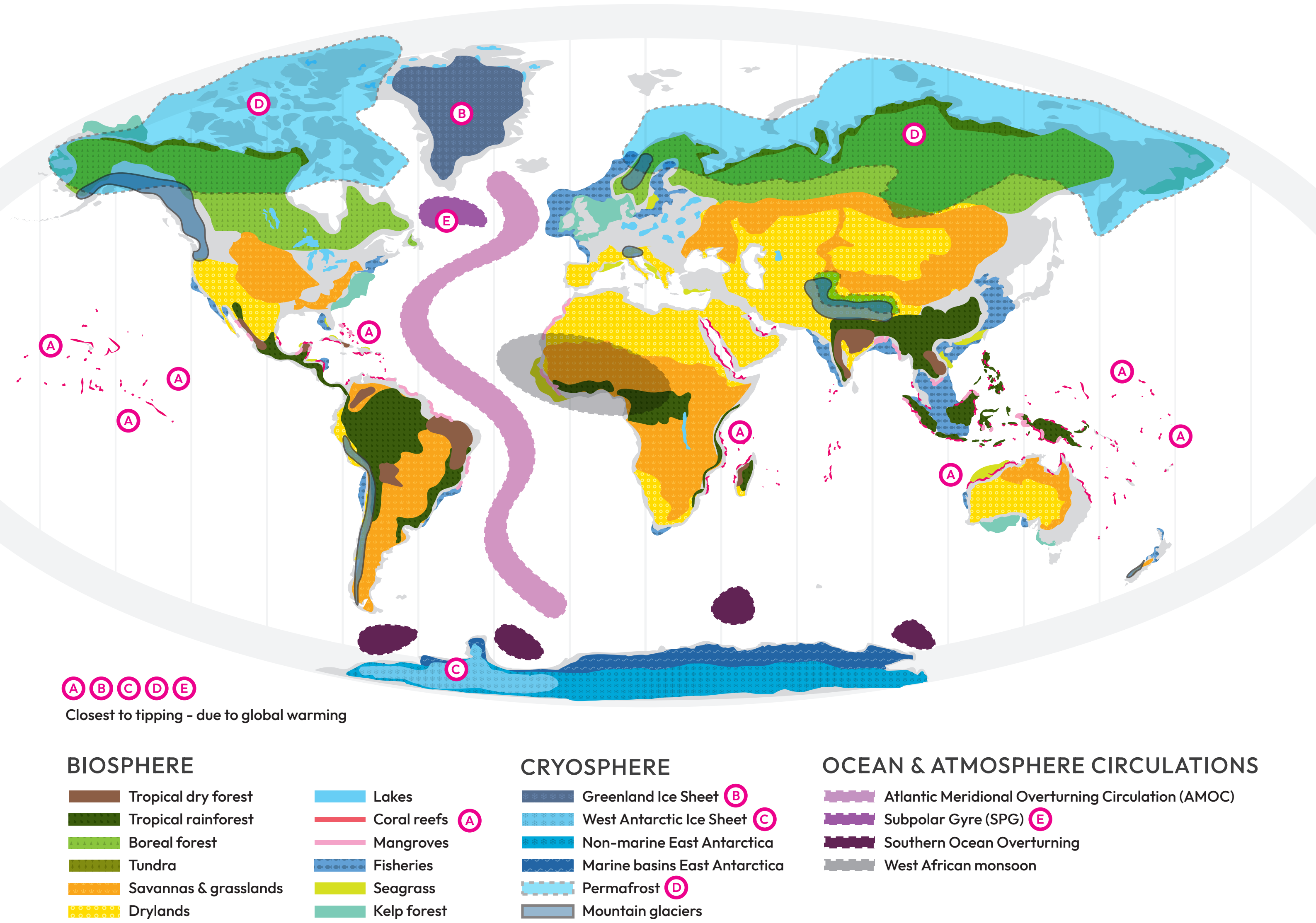


Figure 1: Parts of the Earth system identified in this report as featuring tipping points.

Priorities to advance knowledge

A.6. Deep uncertainties about Earth system tipping points can be reduced. (Chapters 1.2, 1.3, 1.4)

A.6.1. Short observational records and limited resolution of important feedback processes in models make assessing the existence and likelihood of tipping points difficult for many systems. (Chapters 1.2.2, 1.3.2, 1.4.2)

A.6.2. Key process uncertainties include: in the cryosphere, the potential for a marine ice cliff instability; in the biosphere, the complex interactions between ecohydrological and fire feedbacks; and in ocean and atmosphere circulation, the resolution of small-scale processes such as ocean mixing. (Chapters 1.2.2, 1.3.2, 1.4.2)

Recommendation:

A.6.3. Research funders, knowledge institutions and scientists should invest in reducing uncertainties surrounding the existence and likelihood of specific Earth system tipping points through targeted palaeo-data gathering, Earth observations, model development, knowledge sharing across disciplines, and a systematic model intercomparison project.

A.7. Assessment of Earth system tipping point interactions and possible cascades can be improved. (Chapter 1.5)

A.7.1. Earth system models can be improved to represent more tipping system interactions. Large ensembles of model runs can be used to detect less common but potentially important interactions. Direct causal interactions and indirect feedbacks – e.g. via changes in temperature – can be better quantified. (Chapter 1.5.5)

A.7.2. Palaeoclimate records of past abrupt changes can help identify and understand tipping point interactions and possible cascades. Methods of inferring causality can be applied to observational data to detect tipping system interactions. (Chapters 1.5.3, 1.5.5)

A.7.3. A fresh elicitation of expert knowledge could help identify potential tipping system interactions. (Chapter 1.5.5)

Recommendation:

A.7.4. Research funders, knowledge institutions and scientists should invest in improving assessment of tipping point interactions and possible cascades through the development and use of Earth system models, causal analysis of palaeoclimate and observation data, and expert elicitation.

A.8. Early warning of Earth system tipping points can be improved. (Chapter 1.6)

A.8.1. Model experiments can be designed and used to identify which observable variables and associated statistics are most promising to provide early warning signals of specific tipping points, and thus guide monitoring efforts. (Chapter 1.6.3)

A.8.2. Tipping point detection and early warning methods can be improved, with the application of machine learning showing promise. (Chapter 1.6.3)

A.8.3. For slow-tipping systems, such as ocean overturning circulations, investment in palaeo-data reconstructions can improve the potential to detect tipping point early warning signals. (Chapters 1.6.2, 1.6.3)

A.8.4. For fast-tipping systems, such as ecosystems, the reliability of early warning signals can be improved by reducing biases in satellite remote sensing data caused by missing data and by merging of data. (Chapter 1.6.3)

Recommendation:

A.8.5. Research funders, knowledge institutions and scientists should invest in improving early warning of Earth system tipping points through refining methods, use of models to guide monitoring efforts, palaeo-data gathering and improving remotely sensed datasets.

Section 2

Tipping point impacts

Current state of knowledge

B.1. Crossing Earth system tipping points would have severe impacts on people and biodiversity. (Chapter 2.2)

B.1.1. Amazon dieback, ice sheet collapse, permafrost thawing and collapse of the AMOC have the potential for severe impacts on water, food and energy security, health, ecosystem services, communities and economies. (Chapter 2.2)

B.1.2. Amazon dieback would be a catastrophe for biodiversity, would add to global and regional warming, could put 6 million people at direct risk from extreme heat stress and cause between US$1 trillion and US$3.5 trillion in economic damages. (Chapter 2.2.3.1)

B.1.3. Antarctic ice sheet instability leading to a potential sea level rise of two metres by 2100 would expose 480 million people to annual coastal flooding events. (Chapter 2.2.2.1)

B.1.4. Permafrost thawing would add significantly to global warming, it already damages property and infrastructure, and 70% of current infrastructure in permafrost regions is in areas with high potential for thaw by 2050. (Chapter 2.2.2.4)

B.1.5. An AMOC collapse could substantially reduce crop productivity across large areas of the world, with profound implications for food security. (Chapters 2.2.4.1, 2.2.6.2)

B.2. Negative social tipping points triggered by climate change and Earth system tipping could have catastrophic impacts on human societies. (Chapter 2.3)

B.2.1. Escalating Earth system destabilisation threatens to disrupt societal cohesion, increase mental disorders and amplify radicalisation and polarisation. It has the potential to escalate violent conflicts, mass displacement and financial instability. (Chapter 2.3)

B.2.2. Negative social tipping points would hamper collective mitigation efforts and capacities to respond effectively to Earth system destabilisation, thus impeding the realisation of positive futures. (Chapter 2.3)

B.2.3. If societies fail to re-stabilise the Earth system we will not stay in a business-as-usual state. Instead, negative social tipping will bring about another social system state, likely characterised by greater authoritarianism, hostility, discord and alienation. (Chapter 2.3).

B.3. Negative social tipping points could cascade to create systemic risk. (Chapter 2.4)

B.3.1. Although empirical evidence is currently scarce, extrapolating known feedbacks in complex human-natural systems suggests that tipping points in social and natural systems could plausibly cascade, with catastrophic risks for human wellbeing. (Chapter 2.4)

B.3.2. Less is known about cascades from Earth's tipping systems to socio-economic systems than those between Earth's tipping systems. This is due to limited experience, and time lags between crossing Earth system tipping points and the reaction of social systems. (Chapters 2.3, 2.4)

B.3.3. Research on tipping cascades in human systems thus far has focused on accelerating mitigation action, rather than preparing for potential consequences of physical climate risks. (Chapters 2.2, 2.3, 2.4)

B.4. Early warning signals can be used to anticipate impact tipping points. (Chapter 2.5)

B.4.1. Methods used to detect tipping points and loss of resilience in Earth's tipping systems (e.g. the Amazon rainforest) can be applied to anticipate tipping points in socio-economic impacts. (Chapter 2.5)

B.4.2. Recent applications of these methods have shown valuable early warning information of changes in food insecurity, and of land degradation in managed vegetation systems. (Chapter 2.5)

B.4.3. New datasets such as social media data and new technologies like deep learning have the potential to enhance the ability to anticipate tipping points in socio-economic impacts. (Chapter 2.5)

Priorities to advance knowledge

B.5. Improved assessments of the impacts of Earth system tipping points and negative social tipping points are urgently needed. (Chapters 2.2, 2.3)

B.5.1. There is uneven and incomplete assessment of the impacts of Earth system tipping points on people, social systems and ecosystems, with almost no work on understanding the vast range of potential human and social impacts. (Chapters 2.2, 2.3)

B.5.2. Existing assessments of the economic impacts of crossing Earth system tipping points often systematically underestimate the risks. (Chapters 2.2, 2.3)

B.5.3. Assessments need to go beyond economic damages to broader human, social and cultural impacts of crossing Earth system tipping points. (Chapters 2.2, 2.3)

Recommendations:

B.5.4. Research funders should invest in improving assessment of the impacts of Earth system tipping points, starting with systematic application of existing Earth system models and impact models to tipping point scenarios. (Chapter 2.2)

B.5.5. Research funders and knowledge institutions should foster interdisciplinary collaboration between natural and social scientists to improve assessment of the economic, social and cultural impacts of tipping points. (Chapters 2.2, 2.3)

B.6. Assessment of the interactions of impact tipping points and possible cascades can be improved. (Chapter 2.4)

B.6.1. Knowledge of negative social tipping points and their impacts needs to be coupled to knowledge of Earth system tipping points through the interdisciplinary consideration of potential causal chains of propagation of systemic risk. (Chapters 2.3, 2.4)

B.6.2. Focused research is needed on the mechanisms and consequences of tipping interactions, including identifying distinct feedbacks fuelled by policy, economic, financial and behavioural dynamics that can potentially lead to cascades. (Chapter 2.4)

B.6.3. Monitoring programmes are needed to systematically gather data about potential tipping point interactions over long periods of time, founded on research into which variables to monitor. (Chapter 2.4)

Recommendation:

B.6.4. Knowledge institutions and research funders should support coordinated, interdisciplinary research programms focused on building understanding of interactions between climate and social tipping points and their role in the emergence of systemic risk. (Chapter 2.4)

B.7. Improving capacity to anticipate negative tipping points can provide increased opportunity to pre-emptively adapt and reduce vulnerability to their impacts. (Chapter 2.5)

B.7.1. Existing knowledge of negative tipping points should serve as enough 'early warning' to motivate urgent action, but could be augmented by more formal early warning of specific Earth system tipping points (A.4) to aid impact management. (Chapter 2.5)

B.7.2. While there is considerable room for further development (A.8) it is timely for interdisciplinary research to consider how, where and when early warning systems for Earth system tipping points should be developed. (Chapter 2.5)

B.7.3. Further research is needed into early warning of negative tipping points in socio-economic systems (B.4), particularly to determine appropriate data sources, their relevant characteristics, and the types of statistics that can provide robust early warning information. (Chapter 2.5)

B.7.4. There is considerable potential for research on negative tipping points, and early warning thereof, to contribute to wider initiatives to accelerate systemic risk assessment. (Chapter 2.5)

Recommendation:

B.7.5. Knowledge institutions and research funders should invest in interdisciplinary early warning systems research to identify indicators and techniques that empower decision makers to anticipate tipping points and take preemptive, resilience-building actions. (Chapter 2.5)

Section 3

Governance of Earth system tipping points

C.1. Governance of Earth system tipping points is lacking. (Chapter 3.1)

C.1.1. Governance efforts need to cover multiple domains, including prevention and impact management, and carefully consider the diversity of tipping processes – each tipping system requires a distinct governance approach. (Chapter 3.1)

C.1.2. Governance of Earth system tipping points should be polycentric and networked, crossing multiple scales and institutions, including the scale of the tipping system. (Chapter 3.1)

C.1.3. Existing sustainability governance institutions across multiple scales, especially those related to the international climate change regime complex, should consider including Earth system tipping points in their mandates and action agendas. (Chapters 3.1, 3.2, 3.2)

C.1.4. Governance of Earth system tipping points should include redundancies to avoid governance failure, and be flexible/adaptive to enable rapid shifts in attention and resources towards emerging problems. (Chapter 3.1)

C.1.5. Short-term decisions have consequences on multiple time horizons (years to millennia) that require anticipatory governance and new risk assessment approaches for Earth system tipping points. (Chapter 3.1)

C.1.6. Actors and institutions across multiple scales and domains (state, industry, civil society) require long-term governance capacities, especially future thinking (anticipation/imagination), complex-systems thinking and long-term agency. (Chapter 3.1)

Recommendation:

C.1.7. Now is the time for governance actors, including UN bodies, international organisations, national governments and non-state actors, to engage in setting the agenda for the governance of Earth system tipping points. (Chapter 3.1)

C.2. Preventing the passing of Earth system tipping points should become the core goal and logic of a new and urgently needed governance framework to address the risks they pose. (Chapters 3.1, 3.2)

C.2.1. Given that Earth system tipping point risks are already moderate at current levels of warming and increase substantially above 1.5°C above pre-industrial levels, a short window for preventive action is open now and will close at different points in time for each tipping system – for some, potentially as early as the 2030s. (Chapter 3.2)

C.2.2. Preventing Earth system tipping requires addressing multiple drivers of tipping at different scales, especially rapidly strengthening current climate mitigation efforts to minimise temperature overshoot (both peak temperature and duration). (Chapter 3.2)

C.2.3. Speculative solar geoengineering approaches to preventing Earth system tipping points face deep ethical, technical and political uncertainties, and should not be considered technically available to use safely and swiftly at present.

Recommendations:

C.2.4. Countries need to rapidly and dramatically reduce greenhouse gas emissions, phasing out fossil fuels and bringing forward their decarbonisation timelines, to minimise the risk of crossing Earth system tipping points. (Chapter 3.2)

C.2.5. This must include reducing both long-lived – especially carbon dioxide (CO_2) – and short-lived – especially methane (CH_4) – greenhouse gas emissions to limit the magnitude and rate of warming, and to minimise peak temperature and the duration of overshooting 1.5°C. (Chapter 3.2)

C.2.6. Governments should ban commercial deployment of solar geoengineering, declare a moratorium on any other deployment, and develop a multilateral regime to regulate research and experimentation. (Chapter 3.2)

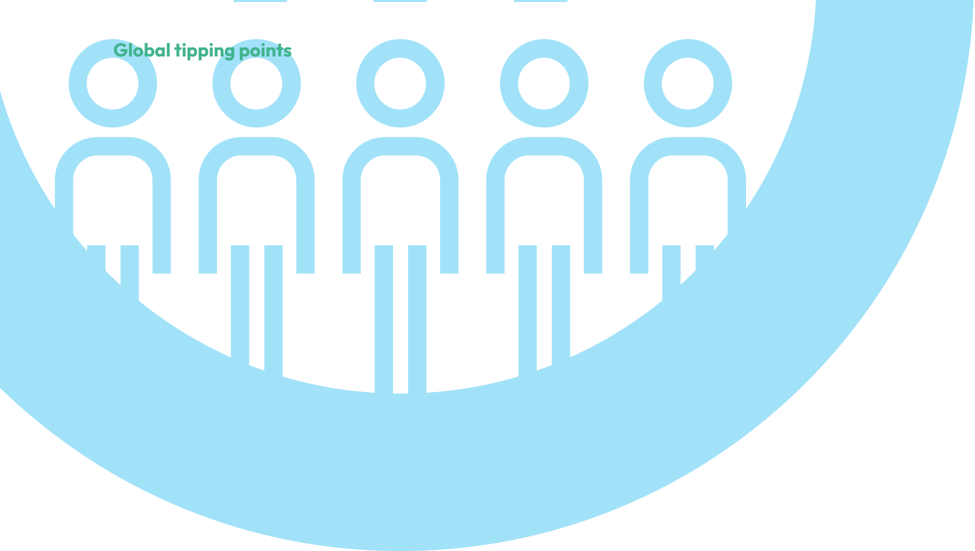
C.3. Managing the impacts of tipping points has diverse and immediate governance implications.

C.3.1. Governance of climate change adaptation needs to significantly expand anticipatory work and adopt a multi-temporal perspective tied to the dynamics of specific tipping systems. (Chapter 3.3)

C.3.2. The loss and damage framework needs rapid development, including consideration of the loss of entire biomes. (Chapter 3.3)

C.3.3. Vulnerability to tipping point impacts can be reduced by building resilience, fostering sustainable development and just transformations to sustainability. (Chapter 3.3)

C.3.4. In some locations, existing response mechanisms, including adaptation, could be overwhelmed by the impacts of Earth system tipping processes. Planned relocation in close collaboration with affected communities will become increasingly necessary. (Chapter 3.3)



C.4. There are relevant institutions and expertise that can contribute to governance of Earth system tipping points, but these need significant adjustments to be effective.

C.4.1. Mitigating climate tipping points should be addressed within the Paris Agreement framework, including considering tipping points in the interpretation of global goals and narrowing acceptable mitigation pathways to prevent tipping (i.e. minimising peak temperature and overshoot duration). (Chapter 3.2)

C.4.2. Carbon removal strategies need to be aligned with building resilience to tipping points and nature-based solutions need to be resilient to the passing of tipping points if that cannot be avoided. (Chapter 3.2)

C.4.3. Innovation is needed to address a lack of meaningful governance capacities at the scale of the tipping system – for example, the tropical coral reefs or major ocean currents. (Chapters 3.1, 3.2)

Recommendations:

C.4.4. Parties to the Paris Agreement should include Earth system tipping points in future Global Stocktake processes, assessing collective progress towards their prevention and impact governance. (Chapter 3.2)

C.4.5. Parties to the Paris Agreement should include a discussion of Earth system tipping points in future revisions of their Nationally Determined Contributions (NDCs) and mid-century decarbonisation strategies, including an assessment of how the country contributes to tipping point risks, how it will be affected by their impacts, and national measures and plans to prevent their transgression and to prepare for their impacts. (Chapter 3.2)

C.4.6. Parties to the Paris Agreement should initiate an evaluation of the adequacy of current mechanisms for addressing climate change impacts (e.g. adaptation, loss and damage, finance) in light of the specific risks posed by Earth system tipping points. (Chapter 3.3)

C.4.7. Countries within the geographic scope of a specific Earth system tipping element (e.g. all countries with tropical coral reefs, Amazon rainforest, or around the North Atlantic) should consider launching new initiatives for collective impact governance, including the development of knowledge and early warning systems specific to the tipping system, fostering adaptation, addressing potential losses and damages, and mutual learning/sharing of experience. (Chapters 3.1, 3.3)

C.5. Improved knowledge production and science-policy engagement processes are needed to support governance of Earth system tipping processes.

C.5.1. Scientific knowledge, especially regarding the temporal and spatial scales, of Earth system tipping processes must be translated into actionable, actor-relevant understanding, across scales and actor types, to support governance of Earth system tipping processes. (Chapter 3.4)

C.5.2. Existing international knowledge institutions need to be reformed to better support this kind of knowledge production. (Chapter 3.4)

C.5.3. Learning challenges specific to tipping points are significant and could slow down or impede effective governance and public engagement. (Chapter 3.4)

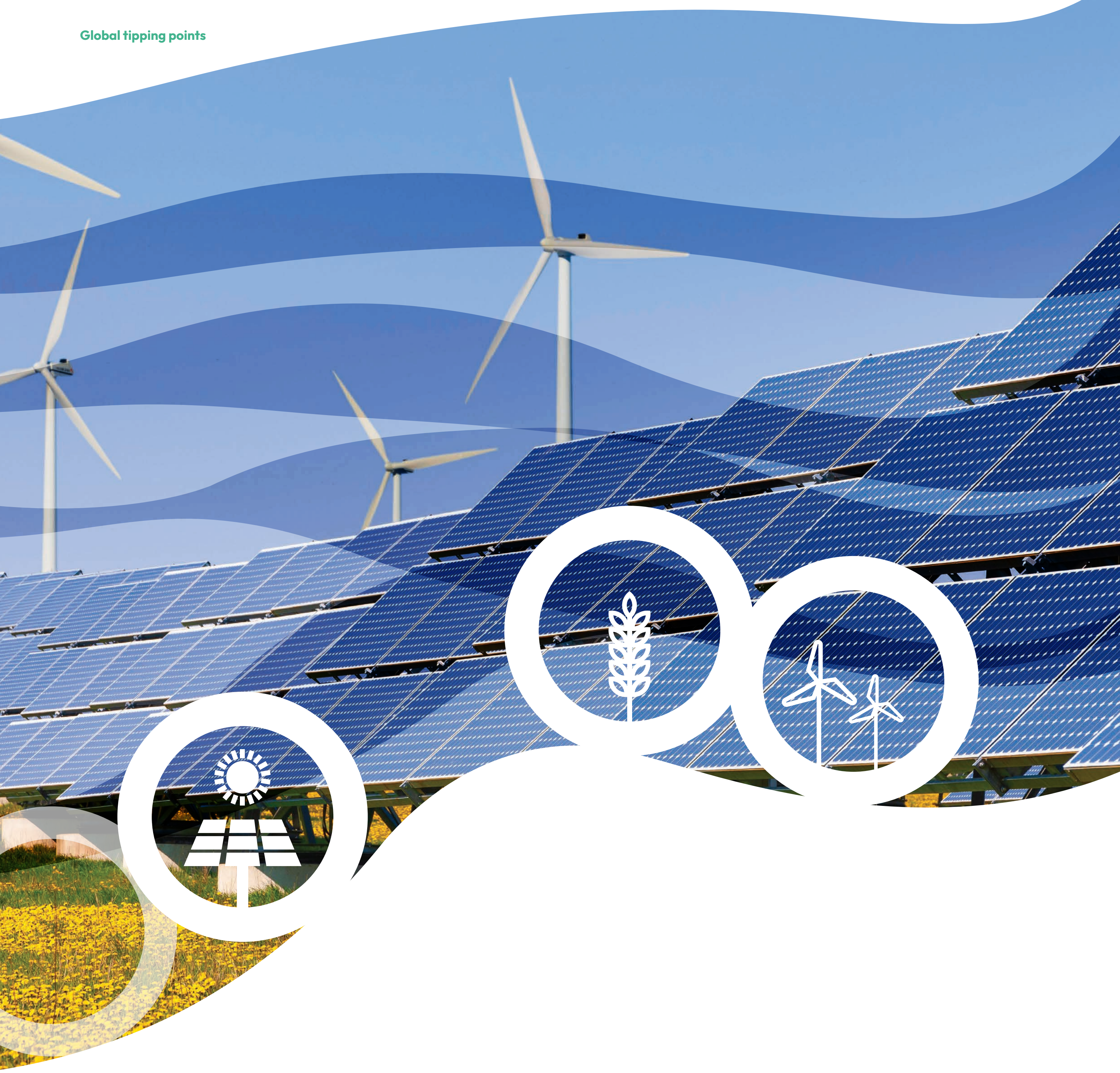
C.5.4. Currently, knowledge gaps are biggest in the social sciences and humanities. (Chapter 3.4)

C.5.5. Novel knowledge co-production processes that can engage scientists, policymakers and stakeholders in systems and future thinking are needed to foster anticipatory capacities. (Chapter 3.4)

Recommendations:

C.5.6. International organisations, national governments and science funders should foster urgent international research collaboration, especially in the social sciences and humanities, by promoting open, transdisciplinary and interdisciplinary, solutions-oriented, networked knowledge systems focusing on Earth system tipping points.

C.5.7. Regional and national science and knowledge institutions (e.g. national academies of science, EU foresight initiatives) and boundary organisations should foster anticipatory capacity building with participatory co-production processes involving policy-makers, scientists, other knowledge holders, artists, and designers.



Section 4

Positive tipping points in technology, economy and society

D.1. Positive tipping points offer the prospect that coordinated, strategic interventions can lead to disproportionately large and rapid beneficial results that mitigate existential climate risk and help redirect humanity along more sustainable pathways.

D.1.1. We are now so close to Earth system tipping points that positive tipping points to accelerate social change are the only realistic systemic risk governance option. (Chapter 4.2)

D.1.2. Positive tipping points don't just happen, they need to be actively enabled. Most positive tipping points require interventions – technological innovation, political and social action, behaviour/norm change, and financial investment – that create the enabling conditions and alter the balance of feedback for tipping to occur. (Chapter 4.2)

D.1.3. Changemakers could benefit from more diverse perspectives to open up the solution space, leveraging a shift in worldviews as well as reconfiguring systems, technologies, markets and materials. (Chapters 4.2, 4.3, 4.4, 4.6)

Recommendation:

D.1.4. Science funders and knowledge institutions should urgently foster a comprehensive, systematic and transdisciplinary programme of research and development of positive tipping points concepts, theory, methods and applications.

D.2. Positive tipping points provide new opportunities and challenges for decision makers. (Chapter 4.2)

D.2.1. Human systems are complex. Decision makers need reliable information and frameworks to assess the effects, opportunities and risks of interventions. (Chapter 4.2)

D.2.2. An avoid-shift-improve logic can be used in many sectors to decide which form of intervention is most effective. (Chapter 4.3)

D.2.3. High-emitting sectors need coordinated supply-side and demand-side approaches. There are key feedbacks between them that can lead to positive tipping points. (Chapter 4.3)

D.2.4. Small-group coalitions of state and non-state actors (e.g. cities) may be more effective in accelerating ambitious climate leadership than larger groups. (Chapter 4.4)

D.2.5. Rapid systemic change usually creates losers as well as winners. The required scale and speed of change will only be possible with sufficient public consent. (Chapter 4.6)

D.2.6. The public must be involved in relevant decision making and equipped with a clear understanding of the enormous opportunities (lives saved, improved health/wellbeing, better jobs, clean and cheap energy) as well as the risks of rapid change. (Chapter 4.4.2)

Recommendations:

D.2.7. National and regional policymakers need a systems-thinking approach and coordinated strategies across all sectors, departments and levels of government. Both supply-side and demand-side interventions are needed to maximise the potential of positive tipping points. (Chapters 4.2 and 4.3)

D.2.8. Countries and relevant non-state actors should form small-group coalitions (climate clubs) of shared interests that can enable positive tipping points. For example, a global tipping point for electric vehicles could be brought forward if China, EU and US introduce future bans on the sale of internal combustion engine vehicles. (Chapter 4.4.2)

D.2.9. Governments, cooperating with relevant industries and trade unions, must ensure that those who might otherwise be losers from positive tipping points – e.g. livestock farmers, workers in fossil-fuel industries, or exploited workers mining rare-earth metals for the new economy – are given the support needed for a just transition. (Chapter 4.6)

D.3. Positive tipping points are starting to occur in energy systems and can be brought forward by demand-side interventions. (Chapter 4.3.1)

D.3.1. The power sector in many countries recently passed a tipping point of cost parity for renewable power generation. Declining prices of renewable electricity below cost parity with fossil-fuelled power generation further reinforce exponential growth. Over 80% of new electricity generation in 2022 was solar and wind. (Chapter 4.3.1)

D 3.2. Affordable renewable electricity supply is driving tipping points across systems and technologies such as EVs and heat pumps. (Chapter 4.3.1)

D.3.3. Reducing energy demand by avoiding energy-intensive activities, shifting to less energy-intensive activities and improving energy service efficiency can accelerate decarbonising the energy system. (Chapter 4.3.1)

Recommendations:

D.3.4. Investors, policymakers and technology providers need to focus on clean energy technology development, the achievement of cost parity with 'sunset' technologies, and exponential diffusion worldwide, especially in emerging markets. (Chapter 4.3.1)

D.3.5. Policymakers need to introduce strong regulations, such as minimum efficiency levels for buildings and appliances, that incentivise demand reductions through the adoption of low-carbon technologies and behaviours. (Chapters 4.3.1, 4.3.2)

D.3.6. Policy to support both supply-side and demand-side reductions should be designed to support sustainable and durable changes. (Chapter 4.3.1)

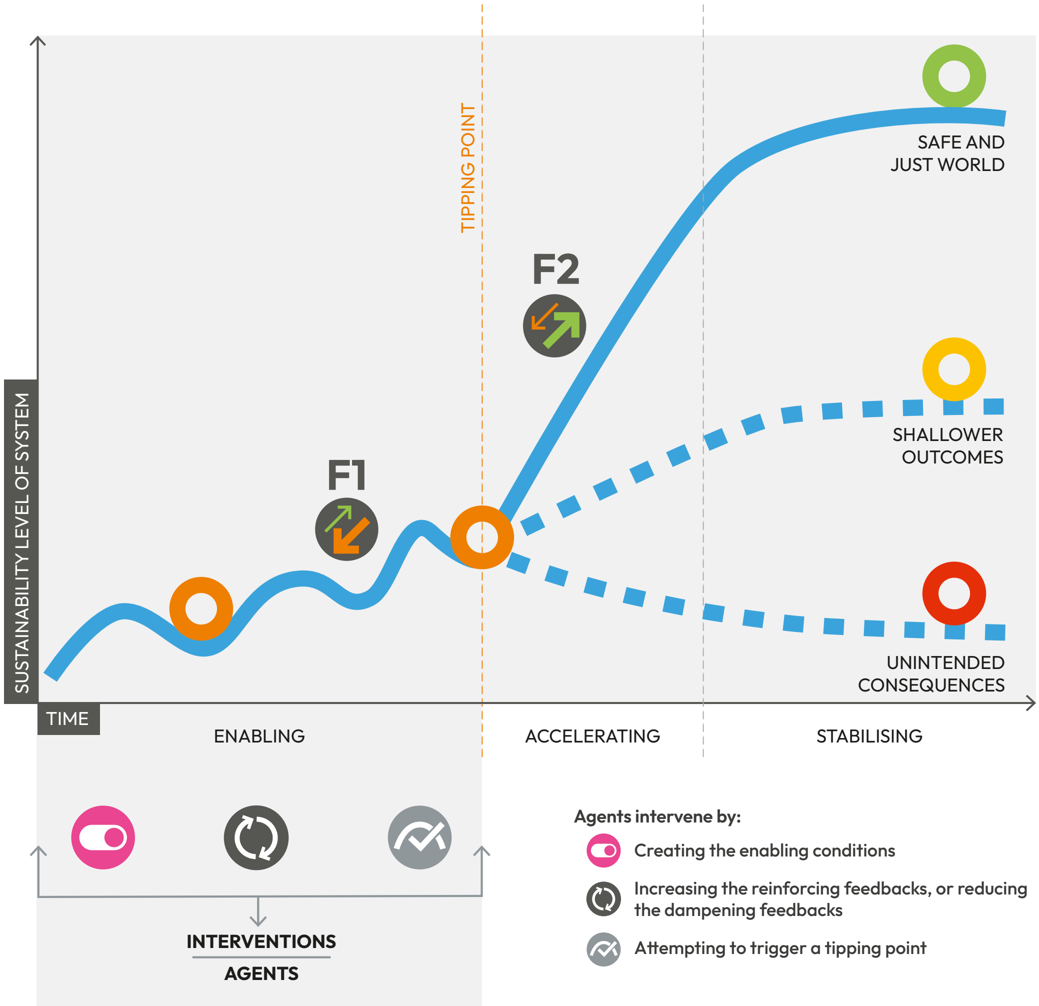


Figure 2. Visual summary of the concept of positive tipping points. The current state of the target system is unsustainable. The desired outcome is consistent with a safe and just world. The process of positive tipping typically entails three different phases of enabling, accelerating and stabilising. To encourage the desired outcome, agents can strategically intervene to leverage change during the enabling phase in three ways, by: 1) Creating the enabling conditions; 2) Increasing the amplifying feedbacks that increase instability/decreasing the dampening feedbacks that maintain stability; or 3) Attempting to trigger the positive tipping point. Once the tipping point has been crossed, the system enters an accelerating phase of nonlinear change dominated by amplifying feedbacks, then stabilises again in a qualitatively different state. The primary characteristic of a tipping point is a shift in the balance of feedbacks: at point F1, prior to the tipping point, dampening feedbacks are dominant and system stability is maintained; at point F2, beyond the tipping point, amplifying feedbacks are temporarily dominant and change accelerates exponentially. Other outcomes are also possible, including 'shallower', less sustainable outcomes, and unintended consequences.

D.4. Positive tipping points are starting to occur in electric vehicle markets which need to be complemented by systemic changes in transport and mobility systems. (Chapter 4.3.2)

D.4.1. Electric vehicles show evidence of passing or approaching tipping points in major markets including China and Europe. (Chapter 4.3.2)

D.4.2. There is an urgent need for tipping points in transport demand as freight and personal transport continue to increase with diverse negative impacts. (Chapter 4.3.2)

D.4.3. There are encouraging localised examples of tipping points in urban mobility, with a decrease in individual motorised transport and a shift to more active transport modes which can be upscaled. (Chapter 4.3.2)

Recommendations:

D.4.4. Policymakers need to prioritise integrated planning to enable tipping in transport, foremost regional planning for public transport and active travel infrastructure to avoid material-intensive individual mobility. (Chapter 4.3.2)

D.4.5. Policymakers need to steer the transition of the transport sector with tools such as zero emission vehicle mandates, which can induce EV tipping points across markets.

D.5. Positive tipping points have yet to occur at scale in food systems, but there are a range of interventions that can create enabling conditions. (Chapter 4.3.3)

D.5.1. Shifting to more plant-based diets, avoiding food loss and waste, and improving farming practice have synergistic benefits for meeting the Paris targets, biodiversity protection goals and Sustainable Development Goals. (Chapter 4.3.3)

D.5.2. Potential positive tipping points can be enabled in the uptake of alternatives to livestock products, spread of sustainable agriculture, and green ammonia production for fertiliser. (Chapter 4.3.3)

Recommendations:

D.5.3. Policymakers should focus on designing and sequencing policies strategically to incentivise production shifts away from livestock. Adaptive and deliberative governance can help ensure positive outcomes for potential 'losers' (e.g. livestock farmers). (Chapter 4.3.3)

D.5.4. Policymakers should enable diversified income opportunities for farmers, to make agroecological or sustainable landuse practices economically attractive (e.g. through carbon markets, agri-photovoltaics). (Chapter 4.3.3)

D.5.5. New emission-pricing (e.g. for methane and nitrogen), especially focused on large producers, could generate revenues to support most affected regions and low-income groups, foster innovation (e.g. via reducing VAT rates on plant-based food), and create additional income sources for farmers. (Chapter 4.3.3)

D.5.6. Policymakers, retailers and public cafeterias should use nudging and public procurement of more plant-based and sustainable food to accelerate the adoption of new sustainable, healthy diets. (Chapter 4.3.3)

D.5.7. Policymakers, investors, NGOs and food retailers should support innovation, health and sustainability transparency criteria, accessibility, and certification to facilitate market penetration of sustainable and healthy alternative proteins. (Chapter 4.3.3)

D.6. Social behaviour and politics can enable positive tipping in other key systems and can themselves be viewed as systems with tipping points. (Chapter 4.4)

D.6.1. Changes in social-behavioural systems often precede and fuel wider changes and can exhibit tipping dynamics through social contagion processes. (Chapter 4.4)

D.6.2. Elements of civil society, including social movements, tend to be at the vanguard of radical social change. However, to successfully disrupt and replace an incumbent regime, they also need to cultivate a broad coalition of public, business and political support. (Chapter 4.4)

D.6.3. 'Free social spaces' are places where social movements and other alternative communities of practice can gestate, experiment and build their networks, partly protected from more powerful mainstream influences. (Chapters 4.2, 4.4.1)

D.6.4. New social norms that could help transform society include anti-fossil fuel norms and sufficiency norms. However, replacing deeply entrenched norms around consumerism in favour of sustainable sufficiency would be challenging. (Chapter 4.4.1)

Recommendations:

D.6.5. Governments should pursue policies such as fossil-fuel phase-out and post-carbon infrastructure investment in ways that make the desired behaviours the most affordable and convenient options. (Chapter 4.4.1)

D.6.6. Policymakers should design policies to create increasing returns for shifts towards sustainable behaviours, compensate for losses, and ensure the autonomy and capacity of key actors. (Chapter 4.4.2)

D.7. The financial system can play a key role in enabling positive tipping points if it is appropriately regulated. (Chapter 4.4.3)

D.7.1. Policy interventions can enable transformative shifts within and beyond the financial sector, capitalising on nonlinear dynamics. (Chapter 4.4.3)

D.7.2. Public finance can mitigate market uncertainty and encourage private investment, helping to trigger positive tipping points (e.g. in offshore wind). Premature withdrawal of public finance (e.g. subsidies) can delay or jeopardise positive tipping points. (Chapter 4.4.3)

D.7.3. Promoting alignment of investors' expectations regarding the timing and pace of the transition can help to scale sustainable investment. (Chapter 4.4.3)

D.7.4. Policy mixes that combine command-and-control and market-based instruments can initiate virtuous cycles, driving technological development and reducing the overall need for public investment. (Chapter 4.4.3)

Recommendations:

D.7.5. Governments and development finance institutions need to provide support to overcome climate investment traps in developing countries by reducing capital costs and establishing an investment track record. (Chapter 4.4.3)

D.7.6. Governments and financial regulators should provide prudential regulation and financial supervision tools to facilitate a managed decline in fossil fuel lending, together with coordinated transition plans to enhance their collective impact on debt markets (e.g. through the Net Zero Banking Alliance). (Chapter 4.4.3)

D.8. Digital technologies can be key enablers of positive tipping across sectors if appropriately governed and supported. (Chapter 4.4.4)

D.8.1. Digital technologies are already enabling positive tipping points in renewable electricity and light road transport and will likely do so in other sectors. (Chapter 4.4.4)

D.8.2. The potential of digitalisation as an enabler of positive tipping points can be best realised in a public policy framework that prohibits or limits environmental degradation while promoting the purposeful use of digital technologies towards climate mitigation and sustainable development. (Chapter 4.4.4)

Recommendations:

D.8.3. Governments need to implement regulations to ensure the benefits of digitalisation are universal and not limited to specific groups. (Chapter 4.4.4)

D.8.4. Public sector actors need to invest in capacity building and the granting of access to appropriate digital hardware, software and infrastructure. (Chapter 4.4.4)

D.9. 'Early opportunity indicators' of positive tipping points could be used to maximise the leveraging effect of targeted interentions. (Chapter 4.4.5)

D.9.1. 'Early opportunity indicators' of approaching tipping points in electric vehicle markets have been detected in country-level data. (Chapter 4.4.5)

D.9.2. These generic indicators could provide early indication of opportunities for interventions to accelerate positive tipping points in other sectors and could be used to assess the impact of previous interventions. (Chapter 4.4.5)

Recommendation:

D.9.3. Research funders and investors should support efforts to develop early opportunity indicators of positive tipping points in other systems, including indicators that capture more than one domain of systemic change (e.g. market data and public attitudes).(Chapter 4.4.5)

D.10. 'Super-leverage points' can be identified with the potential to trigger positive tipping cascades. (Chapter 4.5)

D.10.1. Cascading effects involve multiple systems, for example when one sector drives down the cost of a shared technology or when the output from one sector provides a low-cost input to another.

D.10.2. Cascading effects can also occur within and between social, political and financial systems, potentially leading to rapid changes in social norms, values and policies. (Chapter 4.5)

Recommendation:

D.10.3. Government, business, finance and research sectors need to develop a coordinated, international, systems-thinking approach to super-leverage points and tipping cascades. For example, mandates for green ammonia for fertiliser manufacturing could trigger a tipping point in demand for hydrogen electrolysers, reducing the cost of green hydrogen and increasing the viability of green hydrogen-based solutions in other sectors, including steel and shipping. (Chapter 4.5)

D.11. The prevention of Earth system tipping points and the promotion of positive tipping points must ensure just and equitable outcomes. (Chapter 4.6)

D.11.1. Considerations of what needs to change, who is being asked to change, where the change and its impacts will be felt, and by whom, require reflexivity, inclusiveness and cooperation between all actors in all branches of society. (Chapter 4.6)

D.11.2. Supportive and inclusive financial investment is needed for equitable interventions. (Chapter 4.6)

Recommendations:

D.11.3. All sectors of society should increase pressure on governments to provide the resources and regulations needed for a just and equitable transition to a sustainable future. Consistency is key: conflicting standards and policy backtracking delay progress and investment. (Chapter 4.6)

D.11.4. All commentators, particularly media organisations, need to be aware of the politics of language and power dynamics in framing their content and key messages. (Chapter 4.6)

D.11.5. Researchers and practitioners need to engage with diversity and employ inclusive approaches from the earliest stages of project design. (Chapter 4.6)

D.11.6. Public engagement and education on the opportunities, risks and ethical complexities of a just transition must be at the heart of an international climate action plan. (Chapter 4.6)

Introduction

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Why we need to talk about tipping points

The 21st century has already witnessed extraordinary, abrupt and potentially irreversible changes in the world around us. With global warming now at around 1.2°C above the pre-industrial level, massive coral reef die-off events are occurring, the Amazon rainforest is suffering droughts, large regions of permafrost are thawing, and part of the West Antarctic Ice Sheet may be irreversibly retreating, to name but a few of the tumultuous changes happening in the Earth system.

In the last decade, climate impacts have escalated, harming the economy and resulting in insurance being withdrawn from some of the most vulnerable communities. The global financial crisis of 2007-2008 and ensuing Great Recession have shown us how fragile the economy can be, and the COVID-19 pandemic gave us all a profound lesson in abrupt, cascading change. At the same time, we have started to see evidence of accelerating social and technological change towards sustainability, including numerous political declarations of a 'climate emergency' and exponential growth of renewable energy deployment.

All of this experience challenges a worldview that many of us were brought up with – to see the world like a machine. The world is not behaving in a linear fashion. Instead, our expectations of smooth, predictable and reversible changes are being confronted with a reality of abrupt, unexpected and irreversible ones. We wrote this report during 2023 against a backdrop of unprecedented climate extremes, including severe heat waves across much of Asia, massive loss of Antarctic sea ice, and Canadian forest fires way off the scale of even recent experience.

The pace and scale of these events has attracted use of the term 'tipping points' – originally popularised by Malcolm Gladwell – which describes the phenomenon that occurs when a small change makes a big difference to a system. Tipping points in the Earth system are arguably the biggest risk we face in a changing world, because they can lead to profound damages that are abrupt or irreversible – or both.

The level of global warming that could trigger known climate tipping points is uncertain; there is little assessment of tipping point impacts and even less consideration of who or what is most vulnerable to those impacts. Yet we know enough to argue that any credible climate change risk assessment must consider the risks from climate tipping points – as they could profoundly affect the economy and societies.

> **For too long, the climate change assessment process has tended to focus on the most likely outcome, rather than evaluating the highest-risk outcomes. But this is poor risk assessment and it is leaving society ill equipped for what lies ahead.**

Furthermore, while climate tipping points are often portrayed as 'high-impact, low-likelihood events', some are rapidly becoming 'high-impact, high-likelihood events'.

The risks from anthropogenically triggered Earth system tipping points, and our perception of them, may in turn influence tipping points in human systems. These 'social tipping points' can take many forms – from the escalation of wars to the sudden uptake of new technologies. The global financial crisis and the COVID-19 pandemic demonstrated how undesirable impacts can cascade through our networked world. But this potential also exists for desirable impacts. The same feedback principles underlie both undesirable tipping points in the Earth system and those in human systems, both desirable and undesirable.

As experience starts to show how risks can cascade between the different realms of climate, ecology and human society, there is a growing sense that we are in a 'polycrisis'. But experience has barely scratched the surface of what could occur as the impacts of global change – especially climate change – accelerate and accumulate. Hence, there is an urgent need to assess how Earth system tipping points can impact human systems, especially whether and how they could trigger undesirable social tipping points. This is essential information to enable mitigation of the worst impacts and to build resilience to impacts that cannot be avoided.

Growing recognition and knowledge of tipping point risks in turn begs the question of how best to govern those risks. Can our current institutions and processes deal with tipping point risks? Or do the unusual qualities of tipping points (abruptness, irreversibility, unpredictability, and having large but unevenly distributed impacts) demand new governance approaches?

Against this backdrop of profound risks, the opportunities for creating and enabling 'positive tipping points' to accelerate action to tackle climate change, biodiversity loss and other sustainability challenges are just starting to be widely recognised. They may offer the most credible way of achieving the acceleration of action that is required – by leveraging strongly reinforcing feedback processes that are self-propelling.

When presented with such complexity and tumultuous change, we cannot continue looking at the world in an outdated way. We need an effective and comprehensive risk assessment of 'negative' tipping points; we need an opportunity analysis of realised and potential 'positive' tipping points; and we need to consider how to navigate both, in a just way, in the face of uncertainty. The experience of the author team tells us many people are hungry for this knowledge.

Who this report is for

This report is for all those concerned with tackling escalating Earth system change and mobilising transformative social change to alter that trajectory, achieve sustainability and promote social justice.

Our primary audience is decision makers, including policymakers and leaders in the public, private and voluntary sectors. Governance has a particular social position and collective responsibility to lead in the protection of public goods and the effective distribution of public money. Leaders in other sectors can play an equally vital role in creating (or inhibiting) transformative change through the mobilisation of human capital and private finance. Those in the media can choose to amplify (or not) key risk and opportunity information. But we also want to reach a broad audience. As citizens, all of us can contribute to transformative social change, and we can also seek to influence those who are more powerful than us.

The authors and origins of this report

A total of 200 researchers have contributed to this report, which was initiated alongside an international meeting on 'Tipping Points: from climate crisis to positive transformation' at the University of Exeter, UK, in September 2022. The meeting and associated recent research on tipping points attracted widespread interest and media attention. The meeting also served to crystallise a community of tipping point researchers – making it clear that there was both a niche to fill with this report, and a community ready to fill it. A core writing team was formed, from the University of Exeter and international partners, and an open call was made for researchers to contribute their expertise to the report and a corresponding special issue of the open-access journal *Earth System Dynamics* on 'Tipping Points in the Anthropocene'. Consequently, most of the research content of this report has undergone, or is undergoing, peer review.

Aims of this report

Our overarching aim is to provide a first-ever comprehensive (but not exhaustive) assessment of currently recognised tipping points in the Earth system and in human systems that are relevant to urgent contemporary global change – especially climate change and biodiversity loss – and associated transformative social change.

The report aims to help improve climate risk assessment by comprehensively assessing the risks from Earth system tipping points. It considers the systemic risks of how Earth system tipping points can impact human systems, especially whether and how they could trigger undesirable social tipping points. Then it aims to assess how to govern the risks from Earth system tipping points. It further aims to synthesise knowledge of positive tipping points and their potential to accelerate transformative social change, as well as explain how to govern these opportunities (and their associated risks), building in part on our previous 'Breakthrough Effect' report with SYSTEMIQ (Meldrum et al., 2023).

This report as a whole is intended to provide a foundation for future regular updates on the status of tipping points in the Earth system and in human systems. At the time of writing, there is a shortage of assessment of these, particularly at the level of synthesis across the climate, ecological and social realms. There is a proposal under consideration for an IPCC Special Report on Tipping Points, which we support. That would have a different style and emphasis and would be subject to inter-governmental approval. We trust that this report would provide a useful stepping stone.

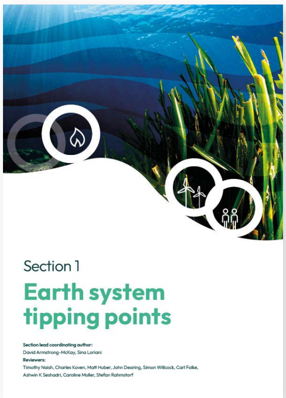
Scope

The report's title conveys that we are concerned with tipping points associated with global change and ones whose consequences are (or have the potential to be) of global interest or concern. It does not imply that the tipping mechanisms are global in scale, although this possibility is assessed within the report. Some tipping points have global consequences; others with (potentially) global implications start out on a much smaller scale and warrant our consideration. There are many smaller-scale tipping points that are important in a regional and/or cultural context but may not be (or ever become) of global interest. The dividing line of inclusion is necessarily imprecise. We include some case studies of fairly localised tipping points with what we assess to be considerable potential to spread. We expect that with further research such selections will change.

Style and structure

The report tackles diverse subject matter and complex concepts, and marshalls myriad data. It is drawn from an extensive and growing body of academic research, but is written for a non-academic audience. Hence we have worked hard to ensure it is comprehensible.

To this end, it adopts a layered structure. After this introductory section there are four major sections. Each begins with an introduction to and synthesis of its subject matter, drawing out key messages and recommendations. Each section is divided into chapters and each chapter delves into greater detail on key target systems or issues, as well as containing a summary of key messages and recommendations.

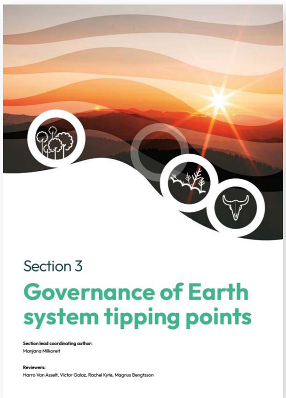


Section 1

considers Earth system tipping points. These are reviewed and assessed across the three major domains of the cryosphere, biosphere and circulation of the oceans and atmosphere. We then consider the interactions and potential cascades of Earth system tipping points, followed by an assessment of early warning signals for Earth system tipping points.

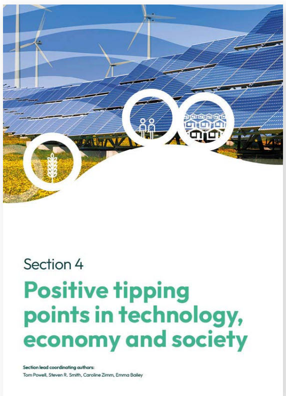
Section 2

considers tipping point impacts. First we look at the human impacts of Earth system tipping points, then the potential couplings to negative tipping points in human systems. Next we assess the potential for cascading and compounding systemic risk, before considering the potential for early warning of impact tipping points.



Section 3

considers how to govern Earth system tipping points and their associated risks. We look at governance of mitigation, prevention and stabilisation then we focus on governance of impacts, including adaptation, vulnerability and loss and damage. Finally, we assess the need for knowledge generation at the science-policy interface.



Section 4

focuses on positive tipping points in technology, the economy and society. We highlight case studies across energy, food, and transport/mobility systems, with a focus on demand-side solutions, then look at the cross-cutting enabling roles of political, financial and social-behavioural systems, digitalisation and early opportunity indicators. We also identify potential positive tipping cascades and consider risks, equity and justice in the governance of positive tipping points

The report broadly proceeds from tipping point risks to opportunities. It starts in the biophysical science realm of tipping points in the Earth system, zooms into the social science of undesirable tipping points in social systems, considers the governance of Earth system tipping points, then shifts to considering positive tipping points in social systems and their governance.

Before launching in, we define the key concepts and terms related to tipping points that are used throughout this report. We also outline in a little more depth some key aspects of our approach, including some key risk, equity and justice considerations across both negative and positive tipping points.

Key concepts

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The academic literature is full of terminology related to tipping points. Here we try to explain what the key terms mean. A separate glossary of the terms in bold is included as an appendix.

What is a tipping point?

Figure 1: Forcing a system past a tipping point. The system starts (blue) in one of two alternative stable states, represented by the ball in the left hand valley. Under external forcing over time (left to right) this state loses stability (purple), represented by the valley getting shallower, lowering the hilltop. Past a tipping point the initial stable state disappears and the system undergoes an abrupt, self-propelling change into the alternative, remaining stable state (red). Watch a movie of tipping here.

In everyday usage, a tipping point is where a small change makes a big difference to a system (Gladwell, 2000) (*Figure 1*) or "the point at which a series of small changes or incidents becomes significant enough to cause a larger, more important change" (Oxford English Dictionary). Here a system is any group of interacting or interrelated things that act according to a shared set of rules to form a recognisable, unified whole – for example, an ice sheet, or an economy. A tipping point is a type of threshold. The small change that causes a system to pass a tipping point can be described as a trigger. The resulting large change can be described as a qualitative change in what a system looks like or how it functions – for example from a Greenland Ice Sheet to a largely ice-free 'green' Greenland, or from an economy powered by fossil fuels to one powered by renewable energy. The change associated with passing a tipping point also commonly includes qualities of: abruptness (change is rapid relative to the drivers forcing it); self-perpetuation (change will continue even if the forcing is removed, until a new state is reached); and irreversibility (change is difficult or impossible to reverse) (Milkoreit et al., 2018).

Here we define a **tipping point** 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 (inspired by Armstrong McKay et al., 2022 and Milkoreit et al., 2018). This definition includes the possibilities of non-abrupt and reversible tipping points.

A **tipping system** is any system that can pass a tipping point. The term **tipping element** was originally introduced to describe large parts (subsystems) of the **climate system** (greater than ~1,000km-length scale) that could pass a tipping point (Lenton et al., 2008). Some other disciplines have started to use 'tipping element' more broadly to describe those parts or subsystems of a larger system that can undergo tipping point dynamics (e.g. Otto et al., 2020). When used in other contexts a qualifier such as 'social' tipping element (Otto et al., 2020) is important to avoid confusion.

Two other terms are widely used in the academic literature often interchangeably with tipping points, and with each other (Dakos, 2019): **Regime shift** describes an abrupt and/or persistent shift in the current state of an ecosystem from one stable state to another (Biggs et al., 2009; Maciejewski et al., 2019) and **critical transition** describes an abrupt shift in a system that occurs at a specific (critical) threshold in external conditions (Scheffer, 2009). Thus both describe the change that may be *associated* with a tipping point, but not the tipping point itself. In this report, we use **tipping event** to describe the crossing of a tipping point and **tipping dynamics** to describe the resulting changes that unfold. (Where regime shift or critical transition are used, we define them on a case-by-case basis.)

Sources of tipping point behaviour

The qualities of tipping points described above can come about because of several generic characteristics of the systems in which they occur, and the forces they are subject to.

A **feedback mechanism** (or feedback loop) is a closed loop of causality whereby a change in a system feeds back to amplify or dampen that change. Feedback mechanisms can be mathematically positive or negative, depending on whether they amplify or dampen the effects of a change. An example of amplifying/reinforcing **positive feedback** is when warming in the Arctic causes sea-ice to melt, exposing a much darker ocean surface that absorbs more sunlight, amplifying the warming. An example of damping/balancing **negative feedback** is when demand for specific goods in the economy exceeds supply, prices rise and this suppresses demand.

Tipping can occur when amplifying/reinforcing (positive) feedback mechanisms overwhelm damping/balancing (negative) ones and get strong enough to support self-perpetuating change. For example, when one person infected with COVID-19 can infect four others, who can infect 16, and so on, the spread of infection is self-perpetuating. Only a (small) subset of all amplifying (positive) feedback loops can get strong enough to support self-perpetuating change. Also, self-perpetuating change is transient – it cannot continue indefinitely because at some point it will reach a limit. In the spread of an epidemic or pandemic that limit can be when the majority of the population has become infected.

Systems typically exhibit at least one **stable state** or **attractor** that the system will return to from a set of initial conditions. The quality of 'attraction' or dynamical stability exists because of a predominance of damping (negative) feedback that resists change. For example, if you push back just a little bit on a chair, the resulting change in the balance of forces acts to bring you back upright. This is an example of perturbing the system away from a stable state. It will tend to return to that state – at least for some range of sizes of perturbation. But if you push back too far on a chair you may find yourself rapidly transitioning into an alternative stable state – sprawled on your back on the floor.

This is an example of **bi-stability** – you and the chair are a system with two alternative stable states. In between there is a balance point, which is an unstable state, because a small nudge either way will send you back upright or on to the floor. There also exist systems with **multi-stability** (more than two alternative stable states). For a system with alternative stable states, there are three main ways that a tipping point can occur (Figure 2).

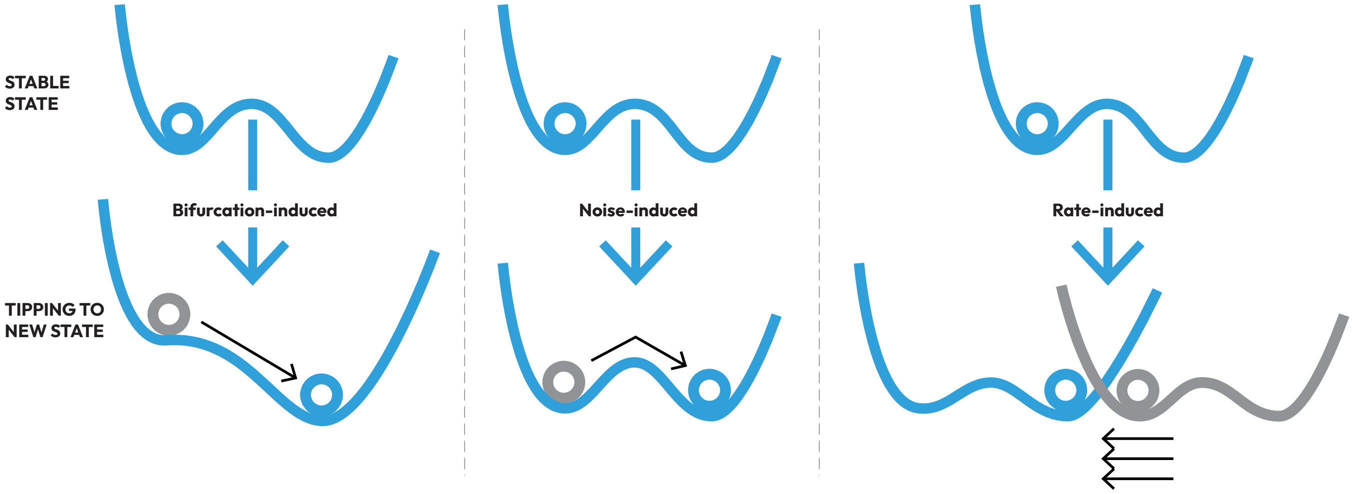

Figure 2: Three types of tipping point. Schematic representations of: (left) bifurcation-induced tipping (Figure 1); (middle) noise-induced tipping, and; (right) rate-induced tipping.

Sometimes when a system is forced by changing external 'boundary' conditions – such as global warming of an ice sheet – the state that it is in can lose stability. It may reach a **bifurcation point** where the current stable state disappears and the system moves to another (stable) state or attractor, with a corresponding qualitative change in behaviour. Such shifts can be smooth – such as when a previously stable system begins to oscillate. Or the system may undergo a **catastrophic bifurcation** where it moves discontinuously to a different state/attractor. This is the most widely discussed type of tipping point in the literature and is referred to as **bifurcation tipping** (Figure 2, left). An example is the loss of the Greenland Ice Sheet – as the surface melts it declines in altitude, putting it in warmer air and causing further melt. A bifurcation tipping point can be reached where this reinforcing feedback becomes self-propelling – meaning smaller sizes of the ice sheet are not stable, and the ice sheet is committed to irreversibly shrinking to a much smaller size, or disappearing altogether.

When a system has alternative stable states (attractors) it can exhibit **hysteresis**, meaning the state the system is in depends on its history (Figure 3). When forced in one direction, the system may pass a tipping point from one stable state (attractor) to another, but when the forcing is reversed to the same level it may remain in the other state (attractor), and further reduction in forcing is needed until a different tipping point is reached. Such hysteresis is a key source of irreversibility when crossing a tipping point. For example, while the Greenland Ice Sheet requires some global warming to be tipped into irreversible loss, if the ice sheet is lost it will not regrow at the same temperature level, nor at the preindustrial temperature level– instead it would require global cooling. Hysteresis is an example of **path dependence**, where past events constrain future events. The existence of the Greenland Ice Sheet today is a legacy of the last ice age. In such cases, to predict future changes it is important to know a system's history.

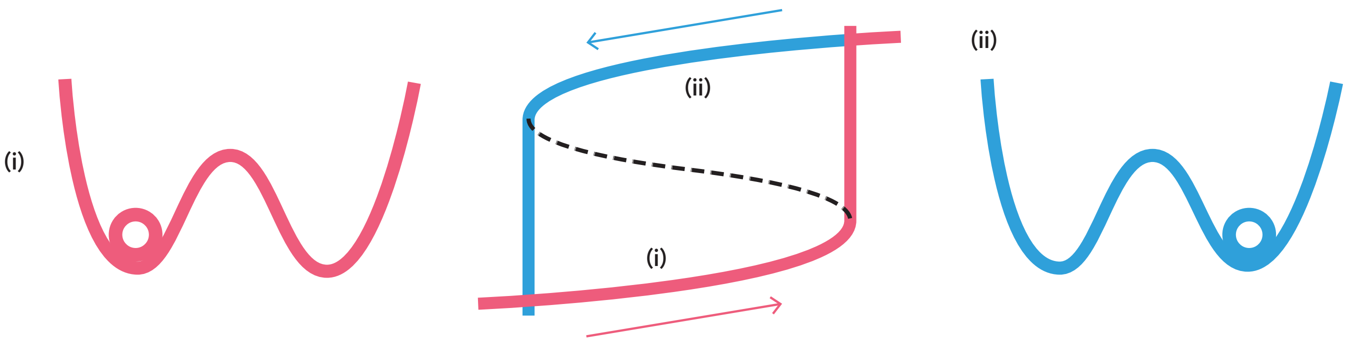

Figure 3: A simple representation of hysteresis. A system starts in one of two alternative stable states (red) at position (i). Forcing the system in one direction (red arrow from left to right) causes it to pass a tipping point into the other stable state (blue). Then when the forcing is reversed (blue arrow from right to left), there is a path dependence: The system remains in the alternative stable state, passing through position (ii). An alternative tipping point has to be passed to tip the system back into the original stable state.

In a system with alternative stable states (attractors), where the current state has lost some of its stability (but a bifurcation point has not been reached), it can be vulnerable to small perturbations termed **noise** (i.e. stochastic variability). A nudge in the wrong direction can be enough to tip the system out of its present state, past the unstable state into an alternative state. This phenomenon is called **noise-induced tipping** (Figure 2, middle). In reality where a system is subject to both noise and steady forcing towards a bifurcation point, the tipping out of the initial state usually happens due to noise before the bifurcation point. In the climate system, the weather can be thought of as noise (short-term internal variability). In the Greenland Ice Sheet example, a summer heatwave may melt enough of the ice sheet to take it past the tipping point, whereas without that heatwave the tipping point would not have been crossed.

Sometimes a small change in the rate at which a system is forced can produce a large change in outcome. Forcing a system rapidly may bring it towards an unstable state because the system's damping feedbacks are not acting fast enough to counter the forcing. Then just a small further increase in the rate of forcing may be enough to cause the system to tip. Whereas slower forcing to the same level would not cause it to tip. This is referred to as **rate-induced tipping** (Figure 0.2, right). An example in a human system are some power grid blackouts (Ritchie et al., 2023): Power grid controllers act as a damping feedback in the system trying to increase electricity supply (by switching on power stations) to match increases in demand. However, if demand for electricity rises faster than they expect, this can lead to a blackout.

A further important source of tipping can be a **cascade effect** (or domino effect or chain reaction). This is a causal chain whereby a small change in a subsystem causes a further change to another subsystem, and a further one, and so on, resulting in a large overall change to a wider system. For example, the extermination of wolves from Yellowstone National Park triggered a cascade that changed the whole ecosystem, and reintroducing wolves tipped the system back through another cascade. Within one species, cascading change can spread through networked populations of (human or non-human) **agents** through the process of **contagion,** whereby information or behaviour is passed from one agent to another. Simple contagion only requires contact with one other agent for adoption of new information or behaviour to occur. Complex contagion depends on contact with multiple agents before adoption occurs. Equally, when adding nodes or links to a network, a point can be reached where **percolation** occurs and a previously disconnected network becomes globally connected, allowing change to spread abruptly throughout.

Focal types of system and tipping point

Many types of systems can exhibit tipping points. This report focuses on a subset of types of systems, relevant to global change, in which tipping points can occur.

The systems we consider are all **complex systems** consisting of a large number of interconnected components that interact with each other, often giving rise to feedback loops, nonlinearity, and **emergent properties** (which cannot be reduced to the properties of the component parts). Some of the systems we consider are **complex adaptive systems** characterised by the ability to change in response to changing (internal or external) conditions in a way that maintains or enhances their function. They are typically composed of interacting heterogeneous **agents**, which may be humans or other organisms, with their own behaviours, preferences and decision-making processes.

The **Earth system** is 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) (Lenton, 2016). The **climate system** is the parts of the Earth system that govern the **climate** at the surface of the Earth. Referring to the climate system rather than the Earth system tends to involve a shift in emphasis towards shorter timescales and those subsystems most affecting climate (e.g. the atmosphere and oceans).

A **climate tipping point** occurs when change in part of the climate system becomes self-perpetuating beyond a threshold, leading to substantial and widespread Earth system impacts. For example, the irreversible loss of the Greenland Ice Sheet would ultimately lead to around seven metres of global sea-level rise. The climate tipping points we are particularly interested in here are ones that occur beyond a particular threshold level of global warming. **Earth system tipping points** include climate tipping points and other cases of large-scale self-perpetuating change beyond a threshold involving non-climate variables – for example, tipping points into or out of oceanic anoxic events in Earth's past.

Ecosystems are complex, sometimes adaptive systems composed of living organisms (ecological agents) coupled to their physical and chemical environment in a particular spatial (geographic) area. Ecosystems are smaller in spatial scale than the whole biosphere, which is sometimes referred to as the 'global ecosystem'.

An **ecological tipping point** occurs when change in a biological population, community, or ecosystem becomes self-perpetuating beyond a threshold. For example, when increased fires or grazing trigger a tropical woodland to tip into a savanna. Changes resulting from tipping points in ecosystems are also often referred to as regime shifts, or sometimes as critical transitions. They can be triggered by both natural and human-induced disturbances, such as habitat loss, species invasions, pollution and climate change.

Social systems are complex, often adaptive, collective **human systems**, which have rich dynamics (Parsons, 2010) and operate within an ecological and Earth system context (Otto et al., 2020; Eker and Wilson, 2022; Winkelmann et al., 2022). Social systems are composed of massively entangled formal and informal organisations and networks. They may be an interconnected web of hierarchical, bureaucratic organisations or networks of small formal and informal groups, communities or family systems, all of which have their own institutions and/or norms. In common language, 'system change' refers to changing social systems.

Social systems, like physical and ecological systems, can have stable states (attractors) that resist change; they can exhibit path dependency and hysteresis; they can undergo **non-linear** change with positive feedback; and they can cross **social tipping points** into new stable states, over various timescales. For example, in the **diffusion of innovation** whereby new ideas, products or services spread through social systems over time, there can be **critical mass** tipping points where, for example, one more person adopting a behaviour or technology causes everybody else to adopt. Similar dynamics can underlie tipping points into escalating political protests, riots, or revolutions. Communities may also tip into a state of **anomie** characterised by a breakdown of social norms, social ties and social reality.

Humans have greater **agency** and ability to learn than other species, and a growing collective awareness of their impacts on the larger systems of which they are a part. This gives us humans greater potential to alter the fate of those larger systems than is the case for other species.

Different types of social systems can be identified. A **socio-behavioural system** encompasses social norms, behaviours and lifestyles, communities and their cultures, and institutions. A **social-ecological system** includes interacting social and ecological components which together shape the behaviour and functioning of the system. For example, fisheries include both the aquatic ecosystems, and the people who live in, depend on, and shape these systems. A **socio-technical system** (or social-technological system) comprises interacting social and technological components often with a common goal (or goals). Examples include transportation networks, energy systems, and healthcare systems. They are often designed to meet societal needs, but they also shape and are shaped by social norms, values and practices. A **social-ecological-technological system** comprises interacting social, ecological and technological components – for example, food systems.

Corresponding types of tipping point can be identified. A **social-ecological tipping point** is one that arises because of the coupling of the social and ecological components (and is not present in either of them independently). A **socio-technical tipping point** is one that arises because of the coupling of social and technological components (and is not present in either of them independently). A **social-ecological-technological tipping point** is one that arises because of the coupling of social, ecological and technological components. For example, the 'Green Revolution' in agriculture in the 1960s and 1970s that led to a reduction in poverty through greater crop yields from genetic selection and the use of fertilisers.

A **tipping cascade** occurs when passing one tipping point triggers at least one other tipping point. It can occur within climate, ecological or social realms, or across them. For example, a climate tipping point can trigger ecological tipping points with cascading impacts that trigger social tipping points.

In this report we often add a normative interpretation of the impacts and consequences of reaching particular tipping points in different systems. We use the emotional meanings of 'positive' and 'negative' as simple normative labels, aware that these should not be confused with their mathematical meanings (particularly in the context of feedback loops). Thus, in the most general sense, a **positive tipping point** is one that is predominantly beneficial for humans and the natural systems we depend upon, and a **negative tipping point** is one that is predominantly detrimental for humans and the natural systems we depend upon.

More specifically, we define positive tipping points as those that accelerate change which reduces the likelihood of negative Earth system tipping points, and/or increases the likelihood of achieving just social foundations. Both are needed to ensure a sustainable future within safe and just Earth system boundaries (Gupta et al., 2023; Rockström et al., 2023; Raworth, 2017).

We acknowledge that 'positive' and 'negative' are value judgements; one person's positive outcome may be another's negative outcome, and distinguishing between the two is often subject to debate. However, the normative force in our usage of these terms is based on the science of biophysical capacities and the ethics of human wellbeing. Almost all people, regardless of their differences, believe that human flourishing is better than human suffering, and share a common interest in achieving sustainability. We define the latter as an *aggregate* measure of the biophysical capacities (planetary boundaries) and social foundations that can ensure a minimum level of wellbeing for a given population, indefinitely. Achieving a sustainable future will require a high level of collective responsibility and action, especially in relation to the global challenge of climate change. It is, however, a highly contested concept: different actors and groups tend to disagree about the speed and depth of transformation required.

Related concepts

Several key concepts related to tipping points are widely used in this report.

Before reaching a tipping point, a system typically loses **resilience**, which is defined here in a narrow sense to refer to its capacity to resist (or absorb) change and continue to function in its present state. In quantitative analyses of tipping points, 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. In development practice, the resilience of social and social-ecological systems is often used in a normative way (i.e. resilience is good/desirable). It is also sometimes used more broadly than we do here, to refer to the capacities to persist, adapt, or transform in response to change (Moser et al., 2019, Folke, 2016).

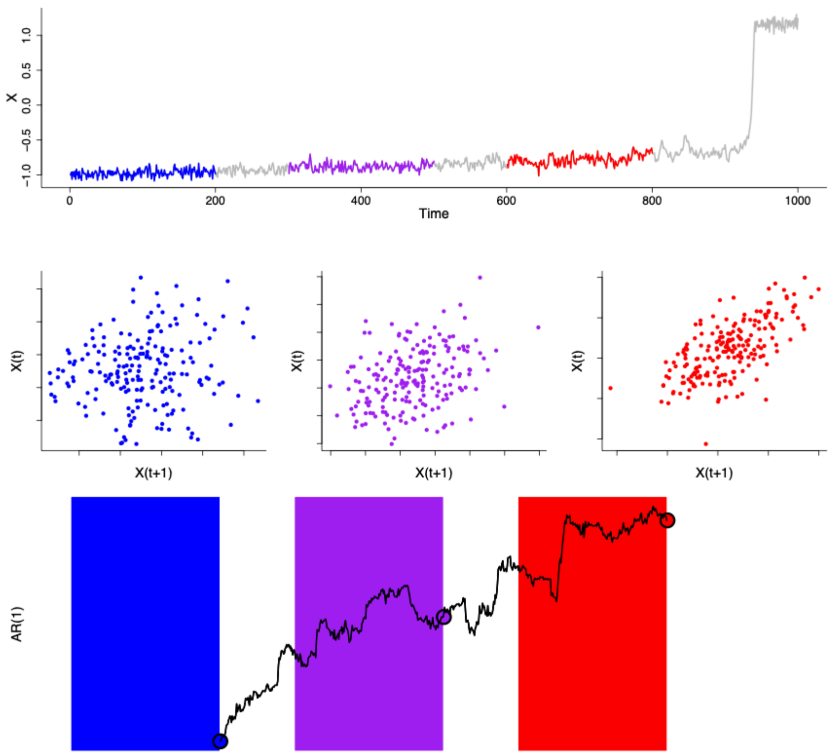

Figure 4 : Early indicators before a tipping point. *(Top row) The time-series of the state of a system ('X') that is being slowly forced towards a tipping point (blue, purple, red), exhibits slowing recovery from fluctuations. (Middle row) This 'critical slowing down' can be seen as an increase in correlation between the state of the system from one time point, X(t), to the next, X(t+1). (Bottom row) This property (lag-1 temporal autocorrelation; AR(1)) can be measured on a 'window' of data (e.g. the blue interval) and plotted at the end of that window (the blue dot). The window can then be moved along the time-series, recalculating the indicator at each time step (e.g. purple and red intervals and dots). The resulting overall increase in autocorrelation (AR(1)) provides an early indicator that a tipping point is being approached.*

The loss of resilience is a generic **early indicator** of approach to a bifurcation tipping point (Figure 4). It is a manifestation of the weakening of damping negative feedback in a system before strong amplifying positive feedback takes over at a tipping point. This causes a phenomenon called **critical slowing down**, whereby a system approaching a tipping point tends to undergo larger changes in response to perturbations and takes longer to recover from them. The associated loss of resilience can be detected in changing statistical indicators of system behaviour (Scheffer et al., 2009). In the context of undesirable, negative tipping points in systems, these are often referred to as **early warning signals**. In the context of desirable, positive tipping points in systems, we refer to them as **early opportunity indicators**.

The change in a system that accompanies a tipping point is sometimes described as a **transformation** of that system. We use transformation more specifically to refer to rapid and fundamental changes in human systems required to achieve sustainability (Patterson et al., 2017). Dramatic socio-cultural, political, economic and technological changes are required to move societies toward more desirable futures in the Anthropocene (Pereira et al., 2018, Bennett et al., 2016), yet their empirical assessment remains challenging (Salomaa and Juhola, 2020). In contrast, **transition** has a narrower usage to describe managed, often sector-specific, processes of social-technological change.

Where there is the desire and agency to try and cause a positive tipping point in a system, it is important to understand the **strategic interventions** that can bring it about and how effective they may be. Meadows (1999) originally identified a series of general **leverage points** or 'places to intervene in a system', and identified their relative effectiveness (from most to least):

1. The mindset or paradigm out of which the system arises;
2. The goals of the system;
3. The distribution of power over the rules of the system;
4. The rules of the system;
5. Information flows;
6. Material flows and nodes of material intersection;
7. Driving positive feedback loops;
8. Regulating negative feedback loops;
9. Constants, parameters, numbers.

More recently, examples of leverage points that can trigger positive tipping points in social-ecological-technological systems have been termed **sensitive intervention points** (Barbrook-Johnson et al., 2023; Mealy et al., 2023; Farmer et al., 2019; Hepburn et al., 2020;) or **social tipping interventions** (Otto et al., 2020). **Super-leverage points** have been proposed, which are capable of catalysing tipping cascades across multiple sectors (Meldrum et al., 2023).

Enabling conditions are the system conditions that can allow a tipping point to be triggered (Lenton et al., 2022). For example, with respect to positive tipping points, enabling conditions include the diffusion of social norms promoting sustainable behaviours, price reductions and availability of sustainable alternatives. Feedback processes between policy, technological and behavioural change (e.g. in terms of social norms, availability, prices and political support) can create favourable conditions that can enable positive tipping points (Smith, 2023; Fesenfeld et al., 2022). In this context, **demand-side solutions** are ones that reduce greenhouse gas emissions and other harmful stressors by changing consumption habits, norms and lifestyles; whereas **supply-side solutions** are ones that do so through technological innovations and their diffusion.

What is *not* a tipping point?

The term 'tipping point' has become increasingly popular in the media and public discourse in recent years, with many journalists and commentators using it to describe a wide range of phenomena. Sometimes the term is misused, creating misunderstanding and its own risks (Milkoreit, 2023). Wrongly asserting a negative tipping point could lead to a false sense of inevitability, leading to disempowerment, nihilism or despair. Wrongly asserting a positive tipping point could lead to false optimism, potentially interrupting difficult but necessary actions to affect change.

Tipping points are general features of a system. Events, people or historical junctures are not tipping points. They might have something to do with the crossing of a tipping point, but they are not its defining feature. For example if a fishery collapses, it is not the last fish caught or the person that caught it that represents the tipping point, because in a **counterfactual** situation the system would have tipped if a different fish was caught or a different person (or creature) caught it. Thus an election or a treaty are not tipping points (although they may have something to do with them).

Situations where a big change makes a big difference to a system are not tipping points. They are cases of linear, proportional change. Equally, many cases where a change gets amplified by positive feedback are not strong enough to produce a tipping point of self-perpetuating change. Hence it is critical to assess how strong amplifying feedback loops are, and to consider what damping feedback loops are present, before asserting a potential tipping point. Equally, in cases of cascading consequences it is important to assess how strong they are before asserting a tipping point.

When talking about tipping points in this report, we describe them in terms of general system features and distinguish that from the actions and forces that can bring a system towards a tipping point – the strategic interventions that can create enabling conditions and can trigger tipping.

Approach

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Our overall approach in this report is to synthesise knowledge about tipping points across multiple relevant disciplines spanning natural and social sciences. In general, we try to give primacy to empirical evidence of tipping point changes that have occurred, before considering potential ones that have yet to occur. In both cases, we try to provide underpinning theoretical evidence for tipping points. This means providing evidence of underlying causal mechanisms – notably self-propelling feedback mechanisms. This aims to counter the risks of promoting gratuitous alarmism (in the case of postulated negative tipping points) or naive optimism (in the case of postulated positive tipping points).

Systemic risk

Risk is widely understood to be the combination of hazard (likelihood of an event), exposure (to impacts of that event), and vulnerability (of people/other species who are exposed to those impacts). This is the approach to risk used by the Intergovernmental Panel on Climate Change (IPCC). It can be applied to assess the risk of individual Earth system tipping points, as these can be imagined as isolated, specific events. But in reality they will not occur in isolation. As Sections 1 and 2 explore, they can interact with each other and with social systems, including having the potential to trigger negative social tipping points. As a consequence, a 'static' framing of risk that seeks to isolate the risk of specific events, soon runs into considerable difficulties when dealing with tipping points. As a result, we adopt a 'dynamic' framing of systemic risk (UNDRR, 2019). The key notion of systemic risk is that risk depends on how elements of affected systems interact with each other. We endeavour to highlight throughout the report what these interactions are and how they may affect risk.

Handling uncertainty

Tipping points are highly non-linear phenomena occurring in complex (and often adaptive) systems, where our knowledge of those systems is imperfect. The associated uncertainty may sometimes seem huge, and we must deal openly with it. The most fundamental uncertainty are unknown unknowns. It is quite conceivable that, when tipping events occur, they will happen in a way that we did not expect and may not fully understand. This report synthesises the known knowns and the known unknowns of tipping points, but recognises the existence of unknown unknowns and seeks to offer guidance that is robust to them.

For the known unknowns, uncertainty is present in both reducible and irreducible forms. Reducible uncertainty is that which arises due to a lack of knowledge. Throughout the report we highlight ways in which knowledge about tipping points can be further improved. Irreducible uncertainty is that which cannot be resolved just by learning or observing more. For example, tipping points can be triggered by random perturbations ('noise') that cannot be forecast in advance – such as the weather in the climate system, which is known to exhibit extraordinary sensitivity to initial conditions (chaotic behaviour).

Despite the presence of irreducible uncertainties, it would be wrong to over-generalise that 'all tipping points are inherently unpredictable'. There can still be predictive skill for some tipping points, it is just not a perfect predictive skill – as with the weather. Predictability exists because the systems we consider generally have a deterministic component to their dynamics – meaning they are governed by some laws that do not change over time. We may not know what those laws are, but we do not have to know them to detect their consequences. Notably, the phenomenon of critical slowing down gives measurable signals if and when a system is heading towards a tipping point. Usually we do know something about the laws governing the behaviour of a system, and sometimes we know enough to produce a process-based model of a system and its tipping point(s).

We can usefully separate out some specific uncertainties surrounding tipping points, accepting the limitations (noted above) of a 'static' risk framework.

First (and foremost) is uncertainty about whether a tipping point exists or not. We address that throughout the report, with reference to observations (past behaviour), theory (particularly regarding key feedback mechanisms) and models (including projections of future behaviour). For Earth system tipping points, we evaluate our confidence in their existence. We evaluate several candidates that we (currently) conclude are not tipping points, but nevertheless exhibit properties of non-linear change. These cases are clearly indicated. For tipping points in social systems, we evaluate their existence or not, but do not assign a confidence level to those assignments, because research is nascent in this area.

Second is uncertainty about how close (or far away) a tipping point is. Here 'distance' is best thought of in terms of some key driver (or drivers) forcing a system. An example is global temperature change in the case of climate tipping points. The uncertainty about the 'location' of a tipping point can be expressed in terms of an uncertain range in a key driver (or drivers). An example is the uncertainty in global warming at which a particular climate tipping point may occur. Within this uncertain distribution a most likely value may be assigned. This approach allows probabilities of a particular tipping point occurring under a particular forcing scenario to be derived and expressed in probabilistic (likelihood) language. While this is becoming possible for Earth system tipping points, it is not yet possible for social system tipping points. We discuss ways in which distance to a social tipping point could be derived, while recognising that, with multiple human agents continuously adapting their decisions and behaviour, that distance could be continually changing due to many drivers.

Third is uncertainty about the consequences of crossing a particular tipping point. Evaluating this assumes a situation where the tipping point has happened. Hence the consequences can (in some cases) be more certain than the likelihood of the tipping point itself. They do, however, carry their own uncertainties.

Fourth is uncertainty about who (or what) is exposed to those consequences. Evaluating human exposure requires a scenario or assumptions about the human population and its distribution, which carries its own uncertainties. These combine with the uncertainties in 'mapping' from consequences to those people. That 'mapping' may involve causal consequences propagating through complex networks.

Fifth is uncertainty about different people's response to being exposed to the consequences. In the case of negative tipping points, this is termed vulnerability. In the case of positive tipping points, it can include being exposed to opportunities. In both cases responses depend on the state of individuals within families and communities, and on the state of wider social systems such as the global economy.

Our normative position

The value judgements expressed in this report are based on applying principles of Earth system justice (Gupta et al. 2023). We all have a right to expect, and a responsibility to help secure, a world in which all people and all the other living things and ecosystems we depend on, can thrive in a way that does not diminish the ability of future generations to do and enjoy the same.

We have defined above how we assign 'positive' and 'negative' to particular tipping points, based on whether they are predominantly beneficial (positive tipping point) or detrimental (negative tipping point) for humans and the natural systems we depend upon. However, we acknowledge that one person's positive outcome may be another's negative outcome, and hence these assignments may be subject to debate. Here we expand on our rationale.

As a rule, the impacts of the Earth system tipping points are clearly 'negative' for most (if not all) people and many species. However, the actions driving us towards them may benefit some people in some ways – for example, through the extraction and use of fossil fuels. The impacts of smaller-scale social-ecological tipping points – such as abrupt collapse of fisheries or desertification – are also often clearly 'negative' for many participants in those systems. But again the actions driving the system past a tipping point may disproportionately benefit some people.

It is tempting to assign any and all actions – including social tipping points – that reduce the risk of negative Earth system tipping points as 'positive' – as they will reduce environmental harm for the majority, if not everyone. However, the associated social, technological and ecological changes can have costs as well as benefits that can be unequally distributed, calling for governance intervention. Otherwise, what is positive for a majority of people (or species) may still be deemed negative by some.

Societies need to carefully consider the equity and justice implications of social tipping points that are 'Earth system positive', to try and minimise instances where they could be 'socially negative'. This first means seeking to ensure they do not increase overall (global) harm and injustice, which means weighing up overall harms and benefits. Then, in cases where there are localised social injustices, good governance is needed to limit and mitigate these. For example, governments can provide social safety nets for those losing out – like supporting coal miners, their communities and regions in finding different employment and flourishing. At a deeper level, governance needs to decide the 'welfare function' – meaning what are we trying to maximise, what are we trying to minimise, and who do we accept is going to lose out.

Governance

This brings us to our approach to governance of tipping points – whether 'negative' or 'positive'. We take 'governance' to refer to rules, regulations, norms and institutions that structure and guide collective behaviour and actions, including the processes that create governance, which often involve politics, policymaking and mechanisms for holding actors accountable for their actions and omissions. We take a global governance approach that goes beyond state actors.

"We consider not only governments as key governance actors and their intergovernmental initiatives, but also corporate and industry actors, civil society organisations, traditional authorities (e.g. village elders, monarchs), cities and municipalities, and transnational networks.

While attention to the threats posed by Earth system tipping points is growing, explicit governance efforts to address those threats do not yet exist. Section 3 addresses the key task of establishing a novel governance agenda and framework for Earth system tipping points, while recognising the difficulties for already-complex governance regimes to integrate a new set of challenges into their already-crowded agendas. Consequently, discussions about governing tipping points need to provide a clear and convincing logic for action, grounded in scientific knowledge, which this report aims to provide.

The governance of positive tipping points poses its own challenges, which are addressed in Section 4. In particular, interventions designed for exponential and irreversible positive change can also carry the risk of exponential and irreversible negative change. A precautious, considered, systemic approach is therefore necessary to understand the potential consequences and to whom they might apply. Governance approaches that prioritise principles of equity and justice must anticipate and take steps to avoid risks and negative distributional impacts using compensatory and redistributive mechanisms.

A particular risk is the creation of green sacrifice zones. These are 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 (Zografos and Robbins, 2020). More broadly, we seek to avoid (and counter) climate colonialism, defined as *"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"* (Zografos and Robbins, 2020: p543).

The desire to avoid damaging, potentially abrupt and/or irreversible Earth system and ecosystem tipping points is a key source of urgency in accelerating action on climate change and ecological crisis. Equally, triggering positive tipping points to accelerate action is a key response to that sense of urgency. However, for many Indigenous peoples and local communities who have faced the existential crisis of colonialism and who are now at the forefront of the climate crisis (Gilio-Whitaker, 2019), it may already be too late to avoid environmental injustices and so urgency to respond takes on a new perspective (Whyte 2021, 2020). Crucially, the urgency of tipping points needs to avoid overshadowing the slow process of rebuilding trust and relationships that have been broken through past harms (Whyte, 2020).

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Section 1

Earth system tipping points

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Section summary

Tipping points exist across the Earth system – the interconnected systems that support life on this planet, including the cryosphere (ice-bound domains), biosphere (the living world), ocean and atmosphere. It is often assumed that environmental systems respond relatively linearly to human-driven pressures (such as climate change, habitat destruction and pollution). However, in some systems, pressure beyond a threshold causes them to shift to a very different state, often abruptly or irreversibly, as a result of self-sustaining feedbacks – they pass a tipping point.

In this section we compile evidence for tipping dynamics across the Earth system, noting where certainty and confidence is low and more research is needed. We also review the potential for interactions between climate tipping points to trigger tipping cascades, and the scope for detecting early warning signals before tipping points in monitoring data.

There is evidence for tipping points across the Earth system, including in major ice sheets, which could lock in multiple metres of sea-level rise, in ecosystems like the Amazon rainforest, which could die back to a degraded state, and in major ocean circulation patterns, which could abruptly shut down. Monitoring and early warning signals suggest some of these systems are already destabilising, indicating that tipping points could be approaching. Interactions between climate tipping points are destabilising in most (but not all) cases, and could lead to tipping cascades that destabilise wider parts of the climate system.

However, how close some Earth system tipping points may be is uncertain, with threshold estimates often spanning a large range. Established models, though capturing past and current climate trends well, often have a limited resolution of some processes that are key for making more accurate tipping dynamics estimates. However, they do hold evidence for potential tipping, which is strongly supported by conceptual models and palaeo reconstructions, which show that certain systems likely tipped in the past.

Given that tipping is possible, and that human-driven emissions are rapidly pushing the Earth to a climate unseen in at least the past 120,000 years, this provides strong motivation for rapidly reducing human-driven pressures on the Earth system (see Sections 3 and 4). It lays the foundation for preparing adaptation plans for the societal impacts of Earth system tipping points that cannot be avoided (see Section 2). Even if some tipping points are reached, mitigation to prevent further tipping points remains critically important.

Key messages

- **We identify more than 25 parts of the Earth system that have tipping points,** based on evidence from palaeoclimate records, observations, theory and complex computer models, including:
  - » In the cryosphere, evidence exists for large-scale tipping points in Greenland and Antarctic ice sheets, and for localised tipping in glaciers and permafrost.
  - » In the biosphere, tipping points are present in a variety of ecosystems, including Amazon forest dieback, savanna and dryland degradation, lake eutrophication, coral reef and mangrove die-offs, and the collapse of some fisheries.
  - » In ocean-atmosphere circulations, there is evidence for tipping points in Atlantic and Southern Oceans overturning, as well as for the West African monsoon.
- **Multiple drivers are destabilising these systems.** Climate change is a key driver for most, as well as habitat loss (e.g. deforestation), exploitation (e.g. overfishing), and pollution (e.g. aerosols or nutrients) particularly in the biosphere.
- **Some Earth system tipping points could be very close already.** Coral reefs and some ice sheets could tip at current warming levels, and other systems' thresholds will soon be reached on current warming trends. Complex co-drivers, interactions, and feedbacks, as well as limited observational records, can make tipping thresholds difficult to assess for other systems, particularly in the biosphere.
- **Some climate tipping systems closely interact, and most interactions tend towards destabilising, making tipping 'cascades' possible.** There are large uncertainties around these cascades, but warming is approaching levels where they are becoming possible.
- **'Early warning signals' can sometimes indicate that a system is losing resilience** and so may be approaching a tipping point. Parts of the Greenland Ice Sheet, Atlantic Meridional Overturning Circulation, and the Amazon rainforest show such early warning signals, which is consistent with these systems approaching tipping points. However, these signals don't show for certain if or when a tipping point will occur.

Recommendations

- **Prevent destabilisation of the Earth's tipping systems** through urgent and ambitious elimination of greenhouse gas emissions and reduction of other pressures such as deforestation, black carbon emissions and nutrient pollution.
- **Reduce deep uncertainties,** for example related to key processes and feedbacks like marine ice cliff instabilities, ecosystem responses to increasing extreme events and fine-scale ocean mixing, through further research and model intercomparison. Co-design research, bringing together the natural and social sciences, scholars across the Global South and North and multiple knowledge systems including Indigenous and traditional ecological knowledge.
- **Improve risk assessments of potential tipping cascades** through: i) representing more tipping system interactions in Earth system models, ii) large model ensembles to allow less common events to emerge, iii) studying possible cascades in ancient climate records, and iv) a fresh elicitation of expert knowledge to identify missed interactions.
- **Support development of novel and improved early warning techniques** (such as using machine learning) to detect declining resilience and other potential signs of tipping. Expand remote sensing capabilities and palaeorecords to improve datasets for early warning detection. Foster international data sharing and collaboration, and improve observational coverage in under-monitored regions such as Africa and Asia.

1.1 Earth system tipping points

Introduction

In this section we scan different parts of the Earth system for evidence of tipping dynamics and assess whether they are likely to be tipping systems or not, providing confidence levels for each proposed tipping point and identifying knowledge gaps to be targeted with further research. We focus on the biophysical aspects of Earth system tipping points, with the societal impacts of these tipping points and adaptation to them explored in more depth in Section 2, and ways to govern the prevention of, and adaptation to, them examined in Section 3. We also consider how Earth system tipping points interact and potentially 'cascade' (where one tipping point triggers another, and so on) and assess the extent to which observations of these systems could give early warnings of impending tipping points.

Figure 1.1.1: Illustration of the Earth system, showing the different 'spheres'. The shown systems are a selected subset of the many components making up the Earth system.

The Earth system describes the interconnected complex system at the surface of the planet that sustains life (Figure 1.1.1). It is comprised of multiple subsystems (or spheres), including the cryosphere (ice-related systems, including ice sheets, sea ice, glaciers and permafrost), biosphere (global ecosystems), atmosphere, hydrosphere (water-based systems, including oceans, rivers and lakes) and the lithosphere (the Earth's solid surface) (Kump, Kasting, and Crane, 1999; Lenton, 2016). Together these subsystems and their interactions – referred to by the IPCC as the 'climate system' – determine the climate (the average long-term weather conditions at a place or across the Earth, usually measured over 30 years) (IPCC AR6 WG1 Annex VII).

At a smaller scale, ecosystems describe the complex systems composed of assemblages of living organisms and their physical environment in a particular location (e.g. a patch of rainforest in the Brazilian state of Amazonas), which at a larger scale form ecoregions, biomes and, ultimately, the whole global biosphere (Dinerstein et al., 2017; Keith et al., 2022). Humans, too, are a part of the biosphere, forming 'social-ecological systems' in which social and ecological dynamics have been inextricably long intertwined (Folke et al., 2016, 2021; Ellis et al., 2021).

Evidence from modelling, observations, theory based on understanding of fundamental biophysical processes, and geological records of ancient climate change (referred to as *palaeorecords*) suggests some of the Earth's systems can exhibit tipping points and associated dynamics (Lenton et al., 2008; Armstrong McKay et al., 2022; Wang et al., 2023). For example, there are multiple self-reinforcing feedback processes in ice sheets that not only amplify the effects of human-caused global warming, but may also lead to self-sustained melting beyond a critical warming threshold (Robinson et al., 2012; Garbe et al., 2020). Palaeorecords show that such collapses have happened before (Christ et al., 2021; Turney et al.,, 2020), and evidence from models and contemporary observations suggest some of these systems show increasing proximity to or may even be beyond tipping points (Feldmann and Levermann, 2015; Waibel et al., 2018; Rignot et al., 2014; Joughin et al., 2014; Boers and Rypdal, 2021).

Similar evidence for tipping points and destabilisation exists for ocean currents – such as the Atlantic Meridional Overturning Circulation (AMOC) (Böhm et al., 2015; Boers, 2021; Ditlevsen and Ditlevsen, 2023) – and ecosystems (Scheffer et al., 2009; Staal et al., 2020; Boulton et al., 2022). Tipping is often relatively rapid and irreversible, and has far-reaching implications for the climate, ecosystems and humans.

In this section we use the following tipping point definition to categorise proposed tipping systems, with key terms (defined in the Glossary) italicised:

Box 1.1: Our Earth system tipping point (ESTP) definition:

Tipping points occur when change in a *tipping system* (also known as a *tipping element*) becomes self-sustaining once a *forcing threshold* is passed, leading to a qualitative *state change* (e.g. an ecological *regime shift*) driven by one or more *positive/amplifying feedback loops*.

Climate tipping points, for example, occur when parts of the climate system reach global warming thresholds beyond which positive/amplifying feedbacks propel a shift to a totally different state, such as the inevitable collapse of an ice sheet or shutdown of a deep ocean convection site (Figure 1.1.2). Recent research suggests that five such tipping points may become likely beyond 1.5°C warming, including Greenland and West Antarctic ice sheet collapse, warm-water coral reef die-offs, overturning circulation collapse in the North Atlantic Subpolar Gyre, and widespread localised abrupt thaw in permafrost (Armstrong McKay et al., 2022). Earth system tipping points can occur due to a wider set of environmental drivers, including for example deforestation or nutrient pollution, as well as climate change.

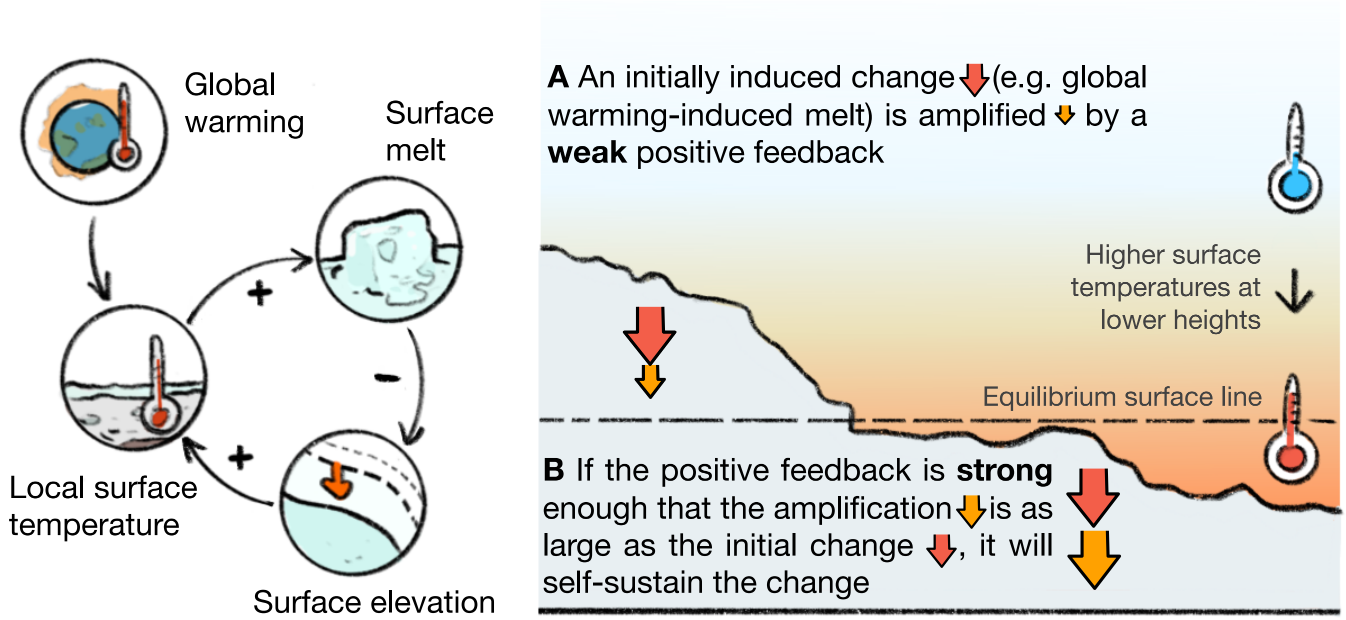

Figure 1.1.2: Self-sustaining change due to strong positive/amplifying feedbacks. Left shows one exemplary positive/amplifying feedback loop, the melt-elevation feedback that exists, e.g. in ice sheets. An increase in local surface temperatures leads to increasing melt, such that the melting ice sheet gets to lower heights. Since it gets warmer with lower altitude (atmospheric lapse rate), the local surface temperature is increased, restarting this circle. Such positive feedbacks amplify the initial change – however, if there is a critical threshold, beyond which the amplification leads to a change that is as large as the initial change, this leads to a vicious circle, self-sustaining the change.

We consider potential Earth system tipping systems in Chapters 1.2, 1.3, and 1.4 based on the scientific literature. In the cryosphere chapter (Chapter 1.2) we assess the ice sheets on Greenland and Antarctica, as well as sea ice in the Arctic and Southern Oceans, glaciers outside of polar regions, and permafrost. In the biosphere chapter (Chapter 1.3), on land we consider forests in tropical, temperate and boreal zones, as well as savannas, drylands and freshwater systems (lakes and rivers), and in the ocean we consider coral reefs, coastal and open ocean ecosystems. In the ocean and atmosphere circulation chapter (Chapter 1.4), we assess circulation in the North Atlantic and Southern Oceans, as well as atmosphere systems including monsoons, climate oscillations like the El Niño Southern Oscillation (ENSO), mid-latitude weather patterns like jet stream changes, as well as climate sensitivity and circulation linked to tropical clouds.

In many cases, the consequences of passing one tipping point make other connected tipping systems more or less likely to tip as a result. If passing one tipping point makes another tipping point more likely, then tipping points could cascade, with a chain of tipping points triggering each other. In Chapter 1.5 we present what is known about tipping point interactions in the climate system, including between the AMOC and ice sheets, Amazon and Arctic sea ice and between ENSO and coral reefs, Amazon and the West Antarctic ice sheet, and present some palaeoclimate case studies.

It may sometimes be possible to detect tipping points before they happen. Theory suggests that before some types of tipping point, subtle changes may be observable in the statistical properties of monitoring data, known as early warning signals (EWS). The most common type of EWS is critical slowing down, where natural fluctuations in an observed property of a system (such as temperature or tree cover) become bigger and longer, leading to larger values of variability (e.g. in variance) or self-similarity to recent values (e.g. in autocorrelation). In Chapter 1.6 we present different techniques and some case studies of detecting EWS before Earth system tipping points, and discuss both their limitations and future opportunities.

Chapter 1.2: Tipping points in the cryosphere

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Summary

Drastic changes in our planet's frozen landscapes have occurred over recent decades, from Arctic sea ice decline and thawing of permafrost soils to polar amplification, the retreat of glaciers and ice loss from the ice sheets. In this chapter, we assess multiple lines of evidence for tipping points in the cryosphere – encompassing the ice sheets on Greenland and Antarctica, sea ice, mountain glaciers and permafrost – based on recent observations, palaeorecords, numerical modelling and theoretical understanding.

With about 1.2°C of global warming compared to pre-industrial levels, we are getting dangerously close to the temperature thresholds of some major tipping points for the ice sheets of Greenland and West Antarctica. Crossing these would lock in unavoidable long-term global sea level rise of up to 10 metres. There is evidence for localised and regional tipping points for glaciers and permafrost and, while evidence for global-scale tipping dynamics in sea ice, glaciers and permafrost is limited, their decline will continue with unabated global warming.

Because of the long response times of these systems, some impacts of crossing potential tipping points will unfold over centuries to millennia. However, with the current trajectory of greenhouse gas (GHG) emissions and subsequent anthropogenic climate change, such largely irreversible changes might already have been triggered. These will cause far-reaching impacts for ecosystems and humans alike, threatening the livelihoods of millions of people, and will become more severe the further global warming progresses.

The scientific content of this chapter is based on the following manuscript in preparation: Winkelmann et al., (in prep)

Key messages

- Large-scale tipping points exist for the Greenland and Antarctic ice sheets, as inferred from multiple lines of evidence. Crossing these tipping points would lead to multi-metre sea level rise over hundreds to thousands of years.
- There is evidence for localised and regional tipping points in glaciers and localised tipping points in permafrost, but evidence for large-scale tipping dynamics in sea ice, glaciers and permafrost is limited.
- Some ice sheet tipping points could be close at current warming levels, with further warming increasing their likelihood. Localised tipping can already be observed for permafrost, and will worsen with further warming, along with non-tipping impacts.

Recommendations

- Protect the cryosphere through urgent and ambitious phase-out of GHG emissions, as well as reducing co-drivers such as black carbon.
- Reduce and/or better understand deep uncertainties, including: 1) instabilities in marine-based ice sheet dynamics; 2) the coupled dynamics of the Southern Ocean, sea ice, and ice shelf system; 3) integrating local glacier feedbacks into glacier modelling; and 4) the impact of abrupt permafrost thaw dynamics on the global permafrost-carbon feedback.
- Invest in observations and improved modelling to constrain projected impacts for the next decades and beyond, and detect early warning signs of cryosphere tipping. Foster data sharing and international collaboration.
- Co-design research, bringing together natural and social sciences and multiple knowledge systems, including Indigenous knowledge, to improve decision making under deep uncertainty, reduce risks and effectively adapt to unavoidable impacts.

1.2.1 Introduction

The Earth's cryosphere, encompassing large expanses of frozen landscapes, is critical to its climate system (Fox-Kemper et al., 2021). From the vast ice sheets on Greenland and Antarctica to mountain glaciers, sea ice and the permanently frozen soils of the Arctic, the cryosphere plays a crucial role in storing freshwater and carbon, regulating global climate patterns and influencing major ecosystems (Figure 1.2.1). However, it is also one of the parts of the Earth system most vulnerable to climate change. As our climate undergoes unprecedented shifts due to human-induced global warming, the cryosphere is at risk of crossing potential tipping points (Lenton et al., 2012; Armstrong McKay et al., 2022; Wang et al., 2023).

Cryospheric tipping dynamics are triggered when changes in part of a system become self-perpetuating beyond some threshold, leading to substantial, widespread, often abrupt and often irreversible impacts (see section 1 Introduction). This definition highlights different characteristics of tipping systems that have been discussed previously – namely the existence of critical thresholds and the potential for abrupt and possibly irreversible change, all of which we assess here for ice sheets, sea ice, glaciers and permafrost.

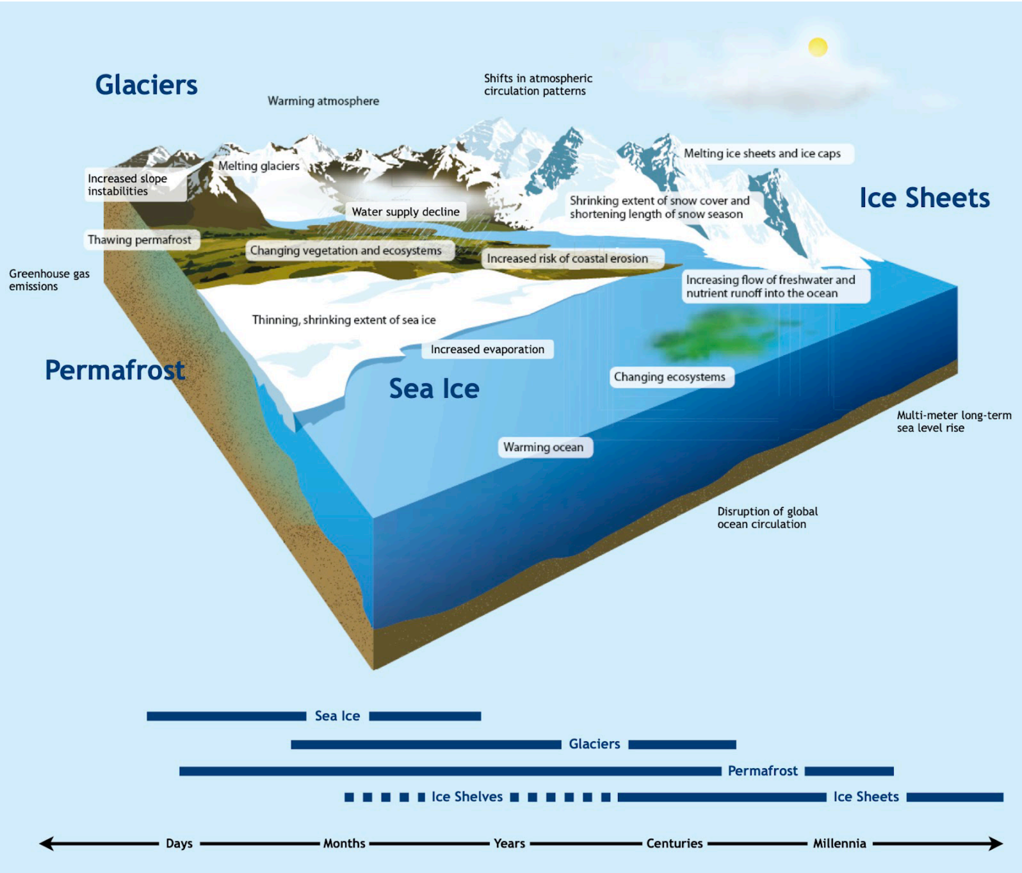

Figure 1.2.1: Key biophysical impacts resulting from crossing tipping points in the cryosphere. Diagram below gives approximate timescales of changes in the respective domain/system. Background graphic from: AMAP (2017).

The consequences of crossing cryospheric tipping points amplify the effects of climate change and have widespread impacts, affecting sea level, ecosystems, wildlife habitats, coastal infrastructure, human livelihoods and regional climate patterns (Fox-Kemper et al., 2021). They could further lead to cascading effects to other climate tipping systems, which would result in far-reaching consequences for the entire Earth system (Steffen et al., 2018; Wunderling et al., 2021; Wunderling and von der Heydt et al., preprint).

1.2.2 Current state of knowledge on cryosphere tipping points

In this section we assess available scientific literature relating to tipping points in the cryosphere, as summarised in Figure 1.2.2 and Table 1.2.1. We focus on the following systems: the ice sheets on Greenland and Antarctica, sea ice (in the Arctic and Antarctic), mountain glaciers, and permafrost.

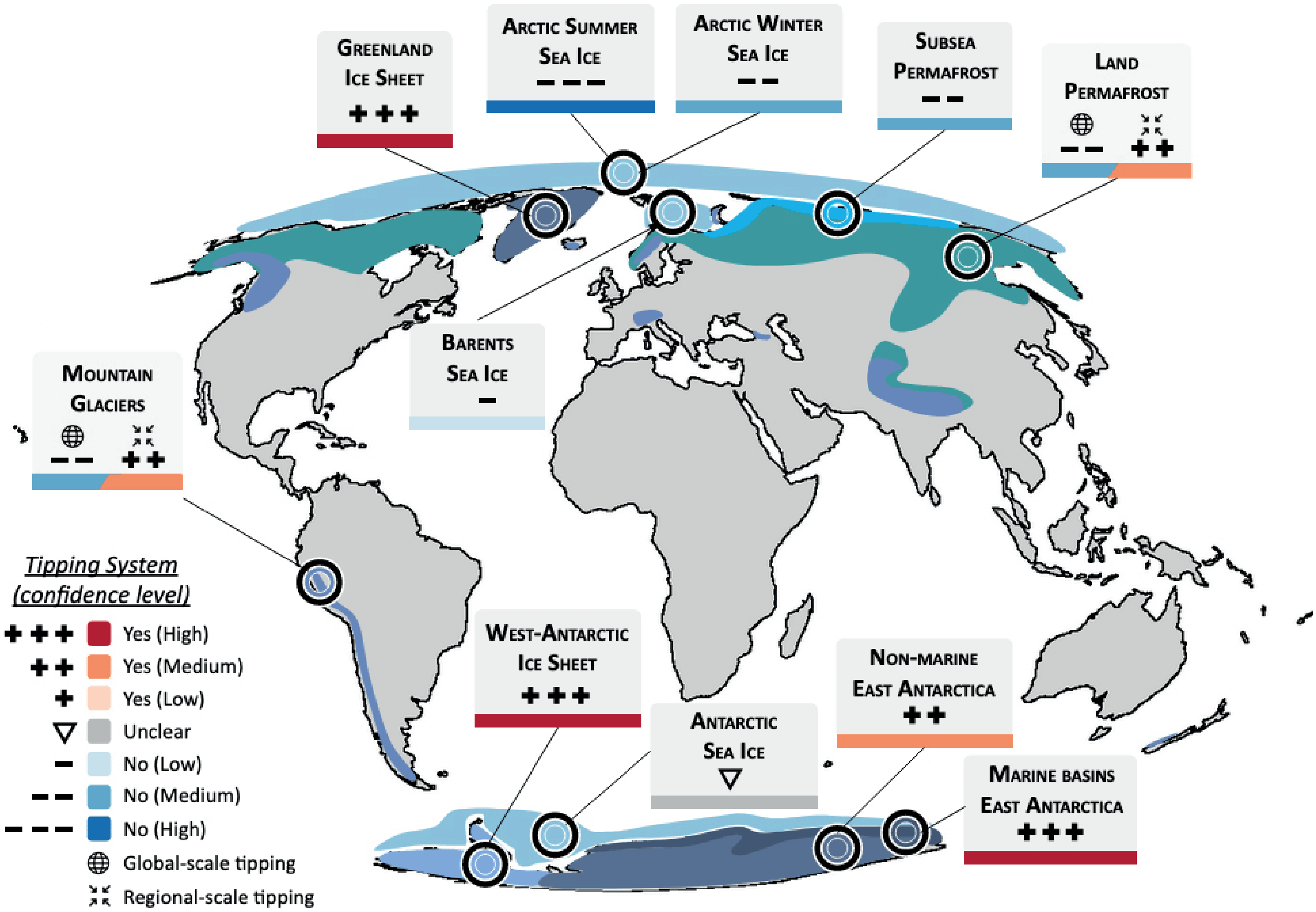

Figure 1.2.2: Map of cryosphere systems considered in this chapter (shading). The markers indicate which of the systems are in this report considered a tipping system (+++ high confidence, ++ medium confidence and + low confidence) and which are not (- - - high confidence, - - medium confidence and - low confidence), ∇ indicates systems for which a clear assessment is not possible based on the current level of understanding.

Table 1.2.1: Summary of evidence for tipping dynamics, key drivers and biophysical impacts in each system considered in this chapter

Key: +++ Yes (high confidence), **++** Yes (medium confidence), **+** Yes (low confidence), **- - -** No (high confidence), **- -** No (medium confidence), **-** No (low confidence)

Primary drivers are bolded, DC: Direct Climate driver; **CA:** Climate-Associated driver (including second-order and related effects of climate change); **NC:** Non-Climate driver**, PF:** positive (amplifying) feedback (FB), **NF:** negative (damping) feedback. Drivers can enhance **(↗)** the tipping process or counter it **(↘)**

System (and potential tipping point)	Key drivers	Key biophysical impacts	Selected key feedbacks	Abrupt / large rate change?	Critical threshold(s) (warming > preindustrial)	Irreversible? (decadal / centennial)	Tipping system?
Ice Sheets							
Greenland Ice Sheet (collapse)	DC: atmospheric warming (↗) DC: precipitation increase (↘) DC: ocean warming and circulation changes (↗/↘) DC: black carbon deposition (↗) CA: sea ice decline (↗) CA: atmospheric circulation changes (↗|↘)	• Sea level rise (up to 7m) over centuries to millennia • Disruption of global ocean circulation • Substantial shifts in atmospheric circulation patterns	• PF: melt-elevation • PF: melt-albedo	+++	0.8-3°C	+++	**+++**
West Antarctic Ice Sheet (collapse)	DC: ocean warming and circulation changes (↗) DC: atmospheric warming (↗) DC: precipitation increase (↘)	• Sea level rise (up to 3m) over centuries to millennia • Disruption of global ocean circulation • Substantial shifts in atmospheric circulation patterns	• PF: marine ice sheet instability • NF: glacial isostatic adjustment • ?: melt-stratification	+++	1-3°C	+++	**+++**
Marine basins East Antarctica (collapse)	DC: ocean warming and circulation changes (↗) DC: atmospheric warming (↗) DC: precipitation increase (↘)	• Sea level rise (up to 19m) over centuries to millennia • Disruption of global ocean circulation • Substantial shifts in atmospheric circulation patterns	• PF: marine ice sheet instability • NF: glacial isostatic adjustment • ?: melt-stratification	+++	2-6°C	+++	**+++**
Non-marine East Antarctic Ice Sheet (collapse)	DC: atmospheric warming (↗) DC: precipitation increase (↘)	• Sea level rise (up to 34m) over centuries to millennia • Disruption of global ocean circulation • Substantial shifts in atmospheric circulation patterns	• PF: melt-elevation	+++	6-10°C	++	**++**

System (and potential tipping point)	Key drivers	Key biophysical impacts	Selected key feedbacks	Abrupt / large rate change?	Critical threshold(s) (warming > preindustrial)	Irreversible? (decadal / centennial)	Tipping system?
Sea Ice							
Arctic summer sea ice (loss)	DC: atmospheric warming (↗) DC: atmospheric circulation shifts (↗/↘) DC: ocean warming (↗) DC: ocean circulation shifts (↗/↘) DC: black carbon deposition (↗) DC: storminess increase (↗) CA: ocean stratification increase (↘)	• Regional warming (polar amplification) • Ecosystem disruption • Impacts on ocean circulation • Impacts on atmospheric circulations • Increased evaporation	• PF: Ice-albedo FB • NF: Snow FB • NF: Growth FB • NF: Radiation FB	- - -	N/A	- - -	- - -
Arctic winter sea ice (loss)				+++	3-6 °C	- -	- - (abrupt loss due to Arctic geometry)
Barents sea ice (loss)				- (linear relationship in most models)	unclear	unclear	-
Antarctic sea ice (loss)				unclear	unclear	+ (reversible over millennia)	unclear
Glaciers							
Glaciers (retreat)	DC: atmospheric warming (↗) DC: deposition of dust, black carbon, etc. (albedo) (↗) DC: reduced snow (input and albedo) (↗) DC: local thermokarst (↗)	• Water supply decline • Ecosystem disruption (e.g. wetlands, water chemistry) • Increase in number and size of glacier lakesIncrease in slope instabilities • Transition from glacial to para-glacial landscapes • Sea level rise	• PF: melt-elevation FB • PF: calving front retreat • PF-: ice-dynamic FBs • NF: retreat to higher altitudes	+ + (regional) - - (global)	Regionally variable	- -	**++ (regional)** - - (global)
Permafrost							
Land permafrost (thaw)	DC: atmospheric warming (↗) CA: vegetation increase (increase albedo ↗, increase summer shading ↘, and vice versa for forest die-back) CA: wildfire intensity increase (↗) CA: precipitation increase (rain extremes, snow cover albedo ↗)	• Greenhouse gas emissions • Landscape disruption • Ecosystem disruption	• PF: carbon-climate FB • PF: thermokarst development • PF: summer soil drying • PF-: vegetation interaction	- - (global) ++ (regional)	N/A	+++ (wrt carbon loss) - - - (wrt frozen soil)	**++ (regional)** - - (global, on 10s-100s year timescale)
Subsea permafrost (thaw)	DC: ocean warming (↗) CA: sea ice loss (↗) CA: water pressure reduction (↗)	• Greenhouse gas emissions	• PF: Carbon-climate FB • NF: sediment sink • NF: water column sink	+	N/A	+ + (w.r.t. gas hydrate dissociation) + + (w.r.t. frozen sediment)	- - (global, on 10s-100s year timescale)

1.2.2.1 Ice sheets

Most of Earth's freshwater is stored in the ice sheets of Greenland and Antarctica (Figure 1.2.3). These represent by far the largest potential sources for sea level rise under ongoing and future warming: if the Greenland Ice Sheet (GrIS) were to melt entirely, global sea levels would rise by about 7 metres (Morlighem et al., 2017), for the Antarctic Ice Sheet, the total sea level rise potential is 58 metres (Fretwell et al., 2013; Morlighem et al., 2020). Even if only part of these masses were to undergo abrupt ice loss or tipping behaviour, this would have far-reaching consequences for coastal communities, infrastructure and ecosystems worldwide (Fox-Kemper et al., 2021).

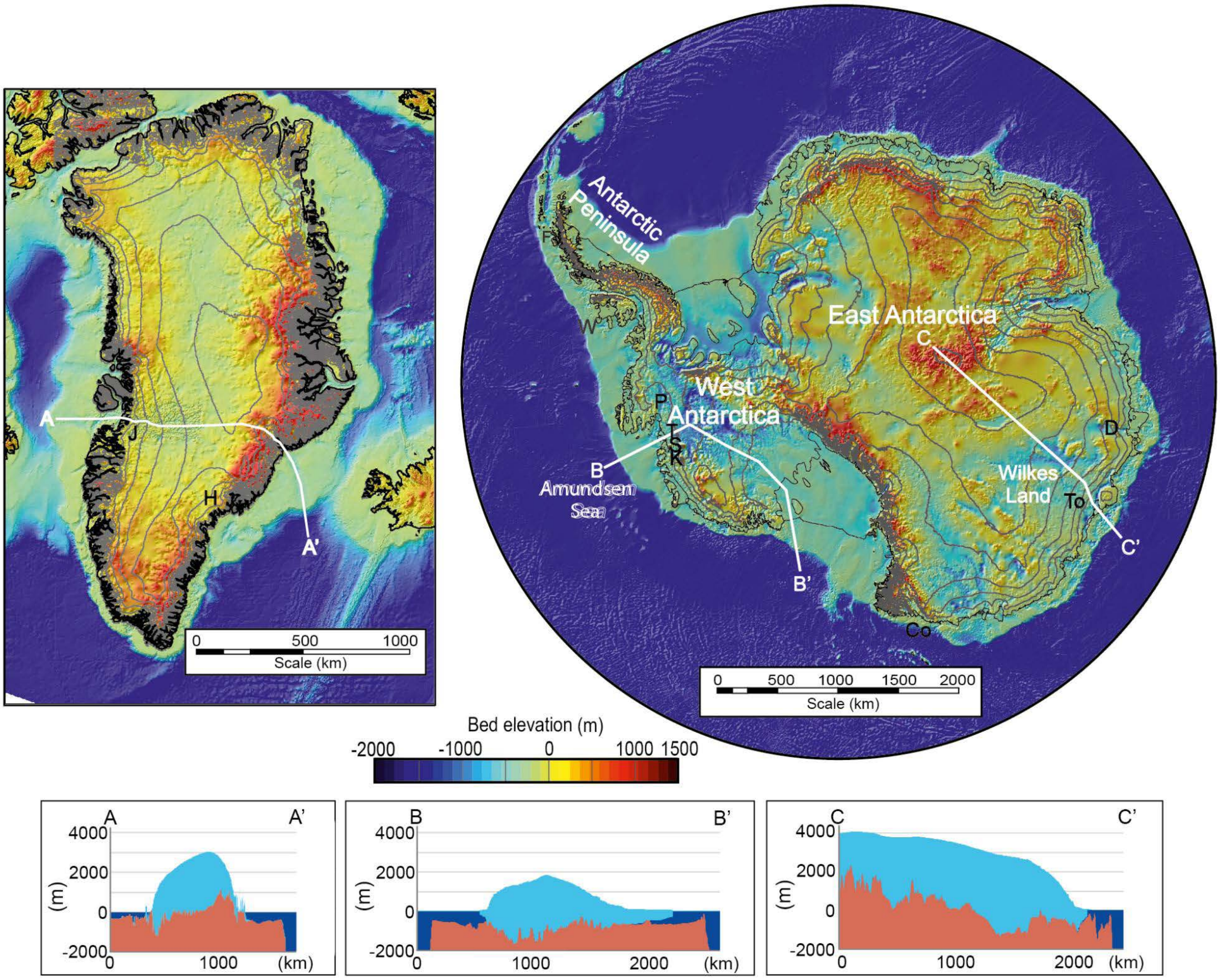

Figure 1.2.3: Greenland and Antarctic ice sheets. Given is the bedrock topography of the GrIS (left, based on Bamber et al., 2013) and the Antarctic Ice Sheet (middle and right, based on Fretwell, 2013) alongside cross sections marked in the maps by white lines. In marine ice sheet sectors (blue-green shading in the maps) the ice sheet rests on a bed submerged below sea level.

The ice sheets have been losing mass at an accelerating rate: from an average of about 105 gigatonnes (Gt – i.e. one billion tonnes) per year between 1992 and 1996 to around 372 Gt per year between 2016 and 2020 (Otosaka et al., 2023) (Figure 1.2.4). The Greenland ice sheet is (still) the major player, with an average mass loss rate of 169±9 Gt per year between 1992 and 2020, similar to the mass lost from glaciers outside of Greenland and Antarctica (Fox-Kemper et al., 2021; Hugonnet et al., 2021). Over the same period, ice losses in Antarctica were predominantly occurring in West Antarctica (The IMBIE team, 2018; Otosaka et al., 2023).

The long-term stability of the ice sheets depends on a complex interplay of amplifying (including self-sustaining) and damping feedbacks (e.g. Fyke et al., 2018). Based on multiple lines of evidence from modelling studies, observations and palaeo evidence, the ice sheets or parts thereof are considered 'global core' climate tipping systems (Armstrong McKay et al., 2022). In the following, we describe the underlying mechanisms, critical thresholds, timescales and potential for (ir)reversibility. Since the ice loss is dominated by different processes, we differentiate between the GrIS, the West Antarctic Ice Sheet (WAIS), the marine basins of East Antarctica and non-marine parts of East Antarctica.

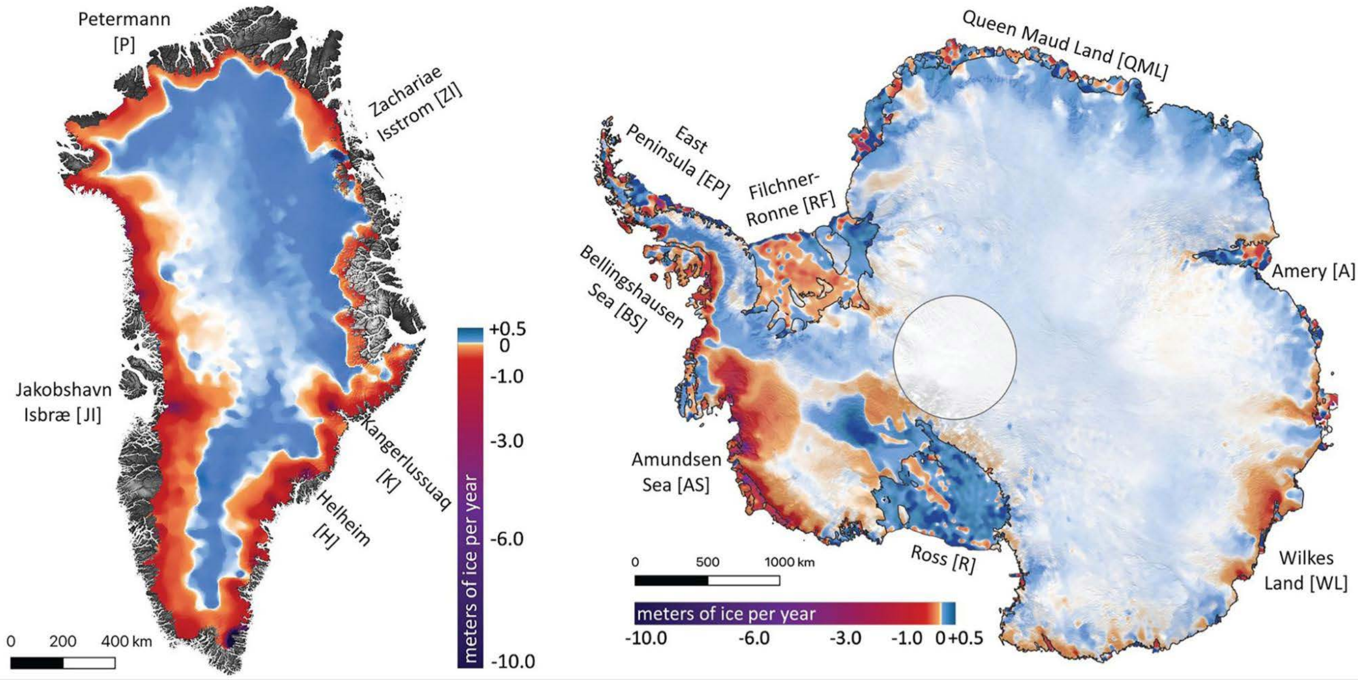

Figure 1.2.4: Observed mass change of Greenland and Antarctic ice sheets. Mass change (mass loss in red, mass gain in blue) between 2003 and 2019 for Greenland and Antarctica, given in metres of ice equivalent per year (from Smith et al., 2020).

Greenland Ice Sheet

The GrIS is a land-based continental ice sheet, with an area of 1.71 million square kilometres. At its margins, ice flows to the sea through marine-terminating outlet glaciers. The currently observed mass loss predominantly occurs through enhanced surface melting and iceberg calving (breaking at the edges) (King et al., 2020; Shepherd et al., 2020). Interactions with the atmosphere play an important role for the overall stability of the ice sheet. Several amplifying and damping feedbacks between the ice sheet and atmosphere are active in a warming climate, and these are associated with different timescales. On short timescales, a warmer climate will, on average, produce more precipitation via the added moisture-carrying capacity of the air. This mitigates some of the mass losses, since it increases accumulation (snow fall) as the climate warms. Atmospheric circulation and wind patterns will also change in response to a changing ice sheet geometry, but the effect on the overall mass balance (i.e. the balance between snow inputs and meltwater/calving outputs) of the ice sheet is not well understood.

Evidence for tipping dynamics

Associated with surface melting is a self-amplifying feedback, the *melt-elevation feedback* (Oerlemans, 1981), in which substantial melt can cause parts of the ice sheet surface to sink to lower elevations, exposing the surface to warmer air masses which in turn can lead to further melt (Figure 1.2.5). This effect is compounded by the *melt-albedo feedback*: as snowpack melts to bare ice, surface albedo (level of reflection) reduces, leading to increased absorption of solar radiation. This in turn leads to further melting and a further albedo reduction (e.g., Box et al., 2012). Glacier algae growing on bare ice can lower albedo further, a process known as the biological albedo feedback (Cook et al., 2020). Both ice sheet modelling and palaeoclimate data indicate that a tipping point can occur when the melt-elevation feedback gets strong enough to support self-accelerating mass loss (Huybrechts, 1994; Robinson et al., 2012; Ridley et al., 2010; Levermann and Winkelmann, 2016).

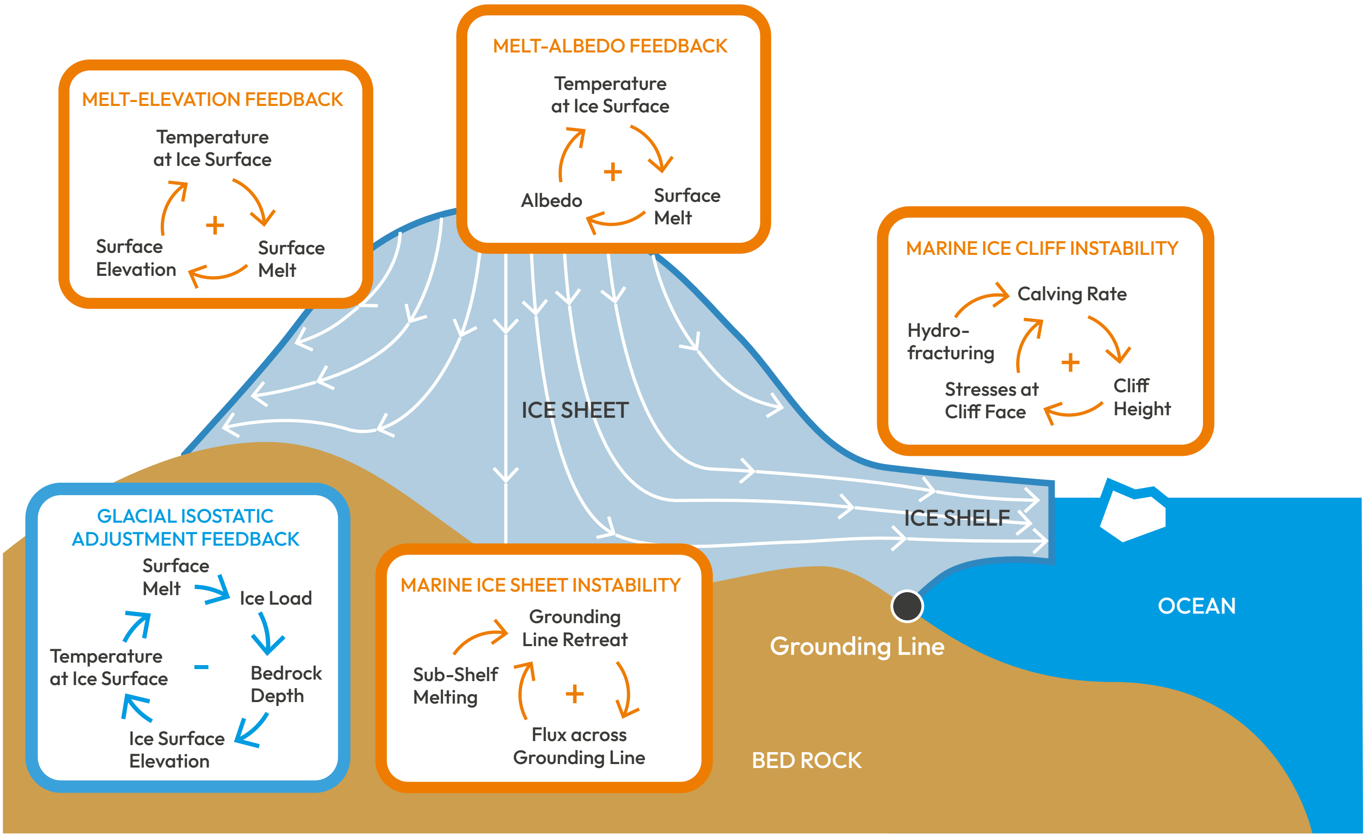

Figure 1.2.5: Schematic illustrating some of the key feedbacks in the ice sheet-climate system. Note that this depiction is limited to the most relevant and widely examined feedbacks, further self-amplifying or damping feedbacks may, however, exist.

On longer timescales (over the course of centuries to millennia), isostatic rebound can also act as a negative/damping feedback on ice sheet retreat (*glacial isostatic adjustment (GIA)*; Whitehouse et al., 2019): a decrease in ice load leads to a slow rebound of the bedrock underneath – as the ice surface is thus lifted to higher elevations with colder surrounding air masses, this can lead to a reduction in surface melt, or even to net accumulation at the surface.

Current estimates for a critical threshold for the GrIS range from 0.8°C to 3°C of warming relative to pre-industrial levels, with a best estimate of about 1.5°C (Robinson et al., 2012; van Breedam et al., 2020; Noël et al., 2021; Höning et al., 2023). This is supported by palaeorecords which indicate that GrIS had at least partially retreated during the MIS-5 interglacial, and likely collapsed during MIS-11, which was 1-2°C warmer than pre-industrial (Christ et al., 2021). At lower warming levels, simulations with a coupled ice sheet atmosphere model indicate that additional atmospheric dynamic changes in precipitation patterns can restabilise the ice sheet, but above 2°C warming, positive/amplifying feedbacks leading to loss of the majority of the ice sheet cannot be overcome (Gregory et al., 2020).

While the respective warming threshold could be reached within the coming decades (Fox-Kemper et al., 2021; Tebaldi et al., 2021), the response times of the ice sheet are such that the ice loss and resulting sea level rise would unfold over several millennia (Robinson et al., 2012; van Breedam et al., 2020). The timescales of ice sheet decline depend on the magnitude of warming beyond this threshold, where stronger warming leads to a faster ice sheet decay (Robinson et al., 2012). Several studies further indicate a strong hysteresis of the GrIS, meaning that substantial ice loss is likely irreversible on multi-millennial timescales (Robinson et al., 2012; Höning et al., 2023).

Slow-onset tipping processes such as ice sheet collapse might also be able to withstand a short period of temperature overshoot if the overshoot time is short compared to the effective timescale of the tipping system (Ritchie et al., 2021). For ice sheets this overshoot time could be in the order of decades to centuries (Ritchie et al., 2021; Bochow et al.,2023), which might for example theoretically allow global warming to overshoot a tipping threshold of 1.5°C and return below it by 2100 without triggering ice sheet collapse (Armstrong McKay et al., 2022). However, such overshoot times are very uncertain, and given the distinct challenges of reducing global temperatures over short time horizons, this possibility should not be relied upon in policy.

Assessment and knowledge gaps

Given the broad evidence base, we have high confidence that the GrIS is a tipping system. This is in line with previous assessments (Fox-Kemper et al., 2021; Armstrong McKay et al., 2022).

West Antarctic Ice Sheet (WAIS)

Since temperatures in Antarctica are generally lower than in Greenland (being centred over the South Pole) and the surface is generally brighter, there is overall less surface melt (Broeke et al., 2023). Recent observations show melt occurrences on ice shelves along the coastline of Antarctica, with most intense melting occuring on the Antarctic Peninsula (Trusel et al., 2013; Jakobs et al., 2020; Lenaerts et al., 2016; Stokes et al., 2019). In contrast to Greenland, however, the currently observed mass loss, especially in the WAIS, is dominated by ocean-induced melting at the underside of the floating ice shelves (e.g., Otosaka et al., 2023; Millilo et al., 2022; Paolo et al., 2015; Adusumili et al., 2020).

Large parts of the WAIS are grounded below sea level (so-called marine basins), surrounded by floating ice shelves, and where these ice shelves are in contact with warmer ocean waters, melting at their base occurs. While the direct contribution to sea level rise of this ice shelf melting is negligible, it plays an important indirect role for the overall mass balance. Due to the thinning of the ice shelves, the buttressing (i.e. the backstress imparted to the grounded ice) is reduced, causing the movement of grounded ice upstream to accelerate, which in turn can lead to substantial sea level rise (Scambos et al., 2004; Rignot et al., 2004; Reese et al., 2018). Substantial ocean warming and ice shelf basal melting is committed in the Amundsen Sea over the 21st Century, which will likely accelerate the retreat of several key WAIS outlet glaciers including the Thwaites and Pine Island glaciers (Naughten et al. 2023).

Evidence for tipping dynamics

Different amplifying feedbacks can lead to self-sustained ice loss from the WAIS once a critical threshold is passed (Figure 1.2.5). One of the key feedbacks is the *marine ice sheet instability* (MISI – Figure 1.2.6, top) (Weertman, 1974; Schoof, 2007; Mengel and Levermann, 2014; Feldmann and Levermann, 2015; Garbe et al., 2020), which can occur where the grounding – the separation line between the grounded ice sheet and floating ice shelves – sits on retrograde bedrock slopes. If the grounding line retreats into regions of greater ice thickness, for instance due to enhanced sub-shelf melting, this increases the flux across the grounding line, leading to further retreat. Such self-sustained retreat may be stabilised by the buttressing effect of ice shelves (Gudmundsson et al., 2012; Pegler, 2018; Haseloff and Sergienko, 2018).

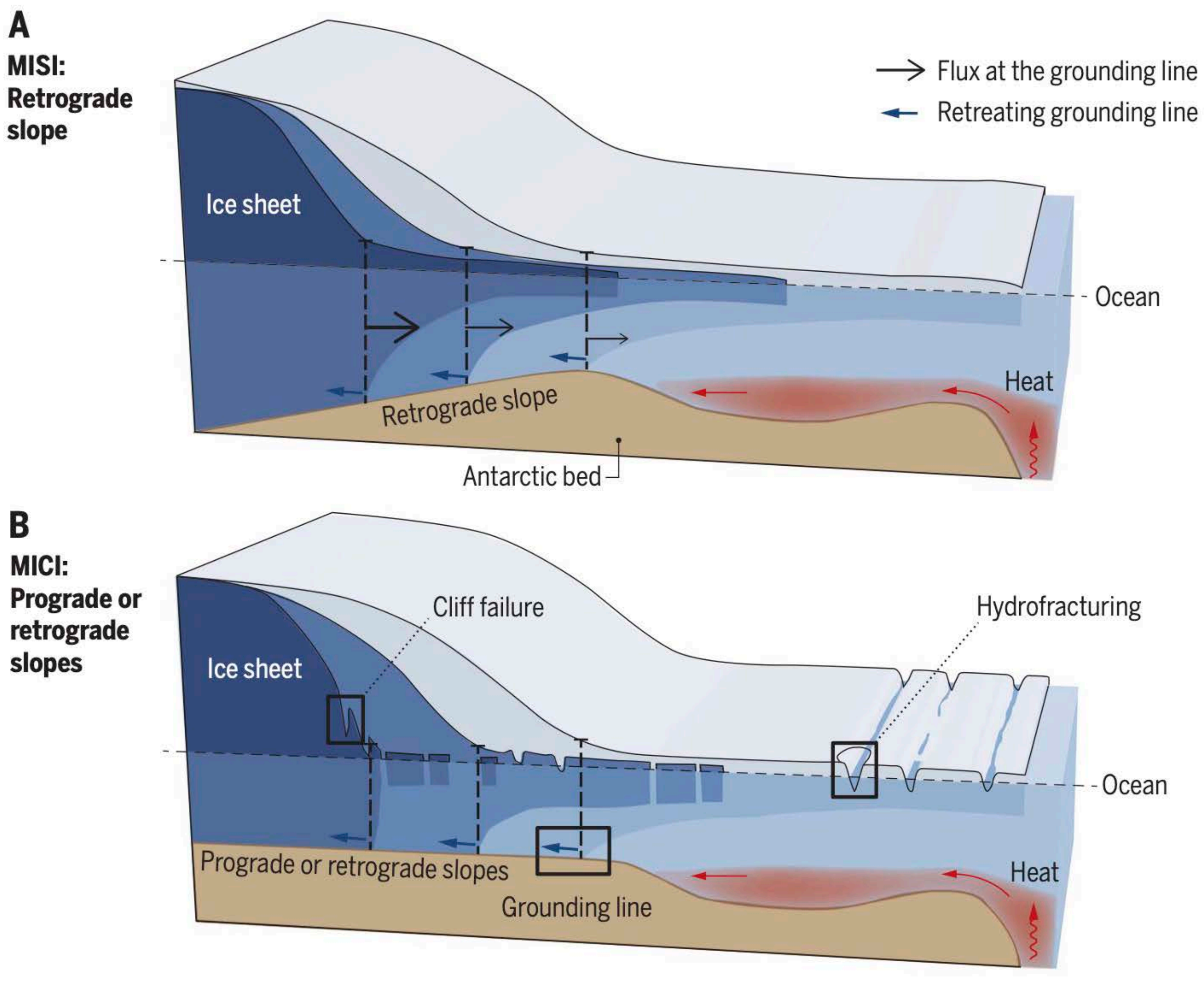

Figure 1.2.6: Schematic illustration of marine ice sheet instability (MISI; top) and marine ice cliff instability (MICI; bottom). From Pattyn and Morlighem (2020) .

The MISI has been suggested to have driven the collapse of WAIS during previous interglacials (Pollard et al., 2015; DeConto and Pollard, 2016; Sutter et al., 2016; Turney et al., 2020; Thomas et al., 2020; Weber et al., 2021). There is also palaeoclimate evidence for a collapse of WAIS and around 20m higher sea level (implying substantial Antarctic Ice Sheet loss) during ~2-3°C warmer periods of the Pliocene, (Naish et al., 2009; Grant et al., 2019; DeConto et al., 2021). It has further been suggested that this instability might already be underway in the Amundsen Sea Embayment, including at the Thwaites and Pine Island glaciers (Rignot et al., 2014; Joughin et al., 2014; Favier et al., 2014; Turner et al., 2017; De Rydt et al., 2021).

While a recent intercomparison study using three different ice sheet models (Hill et al., 2023) concluded that the current observed retreat of grounding lines in West Antarctica is not yet driven by this instability, mounting evidence from modelling studies (e.g., Reese et al., 2023; Seroussi et al., 2017; Arthern and Williams 2017; Golledge et al., 2021; Garbe et al., 2020) suggests that, unless the current warming trend is reversed to colder conditions in the near future, parts of the WAIS such as the Amundsen basin would be committed to long-term irreversible grounding-line retreat driven by MISI. The loss of the Amundsen basin alone would raise global sea levels by roughly 1.2 metres, (Morlighem et al., 2020). Additional large-scale ice sheet changes in West Antarctica could be triggered in the coming decades in response to projected warming. Due to the long response time of the ice sheet, the respective mass loss would unfold and sea level thus keep rising for centuries to millennia (Golledge et al., 2015; Winkelmann et al., 2015).

Another proposed destabilising feedback mechanism is known as *marine ice cliff instability* (MICI – Figure 1.2.6, bottom*)* (Bassis and Walker, 2012; Bassis and Jacobs, 2013; Pollard et al., 2015; DeConto and Pollard 2016). The MICI hypothesis proposes that tall marine-terminating ice cliffs, which could result from ice shelf collapse, for example, are inherently unstable and could rapidly collapse, potentially associated with a self-reinforcing and irreversible inland ice retreat on both retrograde and prograde sloping marine beds. Such retreat would proceed until water depths shallow or the ice cliff is buttressed (DeConto and Pollard, 2016). The critical height of the ice cliff resulting in its failure depends on the ice properties and the extent of crevassing, but is currently poorly constrained (Bassis and Walker, 2012). In addition, processes potentially mitigating or slowing the self-sustained ice retreat due to MICI such as mélange buttressing or the speed of the preceding ice shelf disintegration introduce additional uncertainties (Clerc et al., 2019; Edwards et al., 2019; Robel and Banwell 2019; Schlemm et al., 2022; Pollard et al., 2018). Low confidence has been assigned to this process in the latest IPCC assessment (IPCC AR6 WG1 Ch9), partially because it has not yet been observed (Needell and Holschuh, 2023).

Assessment and knowledge gaps

Based on these different lines of evidence, there is high confidence that the WAIS is a tipping system, with the potential for widespread, and at least partly irreversible ice loss. Recent estimates of the respective global warming levels at which such tipping dynamics are triggered range from 1°C to 3°C of warming compared to pre-industrial levels (Garbe et al., 2020; Golledge et al., 2017; Reese et al., 2023). This means that the complete decline of the WAIS could be triggered by warming projected under higher-emission scenarios for this century (Chambers et al., 2022; Golledge et al., 2015).

Due to the complexity of interacting processes with the other parts of the climate system and their lack of representation in fully coupled (Earth system) models, it remains a challenging task to reduce the respective uncertainty range and project the resulting ice loss in the near future. For example, the potential effect of ocean stratification or solid-Earth feedbacks on grounding line migration is currently not well-constrained (e.d., Kachuk et al., 2020; Larour et al., 2019; Gomez et al., 2020; Coulon et al., 2021; Golledge et al., 2019). Given the high vulnerability of the WAIS and the far-reaching consequences of its potential collapse, it is important to narrow down the critical thresholds, and in particular the timing of the onset of potential large-scale retreat.

Marine basins East Antarctica

The East Antarctic marine basins include the Wilkes, Aurora and Recovery Basins, and 19.2 metres of sea level equivalent (Fretwell et al., 2013). They have been proposed as 'global core' climate tipping systems, due to the potential for instabilities in the marine ice sheet and ice cliff (Garbe et al., 2020; Armstrong McKay et al., 2022). The processes affecting the marine basins of East Antarctica are thus similar to those described above for the WAIS.

Evidence for tipping dynamics

Outlet glaciers in the Aurora subglacial basin, for instance Totten and Denman glaciers, already experience acceleration, retreat and mass loss at present (e.g., Rignot et al., 2019; Shepherd et al., 2019; Rintoul et al., 2016; Li et al., 2015, 2016; Miles et al., 2021; Shen et al., 2018). There is limited evidence for change in Recovery and Wilkes basins in current observations (e.g., Gardner et al., 2018). However, palaeorecords and models suggest the ice margin may have undergone substantial retreat deep inland of Wilkes subglacial basin during Pleistocene interglacials (Blackburn et al., 2020; Wilson et al., 2018; Iizuka et al., 2023) and in warm periods of the Pliocene (Cook et al., 2013; DeConto et al., 2021; Blasco et al., 2023 [in review]) with global mean atmospheric warming of at least 1-2°C above pre-industrial, as suggested by palaeorecords (Blackburn et al., 2020). Other work has suggested that ice sheet retreat in the Wilkes subglacial basin remained relatively limited during the Last Interglacial, when Southern Ocean sea surface temperatures were about 1-2°C and Antarctic surface air temperatures were at least 2°C above pre-industrial averages (Capron et al., 2017; Hoffman et al., 2017; Chandler and Langebroek, 2021), placing an upper sea-level contribution from the Wilkes basin during that period at 0.4-0.8 m (Sutter et al., 2021).

Recent model simulations show that the risk of substantial sub-shelf melt-induced or calving-induced ice loss and the associated timescales vary strongly for the individual subglacial basins (Garbe et al., 2020): A drainage of the Recovery basin may be driven by oceanic warming of 1-3°C (Golledge et al., 2017), while self-sustained grounding-line retreat in the Wilkes basin is initiated in models when exceeding an atmospheric warming of 2-4°C above present-day levels (Garbe et al., 2020; Golledge et al., 2017). The decay of the drainage basin may occur over a time period of centuries to tens of thousands of years, as indicated in palaeorecords (Bertram et al., 2018) and model experiments (Mengel and Levermann, 2014), depending on the warming trajectory (DeConto and Pollard, 2016). Modelling studies suggest that ice loss from the Aurora subglacial basin is triggered when sustaining stronger warming of about 5-8°C above present-day levels (Garbe et al., 2020; Golledge et al., 2017; Winkelmann et al., 2015; Bulthuis et al., 2020; Van Breedam et al., 2020; Golledge et al., 2015). Palaeo evidence and models suggest that, once triggered, ice loss from these marine basins can only be reversed if the climate were to cool far below pre-industrial levels, leading to hysteresis behaviour (Garbe et al., 2020; Mengel and Levermann, 2014).

Assessment and knowledge gaps

Being characterised by self-sustained dynamics as well as abrupt and irreversible changes beyond a warming threshold in various studies, we identify the marine basins of East Antarctica as parts of the cryosphere exhibiting tipping behaviour with high confidence, in line with previous assessments (Armstrong McKay et al., 2022). Further work is needed to better constrain existing estimates of critical thresholds and timescales from available ice sheet modelling and palaeoclimate data for individual subglacial basins – for example, by improving the treatment of sub-shelf melt and taking into account model and parametric uncertainty.

Non-marine East Antarctica

In East Antarctica, a major part of the ice sheet initially built up at the Eocene-Oligocene transition is grounded above sea level (DeConto and Pollard, 2003; Liu et al., 2009; Morlighem et al., 2020; Hutchinson et al., 2021). At present, observations still indicate mass gain in this terrestrial part of the Antarctic Ice Sheet (for instance, in Dronning-Maud Land) though mass balance estimates are associated with high uncertainties (Otosaka et al., 2023; Schröder et al., 2019). As such, West Antarctic ice loss over the past decades was balanced to some extent by mass accumulation in East Antarctica (Medley and Thomas, 2019).

Evidence for tipping dynamics

Long-term model assessments suggest that large-scale ice loss from terrestrial regions of East Antarctica may be induced for global mean atmospheric warming of 6°C or higher above pre-industrial levels (Garbe et al., 2020) until East Antarctica potentially becomes completely ice-free. Given the wide range of warming projected in the recent sixth phase of the Coupled Model Intercomparison Project (CMIP6), exceedance of respective critical forcing levels cannot be excluded beyond the end of this century under high emissions (e.g. SSP5-8.5 and SSP3-7.0 in the 22nd century; IPCC AR6 WG1 Ch4) in combination with a high climate sensitivity (Tebaldi et al., 2021). The disintegration of the land-based portions of the East Antarctic Ice Sheet may eventually raise global mean sea level by ~34 m (Fretwell et al., 2013), but unfolding over multi-millennial timescales (~10,000 years or longer) according to modelling studies (Winkelmann et al., 2015; Clark et al., 2016).

Here, the *melt-elevation feedback* (similar to the GrIS) propels self-sustained mass loss by enhancing surface melt once the respective tipping point is crossed. It also gives rise to pronounced hysteresis behaviour with distinct stable ice sheet configurations within a range of climatic boundary conditions (Garbe et al., 2020; Pollard and DeConto, 2005; Huybrechts 1994). A strong cooling is consequently required for regrowth of the terrestrial East Antarctic Ice Sheet, and sustained cooling to at least pre-industrial temperature levels to recover its present-day volume and extents (Garbe et al., 2020). Due to this hysteresis, large land-based portions of the East Antarctic Ice Sheet persisted for more than 8 million years (Shakun et al., 2018) through the warm intervals of the early to mid-Miocene, 23-14 million years ago (Gasson et al., 2016; Levy et al., 2016).

Assessment and knowledge gaps

Self-amplifying feedback mechanisms (such as the melt-elevation feedback) can occur in East Antarctica, contributing to abrupt and irreversible ice sheet changes with a substantial impact through sea level rise beyond a critical threshold. There are few modelling studies on multi-millennial timescales covering the warming range that may be relevant for the potential nonlinear response of the terrestrial ice sheet in East Antarctica.

Thus, there is medium confidence in the assessment of the non-marine East Antarctic Ice Sheet as a cryospheric tipping system. Reducing uncertainties in temperature thresholds and timescales of collapse requires multi-model ensembles and better representation of ice surface processes, as well as the inclusion of interaction with the rest of the climate system. Additionally, more research on how climate forcing varies regionally and interacts with regional processes and feedbacks would help better constrain the drivers and timescale of tipping.

1.2.2.2 Sea ice

Sea ice is frozen sea water that floats on the sea surface. It forms in the polar oceans whenever the temperature of the sea water drops below its freezing point of around -1.8°C. The formation and growth of sea ice therefore requires a sufficient heat loss from the ocean to the atmosphere, which in today's climate occurs in both polar regions from autumn to spring. During this period, sea ice is expanding, while during summer it is retreating.

While the formation of sea ice through heat loss to the atmosphere is similar in both polar regions, the dominating process for sea ice decay in summer differs between the two hemispheres. In the North, where the sea ice is largely landlocked by the land masses surrounding the pole, the loss of sea ice is primarily driven by atmospheric heat input that melts the sea ice. In the southern hemisphere, however, the summer loss of sea ice is primarily governed by the export of sea ice through northward winds that move the ice into regions of warmer sea water, which then melts the ice from below. The freeze-melt cycle of sea ice gives rise to substantial seasonal variations in the polar sea ice coverage (Figure 1.2.7 and Figure 1.2.9), whose magnitude is an indicator for the very fast response time of sea ice, in particular relative to other cryospheric systems such as permafrost, glaciers and ice sheets.

Given the different processes that are relevant for the regional and seasonal response of sea ice to global warming, in the following we differentiate our assessment of tipping potential between Arctic summer sea ice, Arctic winter sea ice, Barents Sea ice, and Southern Ocean sea ice.

Arctic summer sea ice

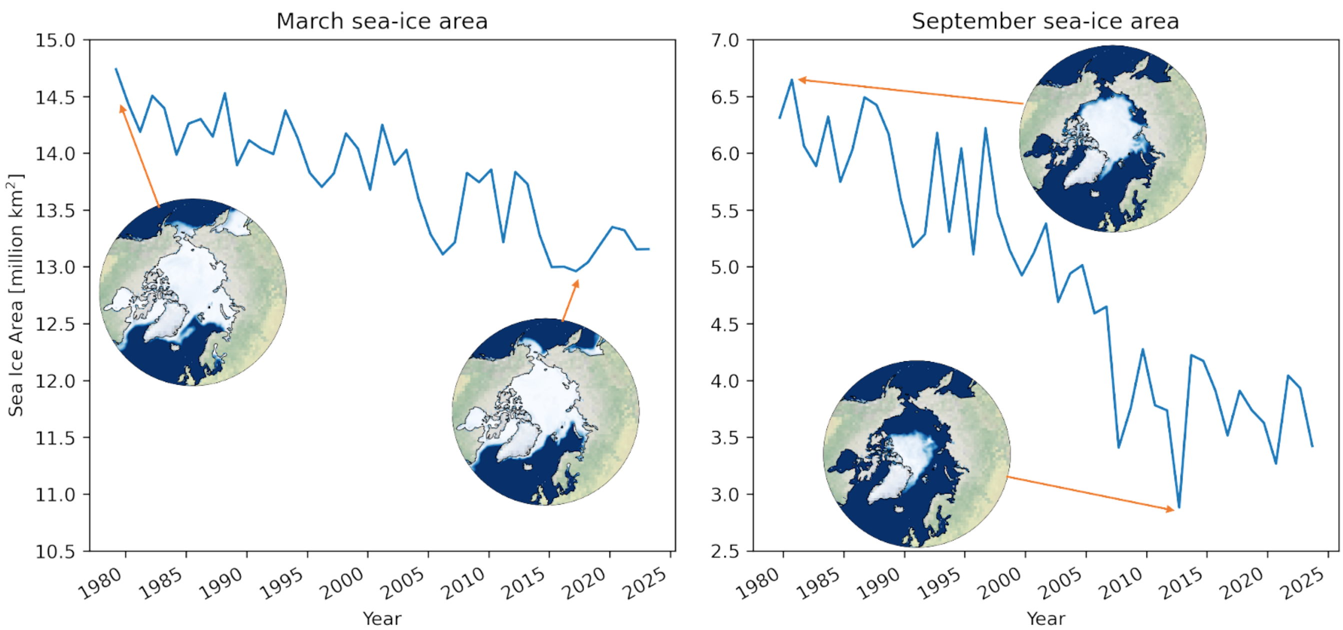

Figure 1.2.7: Arctic sea ice evolution 1979-2023. Time series of Arctic sea ice area, with insets showing sea ice concentration in selected years. March is usually the month of maximum sea ice area ('winter sea ice'), September is usually the month of minimum sea ice area ('summer sea ice'). Data: OSI SAF (Lavergne et al. 2019) [time series: OSI SAF Sea ice index 1978-onwards (v2.2 2023); sea ice concentration before 2020: OSI SAF Global sea ice concentration climate data record 1978-2020 (v3.0, 2022); sea ice concentration after 2020: OSI SAF Global sea ice concentration interim climate data record (v3.0, 2022)].

Evidence for tipping dynamics

In summer, the retreating sea ice cover in the Arctic exposes the much darker ocean surface to the atmosphere, giving rise to the ice-albedo feedback: Less ice implies an additional uptake of heat, implying further ice loss. This mechanism was hypothesised to give rise to a nonlinear tipping point behaviour for the loss of Arctic summer sea ice (e.g., Lenton et al., 2008).

However, a large variety of studies based on both conceptual models and coupled Earth system models have provided convincing evidence that the summer ice-albedo feedback is compensated by damping feedbacks in winter that minimise the long-term memory of the Arctic summer sea ice cover (Figure 1.2.8). This dominance of negative/damping feedbacks gives rise to a linear retreat of the Arctic summer sea ice cover with ongoing global warming (e.g., Gregory et al., 2002; Winton, 2006; Winton, 2008; Notz, 2009; Tietsche et al., 2011; Mahlstein and Knutti, 2012; Wagner and Eisenman, 2015).

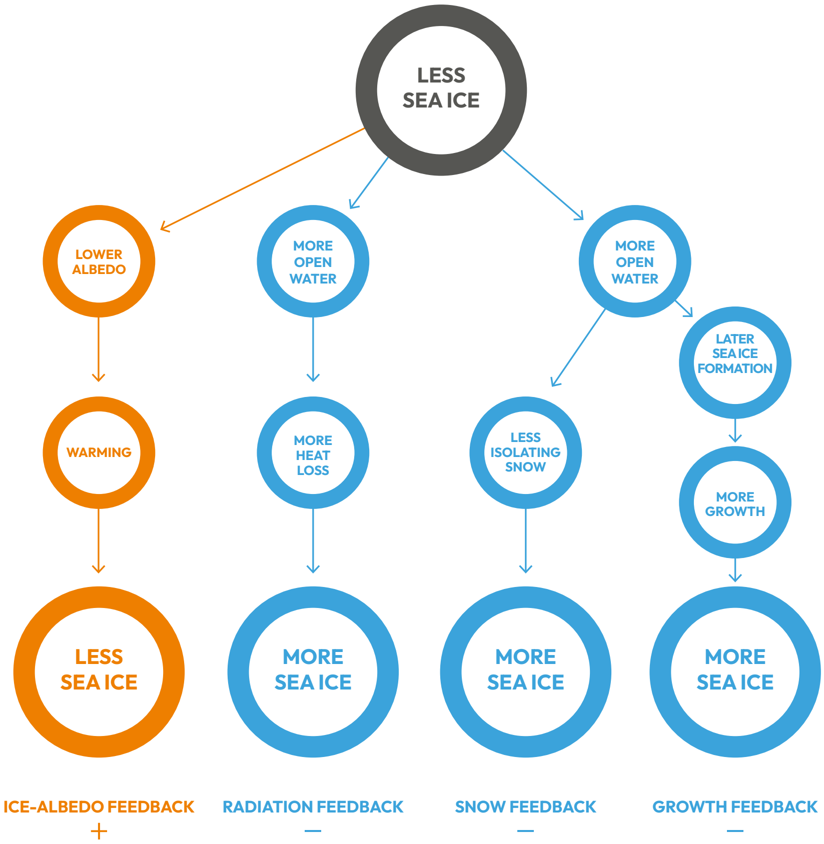

Figure 1.2.8: Schematic illustrating some of the key feedbacks related to Arctic sea ice loss. Note that this depiction is limited to the most relevant and widely examined feedbacks; further self-amplifying or damping feedbacks may, however, exist. Based on Notz and Bits (2016).

Based on this understanding, the response of the sea ice cover to global warming is expected to remain linear as a function of global mean temperature (e.g., Gregory et al., 2002; Winton, 2011; SIMIP 2020) and thus as a function of CO_2 emissions (Zickfeld et al., 2012; Notz and Stroeve, 2016) until the complete loss of the summer sea ice cover that is expected to occur for the first time before 2050 in all future climate scenarios (SIMIP, 2020; Kim et al., 2023). If, in the future, atmospheric CO_2 were to decrease, for example by the technological removal of CO_2, there would be some time lag before global temperature would decrease in response. This hysteresis then carries over to the relationship between CO_2 concentration and sea ice area. The relationship between sea ice area and hemispheric mean temperature, however, has been found to remain linear also for a cooling climate (e.g., Armour et al., 2011; Li et al., 2013; Jahn, 2018).

Assessment and knowledge gaps

The assessment of a linear, threshold-free loss of Arctic summer sea ice is in line with recent assessments (Fox-Kemper et al., 2021; Armstrong McKay et al., 2022). Given the very broad evidence base, we have high confidence in the assessment of Arctic summer sea ice not being a tipping system. This confidence could be increased further if climate models would more reliably capture the observed evolution of the Arctic sea ice cover – for example regarding its linear sensitivity to observed global warming (SIMIP, 2020). A comprehensive assessment of climate model performance is, however, hampered to some degree by the difficulty to obtain reliable, long-term observations of the sea ice thickness distribution (SIMIP, 2020). Some progress in this regard can be expected in the near future, with the recent development of an approach to retrieve sea ice thickness throughout the entire seasonal cycle using remote sensing (Landy et al., 2022).

Arctic winter sea ice

For the loss of summer sea ice, the existing ice cover needs to be melted completely, which is a gradual process. The loss of winter sea ice, however, is governed by a different mechanism: given that the Arctic will already be ice-free in summer, the formation of new ice needs to become impossible to lose the winter sea ice cover. Winter sea ice will form in the Arctic Ocean as long as the water temperature at the ocean surface drops below the freezing point – around -1.8°C for typical saline ocean water – but will no longer form once the water temperature remains above freezing all year round. This binary behaviour of the Arctic Ocean lies at the heart of the analysis of the ongoing loss of the Arctic winter sea ice cover.

Evidence for tipping dynamics

Both in some simple models and in some complex climate models, the loss of Arctic winter sea ice area accelerates drastically once a given warming threshold has been reached (e.g., Winton, 2006; Eisenman and Wettlaufer, 2009; Bathiany et al., 2016). However, this acceleration is simply a consequence of the geometry of the Arctic Ocean: as the climate warms, the winter sea ice edge moves northward. As long as the ice edge is located in the narrow straits that connect the Arctic Ocean to the south, the freely moving ice edge is short and only a little ice is lost by its northward movement. Once the ice edge becomes located in the central Arctic Ocean, more sea ice area is lost for a given retreat of the ice edge, and ice loss accelerates. This acceleration therefore occurs in most models as soon as the winter maximum sea ice area drops below around 8m sq km, which is roughly the area of the Arctic Ocean and its adjacent seas (Goosse et al., 2009; Eisenman, 2010).

Beyond this threshold, the loss of the winter sea ice cover occurs faster than the loss of the summer sea ice in CMIP5 models. This can be explained by the fact that the future formation of winter sea ice from a largely ice-free ocean will lead to a geographically rather homogenous distribution of winter sea ice thickness, such that larger areas can become ice-free simultaneously (Bathiany et al., 2016).

In modelling studies, the faster loss in winter compared to summer has additionally been found to be related to the increased humidity and the related increased downward longwave radiation, for example from convective clouds in areas of open water (Abbot and Tziperman, 2008; Abbot et al., 2009; Li et al., 2013; Hankel and Tziperman, 2021). While this process could potentially imply hysteresis behaviour of the loss of Arctic winter sea ice, the loss of winter sea ice has been shown to be fully reversible in a number of dedicated modelling studies (Armour et al., 2011; Ridley et al., 2012; Li et al., 2013). In particular, for a cooling of the climate induced by the removal of CO_2, studies have found no hysteresis of Arctic winter sea ice area as a function of hemispheric mean temperature, while they found a time lag between the decrease of atmospheric CO2 concentration and the resulting increase of Arctic winter sea ice area. This can be explained by the delayed response of atmospheric temperature to the removal of CO_2, and the potential nonlinear response of oceanic heat transport (Li et al., 2013; Schwinger et al., 2022).

Assessment and knowledge gaps

Based on this assessment, there is currently only very limited support for a dominating role of self-perpetuating processes that would make Arctic winter sea ice a tipping system. Given the difficulty of climate models to realistically simulate the processes that govern the loss of winter sea ice and the related oceanic response, we have medium confidence in the assessment of Arctic winter sea ice not being a tipping system.

Barents Sea ice

Sea ice in the Barents Sea – the sector of the Arctic Ocean north of Scandinavia and Western Russia – is treated as a sub-case of Arctic winter sea ice in Armstrong et al., (2022), who categorised it as a regional impact climate tipping system with medium confidence.

Evidence for tipping dynamics

In the Barents Sea, which is only ice-covered in winter, sea ice loss is primarily driven by an increase in lateral oceanic heat inflow of warm Atlantic water (Docquier et al., 2020; Smedsrud et al., 2021; Muilwijk et al., 2023). Because of this tight coupling, in almost all models the sea ice loss is largely linearly related to changes in oceanic heat transport (Docquier et al., 2020) with only one model showing an abrupt loss of the Barents Sea sea ice cover in winter in a dedicated study (Drijfhout et al., 2015). The loss of the Barents Sea winter sea ice cover might reinforce itself through related changes in atmospheric circulation, but there is no consensus among studies that examined these linkages (e.g., Haarsma et al., 2021; Smith et al., 2022 and references therein). The sea ice loss could also reinforce itself through a related increase in the inflow of warm Atlantic water (Lehner et al., 2013) but very few studies have examined this in detail.

Assessment and knowledge gaps

In summary, there is currently no clear support for the Barents Sea winter sea ice cover being a tipping system. We have low confidence in this assessment, given the very low number of respective studies.

Southern Ocean sea ice

In the Southern Ocean, the amount of sea ice is much more dominated by the combination of oceanic and atmospheric processes than in the Arctic, which gives rise to a much more pronounced seasonal cycle of the Antarctic sea ice area compared to the Arctic (Figure 1.2.9). Generally, the area of sea ice in the Southern Ocean is determined by the balance of ice formation near the continent and ice melt through oceanic heat further away from the coast, where the ice is advected by the prevailing winds and currents. Variations in ice coverage can therefore largely be explained by weaker northward transport of the ice, by increased melting from increased upward oceanic heat transport, and/or by weakened ice formation (e.g., Maksym, 2019). The regional distribution of sea ice growth with its related brine release, and sea ice melt with the release of freshwater, in turn affects the stratification and circulation of the Southern Ocean (see Chapter 1.4 and e.g., Abernathey et al., 2016).

Over the full satellite record from 1979 onwards, there is no significant trend in Antarctic sea ice coverage (e.g., Fox-Kemper et al., 2021). The maximum sea ice coverage of the observational record was recorded in 2014, while the minimum sea ice coverage was recorded in 2022/2023 (Figure 1.2.9). The low ice coverage of the past two years can be linked to changes in the prevailing wind patterns that are caused by changes in the prevailing large-scale atmospheric modes (e.g., Zhang and Li, 2023; Wang et al., 2023), and 2023's historic low has been suggested to represent a new low ice regime resulting from ocean warming (Purich and Dodderidge, 2023). However, given the shortness of the signal, it is currently unclear whether this change in the sea ice forcing will persist, which then could cause a significant, long-term decline of the Antarctic sea ice cover.

Evidence for tipping dynamics

Given the very long response time of the Southern Ocean to climatic changes, and given the potential long-term changes in the Southern Ocean circulation in response to irreversible changes in ice sheet dynamics, hysteresis behaviour can be expected to exist for the long-term loss of Southern Ocean sea ice. Such hysteresis is indeed identified in a number of dedicated studies (Ridley et al., 2012; Li et al., 2013), but is explained by a lagged response of the sea ice cover to the imposed warming and cooling. This dynamic hysteresis behaviour is therefore a consequence of the long response time of the Southern Ocean. Whether or not one considers this behaviour truly hysteretic is a question of the timescales of relevance.

Assessment and knowledge gaps

There is currently limited evidence for a self-amplification of Southern Ocean sea ice loss, and we cannot estimate a related temperature threshold. We have low confidence in the assessment of the future evolution of Antarctic sea ice given the difficulties of large-scale climate models to reproduce its observed evolution. This shortcoming of the models might be related to the dominating impact of small-scale eddies in the ocean which low-resolution climate models cannot explicitly resolve. Another shortcoming is the current absence of reliable satellite retrievals of Southern-Ocean sea ice thickness that would be crucial for a detailed model evaluation. This is expected to be addressed with new satellite technologies including, for example, the Surface Water and Ocean Topography (SWOT) mission (Armitage and Kwok, 2021).

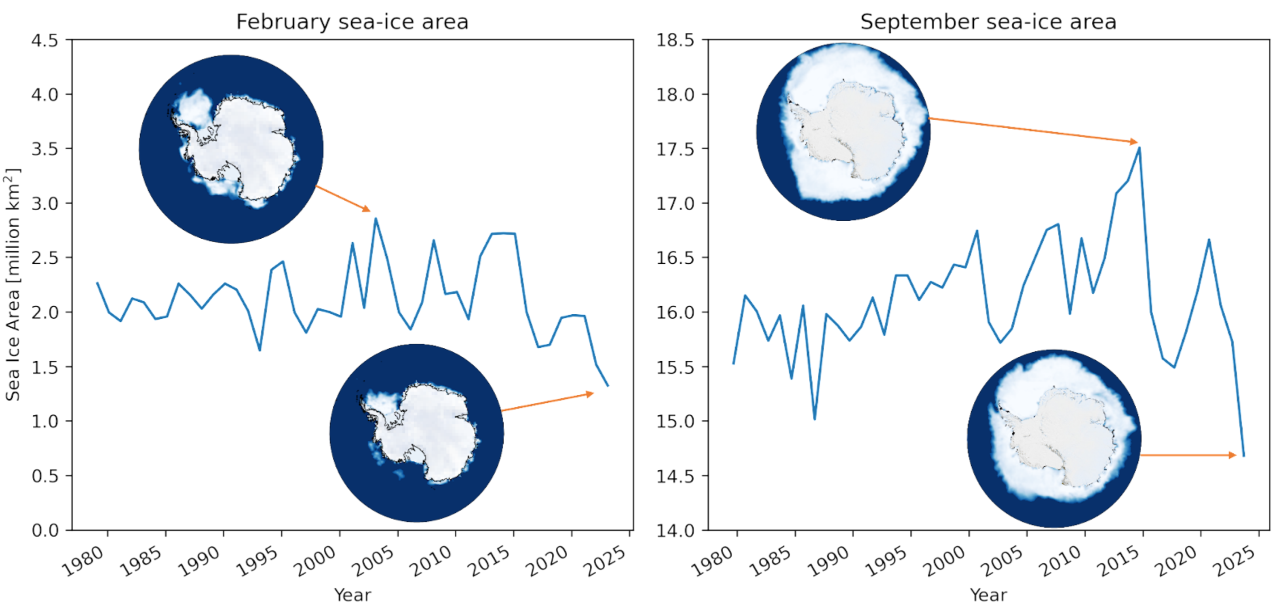

Figure 1.2.9: Antarctic sea ice evolution 1979-2023. Time series of Antarctic sea ice area, with maps showing sea ice concentration in selected years. February is usually the month of minimum sea ice area ('summer sea ice'). September is usually the month of maximum sea ice area ('winter sea ice'). Data: OSI SAF (Lavergne et al. 2019) [time series: OSI SAF Sea ice index 1978-onwards (v2.2 2023); sea ice concentration before 2020: OSI SAF Global sea ice concentration climate data record 1978-2020 (v3.0, 2022); sea ice concentration after 2020: OSI SAF Global sea ice concentration interim climate data record (v3.0, 2022)].

1.2.2.3 Glaciers

Glaciers outside the Greenland and Antarctic ice sheets (here termed mountain glaciers) are spread over high altitudes and high latitudes. A range of processes contribute to their individual mass balances, most notably solid precipitation (mainly snow) and surface melt, but also, among others, calving into lakes or ocean (Hock et al., 2019; Meredith et al., 2019). Mass balance thresholds and feedbacks may impact individual glaciers, but when aggregated to the global scale glacier changes are projected to respond relatively linearly this century (Rounce et al., 2023). At longer timescales and higher warming levels, nonlinear characteristics are projected as glaciers disappear (Marzeion et al., 2018).

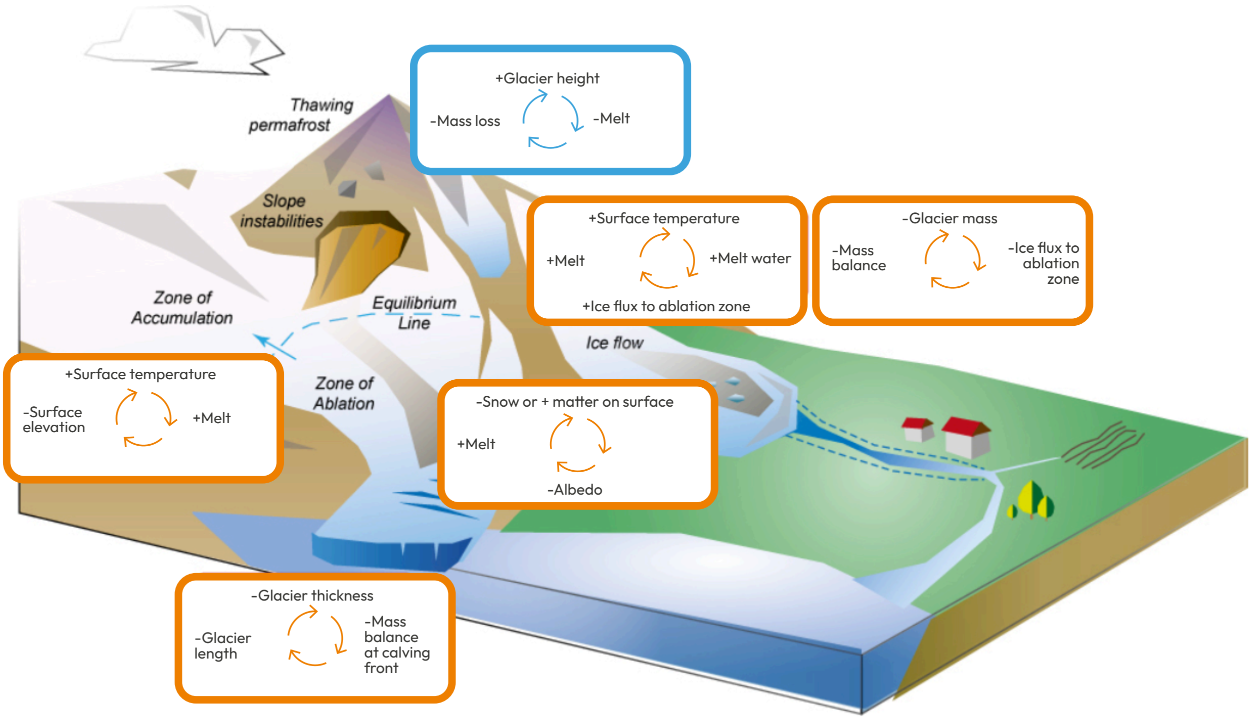

Figure 1.2.10: Terminology and some of the key feedbacks related to mountain glacier retreat. 'Positive' amplifying feedbacks that amplify ice loss are shown by red boxes, and 'negative' damping feedbacks that limit ice loss are shown by blue boxes. Above the equilibrium line (dashed blue line) glaciers accumulate snow and therefore mass, and below they 'ablate' – i.e. melt and lose moss. Note that this depiction is limited to the most relevant and widely examined feedbacks – further self-amplifying or damping feedbacks may, however, exist.

Evidence for tipping dynamics

In glaciers close to the melting point, the physical nature of ice inherently involves nonlinear feedbacks, in particular related to interactions between ice and water such as enhanced subaqueous ice melt, heat transport into the ice, or lubrication at the glacier bed. Such feedbacks act typically on the spatial scale of individual glaciers (Figure 1.2.10).

Dynamic instabilities of glaciers such as surges or even catastrophic detachments, but also less pronounced ice velocity fluctuations, can be related to increased melt-water production through positive/amplifying feedback mechanisms (Truffer et al., 2021; Kääb et al., 2021). However, these processes are still not very well understood and there is little evidence so far indicating that such processes could act synchronously over entire glacier regions (Kääb et al., 2023). On a regional scale, loss of ice thickness appears to rather reduce glacier flow speeds (Dehecq et al., 2019). Significantly increased ice flux, such as through surges, transports ice from high-elevation zones characterised by low rates of ice melt (ablation) to low-elevation zones with high ablation rates.

In contrast, retreat rates of calving glaciers, most of them found in polar regions, are understood to be governed by a feedback where a thinning of the glacier tongue (the narrow floating part of a glacier extending into the sea or a lake) leads to loss of glacier grounding at a topographic pinning point (places where a ridge or valley narrowness slows down glacier flow). This loss of pinning leads to accelerated glacier retreat, associated with increased ice flow velocities, calving rates and further thinning of the tongue, until they stabilise again at a new pinning point or retreat out of the water (Strozzi et al., 2017; Kochtitzky et al., 2022a). Once a destabilisation threshold is passed through processes at the ice-ocean or ice-atmosphere interface, the retreat phase is largely self-perpetuating, independent of climatic conditions or their changes (Pfeffer, 2007). In turn, calving glaciers need typically substantial positive mass balances in order to advance through deep water to a new pinning point. Nonlinear enhanced retreats of calving fronts can be roughly synchronised on regional levels and are in fact a significant component of the current mass loss of polar glaciers, roughly 20-25 per cent (Kochtitzky et al., 2022b).

Glaciers impact atmospheric conditions at their surface by increasing local surface altitude, enabling a feedback between surface elevation and mass balance. Ice thinning can drop glaciers into higher melt ('ablation') zones, while a rise in the equilibrium line altitude (ELA – the elevation where local mass balance, i.e. snow input versus melt output, is zero) can shift glaciers into lower snow accumulation zones, with both potentially leading to disproportionately large shifts when large areas of glacier are concentrated in narrow elevation bands. These elevation feedbacks could possibly be regionally synchronised at similar global warming levels, for instance for Arctic ice caps. These effects are typically included in regional and global glacier mass balance models and thus in projections (Rounce et al., 2023; Marzeion et al., 2020).

Reduced glacier albedo, for instance from deposition of dust, black carbon or thin debris, but also through reduced snow cover, significantly increases glacier mass loss (Cook et al., 2017; Naegeli and Huss 2017). Related mass balance feedbacks can happen when years with particularly negative mass balance lead to enhanced accumulation of albedo-reducing matter on the glacier surface, enhancing in turn glacier ablation (Gabbi et al., 2015). Another type of positive/amplifying feedback is deposition of wind-driven dust originating from adjacent mountain areas, a process that is believed to increase with continued uncovering of glacial sediments from ice and snow. Such feedbacks involving albedo can be assumed to affect nearby glaciers in similar ways, and thus represent potential regional effects that are not included in large-scale models yet.

On local scales, abrupt permafrost thaw processes creating 'thermokarst' features (see 1.2.2.4) can be self-perpetuating by enhancing the ice melt in particular of low-angle glacier tongues with low ice flow speeds. Such processes particularly impact debris-covered glaciers, most prominently through the growth of supraglacial ponds on them. There is evidence that such thermokarst processes can enhance glacier ablation on regional scales (Kääb et al., 2012; Buri et al., 2016, Compagno et al., 2019).

Glacier shrinkage has a range of local to global effects. Several types of glacier hazards can increase in frequency and magnitude as a consequence of glacier retreat, such as debris flows or rock slides and rock avalanches (Hock et al., 2019). Slope instabilities and the uncovering of formerly ice-covered areas leads to increased mobilisation of sediments with both negative (e.g. sedimentation of river infrastructure) and positive (e.g. release of nutrients) downstream impacts. Also the formation of glacier lakes, and thus the potential for glacier lake outbursts, is associated with glacier retreat (Carrivick and Tweed 2016; Linsbauer et al., 2016).

Changes in glacier river runoff can have impacts on ecosystems (Bosson et al., 2023) and humans, in particular where dry-season water supply is to a large extent depending on glacier ablation. Whereas peak water – the shift from increased runoff from enhanced glacier melt to reduced runoff under continued shrinking of glacier ares – constitutes on regional scales a soft decadal-scale transition rather than a threshold (Huss and Hock 2018), drastic declines of dry-season glacier melt runoff can exert strong pressure on ecosystems, hydropower production and irrigation, for example (Hock et al., 2019). It is important to note that the significance of glacier runoff for downstream areas depends on the seasonally variable percentage of glacier runoff in comparison to other sources of runoff, such as liquid precipitation or snow melt (Kaser et al., 2010). Measurements and projections of glacier mass loss alone are thus only meaningful in relation to potential impacts as part of a seasonally resolved hydrological balance. On longer time-scales and regional spatial scales, pronounced regional glacier shrinkage (or even partial disappearance of glaciers) leads to a transition from glacier-dominated to paraglacial landscape systems, with fundamental changes in all abiotic and biotic processes in the region and its downstream areas (Knight and Harrison, 2016).

Such a transition to a paraglacial landscape system may exhibit threshold-like behaviour, if climate change is happening rapidly relative to glacier response times, which can span from decades to centuries (Jóhannesson et al., 1989, Haeberli and Hoelzle, 1995). The lagged response of glaciers can lead to a substantial disequilibrium between glacier extent and concurrent climate conditions, such that a large part of a glacier's mass is committed to be lost, even though this loss has not yet been realised. On the global scale, the committed mass loss for present-day glaciers is estimated around 30 per cent (Bahr et al., 2009, Mernhild et al., 2013, Marzeion et al., 2018), but regionally it can be substantially higher (~60 per cent in central/northern Europe and ~50 per cent in western Canada/US).

Sea level contribution represents the most global but also most integrating consequence of global glacier mass loss and does not show threshold behaviour because any positive/amplifying feedbacks acting at the glacier or regional scale are averaged out in the huge ensemble of individual glaciers (c. 200,000) (Hock et al., 2019, Marzeion et al., 2020, Hugonnet et al., 2021).

Assessment and knowledge gaps

Glacier shrinkage involves a number of nonlinear, self-perpetuating processes that mostly act on local scales. Few of these feedbacks seem to be able to reach magnitudes and regional synchronisations substantial enough to enhance regional glacier shrinkage in a nonlinear way. However, the potentially large disequilibrium between glacier extent and concurrent climate implies that, regionally, glaciers may be synchronously transitioning from one state to another, even if the individual glaciers' tipping points are distributed over a broad temperature range. Such effects might explain the almost synchronous retreat of Arctic tidewater glaciers (Kochtitzky et al., 2022a, Malles et al., 2023). Elsewhere, glacier shrinkage is mostly a reversible response to climatic change, despite the irreversible changes that may happen on local scales, such as glacier-related slope failures.

Glaciers can recover from mass loss, but may need much more time for recovery than for melt. Reversibility of biophysical or social downstream effects of glacier shrinkage also requires long timescales (Hock et al., 2019). It is also important to note that a number of negative damping feedbacks are involved in glacier response to atmospheric warming – most importantly the retreat of glaciers to higher elevations, where they experience lower melt rates, or the thickening of insulating debris covers related to increased production of debris associated with reduced ice cover and permafrost on adjacent mountain flanks (e.g., Compagno et al., 2022). We assess with medium confidence that, while glaciers are not tipping points on a global scale, at a regional scale they may be subject to self-sustained retreat tipping points.

A number of the aforementioned glacier feedback processes are not, or not adequately, represented in numerical models. This limitation of models is motivated by the complexity of the processes and the lack of ability to resolve the relevant local scale in the atmosphere and ocean models providing the boundary conditions for the glacier models. The current regional or global glacier projections are struggling to predict the integrated behaviour of local feedbacks and their interactions accurately, and the thresholds and timescales at which slow but nonlinear associated responses of glaciers might emerge are not well known. First results from recent advances in the representation of local feedbacks indicate so far that also in the future the positive/amplifying feedbacks are mostly relevant at the local scale, hardly affecting regional and global scale projections (Compagno et al., 2022, Malles et al., 2023).

1.2.2.4 Permafrost

Permafrost is defined as ground frozen for at least two consecutive years (Van Everdingen, 2005) (Figure 1.2.11). Permafrost underlies about 14 million sq km (15 per cent of the land surface area) in the Northern Hemisphere (Obu, 2021), mainly in Russia, Canada, the US (Alaska), and China (Tibetan Plateau). In addition, there is about 2.5 million sq km of relict permafrost in the Arctic shelf seafloor (Overduin et al., 2019), which was submerged by rising sea levels at the end of the ice age.

Figure 1.2.11: Thawing coastal permafrost in Arctic Canada, with person for scale. Credit: G. Hugelius, taken from Pihl et al., 2021

Permafrost landscapes are complex. They commonly exhibit an active layer, which is the uppermost layer of soil or ground that thaws during the warmer months of the year and freezes again during colder months (Figure 1.2.12). Permafrost is further characterised by factors such as variable topography, ground ice presence, vegetation dynamics, and soil climatic conditions. For example, the presence of hills, valleys and slopes affects the distribution and characteristics of continental permafrost at different spatial and temporal scales. The interaction and feedback between these factors contribute to the complexity of permafrost environments and suggest a variety of potential responses of the permafrost domain to climatic changes.

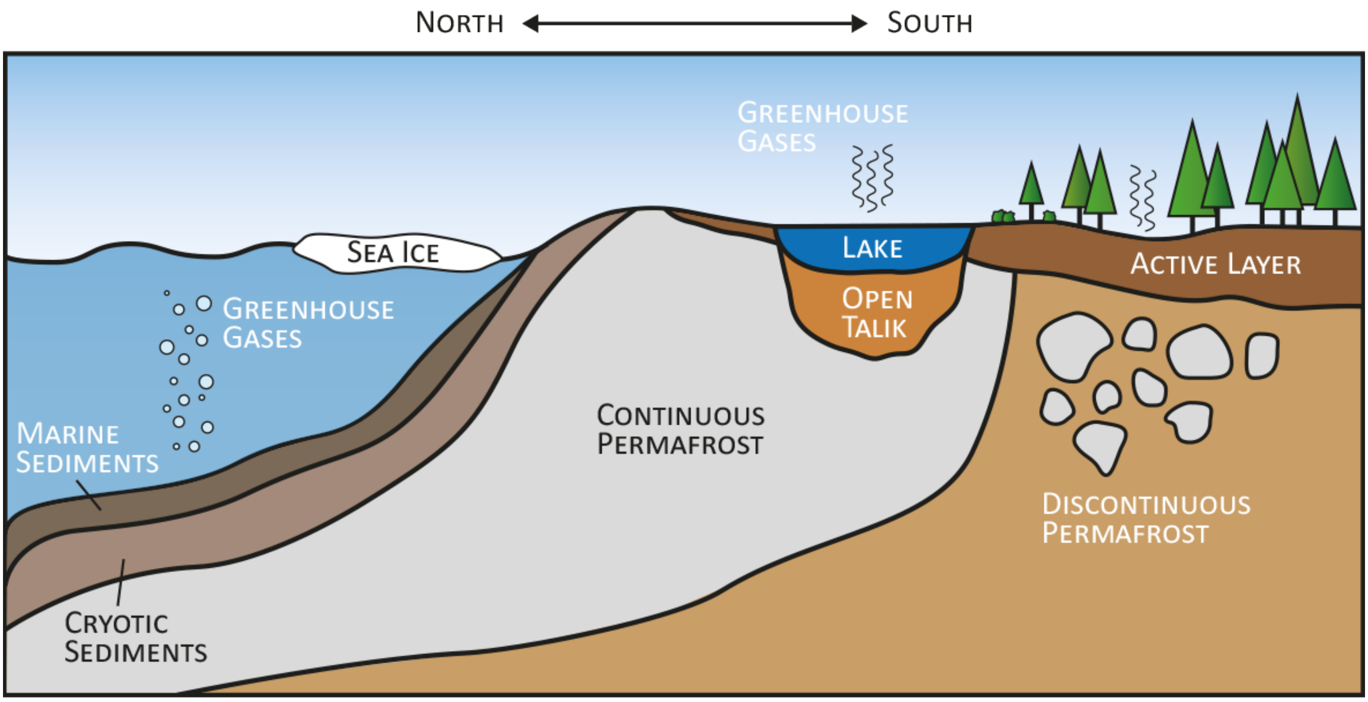

Figure 1.2.12: Schematic showing typical permafrost landscape features. Inspired by Lantuit et al., (2012).

Vast amounts of organic carbon and ground ice that accumulated during past cold climates in northern high latitudes are still preserved in permafrost today. The frozen conditions in permafrost soils prevent the microbial decomposition of organic material accumulated in the past during relatively warm summers. Currently, it is estimated that the upper three metres of permafrost soils contain about 1,035 ±150 GtC (Hugelius et al., 2014) or about 50 per cent more than today's atmosphere (Figure 1.2.13). Subsea permafrost stores additional organic matter estimated at between 560 (Sayedi et al., 2020) and 2,822 (1,518-4,982) GtC (Miesner et al., 2023). Further, permafrost also contains or caps large quantities of frozen methane and other gases. Such deposits are known as permafrost-associated gas hydrates and a conservative estimate suggested that about 20 GtC are currently locked in permafrost-associated gas hydrates (Ruppel, 2015).

Over the last four decades, the Arctic warmed almost four times faster than the rest of the globe (Rantanen et al., 2022). Ongoing climate change causes thawing of permafrost soils (Schuur et al., 2015, 2022; McGuire et al., 2018), which leads to the subsidence, erosion and potential collapse of the previously frozen ground in regions of diverse permafrost landforms. The degradation of organic matter and the dissociation of permafrost-associated gas hydrates are linked to the release of carbon dioxide (CO_2) and methane (CH_4) into the atmosphere as a consequence of permafrost thaw. This carbon loss is irreversible over several centuries.

These permafrost carbon emissions contribute to a positive climate feedback in which GHG emissions lead to additional warming, which, in turn, releases more GHG. This is called the permafrost carbon-climate feedback (Koven et al., 2011, Schuur et al., 2015, 2022, Canadell et al., 2021).

Current-generation climate models suggest a net positive impact of the permafrost carbon-climate feedback on global climate with estimates of additional warming of 0.05-0.7°C by 2100 (Schaefer et al., 2014, Burke et al., 2018, Kleinen and Brovkin, 2018, Nitzbon et al., 2023) based on low- to high-emissions scenarios, respectively. Methane emissions from permafrost could temporarily contribute up to 50 per cent of the permafrost-induced radiative forcing due to its higher warming potential (Walter Anthony et al., 2016, Turetsky et al., 2020, Miner et al., 2022). Overall, however, Canadell et al. (2021) summarise that "thawing terrestrial permafrost will lead to carbon release (high confidence), but there is low confidence in the timing, magnitude and relative roles of CO_2 and CH_4" of the permafrost carbon-climate feedback.

In addition, permafrost thaw impacts society in the permafrost region through changes at the land surface, e.g. wetting or drying of landscapes, ground subsidence due to melted ice, damaged infrastructure (roads, buildings, pipelines), and ecosystem changes such as ocean acidification or eutrophication (Hjort et al., 2018, 2022; Miner et al., 2021, Langer et al., 2023) (see Chapter 2.2 for societal impacts).

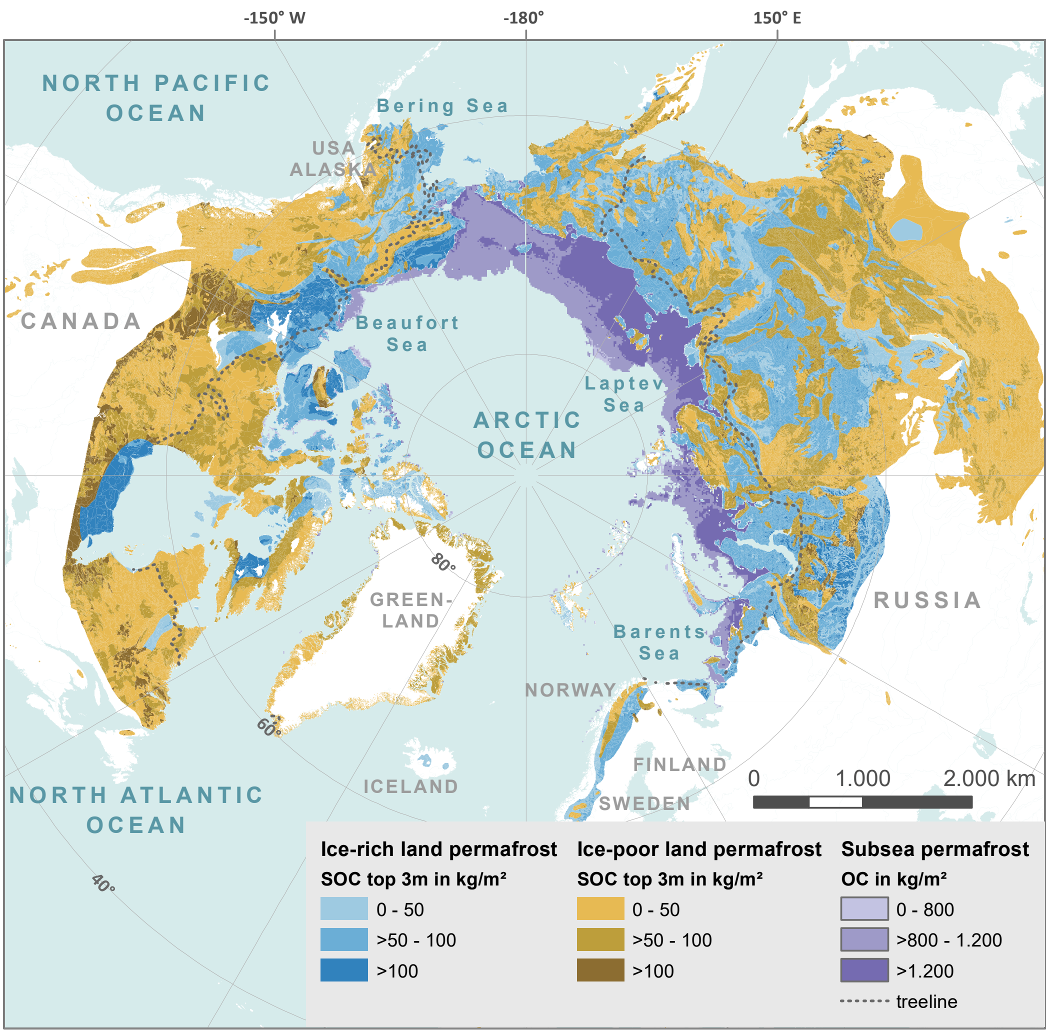

Figure 1.2.13: Map of estimated organic carbon storage (kgCm^{-2}) in the northern circumpolar permafrost region, combining terrestrial soil organic carbon contents (SOC, upper 3m) according to Hugelius et al. (2014) and subsea organic carbon contents according to Miesner et al. (2023). The terrestrial region is further divided into ice-rich and ice-poor regions according to Brown et al. (1997), where the ice-rich region is roughly coinciding with the areas susceptible to thermokarst and rapid thaw processes.

Evidence for tipping dynamics

Permafrost thaw is commonly denoted as gradual or abrupt. On land, gradual thaw occurs wherever the upper layer of thawed soil (active layer) gets successively deeper every year. Based on current projections, there is a high level of confidence that continued warming will result in ongoing, gradual declines in the volume of near-surface permafrost. It is anticipated that for every additional 1°C of warming, there will be a 25 per cent reduction in the global volume of perennially frozen ground found near the surface (Arias et al., 2021), which happens over the course of years to decades. The associated decomposition of permafrost carbon takes place on longer timescales, from centuries to millennia.

These models also suggest that the amount of carbon released from gradual thaw is roughly proportional to the amount of global warming in low- to high-emission scenarios, with the best estimate being 18 (3-41) GtC per degree of global warming (Canadell et al., 2021; Burke et al., 2017, 2018). Permafrost carbon release represents a relatively higher contribution to the remaining carbon budget for low-emission scenarios (Gasser et al., 2018; Kleinen and Brovkin, 2018), specifically when the permafrost carbon-climate feedback is taken into account in the carbon budget estimates (Canadell et al., 2021).

Abrupt or rapid thaw occurs where excess or massive ice is present in the ground and leads to the development of 'thermokarst'. When the ice melts and drains away, the land surface subsides. This leads to the development of characteristic landforms such as thaw lakes, thaw slumps, or eroding gullies and valleys (Figure 1.2.14). Their development is reinforced by increased heat conductivity of water and the decreasing stability of water body edges that further increases their size. Thus, these processes can permanently transform permafrost landscapes. Environments in which these processes are expected to occur are estimated to cover about 20 per cent of the present Arctic permafrost region (Olefeldt et al., 2016).

Thermokarst processes can occur in response to local disturbances or across regions experiencing rapid warming or extreme events, and positive/amplifying feedbacks can drive rapid permafrost loss (Nitzbon et al., 2020). Further, it is estimated that carbon emissions related to abrupt thaw processes could contribute an additional 40 per cent of emissions from newly formed features such as thaw slumps and thermokarst lake and wetland formation, which may double the radiative forcing from circumpolar permafrost-soil carbon fluxes (Turetsky et al., 2020; Walther Anthony et al., 2018). However, these processes are dependent on local environmental conditions that are unevenly distributed across the permafrost region (Olefeldt et al., 2016). Thus, despite the rapid nonlinear response at local-to-regional scale, the permafrost thaw and carbon emissions from thermokarst processes are likely to aggregate to a near linear response globally (Nitzbon et al., 2023).

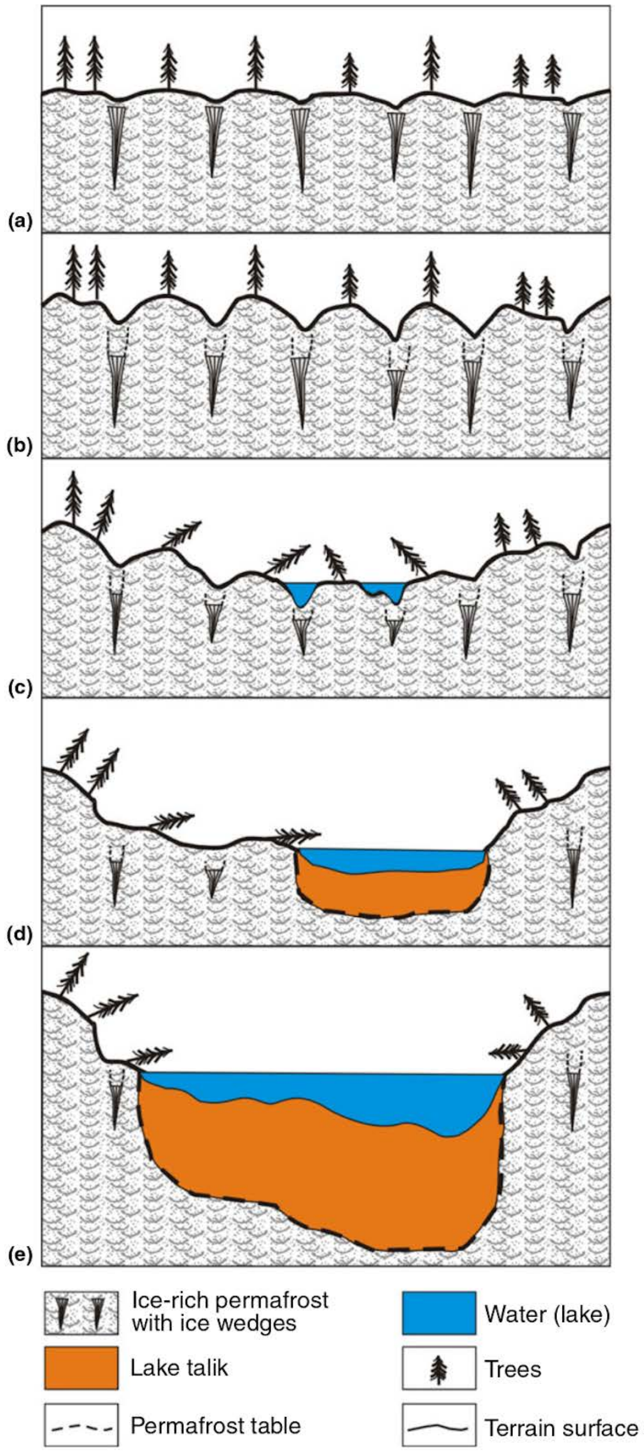

Figure 1.2.14: Schematic of abrupt thaw processes and landforms (thermokarst lake formation in ice-rich permafrost; from top to bottom) in continuous permafrost. Adapted from Grosse et al., (2013).

The loss of ground ice and the ecosystem changes are irreversible, with many local implications on topography and hydrology, including subsidence, drying or wetting, and changes in the microbial communities. In this context, microbial heat production was hypothesised as a possible self-reinforcing feedback on permafrost thaw (Khvorostyanov et al., 2008, Hollesen et al., 2015), but a consequential abrupt release of permafrost carbon through this 'compost bomb' mechanism (Clarke et al., 2021) is assessed to be unlikely. It would require organic carbon of very high quality and large quantity as well as comparably low ice contents, but such environmental preconditions are not prevailing over vast areas of the permafrost region. Accordingly, large-scale modelling studies found this effect to be of minor (Koven et al., 2011) or negligible (de Vrese et al., 2021) relevance to future projections of permafrost region carbon emissions.

While nonlinearity of the permafrost response to warming is exemplified in rapid thaw on local-to-regional scales, it is uncertain how these changes propagate to a larger scale. Some studies argue that an interaction of local feedbacks could lead to a quasi-linear response on a global scale (Schuur et al., 2015, Chadburn et al., 2017, Hugelius et al., 2020, Nitzbon et al., 2023), while others found multiple stable states in the permafrost system with potential nonlinear response on a large scale (de Vrese and Brovkin, 2021).

For the permafrost carbon-climate feedback to have large-scale tipping behaviour, it must be strong enough to cause self-sustaining permafrost loss beyond a certain warming threshold at either a global or subcontinental scale. Current AR6-based estimates yield a small positive amplification factor, indicating that the permafrost carbon-climate feedback is too small to be self-perpetuating on a global scale (Nitzbon et al., 2023). However, for future projections, both 'offline' permafrost models and Earth system models do not capture large-scale abrupt thawing throughout the Arctic.

Important processes such as interactions between fire, vegetation, permafrost, and carbon, as well as the potential for sudden releases through thermokarst phenomena, are currently not consistently considered (Natali et al., 2021). As a result, existing projections of permafrost thaw under various temperature thresholds are likely to be underestimates, indicating that the actual thaw potential may be greater than currently predicted.

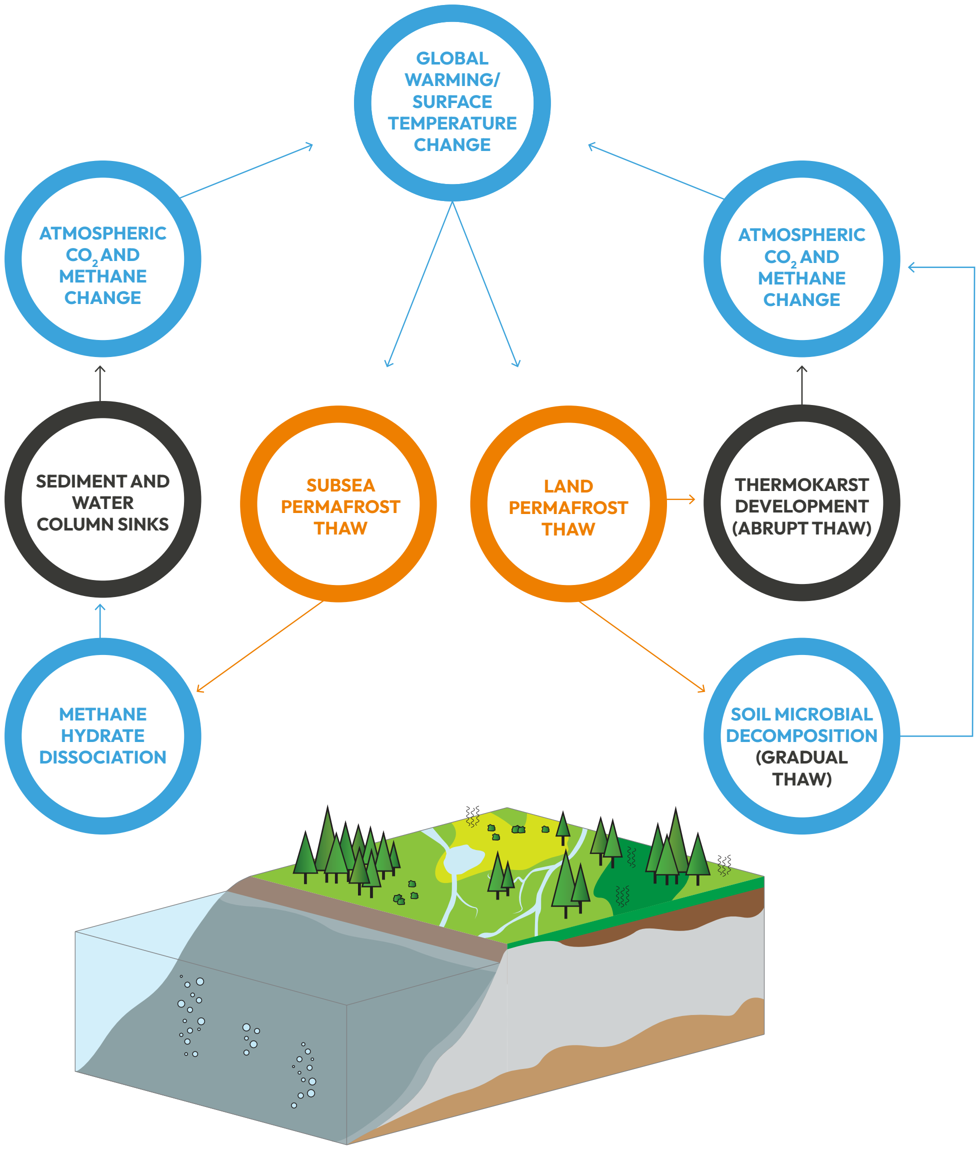

Figure 1.2.15: Schematic showing feedback processes related to land and subsea permafrost.

Since the flooding of the Arctic shelf after the last ice-age, the ocean floor has been exposed to relatively slow warming with small seasonal changes. Therefore subsea permafrost is thawing at a slow but continuous rate, leading to carbon emissions of 0.048 (0.025-0.085) Gt/yr (Miesner et al., 2023), an order of magnitude smaller than terrestrial permafrost carbon emissions (Figure 1.2.15). The disappearance of sea ice that has an insulating effect on ocean water temperature or major circulation changes in the Arctic Ocean may accelerate gradual thaw of subsea permafrost (Wilkenskjeld et al., 2022). However, this degradation process happens too slowly to support abrupt methane release (Reagan and Moridis, 2007; O'Connor et al., 2010). In addition, permafrost-associated gas hydrates within and below subsea permafrost are stabilised by the temperature and pressure conditions created by the permafrost. Permafrost thus acts as a lid on these GHG reservoirs and warming is expected to take centuries to penetrate them (Dmitrenko et al., 2011; Marín-Moreno et al., 2013). Some of these hydrates are relict deposits that are not necessarily stable under current conditions, but are self-preserving.

Subsea permafrost thaw only shows a delayed and dampened response to climate warming. In addition, microbial degradation rates are slow and strong methane sinks in both sediment and ocean likely limit net GHG emissions (James et al., 2016, Ruppel and Kessler, 2016). Another important aspect is the long timescale of permafrost thaw. Instantaneous changes in GHG emissions are quasi-linear, but committed changes on a centennial-to-millennial timescale could be nonlinear – as, for example, when a large area with frozen carbon storages is simultaneously affected by a strong warming. An example from palaeoclimate is a stepwise increase in atmospheric CO_2 concentration in response to an abrupt warming at about 14,700 years ago, plausibly explained by the permafrost thaw (Köhler et al., 2014).

Assessment and knowledge gaps

Accounting for its potential nonlinear response to warming, permafrost was considered a tipping system in numerous previous assessments (Armstrong Mckay et al., 2022, Fabbri et al., 2021, Yumashev et al., 2019, Schellnhuber et al., 2016, Steffen et al., 2018, IPCC AR6, Hamburg Climate Future Outlook). However, the aggregation of nonlinear or rapid local-to-regional permafrost degradation as a result of global warming results in a quasi-linear transient response of global permafrost extent on decadal to centennial timescales (Burke et al., 2020). The resulting permafrost carbon-climate feedback is likely positive, but current climate conditions do not support its self-sustenance, hence permafrost thaw is not expected to cause runaway global warming.

We conclude that permafrost exerts localised tipping points, which, however, do not aggregate to a large-scale tipping point at a global temperature threshold on decadal to centennial timescales. Similarly, subsea permafrost thaw happens relatively slowly, resulting in carbon emissions a magnitude smaller than from terrestrial permafrost. According to the strength of the available evidence, we have medium confidence in these assessments of both land and subsea permafrost.

The communication of a specific tipping threshold for permafrost could give a false sense of a temperature 'safe zone' at which permafrost is less vulnerable.

The effects of permafrost degradation are already seen today with implications for ecosystems and societies, where committed changes will continue to be relevant for centuries. Given the current modelling limitations, improvements in modelling permafrost dynamics will improve the confidence of evaluating permafrost stability, carbon loss, response linearity, and their impact on global climate.

1.2.3 Final remarks

With continued global warming, *all* parts of the cryosphere will be at increasing risk of further decline. For some parts of the cryosphere (like the ice sheets), this is likely to be characterised by tipping dynamics, while for others (like Arctic sea ice), it will occur gradually but surely, following the global warming trajectory. Due to the long response times of these systems, certain cryospheric elements are linked to committed long-term impacts. Major risks for each of the cryosphere elements for different levels of global warming are summarised in Figure 1.2.16. What is evident: despite the different dynamics and characteristics of ice sheet retreat, glacier decline, sea ice loss and permafrost thaw, the consequences of climate-induced changes in the cryosphere will be far-reaching and impact the livelihoods of millions of people.

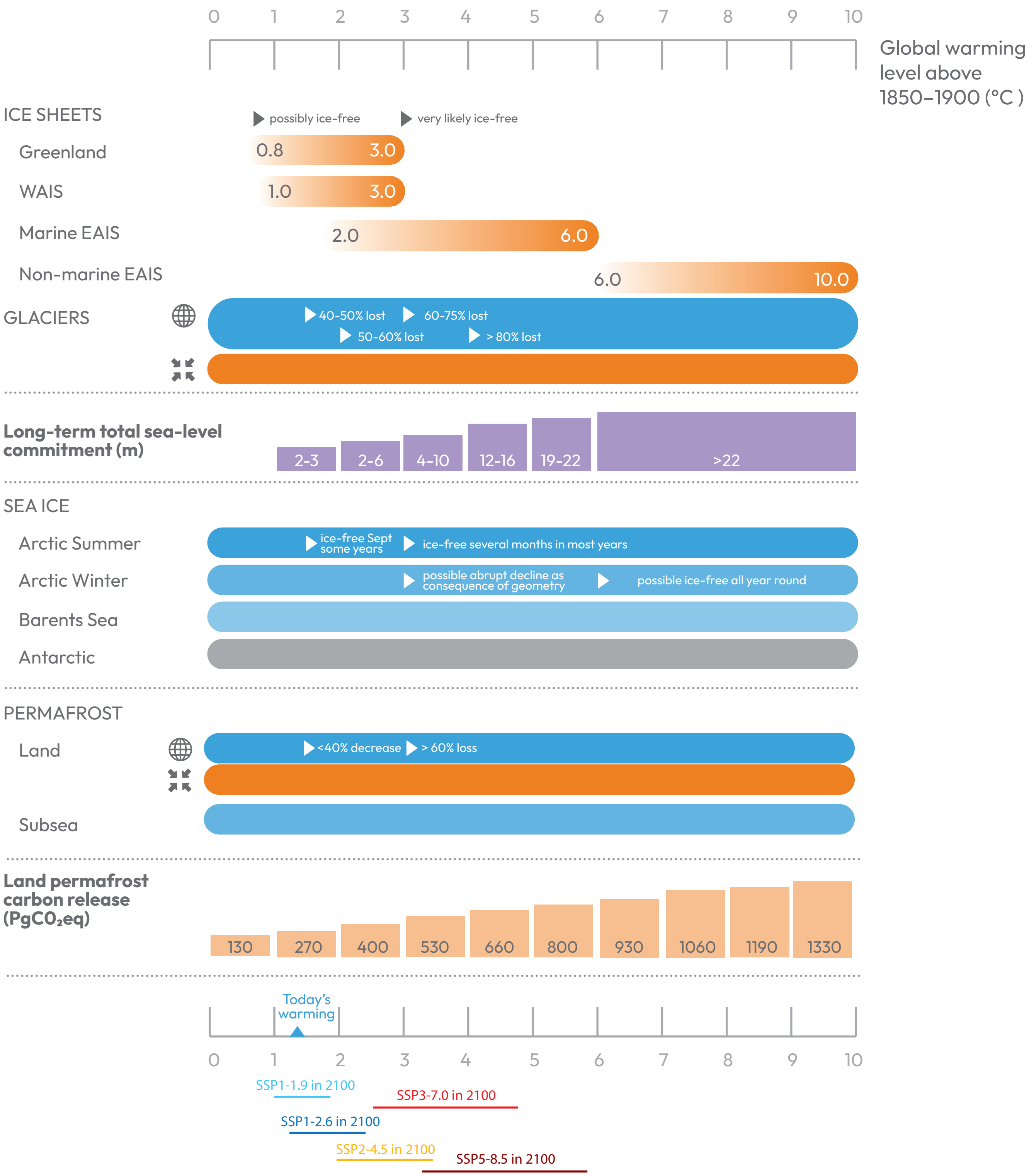

Figure 1.2.16: Increasing risks for cryosphere tipping elements with global warming. Potential thresholds (for ice sheets, glaciers, sea ice and permafrost) and impacts (long-term committed sea level rise and carbon release) are shown for different levels of global warming. Values for glacier thresholds, sea level commitment, Arctic summer sea ice, and land permfrost (for surface permafrost) are from Kloenne et al. (2023), land permafrost carbon release estimates are from Nitzbon et al. (2023), and SSP emission scenarios are from IPCC (2021). Sea level rise is 2000 yr commitment including thermosteric contribution with respect 1995-2014, and permafrost carbon release is relative to1850-1900." This figure is inspired by Kloenne et al., (2023).

Chapter 1.3 Tipping points in the biosphere

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Summary

This chapter assesses scientific evidence for tipping points across the biosphere, which comprises Earth's ecosystems. Human-driven habitat loss, pollution, exploitation and, increasingly, climate change are degrading ecosystems across the planet, some of which can pass tipping points beyond which a 'regime shift' to an alternative (and often less diverse or beneficial) ecosystem state occurs.

Evidence for tipping points emerges across many biomes. In forests, large parts of the Amazon rainforest could tip to degraded forest or impoverished savanna, while tipping in boreal forests is possible but more uncertain, and whether current temperate forest disturbance could lead to tipping is unclear. In open savannas and drylands, drying could lead to desertification in some areas, while in others encroachment by trees and shrubs could see these biodiverse ecosystems shift to a forested or degraded state. Nutrient pollution and warming can trigger lakes to switch to an algae-dominated low-oxygen state. Coral reefs are already experiencing tipping points, as more frequent warming-driven bleaching events, along with pollution, extreme weather events and diseases, tip them to degraded algae-dominated states. Mangroves and seagrasses are at risk of regional tipping, along with kelp forests, marine food webs and some fisheries, which are known to be able to collapse.

Together, these tipping points threaten the livelihoods of millions of people, and some thresholds are likely imminent. Stabilising climate is critical for reducing the likelihood of widespread ecosystem tipping points, but tackling other pressures can also help increase ecological resilience, push back tipping and support human wellbeing.

Key messages

- Evidence exists for tipping points in a variety of ecosystems, including forest dieback, tree and bush encroachment in savanna and grasslands, dryland desertification, lake eutrophication, coral reef die-off and fishery collapse.
- Several biomes (such as mangroves and the Amazon rainforest) are losing resilience and approaching key tipping thresholds, with current warming levels already triggering coral reef die-off tipping points in multiple regions.
- Ecosystem tipping points can be driven by many different drivers (including, but not limited to, climate change) that interact in complex ways across many species and feedbacks, making it harder to assess whether tipping points may be imminent.

Recommendations

- Reduce pressure on global ecosystems through the urgent phase-out of greenhouse gas emissions as well as tackling exploitation, habitat loss and pollution.
- Promote ecological resilience through adaptive management, ecosystem restoration and inclusive conservation, supporting sustainable livelihoods and rights for Indigenous peoples and local communities, and improved governance of land and oceans.
- Address deep uncertainties around feedbacks controlling ecosystem tipping and the impacts of increasingly extreme events, plant adaptability and spatial variability through more and better-integrated observations, experiments, and improved models.
- Invest in observations (field and remote sensing) and experiments to monitor and detect declining ecosystem resilience and potential early warning signals.
- Foster greater data sharing and international collaboration, and co-design research to bring together researchers across natural and social sciences and Global North and South, as well as Indigenous and traditional ecological knowledge.

1.3.1 Introduction

The Earth's biosphere describes the sum of all global ecosystems. It forms a key part of the Earth system, driving the many biogeochemical cycles that maintain the climate system and keep Earth habitable (Kump, Kasting, and Crane, 1999). Ecosystems are the complex systems composed of assemblages of living organisms and their physical environment at the local scale (e.g. an area of rainforest in the Brazilian state of Amazonas).

At a larger scale, they form regional groupings (e.g. Madeira-Tapajós moist forest ecoregion in Dinerstein et al., 2017), ecosystem functional groups (e.g. tropical/subtropical lowland rainforests), biomes (e.g. tropical-subtropical forests), and ultimately the whole biosphere (Keith et al., 2022). Humans are also an integral part of the biosphere, with social systems being so closely intertwined with ecosystems that they can be seen as joint 'social-ecological systems' in which the dynamics of both interact as a single complex adaptive system (Folke et al.,2016; 2021; Ellis et al., 2021).

Ecosystems are being globally degraded by multiple human-driven pressures. At the species level, one million animals and plants face extinction (IPBES, 2019). Extinctions are happening at up to 100 times natural background rates averaged over the last century, leading some to assess that the Earth has now entered the sixth mass extinction event in the nearly 4 billion years of life's history (Barnosky et al., 2011; Ceballos et al., 2015). The Living Planet Index indicates that populations are declining in around half of vertebrate species, with an average decline across all species of 69 per cent since 1970 (WWF, 2022). The key drivers of biodiversity loss in order of importance are land and sea use change, direct exploitation, climate change, pollution, and invasive alien species (IPBES, 2019; Maxwell et al., 2016). Climate change is not currently the leading driver, but will become a substantial threat with further warming (IPBES, 2019). Global warming moving from 1.5 to 2°C increases the number of species facing the loss of most of their ranges from 4 to 8 per cent for vertebrates (e.g. mammals), 8 to 16 per cent for plants, and 6 to 18 per cent for insects, while 3.2°C of warming would increase these to 26, 44, and 49 per cent respectively (Warren et al., 2018). Together these losses are harming many ecosystems' ability to function and so threatening the critical ecosystem services that humanity relies upon, including providing food, clean water, and removing ~31 per cent of human-emitted CO_2 (Friedlingstein et al., 2022)..

As with many other complex systems, ecosystems have been proposed to feature nonlinear changes such as tipping points, beyond which dramatic shifts to a different ecological state are expected, further threatening biodiversity and bio-abundance (Scheffer et al.,2001, 2009). Ecosystems are also subject to many co-stressors with complex interactions, with changing disturbance regimes eroding resilience (e.g. Nystrom et al., 2000; Folke et al., 2004) and making tipping points easier to reach (Willcock et al., 2023). However, complex ecological and social-ecological dynamics crossing multiple scales can make it hard to discern tipping thresholds in observations (Schröder et al., 2005; Hillebrand et al., 2020; Spake et al., 2022). Organisms have agency that enables complex network and spatial dynamics to emerge – with human agency making social-ecological systems particularly complex – making ecosystem tipping dynamics often more difficult to detect and project relative to more physical systems (Kéfi et al., 2022; Rietkerk et al., 2021; Bastiaansen et al., 2022). Furthermore, while ecosystem functions or composition can have threshold responses to biodiversity loss or environmental change, in many cases responses remain relatively linear (Cardinale et al., 2011; Meyer et al., 2017; Hodapp et al., 2018; Strack et al., 2022).

Tipping at the global biosphere scale has been discussed (Barnosky et al., 2012; Hughes et al., 2013; Lenton and Williams, 2013) but is deemed unlikely, with local ecosystem shifts globally aggregating to relatively linear changes in response to human-driven pressures (Brook et al., 2013; Montoya et al., 2017; Rockström et al., 2018). Empirical evidence for tipping has, though, been found in multiple ecosystems from the local to regional scale – for example, in lakes, coastal zones, marine food webs, rangelands and forests (Scheffer et al., 2001, 2009; Folke et al., 2004; Walker and Meyer, 2004; Brook et al., 2013; Rocha et al., 2015; regimeshifts.org), and model evidence suggests tipping is possible in some biomes across sub-continental scales (Armstrong McKay et al., 2022; Wang et al., 2023). As such, ecological tipping points remain a useful concept (alongside gradual and nonlinear change) in understanding and managing ecosystems, despite being sometimes hard to observe in practice (Lade et al., 2021; Spake et al., 2022; Norberg et al., 2022).

In this chapter we follow the wider section's tipping point definition to categorise proposed tipping systems (see Box 1.1). In ecology, the terms 'regime shift' and 'critical transition' have been used interchangeably with 'tipping points', despite differences in meaning (Dakos, 2019). A *regime shift* refers to a shift in the current state of an ecological or social-ecological system from one partially stable state to another that is often large, relatively sudden (depending on system size and feedback timescales) and long-lasting, and entails a reorganisation in the structure and functioning of the system (Biggs et al., 2009; Maciejewski et al., 2019; Cooper et al., 2020). A *critical transition* refers to an abrupt shift in a system that occurs at a specific critical threshold in external conditions (Scheffer et al., 2009). In this Chapter, we use *tipping event* to describe the crossing of a tipping point (which is equivalent to critical threshold), and *regime shifts* to describe the resulting changes that unfold (equivalent to critical transition above). *Resilience* – the ability of ecosystems to maintain functioning in response to change and regenerate in the face of shocks, sometimes adapting and transforming in the process – is also a key concept, with declining resilience being a potential precursor to tipping (see Section 1.6) (Folke et al., 2004, 2016).

1.3.2 Current state of knowledge on tipping points in the biosphere

In this section we assess available scientific literature relating to tipping points in the Biosphere, as summarised in Figure 1.3.1 and Table 1.3.1. We focus on the following biomes: forests, savannas, drylands, lakes, coastal ecosystems and marine environments.

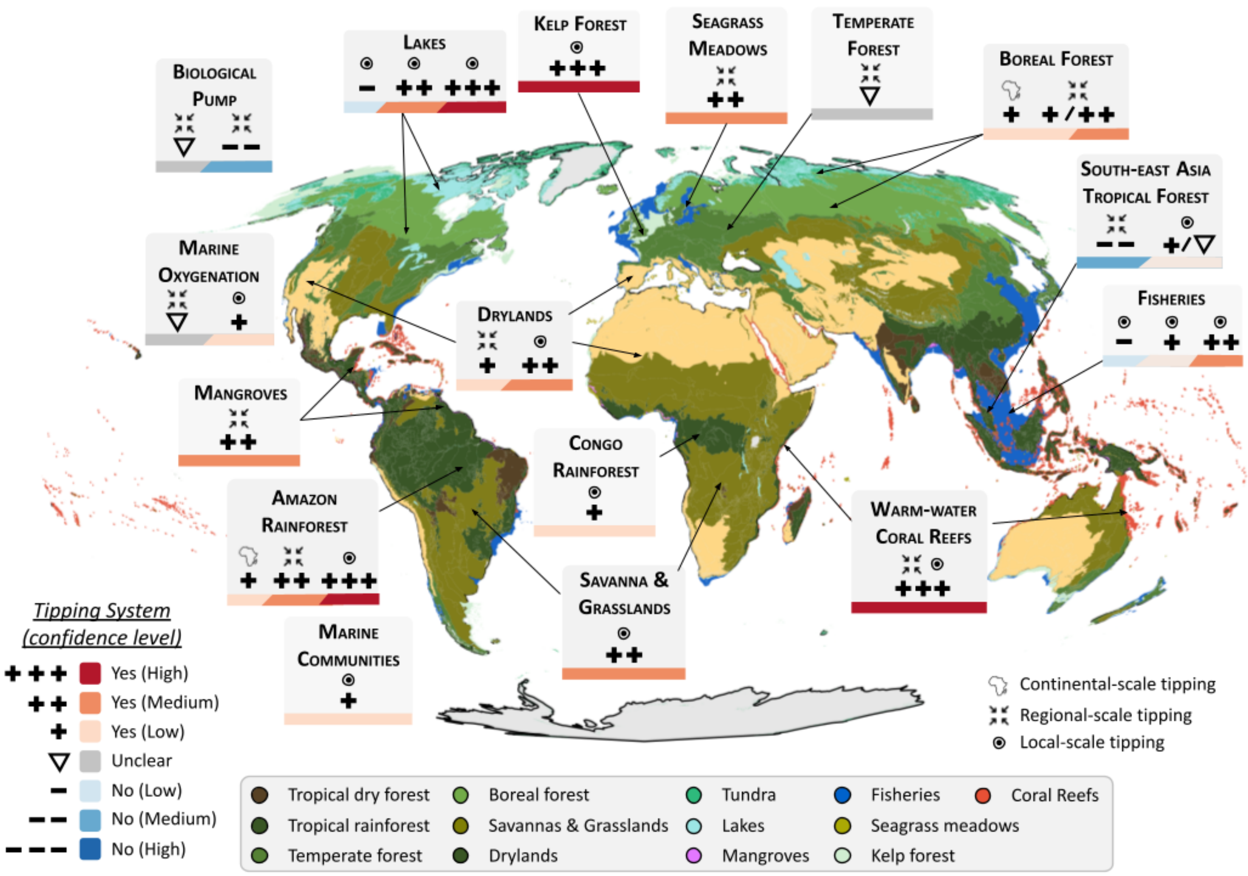


Figure 1.3.1: Map of biosphere systems considered in this chapter. Systems are marked by the coloured areas, with terrestrial biomes and mangroves based on biogeographic biomes (Dinerstein et al., 2017), and lakes and ocean biomes on IUCN functional biomes (Keith et al., 2022) (lakes are shown over other biomes for tundra only; fisheries are spread across the global ocean, but are marked only on key coastal seas for simplicity). 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 (▽).

Table 1.3.1: Summary of evidence for tipping dynamics, key drivers and biophysical impacts in each system considered in this chapter

Key: +++ Yes (high confidence), **++** Yes (medium confidence), **+** Yes (low confidence), **- - -** No (high confidence), **- -** No (medium confidence), **-** No (low confidence), ? Uncertain

Primary drivers are bolded, DC: Direct Climate driver (via direct impact of emissions on radiative forcing); **CA**: Climate-Associated driver (including second-order & related effects of climate change); **NC**: Non-Climate driver, **PF**: positive (amplifying) feedback, **NF**: negative (damping) feedback. Drivers can enhance (↗) the tipping process or counter it (↘)

System (and potential tipping point)	Key drivers	Key biophysical impacts (see S2 for societal impacts)	Key feedbacks	Evidence base	Abrupt / large rate change?	Critical threshold(s)?	Irreversible? (decadal / centennial)	Tipping system?
Forests								
Amazon rainforest (dieback)	**DC: atmospheric warming (↗)** **NC: deforestation / degradation (↗)** **DC: drying (↗)** **CA: fire frequency/intensity increase (↗)** DC: heatwaves (↗) CA: ENSO intensification (e.g. Amazon, SE Asia) (↗) CA: AMOC / SPG weakening / collapse (e.g. Amazon) (↗) CA: terrestrial greening (↘, declining)	• Biodiversity loss • Regional rainfall reduction (e.g. from Amazon dieback across Amazon Basin & Southern American Cone) • Carbon emissions (amplifying global warming) • Remote impacts on rainfall patterns all over the planet	Moisture recycling, fire, albedo	• Models • Observations (local scale)	++	1000-1250mm annual rainfall -400 to -450mm max. accumulated water deficit 7-8m dry season length ~20-40% deforestation ~3.5°C (2-6°C) global warming	++	**+++ (local)** **++ (partial dieback / regional)** **+ (full dieback / continental)**
Congo rainforest (dieback)					+	~1350mm mean annual rainfall; climate change increasing rainfall	+	**+ (local)**
SE Asia rainforest (dieback)					-	~1550mm mean annual rainfall	-	+? (local) - - (regional)
Boreal forest (southern dieback)	**DC: drying (↗)** **CA: fire frequency/intensity increase (↗)** **DC: atmospheric warming (↗)** **CA: permafrost thaw (↗)** **CA: insect outbreaks (↗)** NC: deforestation / degradation (↗) DC: heatwaves (↗) CA: terrestrial greening (↘) CA: vegetation albedo (↗) CA: sea ice albedo decline (↗) DC: precipitation change (↘,↗)	• Biodiversity loss • Carbon emissions from dieback, carbon drawdown from expansion • Complex regional biogeophysical effects on warming - dieback = higher albedo (cooling) but less evaporative cooling (warming) & vice versa for expansion	Fire, albedo, moisture recycling	• Models • Observations • Experiments	++	~4°C (1.4-5°C)	+ [~100 yr]	**++ (partial / regional)** **+ (continental)**
Boreal forest (northern expansion)			Fire, albedo, moisture recycling	• Models • Observations • Experiments	+	~4°C (1.5-7.2°C)	+ [~100 yr]	**+ (partial / regional)**

System (and potential tipping point)	Key drivers	Key biophysical impacts (see S2 for societal impacts)	Key feedbacks	Evidence base	Abrupt / large rate change?	Critical threshold(s)?	Irreversible? (decadal / centennial)	Tipping system?
Temperate forests (dieback)	**DC: atmospheric warming (↗)** **DC: droughts (↗)** **DC: heatwaves (↗)** CA: insect outbreaks (↗) CA: windthrow (↗) NC: deforestation & fragmentation (↗) CA: fire frequency increase (↗)	• Biodiversity loss • Carbon emissions • Regional warming in summer due to less evaporative cooling, less cloud cover • Less atmos. water supply • Less groundwater recharge	Moisture recycling, soil moisture -atmosphere, interacting disturbances, albedo	• Models • Observations • Experiments	++	Widespread thresholds uncertain	- [decades]	? (partial / regional)
Savannas, Grasslands & Drylands								
Savanna & Grasslands (degradation)	**NC: fire suppression (↗)** **NC: overgrazing (↗)** DC: increased precipitation intensity (↗) CA: terrestrial greening (↗) NC: afforestation (↗) CA: ocean circulation shift (e.g. Sahe), ↗)	• Biodiversity loss • Groundwater depletion (with encroachment) • Nutrient cycle disruption • Reduced fires (with encroachment)	Fire, grazing	• Models • Observations (remote sensing & fieldwork)	+	Regionally variable mean annual rainfall; thresholds highly localised; Fire percolation threshold ~ 60% flammable cover	++	**++ (local to landscape)** ? (regional)
Drylands (land degradation)	**DC: drying (↗)** **DC: atmospheric warming (↗)** **NC: land use intensification (e.g. livestock, agriculture, urbanisation)(↗)** DC: extreme events (heatwaves, floods) (↗) DC: increased rainfall variability (↗) CA: terrestrial greening (↘) CA: insect outbreaks (↗) CA: invasive species (↗)	• Biodiversity loss • Aridification / Desertification • Groundwater depletion (with encroachment) • Regional rainfall changes • Shift in species composition (e.g. shrub encroachment) • Vegetation recruitment	Soil fertility, / moisture / microbes, vegetation structure, veg-rainfall, fire, herbivory	• Models • Observations (current & historical) • Field experiment	++	Aridity index (0.54,0.7 and 0.8) (limited reliability of aridity measures; lack of temporal evidences for some thresholds)	+ (shorter timescales possible, e.g. via active restoration)	**++ (local to landscape)** **+ (regional)**

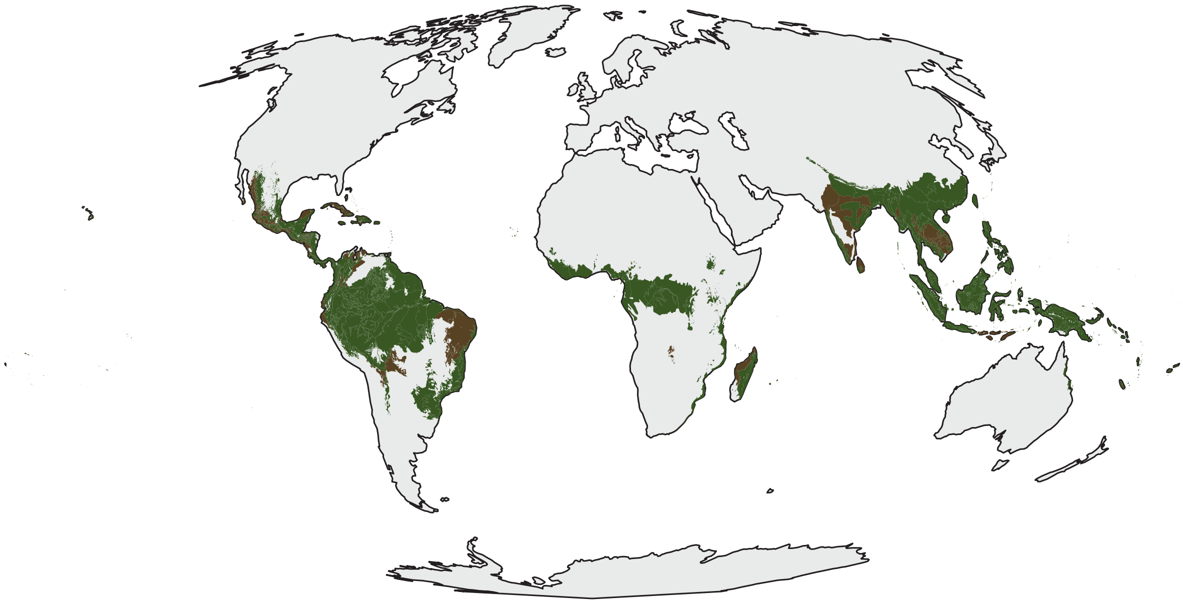
System (and potential tipping point)	Key drivers	Key biophysical impacts (see S2 for societal impacts)	Key feedbacks	Evidence base	Abrupt / large rate change?	Critical threshold(s)?	Irreversible? (decadal / centennial)	Tipping system?
Freshwater								
Lakes (eutrophication-driven anoxia)	**NC: nutrient pollution (↗)** DC: atmospheric warming (↗) DC: precipitation changes (↗)	• Biodiversity loss • Water quality declineIncreased GHG emissions	Anoxia-driven P release, trophic cascades	• Observations • Models • Experiments	+++	20-30 mg P/l No clear warming/ rainfall thresholds	++ (decadal)	**+++ (localised, widespread)**
Lakes (DOM loading - 'browning')	**CA: terrestrial greening (↗)** **NC: afforestation (↗)** DC: atmospheric warming (↗)	• Biodiversity loss • Increased GHG emissions	Anoxia-driven P release	• Observations • Models	+	>10 mg DOC/l	++ (decadal)	**++ (localised, widespread in boreal)**
Lakes (appearance / disappearance)	**CA: permafrost thaw-related thermokarst formation / drainage (↗)** **CA: glacier lake formation / drainage (↗)**	• Biodiversity loss • Increased GHG emissions	(can be driven by thermokarst)	• Observations	+++	As for permafrost thaw	+++ (centennial)	- (localised, widespread on tundra)
Lakes (N to P limiting switch)	**NC: nutrient pollution (atmos. deposition) (↗)**	• Biodiversity loss	N/A	• Observations	++	Related to elemental ratio	++ (decadal)	- (localised, regions with high N-deposition)
Lakes (salinisation)	**DC: atmos. warming (↗)** **DC: drought (in arid regions) (↗)** **CA: water use intensification (↗)**	• Biodiversity loss • Reduced GHG emissions	Salt release from sediment	• Observations	+	Species-specific salinity threshold	++ (decadal)	- (localised, arid regions)
Lakes (invasive species)	**CA: warming-driven range expansion (↗)** **NC: human-mediated introduction (↗)**	• Biodiversity loss	N/A	• Observations • Models	+	Cannot be defined	++ (decadal - centennial)	- (localised, widespread)

System (and potential tipping point)	Key drivers	Key biophysical impacts (see S2 for societal impacts)	Key feedbacks	Evidence base	Abrupt / large rate change?	Critical threshold(s)?	Irreversible? (decadal / centennial)	Tipping system?
Coastal								
Warm-water coral reefs (die-off)	**DC: ocean warming (↗)** **DC: marine heatwaves (↗)** **CA: disease spread (↗)** CA: ocean acidification (↗) NC: pollution (nutrient / sediment) (↗) NC: disruption (ships, over-harvesting) (↗) CA: invasive species (↗) DC: storm intensity (↗) CA: sea level rise (↗)	• Biodiversity loss (ecosystem collapse, ~25% marine species have life stages dependent on coral reefs) • Loss of commercial & artisanal fisheries, and other sectors • Coastal protection loss	Thermal stress leading to symbiont expulsion, decarbonisation, loss of structure (habitat)	• Observations • Models	+++	**Region and reef dependent:** • ~1.2°C (1.0-1.5°C) GW • Temporally variable heat stress (8-12 Degree Heating Weeks) • Long-term consequences of >350 ppm atmospheric CO^2 • Acidification threshold uncertain	++ (decadal)	**+++ (localised)** **+++ (regionally clustered)**
Mangroves (die-off)	**CA: sea level rise (↗)** **DC: increased climate extremes** (tropical cyclones, El Niño-related heat, drought, & flooding, drops in sea level)(↗) **NC: habitat loss (to agri/ aquaculture) (↗)** **DC: increased regional drought (↗)** **NC: shoreline change (erosion, sedimentation) (↗)** NC: nutrient pollution (↗)	• Biodiversity loss • Loss of coastal protection • Loss of carbon sink / increased GHG emissions • Loss of water quality • Sediment salinisation • Subsidence • Enhanced sediment sulphide and methane releases • Hypoxia (seagrasses) • Reduced nutrient recycling	Failed recovery between increasingly frequent extreme events; coastal subsidence and erosion preventing re- establishment	• Palaeo (mangroves) • Observations • Models	+ (sea level induced shifts more gradual than for drought or recurrent extremes)	**Region dependent (see text for priority regions):** • ~1.5-2 °C global warming • ≥ 4-7 mm.yr-1 relative sea level rise rate • Recurrent cyclonic exposure (e.g return period below a decade) • Soil pore hyper salinisation (site dependent)	++ (decadal)	**++ (regional; region dependent)**
Seagrass (die-off)	**DC: marine heatwaves (↗)** **NC: nutrient pollution (↗)** **DC: ocean warming (↗)** **CA: disease spread (↗)** NC: sedimentation (↗) NC: turbidity(↗) NC: invasive species (↗) NC: fishing practices (benthos damage) (↗) CA: sea level rise (↗)				++	**Region dependent:** • ~1.5°C global warming • Degrees heating weeks with higher sensitivity in temperate (site dependent. e.g. 6 -12 °C) • Turbidity (<10-30% of PAR) • Nutrient load (site dependent e.g. N loads >1-5 mg/l; P loads >0.03-0.1 mg/l)	++ (decadal)	**++ (regional; region dependent)**

System (and potential tipping point)	Key drivers	Key biophysical impacts (see S2 for societal impacts)	Key feedbacks	Evidence base	Abrupt / large rate change?	Critical threshold(s)?	Irreversible? (decadal / centennial)	Tipping system?
Marine ecosystems and environment								
Fisheries (collapse)	**NC: over-exploitation (↗)** DC: ocean warming (↗)	• Keystone species collapse • Trophic cascades	Trophic cascades, Allee effect	• Observations • Palaeo/historical records • Models	++	Warming & over-fishing; thresholds highly localised	+ to +++ (decades)	**+++ (cod, regional)** **+ (large fish, regional)** - (small fish, regional)
Marine communities (regime shift)	**NC: over-exploitation (↗)** **DC: ocean warming (↗)** **NC: nutrient pollution (↗)** CA: sea ice loss (↗)	• Regime shifts • Trophic cascades.	Trophic cascades, eutrophication	• Observations • Models	++	Multiple drivers (warming, nutrients, overfishing); thresholds highly localised	+ (decades)	**+ (local)**
Kelp forests (die off)	**NC: urchin overgrazing (linked to overfishing) (↗)** **NC: habitat loss (↗)** **NC: pollution (nutrient/ sediment) (↗)** DC: ocean warming (↗) DC: marine heatwaves (↗)	• Regime shift to more barren state	Sea urchin recruitment & grazing	• Observations • Models	++	Multiple drivers, thresholds highly localised	+++ (months - decades)	**+++ (local)**
Biological pump (collapse)	**DC: ocean warming (↗)**	• Regime shift • Changes to carbon sink • Impacts on ocean biogeochemistry	Diatom recruitment	• Models • Theory	+?	Ocean warming & stratification; thresholds unknown	+ (decades)	? (lipid, regional) - - (gravitational, regional to global)
Marine oxygenation (hypoxia)	**NC: nutrient pollution (↗)** DC: ocean warming (↗)	• Major changes in ocean productivity, biodiversity and biogeochemical cycles	Decomposition, sediment P release	• Models • Observations	+	Nutrient load, warming; thresholds highly localised	++ (months / years to centuries)	**+ (local)** ? (regional to global)

1.3.2.1 Tropical forests

Tropical forests cover around 1.95bn hectares (including degraded portions), and are key components of the Earth system (Pan et al., 2011) (Figure 1.3.2). They are home to a disproportionate amount of Earth's species (e.g. Slik et al., 2015; Pillay et al., 2021), store huge amounts of carbon (circa 471 ±93 GtC) in their soils and biomass, and, through evapotranspiration and their effect on cloud formation through production of aerosols and cloud condensation nuclei, have an overall cooling and moistening effect at regional scales (SPA, 2021; IPCC AR6 WG2 2021). They are also home to many Indigenous peoples and local communities, with a long history of human habitation and high biocultural diversity (Ellis et al.,2021).



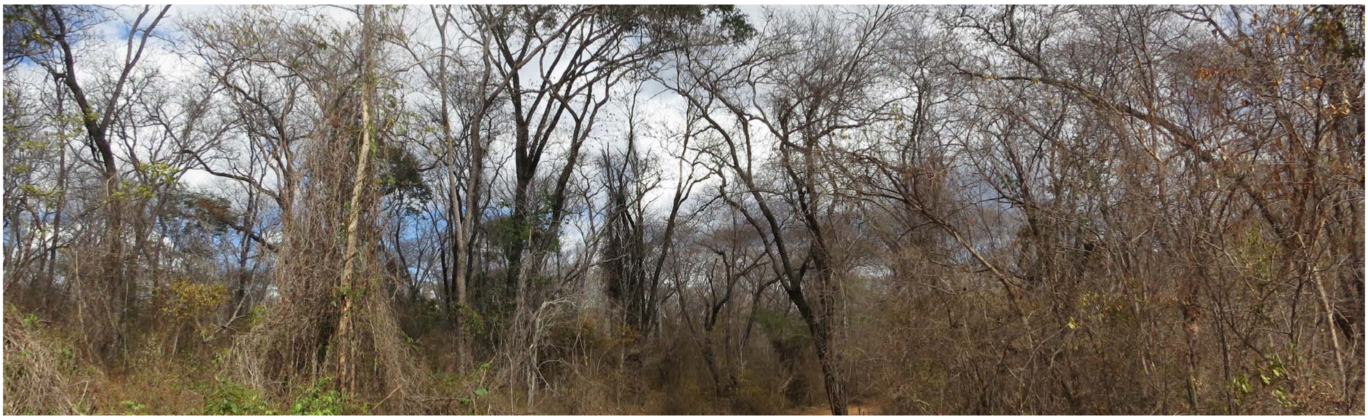


Figure 1.3.2: Top: map showing global extent of tropical forests, including tropical rainforests (dark green) and tropical dry forests (brown) (source: Dinerstein et al. (2017)) . Middle: photo of mature rainforest in Tapajós National Forest, Brazil (credit: Boris Sakschewski). Bottom: photo of arboreal Caatinga, a tropical dry forest formation in Eastern Brazil (credit: Kyle Dexter).

As well as experiencing deforestation and degradation due to land use change across the tropics (IPBES 2019), tropical forests in South America and Asia have been undergoing unprecedented climate-driven disturbances such as increasing dry season length and intensity, more intense and frequent rainfall and temperature extremes (Lapola et al., 2023; SPA, 2021). For instance, recent extreme droughts – mainly driven by climate variability modes such as the El Niño Southern Oscillation (ENSO) in 2014-2016 and the Atlantic dipole in 2005 and 2010 (e.g. Marengo et al., 2008; Marengo et al., 2011; Jimenez-Muñoz et al., 2016; see Chapter 1.4) – have caused extensive tree mortality, even up to 36 months after peak drought (e.g. Phillips et al., 2009; Phillips et al., 2010; Berenguer et al., 2021). Given the variability of forests across the tropics, their responses to global changes are likely to differ (Allen et al., 2017). Nonetheless, even subtle changes in their structure, composition and functioning could affect the global carbon and water cycles (e.g. Esquivel-Muelbert et al., 2019; Barros et al., 2019; Hirota et al., 2021).

Here we also consider deciduous and semi-deciduous forests (often referred to as dry forests) that coexist with evergreen forests in regions with around 1,000-2,000mm of annual rainfall, i.e. non-arid or dryland regions (Dexter et al., 2018). These dry forests may resemble (in terms of tree species composition) the dry forests in arid or dryland regions. However, because they exist in climates that can form continuous, high fuel-load flammable grass layers when canopies are opened (which is not the case in drylands), their dynamics are more comparable to neighbouring moist forests.

Evidence for tipping dynamics

Two positive/amplifying feedbacks are among the most plausible mechanisms that could lead to tipping dynamics in tropical forests, one at broader regional scales potentially causing large-scale forest collapse, and another at local scales potentially causing local forest collapse (Figure 1.3.3 and Box 1.3.2).

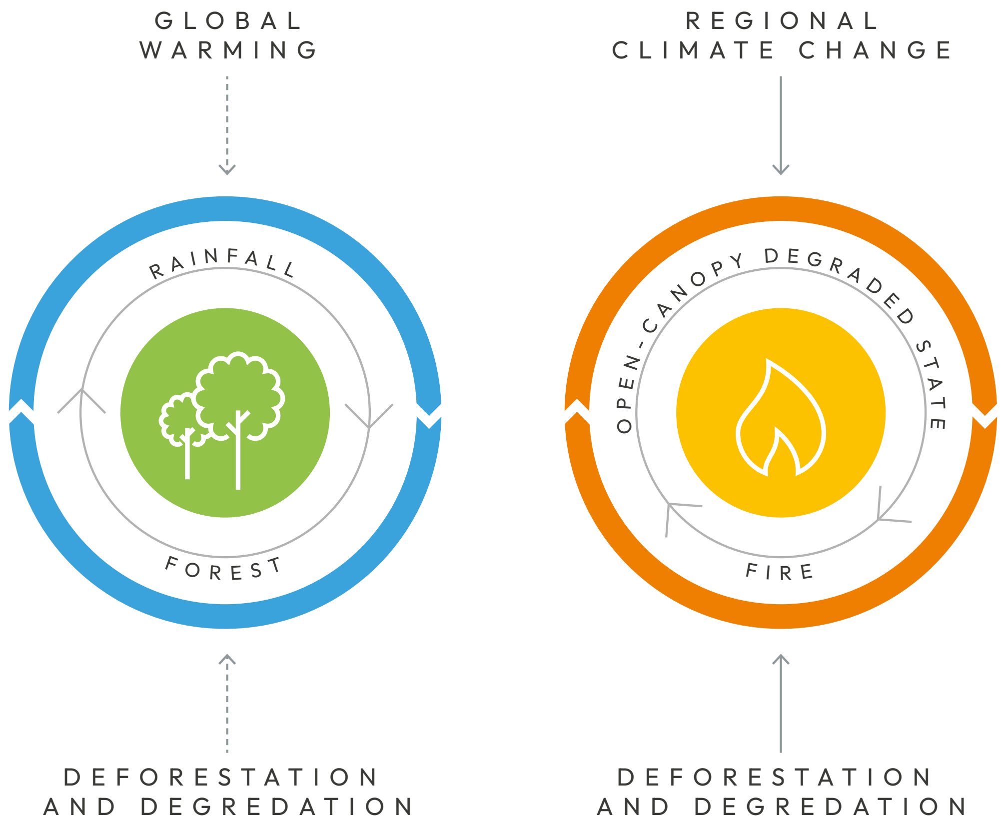


Figure 1.3.3: Diagram with positive/amplifying feedback loops that may cause large- and local-scale tipping events in tropical forests. (a) Regional climatic conditions are changing in response to global warming and also to deforestation, both of which contribute to weakening the forest-rainfall feedback. Reductions in rainfall cause water stress, increasing tree mortality and forest loss, further weakening the feedback, which could cause a large-scale forest collapse of the Amazon. (b) Interactions and feedbacks among the vegetation and fire can arrest the ecosystem in an open vegetation state, thus causing a local-scale forest collapse.

At regional scales, the forest-rainfall feedback is believed to be the dominant mechanism stabilising tropical forests by increasing annual rainfall levels and reducing its seasonal and interannual variability (Staal et al., 2020; Sternberg, 2001). However, under certain conditions it can instead amplify forest loss. Accumulated deforestation or forest loss reduces forest cover, which decreases evapotranspiration and moisture flow downwind, thus reducing regional rainfall (Smith et al., 2023). This in turn may increase tree mortality in downwind forest (Phillips et al., 2009; Berenguer et al., 2021), and beyond a threshold could lead to self-sustaining forest loss in drier areas of forest (Zemp et al., 2017; Staal et al., 2020) (Figure 1.3.3).

In the Amazon, on average, around 30 per cent of the water precipitating has been evaporated within the region beforehand at least once, but with large spatial differences: in the western Amazon, almost all precipitation has previously evaporated from the basin (Zemp et al., 2014; Staal et al., 2018). In the Congo basin, almost half of all precipitation originates from the Congo forest itself (Tuinenburg et al., 2020; Te Wierik et al., 2022). For Australian and Asian forests, evidence is still lacking, but this feedback likely has less effect on forest resilience due to less dependence on precipitation stemming from land evapotranspiration due to the major importance of monsoons (Staal et al., 2020).

At the local scale, evidence from across the tropics (Cochrane et al., 1999; Staver et al., 2011; van Nes et al., 2018) suggests that a fire-vegetation feedback can maintain the ecosystem in an open vegetation state: with less tree cover, fires spread more easily due to more flammable grassy fuels and because the air is drier in an open landscape without the local moistening effect of forest canopies. The resulting enhanced fire occurrence can in turn prevent the re-establishment of trees and maintain a more open vegetation state (Martinez-Cano et al., 2022; Drüke et al., 2023). This alternative open vegetation state could be either a natural savanna with native plant species (Flores and Holmgren, 2021; Beckett et al., 2022) or a degraded open-vegetation state when invasive plants are dominant (D'Antonio and Vitousek, 1992; Veldman and Putz, 2011; Malhi et al., 2014; Barlow et al., 2018) (Figure 1.3.3).

The effects of the fire-vegetation feedback are amplified by the regional forest-rainfall feedback (Staal et al., 2020). Moreover, forest loss may increase global warming by releasing carbon to the atmosphere, which further reduces regional moisture flows, causing more forest loss (Canadell et al., 2021). Also, climate change may change wind directions and residence times of moisture in a warmer atmosphere (Gimeno et al., 2021). Tropical forest loss also may change atmospheric circulation patterns (Portmann et al., 2022) and increase regional and global warming through reductions in cloud cover and evapotranspiration.

Among tropical forests, the Amazon forest has most evidence for potential tipping points. Analysis based on early warning signals (see Chapter 1.6) indicates that over 75 per cent of the Amazon has lost resilience since the early 2000s (Boulton et al., 2022). This decline is focused mostly closer to human disturbance, as well as in the drier south and east previously identified as 'bistable' (i.e. with two possible alternative states) due to the forest-rainfall feedback and thus is more vulnerable to tipping (Staal et al., 2020). While the Amazon has acted as a carbon sink due to CO_2 fertilisation, in mature forest this sink peaked and started declining in the 1990s (Hubau et al., 2020) and when including degraded forest (also predominantly in the drier south and east) the Amazon as a whole is now a carbon source (Gatti et al., 2021). Recent CMIP6 models indicate that localised shifts in peripheral parts of the Amazon forest system are more likely than a large-scale tipping event (IPCC AR6 WG1 Ch5, 2021; Parry et al., 2022). However, the latter cannot be ruled out (Hirota et al., 2021) because several compounding and possibly synergistic disturbances (e.g. combining an extreme hot drought with forest fires) may play a role in reducing forest resilience, with greater resilience loss closer to human activities (Boulton et al., 2022). Such synergies are generally not considered in Earth system models (Willcock et al., 2023).

A global warming threshold of ~3.5°C (2-6°C) has been estimated (Armstrong McKay et al., 2022), partly based on a few modelling studies that simulate some kind of nonlinear decrease in modelled properties of the Amazon forest, at least on small scales (Gerten et al., 2013; Drijfhout et al., 2015; Nobre et al., 2016; Boulton et al., 2017; Parry et al., 2022). However, most CMIP6 models do not include dynamic vegetation modules (Song et al., 2021; Canadell et al., 2021), which might make the forest artificially stable (Zemp et al., 2017). Models including deforestation, fire and dynamic vegetation have simulated widespread local-scale dieback (e.g. Cano et al., 2022; Parry et al., 2022), and also larger scale dieback in potential vegetation models (e.g. Salazar and Nobre, 2010).

Evidence pointing against a large-scale Amazon tipping point stems from palaeoclimate reconstructions suggesting that at least some parts of the Amazon forest have been resilient to past reductions in rainfall (Wang et al., 2017; Kukla et al., 2021) and temperatures as high as projected by climate models for the rest of the century (Steinthorsdottir et al., 2020). However, these were under more stable climate conditions (and before Pleistocene with different geographic effects on climate due to tectonics; (Brierley and Fedorov, 2016), with the current rate of warming far greater than during past climate changes (Zeebe et al., 2016; Osman et al., 2021). Geographically limited data means partial dieback elsewhere cannot be ruled out for drier intervals (Wang et al., 2017; Kukla et al., 2021), particularly in the drier south, where drying is currently leading to greater resilience loss (Boulton et al., 2022). Additionally, compounding disturbances are becoming increasingly widespread across the Amazon, even in remote central parts of the system, which is leading to resilience loss (Boulton et al., 2022) and could help trigger forest dieback at larger scales (Kukla et al., 2021; Wilcock et al., 2023).

Other tropical forests have evidence for local tipping points, but are less likely to cross them. The Congo has also been suggested as a possible tipping system (Staal et al., 2020) as it may also host a large area of bistable forest with some amplification by forest-rainfall feedback (Staver et al., 2011). However, because climate models indicate wetting across large parts of the Congo, it is not considered a tipping system in response to global warming (Armstrong McKay et al., 2022). The south-east Asian rainforests lack a strong regional forest-rainfall feedback and tend to have enough rainfall from ocean proximity for forests to remain stable, thus they are not considered a tipping system in relation to global warming (Armstrong McKay et al., 2022). Other tropical forests such as the Choco in Central America or Brazilian Atlantic Forests have not been assessed in detail.

Plants can reduce moisture transpiration in response to water limitation on very short timescales (hours to days), followed by water cycle feedbacks (weeks). Deforestation has a similarly fast effect on rainfall, as loss of trees can immediately reduce evapotranspiration. Large-scale forest dieback events in response to global warming can only be expected on the timescale of decades to centuries (Armstrong McKay et al., 2022). At a local scale, empirical evidence from the Amazon and from Africa has shown that forests can shift into savannas within a few decades after repeated fires (Flores and Holmgren, 2021; Beckett et al., 2022), and on larger scales tipping may occur faster (Cooper et al., 2020).

An Amazon tipping point would have global impacts from possibly large losses of carbon to the atmosphere. The best estimates suggest that a large-scale collapse of 40 per cent of the forest before the end of this century could lead to emissions of ~30 GtC and an additional global warming of ~0.1°C (Armstrong McKay et al., 2022). The Amazon dieback would also lead to substantial rainfall reductions across the Amazon basin and in to the Southern Cone of South America (Costa et al., 2021), and may also directly influence distant parts of the Earth system via 'teleconnections', for example to the Tibetan Plateau (Liu et al., 2023).

Assessment and knowledge gaps

The feedbacks that could contribute to tipping behaviour are relatively well understood in principle, yet there are large uncertainties surrounding the effects of climate and land use changes on these feedbacks. For instance, CO_2-fertilisation is expected to increase forest resilience locally, but it also increases water-use efficiency, reducing forest transpiration, and may thus weaken the forest-rainfall feedback and regional forest resilience (Brienen et al., 2020; Sampaio et al., 2021; Kooperman et al., 2018; Li et al., 2023). CO_2-fertilisation of tropical forests may also be overestimated in current Earth system models (Terrer et al., 2019; Hubau et al., 2020; Wang et al., 2020). Moreover, the actual thresholds and the extent to which tipping behaviour can be expected across heterogeneous landscapes and forest communities are much less certain (Levine et al., 2016; Longo et al., 2018; Sakschewski et al., 2021).

Considering only the Amazon as a rainforest tipping system, we have medium confidence in its potential for tipping of its bistable area (~40 per cent of the forest, predominantly in the drier south and east; Staal et al., 2020), with low confidence in the estimated tipping points and possibility of a large-scale collapse. The Congo may also be vulnerable to localised tipping (low confidence), but is unlikely to tip as a result of climate change, and localised tipping is possible but uncertain in south-east Asian rainforests.

Confidence in the tipping behaviour of tropical forests can be greatly improved through further development of models. Models can include dynamic vegetation modules and land use change to improve the representation of the forest-rainfall feedback, which would likely result in more drastic drying under high-deforestation scenarios (Parry et al., 2022). Incorporating fire dynamics in these modules would also likely result in a more bistable system (Drüke et al., 2023). In contrast, allowing for local vegetation adaptation (such as rooting depth) by including more plant types and traits in these modules would help better resolve the effect of landscape heterogeneity on tipping dynamics (Langan et al., 2017; Sakschewski et al., 2021), which may reduce the abruptness of the transition to an open degraded state (Levine et al., 2016). Efforts to increase ecological understanding of the feedback mechanisms and processes described here through observations (such as recent field studies on plant characteristics related to drought mortality throughout the Amazon basin (Tavares et al., 2023), or on the growth-survival tradeoff (Oliveira et al., 2021)) would help better understand forest dynamics and represent them in models.

1.3.2.2 Boreal forests and tundra

Boreal forests, also called 'Taiga', span around 1,135 million hectares, all located in the northern hemisphere (Pan et al., 2011) (Figure 1.3.4). They are vital for climate regulation, storing circa 272 (± 23) GtC, mostly below ground (Pan et al., 2011; Mayer et al., 2020). Management varies, but illegal logging constitutes a critical driver of boreal forest loss. Boreal forest growth is constrained by a short vegetation period, and their dynamics involve large-scale disturbances such as insect outbreaks and fire (with fire percolation dynamics important – see 1.3.2.4). While disturbance regimes differ in Eurasian and American forests, an overall increase in disturbances has been observed over past decades, fuelling worries about a wider loss of resilience.

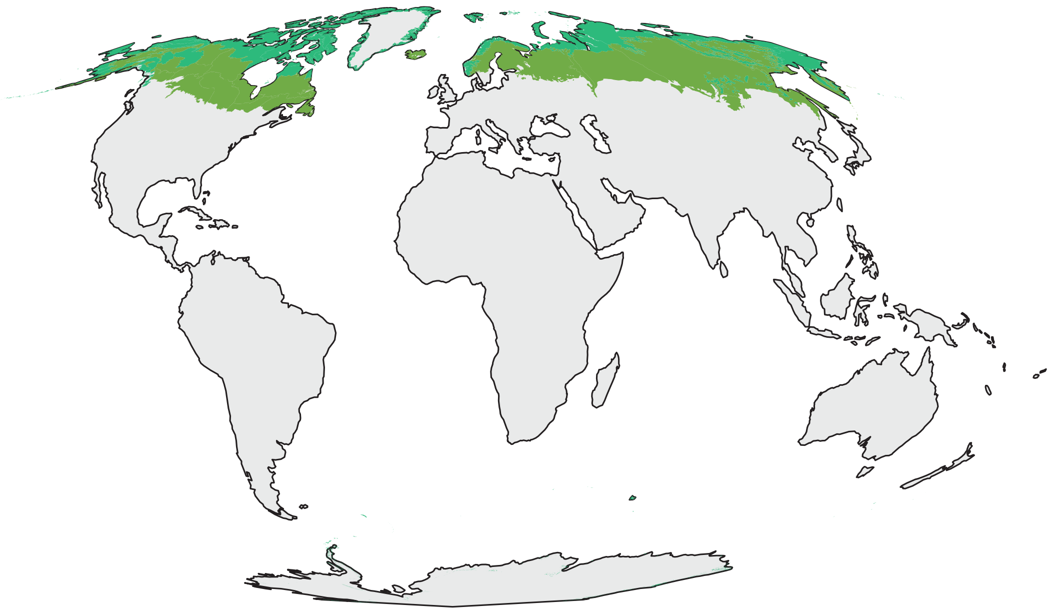


Figure 1.3.4: Top: map showing extent of boreal forests (light green) and tundra (blue-green) biomes (source: Dinerstein et al. (2017)). Bottom: photo of boreal forest and swamps, southern Norway (credit: Boris Sakschewski).

Evidence for tipping dynamics

Boreal forest dieback has already been identified as a potential tipping element in the climate system in Lenton et al., (2008) and further assessed in the IPCC AR5 WG2 Report in 2014 and in the WG1 and WG2 reports of AR6 in 2021 and 2022. The IPCC SR1.5 (Hoegh-Guldberg et al., 2018) and also the most recent assessment by (Armstrong McKay et al., 2022) differentiate between southern boreal forest and northern tundra tipping points. The southern boreal forest tipping point refers to a dieback of southern boreal forests that lead to a state-shift to an almost treeless state (to steppe/prairie), while the northern tundra tipping point refers to an expansion of tree cover into currently treeless tundra ecosystems.

There is little additional evidence for a boreal forest tipping point since the assessment of Armstrong McKay et al., (2022). Significant losses in tree cover driven by fires and logging were identified for the southern boreal forests of North America between 2000 and 2019 (Rotbarth et al., 2023). In contrast, interior boreal forests have become denser. There has been no clear sign of a northward expansion of the boreal forests of North America (Rotbarth et al., 2023). Similarly, Burrell et al. (2021) found that the forests of southern Siberia might have approached a tipping point as fire regimes have intensified, causing widespread regeneration failure. Moreover, Siberian larch foliage is sensitive to warming, with temperatures potentially exceeding a threshold by 2050 after which forest dieback can be expected (Rao et al., 2023).

A range of mechanisms contribute to the feedback processes associated with boreal tipping points (see Box 1.3.2 for more on forest feedbacks). For the southern boreal forest, the recent surge in forest disturbances, such as the extreme forest fires in Canada in summer 2023, is noteworthy because they constitute a substantial change in forest dynamics and resilience that, combined with failure to regenerate, could initiate regional tipping. In particular, the southern trailing edge of boreal forests has been identified as prone to compound and interacting disturbances, including droughts, windstorms, fires, large herbivores and insect outbreaks (Frehlich and Reich, 2010). For instance, increasing water stress reduces tree resistance against insects, and increases the size and severity of wildfires.

Southern boreal tipping points are driven by forest dieback from disturbances (Lenton et al., 2008). Empirical evidence from satellite data suggests that disturbances are responsible for switches between states rather than causing gradual change (Scheffer et al., 2012; Abis and Brovkin, 2017). Rotbarth et al. (2023) confirm that processes dominating the dieback of southern boreal forests and the northward expansion of forests into tundra diverge and that a northward expansion is not compensating for declines in the southern boreal forests of North America.

Climate change will further intensify disturbance regimes (Seidl et al., 2017), with fire regimes expected to increase significantly in boreal forests (Velasco Hererra et al., 2022). In Canada, fire frequency could increase up to 50 per cent by the 21st century under climate change (Flannigan et al., 2013). A doubling of fire frequency and increased wind activity during the 21st century will likely cause a significant decrease in coniferous forests, potentially replaced by early successional broadleaved tree species (Anoszko et al., 2022; Liu et al., 2022).

The increase in fire could potentially modify the forest microclimate, so that subsequent fires and droughts become more likely, causing a change in vegetation dynamics. For instance, Whitman et al. (2019) found that drought after fire exacerbates regeneration failure. Overall, drought-induced mortality will likely rise more in western than eastern North American regions (Peng et al., 2010). Moreover, insects, such as mountain pine beetles might expand into North American boreal forests, causing changes in ecosystem dynamics (Safranyik et al., 2010; Jarvis and Kulakowski, 2015). For instance, severe defoliation could impede birch forest recovery (Vindstad et al., 2018).

If these changes in disturbances cause widespread mortality while, at the same time, forests fail to regenerate, the forest might tip into an almost treeless state. Stevens-Rumann et al., (2022) suggest that a combination of changing climate patterns and disturbance regimes could primarily cause regeneration failure in coniferous forests. Bailey et al., (2021) highlighted the importance of temperature-moisture interactions for successful seedling establishment at the upper treeline in the Southern Rocky Mountains. However, over the past decade, no seedling establishment occurred at any site, suggesting that a threshold for regeneration may have been passed. Regeneration failure of boreal forests might occur with warming alone (+1.6°C to +3.1°C increase in one local warming experiment), but temperature thresholds are reduced if an increase in temperature is combined with reduced precipitation (Reich et al., 2022).

The sensitivity of coniferous tree recruits to climate change is overall higher than for broadleaved tree regeneration (Reich et al., 2022; Stevens-Rumann et al., 2022). In addition, natural disturbances might more likely cause state-shifts of coniferous than broadleaved-dominated boreal forest (Thom, 2023) as broadleaved tree species have an overall higher resprouting ability than conifers (Thom et al., 2021). Topographic complexity and peatlands may act as refugia from fire (Kuntzemann et al., 2023; Rogeau et al., 2018), thus reducing the likelihood of regeneration failure and state shifts. If widespread mortality becomes an increasing issue in northern forests, reduced microclimatic buffering of forests to increasing temperature might accelerate the thawing of permafrost in the boreal biome, causing additional releases of greenhouse gases – further interacting with the climate system [See Chapter 1.2.2.4 on Permafrost].

An increase in abundance of woody plants and advancing shrublines into the Arctic tundra is likely as climate changes (Mekkonen et al., 2021). This shrubification driven by warmer climate is also accompanied by northward treeline migration. A recent review of more than 400 treeline site locations suggested that at about two-thirds of treeline sites' forest cover had increased in elevational or latitudinal extent (Hansson et al., 2021). Main drivers of treeline migration are an increase in the rate of seedling success through warmer summers and increased winter temperatures. The change from tundra and peatlands to boreal forests can be nonlinear. Experimental work in boreal peat bogs reveals positive interactions between shrub cover and tree recruitment in which shrub cover favours tree seedlings and, in turn, higher tree basal area fosters shrub biomass, potentially triggering tipping towards high tree cover (Holmgren et al., 2015). As with southern dieback, interaction with permafrost thaw is also likely, but is complex and currently uncertain.

There are no clear thresholds for boreal forest dieback beyond the initial estimates already presented in Armstrong McKay et al., [2022]. With low confidence, they estimate a southern dieback tipping point at a global warming threshold of ~4°C (1.4-5°C) and a tipping timescale of ~100 (50-?) years, and a northern expansion into tundra tipping point at an estimated global warming threshold of ~4°C (1.5-7.2°C) and a tipping timescale of ~100 (40-?) years. Regeneration failure of southern boreal forests might occur with warming alone, while those thresholds are even lower if precipitation amounts also decrease (Reich et al., 2022).

Assessment and knowledge gaps

We assess with medium confidence that larger parts of boreal forests will approach a southern dieback tipping point and with low confidence that they will expand northwards as global temperatures increase by 3-4°C, if precipitation amounts and patterns remain similar. Yet, this threshold depends on multiple factors such as human and natural disturbances.

The capacity for adaptation and resilience is among the key uncertainties. Biodiversity, among other factors, might influence tipping dynamics as a diverse ecosystem may be more resistant to reaching tipping points, yet the effects of compositional and structural diversity require further investigation. Furthermore, although there is strong evidence and confidence in the increase of natural disturbances in boreal forests it remains uncertain whether they will truly lead to the transgression of a tipping point, pushing the southern range of boreal forests into an alternative, treeless state.

While in the southern boreal region the main mechanisms causing tipping points are relatively clear, for the northern tundra expansion tipping point the mechanisms sustaining large-scale abrupt state-shifts are not as evident.

Disturbances in this region may be weaker and more localised, and the replacement of tundra by forest might occur more gradually. Yet, it is unclear if regeneration failure drives a self-sustaining feedback loop hindering recovery due to soil dryness or extreme conditions, causing a tipping point.

Further uncertainties linked to tipping points requiring further investigation include testing:

- interactions between climate, atmospheric forcing and disturbances;
- cascading and compounding disturbances;
- the existence of a 'fast-in, fast-out' behaviour of release and recovery in boreal forests;
- whether changes are self-reinforcing and perpetuating forest loss (or gain in the case of the northern tipping point);
- the extent of southern forest loss vs. northern forest expansion; and
- the role of human interventions, such as forest management on tipping dynamics.

Box 1.3.2: Forest feedbacks that could lead to tipping

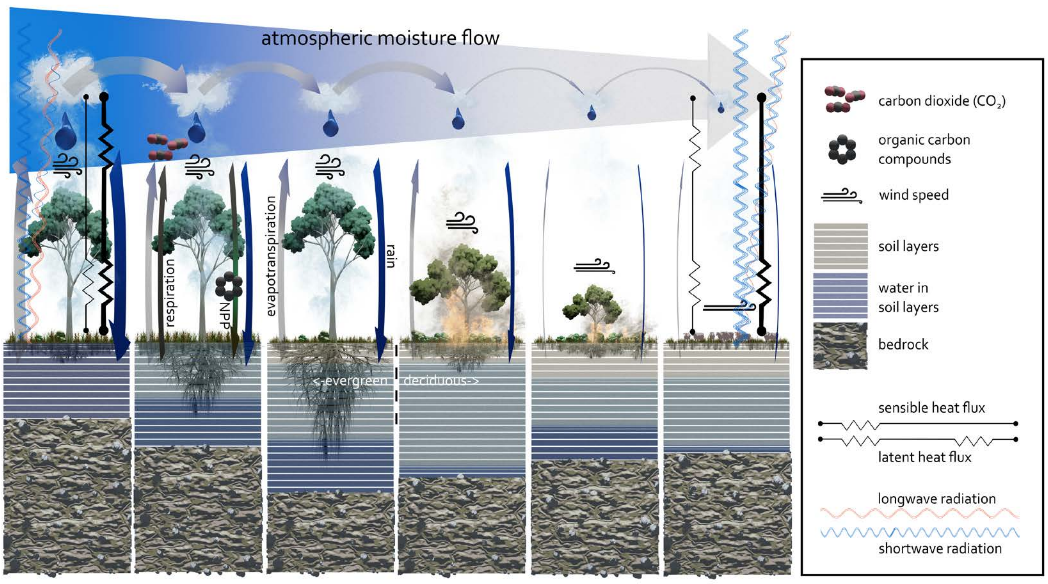


Figure 1.3.5: A conceptual regional transect from moist (left) to dry (right) localities depicting examples of local to regional feedbacks of forest cover with the land and atmosphere.

Less forest leads to ...

- less evapotranspiration (less productivity, less interception, less deep roots, etc.), hence reduced atmospheric moisture supply, and therefore reduced local and downwind precipitation, which leads to...
- less tree-produced volatile organic compounds (VOCs) serving as cloud condensation nuclei and therefore reduced local and downwind precipitation, which leads to...
- decreased roughness length of the landscape and hence increased wind speeds, leading to reduced residence time of moisture in the overall forest system, which leads to...
- decreased cloud formation due to less evapotranspiration, less VOCs, higher wind speeds leading to less reflectivity of sunlight, hence higher temperatures and therefore higher atmospheric water demand i.e. drought stress, which leads to...
- increased temperatures due to less evaporative cooling and decreased shading in canopy and ground proximity, hence higher atmospheric water demand i.e. drought stress, which leads to...
- more open canopy, drier understorey and less decomposition hence potentially larger pools of dead material to burn which all increasing fire probabilities, which leads to...
- higher windspeeds, less soil moisture and less soil retention capacity lead to higher erosion, which leads to...
- a surplus of atmospheric CO_2 by losing biomass carbon and losing a potential future carbon sink (a forest still capable of increasing biomass due to e.g. CO_2-fertilisation) and hence fueling global climate change, which leads to...

... less forest

1.3.2.3 Temperate forests

Temperate forests cover around 767 million hectares (16 per cent of the global forest area) and represent 34 per cent of global carbon sinks, storing around 119 GtC (Hansen et al., 2010; Pan et al., 2011) (Figure 1.3.6). In this report, we only consider temperate forests as defined in Figure 1.3.1. Mediterranean forests are covered under Drylands [see 1.3.2.5].

In most regions their spatial cover is highly fragmented following a long history of human land-use and forestry practices.

In fact there are only a few temperate forests which are considered 'intact' primary forest (Potapov et al., 2017; Sabatini et al., 2021) and the vast majority are managed by humans using vastly varying forest management techniques and intensities. Current managed temperate forests are often monocultures or mixtures of few tree species with relatively low biodiversity and structural diversity, optimised for high timber yields and certain wood features established under the assumption of stable climate and environmental conditions (instead of optimised for long-term forest resilience).

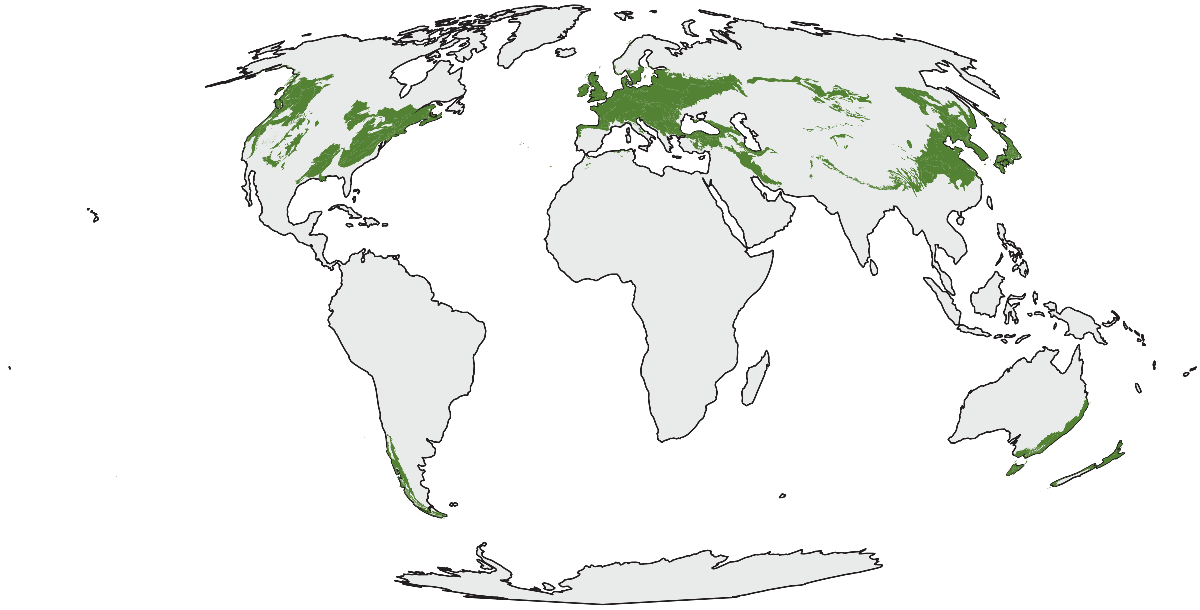


Figure 1.3.6: Top: map showing global extent of temperate forests biomes (green) (source: Dinerstein et al. (2017)). Left: photo of a mature temperate forest, Hainich National Park, Germany (credit: Boris Sakschewski,2022). Right: synchronous landscape-scale forest dieback (spruce monoculture) at Harz National Park, Germany (credit: Boris Sakschewski, 2023).

Evidence for tipping dynamics

In recent years temperate forests globally have suffered enormous damages and losses caused by extreme heat waves and droughts in combination with secondary effects like insect outbreaks and fires (Allen et al., 2010; Buras et al., 2019; Senf et al., 2020; Zhang et al., 2021; Carnicer et al., 2021; Benyon et al., 2023, Forzieri et al., 2022). As many temperate forests are effectively plantations for wood production in most parts of the world, those impacts often occurred in a similar synchronised manner on regional scales. Embedded in landscapes dominated by human land use (segregated by roads, crops, power lines, etc.), many temperate forests feature reduced connectivity and hence less exchange of species or genetic material, which reduces resilience (Sabatini et al., 2021).

More importantly, the extremely low diversity reduces the forest's ability to cope with stress through mechanisms such as portfolio insurance effects or complementarity (Billing et al., 2020). Portfolio insurance effects refer to the idea that having a diverse portfolio of species can help protect the forest against stressors by spreading the risk among different species. Complementarity refers to the idea that different species work together in a complementary way to improve the overall functioning of the ecosystem. However, when there is low diversity, these mechanisms may not be as effective and hence a potential tipping of temperate forests might also be more abrupt than in natural systems. Still, it must be noted that effective support from forest management (by regenerating an area through planting or supporting natural regeneration) can in principle also alleviate some of the pressures that natural systems face.

Besides the clear devastating signals of temperate forest damage and dieback, past assessments have had difficulties classifying temperate forests as tipping systems. In a review by (Thom, 2023) many temperate forest ecosystems were identified as resilient and/or resistant to increasing disturbance regimes and unlikely to shift towards alternative states in the very near future at large scale. However, drastic changes under intensifying future pressures such as climate change cannot be ruled out. In accordance with these findings, the recent assessment of (Armstrong McKay et al., 2022) has categorised temperate forests as an uncertain potential regional impact tipping system.

So far self-amplifying feedbacks in temperate forest dieback were described for more localised landscape-scale stressors like bark beetle attacks and fire in the Boreal forest section (see 1.3.2.2 and Box 1.3.2) (Hlásny et al., 2021; Fettig et al., 2022). On larger spatial scales it remains less clear whether temperate forests might feature self-amplifying feedbacks strong enough to induce tipping behaviour. However, just as in the tropical zone, the principles of cascading moisture recycling also apply to temperate forests. Any loss of forest cover reduces atmospheric moisture supply, hence reducing precipitation downwind and increasing sensible heat, which can amplify drying and warming in the affected areas (Pranindita et al., 2021). The average net cooling effect of temperate forests compared to grassland was found to be 1-2°C, with maxima of up to 5°C (Zhang et al., 2020). A recent study integrating data and modelling results reports continental-scale cooling effects of regrowing temperate forests on abandoned agricultural areas (Huang et al., 2020).

Related to this, cloud formation probability was found to be higher above forests in comparison to other land cover types in the temperate region (Teuling et al., 2017). Therefore, recent forest damages could have decreased cloud cover during recent droughts and heatwaves further intensifying these events. Furthermore, soil moisture-atmosphere feedbacks related to droughts and heatwaves were reported for the temperate zone (Seneviratne et al., 2010; Jaeger and Seneviratne, 2011) and could indicate that droughts might self-propagate in space and time (Schumacher et al., 2022). A recent study for the US west coast suggests cascading effects of soil moisture and biomass during a multi-year drought (Au et al., 2023). The recent large-scale forest damages and losses in the temperate zone (Senf et al., 2020; Lloret and Batllori 2021) could mark the beginning of self-amplifying and potentially self-sustaining feedbacks, but further work is required to confirm this.

The most important mediator between soil moisture and the atmosphere is vegetation, and forests especially stand out since they access water in great depths via their root systems (Sakschewski et al., 2021; Singh et al., 2020; Fan et al., 2017). Hence, larger-scale forest damage or loss means losing this mediator, further decreasing atmospheric moisture supply and downwind rainfall. This becomes particularly significant when, during droughts, precipitation becomes increasingly dependent on water evaporated from land or transpired by vegetation due to altered atmospheric patterns (Pranindita et al., 2021).

Additionally, local mechanisms or secondary effects could increase the likelihood of nonlinear responses, thereby increasing the probability of reaching tipping points. For instance in a more open forest or simply due to warmer and drier conditions at the forest floor, fire occurrences and intensities can easily increase. Moreover, the suppression of forest regeneration can occur due to the invasion of highly competitive light-demanding plant species, forming ecosystems which potentially transpire less moisture back to the atmosphere.

In combination with reduced resilience and resistance due to human interferences, abrupt large-scale damage and dieback of temperate forests is conceivable. Early warning signals in satellite-derived biomass data hint towards such a destabilisation (Forzieri et al., 2022). Yet, large-scale tipping behaviour in temperate forests is not proven. If at all, this will certainly be region-specific and recent forest damage will illuminate such potential feedbacks in the near future.

Assessment and knowledge gaps

It is uncertain if temperate forests have strong enough self-amplifying feedbacks like the Amazon rainforest and boreal forest to result in tipping, hence there is no evidence for larger-scale tipping and confidence is low. There is, however, a lot of evidence and medium confidence for abrupt changes with changing disturbances regimes.

Human forest management practices may have made temperate forests less resilient and therefore more susceptible to abrupt changes, but improved management can assist resilience and adaptation to climate change. Based on the impacts of current extreme events on temperate forests, it can be inferred that an increase in the intensity and/or frequency of such events could severely threaten existing forests in many areas, even without further climate change (Senf et al., 2020, Lloret and Batllori, 2021). The potential feedback to the water cycle requires further investigation. In particular, modelling studies should fully account for extreme events such as droughts, heatwaves and other important disturbances, their increasing frequencies and intensities as well as their potential impact on simulated vegetation and the resulting land-atmosphere feedbacks (Kolus et al., 2019).

1.3.2.4 Savannas and grasslands

Savannas and grasslands are characterised by the ecological dominance of grasses, sometimes with a substantial tree or shrub component (Figure 1.3.7). Savanna ecosystems are biodiverse and home to many people, but are being lost to a range of threats globally, especially because they are extensively targeted for agricultural conversion (Stevens et al., 2022; Strömberg and Staver, 2022). Even intact savannas are under threat, largely due to forest invasion or afforestation and woody encroachment, driven by grazing intensification and active fire suppression, and exacerbated by increasing atmospheric CO_2 (Stevens et al., 2017) and changing rainfall regimes (Kulmatiski and Beard, 2013). Active tree planting efforts further increase the threat to savannas from afforestation and woody encroachment.

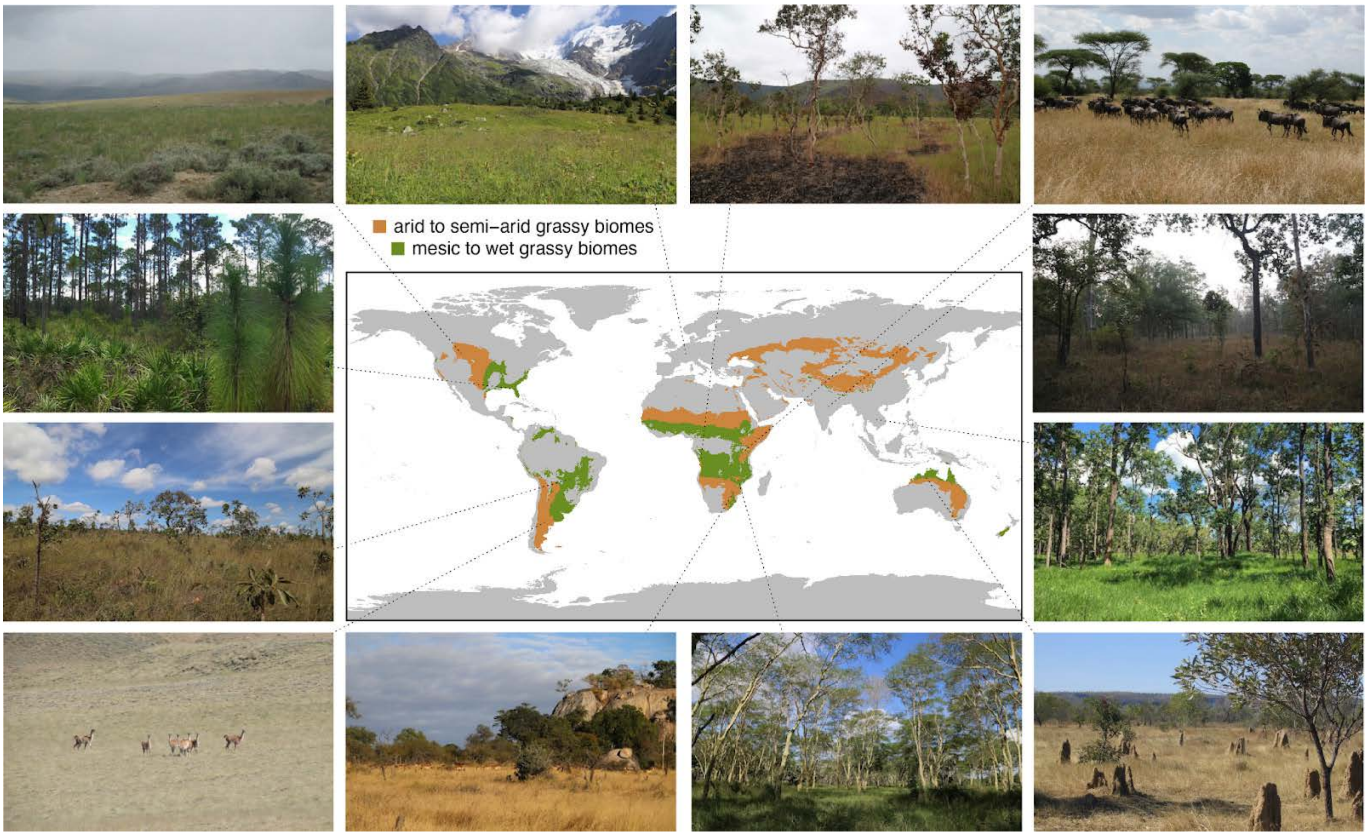


Figure 1.3.7: Global distribution of savannas and grasslands, showing semi-arid vs. mesic distributions (centre, from: Strömberg and Staver (2022), replotted from Dinerstein et al., (2017). Pictured, clockwise from top left, are native grassy ecosystems in 1) Montana near Dillon, USA; 2) Alps near Mont Blanc, France; 3) Pool Department, Republic of Congo; 4) Serengeti NP, Tanzania; 5) Pench NP, India; 6) Chhaeb Wildlife Sanctuary, Cambodia; 7) Kidman Springs Ranch, Australia; 8) Gorongosa NP, Mozambique; 9) Kruger NP, South Africa; 10) Santa Cruz Province near Lago Argentino, Argentina; 11) Instituto Brasileiro de Geografia e Estatística Reserve, Brasilia, Brasil; 12) Apalachicola National Forest, Florida, USA. Photo credits: Carla Staver, Caroline Strömberg, Naomi Schwartz.

Although the converse issue receives extensive attention (e.g. Amazon rainforest collapse), the issue of savanna vulnerability to tipping points is recognised (Staver et al., 2011b) but generally neglected in literature and assessments of tipping points in the Earth system (Armstrong McKay, 2022; Wang et al., 2023). Savanna vulnerability to desertification (corresponding to a self-sustaining loss of ecosystem productivity) is sometimes cited in tipping point syntheses, but the generality of this feedback has been questioned. For example, aridification observed in western Africa's Sahel during the 1970s and 80s has since reversed across much of the Sahel in response to a cyclic increase in rainfall (Nicholson et al., 1998; Prince et al., 2007).

Evidence for tipping dynamics

Savanna and forest are widely considered to be alternative stable ecosystem states in some climates (Staver et al., 2011a, 2011b; Hirota et al., 2011; Dantas et al., 2015; Aleman et al., 2020). In savannas and grasslands, an open tree canopy permits high grass productivity and thus the accumulation of grass fuel for frequent fires (Hennenberg et al., 2006; Lloyd et al., 2008). Fires in turn limit tree establishment (Higgins et al., 2000; Hoffmann et al., 2009), keeping the canopy open and creating a positive/amplifying feedback that potentially stabilises savannas in regions where forest is also a viable stable ecosystem state (Beckage and Ellingwood, 2008; Staver et al,. 2022a), although some apparent bistability may be the result of spatial climate variability (Good et al., 2015; Higgins et al., 2023).

The maintenance of savannas is thus dependent on fires across large parts of their range. This has meant that widespread fire suppression (active or passive via agricultural fragmentation or grazing intensification) has triggered woody encroachment and, in extreme cases, forest invasion (Stevens et al., 2017). These feedbacks between vegetation and fire frequency and intensity have also been implicated in accelerating the invasion of alien grasses that are more flammable and also tolerate higher fire intensities than native grasses (D'Antonio and Vitousek 1992; D'Angioli et al., 2022) (Figure 1.3.8). Fire-related feedback loops may not be as significant in drier savannas where herbivores or low water availability limit the accumulation of grass and thus fuel (Archibald and Hemson, 2016; Dexter et al., 2018), and further research is needed on the tipping dynamics of arid savannas and their potential alternate states (see Drylands 1.3.2.5).

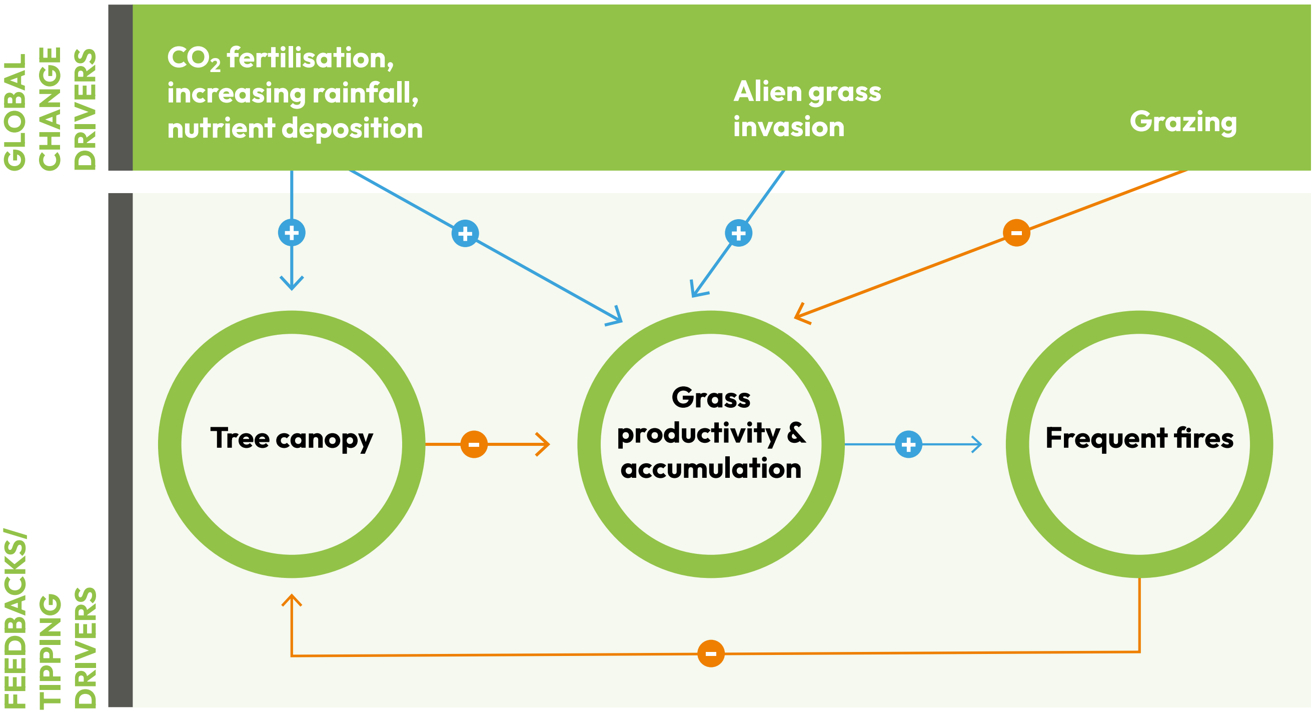


Figure 1.3.8: Key feedbacks that could lead to savanna tipping.

Several important thresholds are involved in this tipping point. First of all, fire spread is widely described as a percolation process (Loehle et al., 1996; Favier, 2004) – whereby a burning patch infects neighbouring or nearby flammable patches, thereby propagating fire in flammable landscapes. However, when not enough of the landscape is flammable (in this case, if trees shade grasses to prevent fuel accumulation), fires extinguish, with a clear threshold in fuel cover between 'connected' flammable vs. 'unconnected' non-flammable landscapes (Cardoso et al., 2022). In theory, this threshold can depend on the model used, but in practice, there appears to be a threshold in fuel cover of ~50-60 per cent, below which fire does not successfully spread (Archibald et al., 2009; Cardoso et al., 2022). Thus, fire suppression initiates woody encroachment or forest invasion, which can in turn decrease landscape flammability further, creating a cascade that results in the irreversible loss of open-canopy savannas.

The rate at which this happens – and ultimately the environmental space in which closed vs. open-canopy ecosystems are viable – depends also on environmental thresholds, but these are more widely disputed. A range of studies has defined the minimum required to sustain a closed forest canopy as ranging between 750 and 1,000mm mean annual rainfall (Sankaran et al., 2005; Staver et al., 2011b; Aleman et al., 2020), but more open but still fire-suppressing canopy can also form at much lower rainfall, for example in the Caatinga (Charles-Dominique et al., 2015; Dexter et al., 2018). The high-rainfall limit for savanna persistence is even less defined, as savannas can occur in areas with well over 1,600mm mean annual rainfall – for example, in the Llanos of Venezuela and Colombia (Huber et al., 2006) or the Beteke Plateau in the Republic of Congo (Nieto-Quintano et al., 2018).

Moreover, increasing atmospheric CO_2 is changing the relative photosynthetic efficiencies of 'C4' grasses vs. 'C3' trees (with C4 being the more efficient photosynthesis process) (Ehleringer and Björkman, 1977; Bond and Midgley, 2012) and is increasing plant water use efficiency across different plant types (Leakey et al., 2009; Norby and Zak, 2011). This has increased the rate of woody encroachment and forest invasion into savannas, suggesting that vulnerability of savannas to tipping points is accelerating and is not stationary with respect to climate (Higgins and Scheiter, 2012). For this reason, defining exactly how much global change might trigger savanna tipping points is not feasible (and indeed a single global tipping point may not exist).

Several lines of evidence provide support for the irreversibility of savanna-to-forest transitions. First, palaeoecological studies have suggested that reversible increases in rainfall can result in irreversible shifts from savanna to forest, consistent with hysteresis (i.e. where reversing the driver of change does not lead to recovery; see Glossary) (Karp et al., 2023). Second, and more directly, fire experiments have demonstrated that, while fire suppression causes savannas to transition to forest-like systems, introductions of fire into forests have much smaller effects (Gold et al., 2023), likely because closed forest canopies prevent fuels from accumulating to fuel intense savanna fires. This demonstrates that managed fire reintroductions are not sufficient to reverse forest encroachment (Gold et al., 2023).

Extreme fires can help reverse encroachment by forests when trees are fire sensitive (Silvério et al., 2013, Brando et al., 2014, Beckett et al., 2022) but extreme fires do not reverse woody encroachment (Strydom et al., 2023). In the case of savanna invasions by non-native grasses, irreversibility of transitions may be further exacerbated by resulting changes in nutrient cycling (Bustamante et al., 2012; D'Angioli et al., 2022). Together, these diverse lines of evidence suggest that savanna invasions, once initiated, may be rapid and irreversible.

The timescale of woody encroachment varies depending on environmental controls, but can happen in less than a decade, with accelerating vulnerability across savanna ecosystems due to rising CO_2 (Stevens et al., 2022) and widespread enthusiasm for climate mitigation via tree planting (Bastin et al., 2019, Fagan et al., 2022).

The climate impacts of woody encroachment and forest invasion are uncertain, however, due to substantial carbon in belowground pools in savannas (Zhou et al., 2022) and large uncertainty in how belowground carbon pools (root biomass and especially soil organic carbon) will respond to increasing woody cover (Veldman et al., 2019; Zhou et al., 2023). Hydrologically, there is evidence that an increasing tree fraction can increase rainfall interception and accelerate ecosystem water use, depleting groundwater recharge and streamflow, with implications for downstream water availability (Jackson et al., 2005, Honda and Durigan, 2016). Feedbacks with albedo (with woody vegetation being 'darker' than grass) have also been discussed, but little studied (Stevens et al., 2022).

Assessment and knowledge gaps

We have high confidence that Savannas are undergoing widespread degradation from woody encroachment, forest invasion, afforestation and alien grass invasion, high confidence that this is related to grazing intensification and active fire suppression and medium confidence that this is exacerbated by increasing CO_2 levels. These changes are increasingly difficult to reverse with the reapplication of fires (medium confidence), although sensitivity of invading vegetation to climate extremes is variable or unknown (Zeeman et al., 2014; Case et al., 2020).

Compounded by agricultural conversion and tree planting, this is rapidly eroding endemic savanna and grassland biodiversity (high confidence) (Smit and Prins, 2015, Andersen and Steidl, 2019, Wieczorkowski and Lehmann, 2022).

Overall, savannas are likely to feature tipping dynamics at local to landscape scales (medium confidence), although large-scale synchrony may be observed if global change drivers trigger tipping points. However, Earth system feedbacks associated with savanna degradation are highly uncertain (low confidence), with particular knowledge gaps about carbon and hydrological cycle outcomes. Potential tipping points in savannas and grasslands associated with herbivory represent another major knowledge gap.

1.3.2.5 Drylands

Drylands are hyper-arid, arid, semi-arid and dry-sub-humid climate zones (Figure 1.3.9) where rainfall is less than 65 per cent of the 'potential evapotranspiration' (i.e. the amount of evaporation that would occur if enough water were available) (Middleton and Thomas, 1992). They occupy over 46 per cent of the Earth's surface and host 38 per cent of the world's human population (more than 2 billion people) (Cherlet et al., 2018). Vegetation types include deserts, grasslands, shrublands, woodlands, savannas, Mediterranean forests and tropical dry forests (see 1.3.2.1 and 1.3.2.4 for tropical dry forests and savannas). Due to their extent and the chronic water deficit, these areas are of particular concern in the face of global changes, and so we assess them separately here, despite some overlap with the tropical forest and savanna and grassland biomes above.

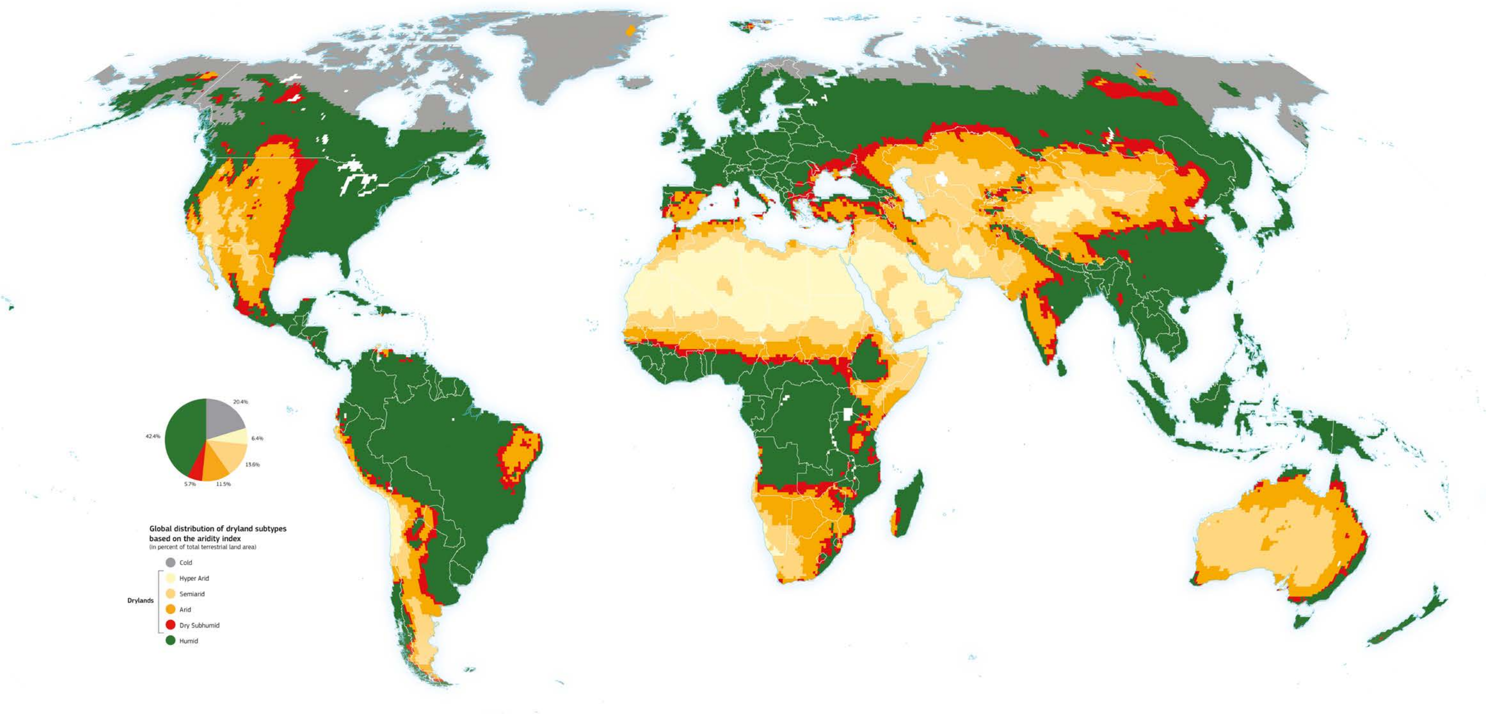


Figure 1.3.9: Global distribution of dryland subtypes based on the aridity index. Source: WAD3-JRC (Cherlet et al., 2018).

Recent estimates suggest that one-fifth of drylands are degraded as a result of climatic variations and human activities (Burrel et al., 2020; about 9 per cent in IPCC SRCCL, 2019). Major pressures on drylands (Cherlet et al., 2018) include:

- Climate change – for example, changes in precipitation, temperature, seasonal and interannual variability and frequency of extreme events. Projections indicate that some drylands might become more humid, whereas others may become drier (Huang et al., 2016; Pravalie et al., 2019). These expectations are uncertain though (Lian et al., 2021).
- Land use intensification – for example, grazing (the main use of drylands, at 62 per cent) (Cherlet et al., 2018), water extraction, deforestation, agriculture and urbanisation.
- Perturbations – for example, fires, insect outbreaks and biotic invasions.

The dynamics of drylands depend strongly on the interaction between these pressures, such as climate change and local perturbations (Rilig et al., 2023).

Evidence for tipping dynamics

Different lines of evidence point toward the existence of tipping dynamics in drylands, including past and current ecosystem transitions, bistability of dryland states at the global scale, thresholds along environmental gradients, and feedback mechanisms maintaining persistent dryland states.

Abrupt transitions have historically occurred in several dryland systems. Palaeo evidence reveals abrupt shifts into and out of African Humid Periods (Pausata et al., 2020), including a notable greening of the Sahara during the early to mid-Holocene, followed by its abrupt desertification around 5,500 years ago (Shanahan et al., 2015; Claussen et al., 2017; Hopcroft and Valdes, 2021, Claussen et al., 1999). Positive/amplifying feedback mechanisms between vegetation and the monsoon in North Africa are thought to be important (Charney et al., 1975). Climate change projections suggest 'Sahel Greening' might partially occur again in the future (Erfanian et al., 2016; IPCC SR1.5, 2018; Dosio et al., 2021). In dune systems, stratigraphic records covering 12,000 years have found coexistence of a vegetated, stabilised state and a bare active state in dune systems in northern China, with occasional sharp shifts in time between those contrasting states and hysteresis (Xu et al., 2020).

Shrub encroachment may also reflect tipping dynamics. Long-term data from Jornada Experimental Range (northern Chihuahuan Desert, New Mexico, USA) showed abrupt transitions from grasslands to shrublands triggered by a combination of climatic and human (i.e. overgrazing) factors during the last 150 years (Beltelmeyer et al., 2011; D'Odorico et al., 2012). Transitions from Mediterranean forests to shrublands have been reported under a combination of dry conditions, wildfires (Baudena et al., 2020; Acacio et al., 2009, Mayor et al., 2016) and herbivory (van der Wouw et al., 2011).

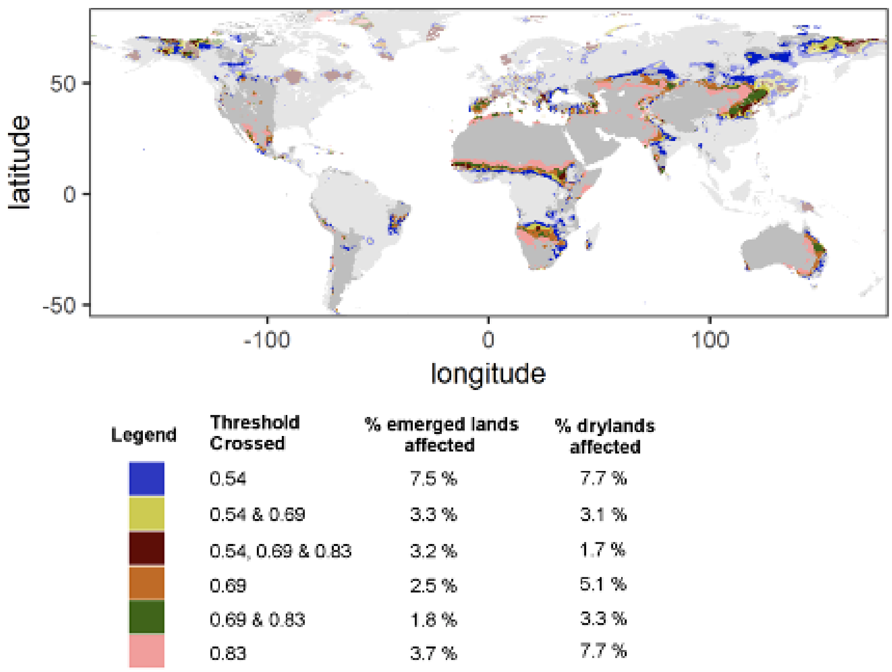


Figure 1.3.10: Map of drylands vulnerability to predicted changes in aridity for 2100 based on the IPCC RCP8.5 scenario (i.e. under the assumption of sustained increase in CO_2 emissions). Abrupt decays in plant productivity, soil fertility and plant cover were identified beyond aridity threshold values of respectively 0.54, 0.7, and 0.8 (Berdugo et al., 2020). The map displays areas that are expected to cross one (or several) of those thresholds in aridity level. Light-grey areas are areas that are not drylands today. Figure from (Berdugo et al., 2020). Satellite observations indicate that 5 per cent of drylands have experienced an abrupt loss of vegetation cover over the last 20 years, while 18 per cent underwent an abrupt increase in vegetation (Berdugo et al., 2022).

Evidence suggests that, in drylands, sequential abrupt shifts in plant productivity, soil fertility and plant cover occur at increasing aridity thresholds, respectively corresponding to aridity values of 0.54, 0.7, 0.8 (Berdugo et al., 2020) (Figure 1.3.10). A higher dependence of vegetation on water has been reported at aridity values of around 0.6 (Nemani et al., 2003), producing a decline in productivity with increasing aridity (Berdugo et al., 2020) and an increase in tree mortality events with hotter droughts (Hammond et al., 2022).

At aridity levels around 0.7, abrupt declines in vegetation are related with losses of soil fertility (Delgado-Baquerizo et al., 2013; Berdugo et al., 2020), changes in vegetation spatial structure, (Kéfi et al., 2007, 2011; Berdugo et al., 2017; Berdugo et al., 2019) which influences soil hydrological connectivity and resource loss at the landscape scale (Mayor et al., 2013; Rodriguez et al., 2018, Mayor et al., 2019), increases in the dominance of shrublands (Berdugo et al., 2020), and rapid shifts in the composition of soil microbial communities and soil functionality (Maestre, 2015; Lu, 2019; Delgado-Baquerizo, 2020; Zhang et al., 2023).

At aridity thresholds of 0.8, abrupt decays in plant productivity and vegetation cover occur (Berdugo et al., 2020) and can lead to a nonlinear increase in soil erosion (Mora and Lázaro, 2013; Elwell and Stocking, 1976; Francis and Thornes, 1990; Mayor et al., 2013).

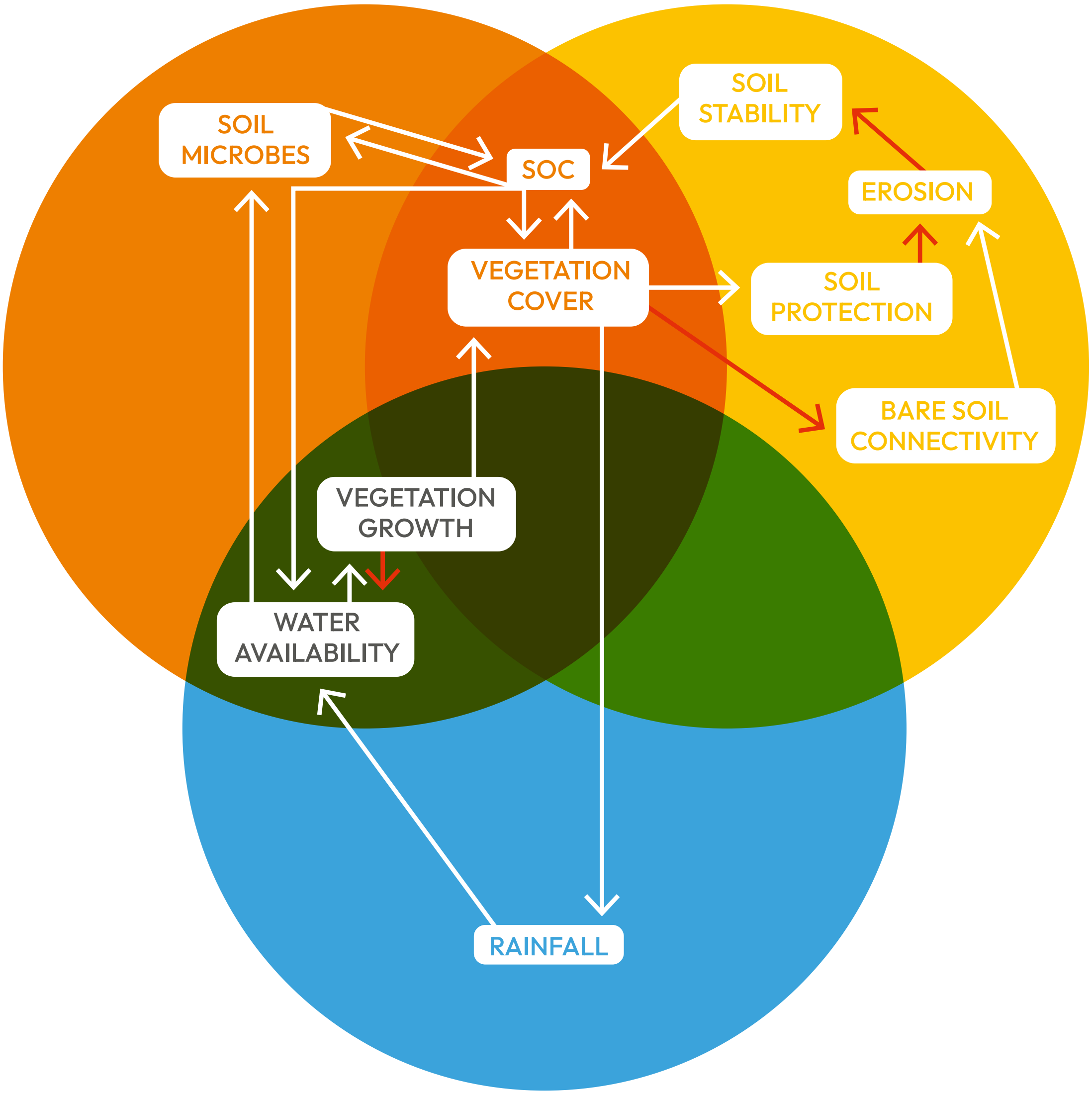


Figure 1.3.11: Schematic showing key feedbacks that could lead to dryland tipping. Coloured disks represent some of the main feedbacks described in the text (vegetation-rainfall in blue, biogeochemical feedback in red and ecohydrological feedback in blue). White arrows represent positive effects (an increase in the variable at the source of the arrow leads to an increase of the variable at the end of the arrow) and red negative effects. SOC stands for Soil Organic Carbon. See (Mayor et al., 2019) for a more detailed version of the ecohydrological feedback.

A number of feedback mechanisms are known to occur in drylands, operating across ecosystem elements and at different spatio-temporal scales. Theoretically, such feedbacks can lead to bistability and abrupt transitions between stable states in drylands (Holling, 1973; Noy-meir, 1975; May, 1977; Scheffer et al., 2001, Walker et al., 2004), although such alternative states do not necessarily exist in all regions (Ma et al., 2023). Several key feedbacks can be identified (Figure 1.3.11):

- **Soil microbial communities (biogeochemical feedback; small scale):** Microbial biomass and diversity in drylands are intricately linked to variations in water availability and organic matter (which change along the global aridity gradient; Zhang et al,.2023). Soil microbes, such as bacteria, fungal decomposers and mycorrhizal fungi, are fundamental for the breakdown of complex litter and organic matter. By decomposing organic matter, microbes are critical in the build-up of soil carbon stocks, which is essential in the maintenance of moisture in dry soils. Soil moisture, in turn, is needed for organic matter decomposition.
- **Plant-plant interactions:** In drylands, plants are known to facilitate the recruitment and growth of other plants, leading to the formation of vegetation patterns. The positive interactions between plants, i.e. facilitative effects, involve effects on microclimate, soil conditions and herbivores impacts:
  - **Plant-soil feedback (small to medium scale):** Plants enhance local soil conditions through several means, such as nutrient and water retention ('islands of fertility'), microclimate influence and erosion prevention (Aguiar and Sala 1999; Schlesinger et al., 1990; Rietkerk et al., 2000; D'Odorico et al., 2007). These processes boost vegetation growth and contribute to the formation of spatial patterns.
  - **Ecohydrological feedbacks (medium scale):** Plants aggregate and form spatial patterns of vegetation patches interspersed in a matrix of bare soil (Aguiar and Sala, 1999). The spatial connectivity of the bare soil (runoff-source areas) affects the redistribution of water, nutrients and sediments at the patch and landscape scale, which in turn shapes vegetation cover and spatial pattern (Mayor et al., 2013, 2019). These local (patch) and global (landscape) connectivity-mediated feedbacks affect the productivity and resilience of the ecosystem (Mayor et al., 2019).
  - **Vegetation-herbivore feedback (medium scale):** Herbivores graze/browse on palatable plants, which stimulates regrowth (McNaughton 1983); they then keep eating at the same places because the resprouts are soft and more easily digestible. This in turn allows the recruitment of unpalatable plants in areas without herbivores. An excess of grazing on palatable plants can prevent regrowth and lead to vegetation transitions from diverse, palatable to unpalatable dominated plant communities (Cingolani et al., 2005).
- **Vegetation-fire feedback (medium to large scale):** Fire can facilitate a transition from forest to shrublands. Shrublands recover faster and burn easier, generating a positive/amplifying feedback (e.g. dry Mediterranean regions in Portugal (Acacio et al., 2009), Spain (Baudena et al., 2020)). Replacement of native Mediterranean forests by pine forest plantations or invasion by exotic non-woody plants can contribute to this feedback (e.g. central Chile) (Pauchard et al., 2008; Gomez-Gonzalez et al., 2018) (see also: Tropical [1.3.2.1] and Boreal [1.3.2.2] forests).
- **Vegetation-rainfall positive/amplifying feedbacks (large scale):** Vegetation is largely controlled by local climate, but modelling studies suggest that it can also influence regional precipitation by modifying the atmospheric energy and water budget (Charney, 1975; Dekker et al., 2007). This large-scale albedo-precipitation and evapo-transpiration–precipitation feedback could have significant implications for ecosystem resilience. (see also: Tropical [1.3.2.1] and Boreal [1.3.2.2] forests).

Global dryland assessments suggest two different ecosystem states can exist at intermediate aridity levels ('bistability'). Drylands with aridity levels between between 0.75 and 0.8 (i.e. in the transition zone between semi-arid and arid drylands) may be in one of two different states, with higher and lower vegetation cover, with large contrasts in soil fertility, nutrient capture and nutrient cycling (Berdugo et al., 2017). Observing different ecosystem states across an area with similar conditions does not in itself prove those ecosystems are bistable. However, the global tendency for these two states to emerge, combined with our understanding of feedbacks in these ecosystems and observations of threshold responses, suggests that these could represent alternative stable states in these ecosystems.

Hysteresis, where reversing the driver of change does not lead to recovery (see Glossary), can also be evidence for alternative stable states and tipping dynamics in dryland ecosystems. In Spain (NE, Ebro Valley), past overgrazing was found to interact with droughts to explain the lack of secondary succession or even decreasing normalised difference vegetation index (NDVI, a remote sensing index for vegetation cover) trends (Vicente-Serrano, 2012). Some long-term field studies provide evidence for hysteresis in drylands. For example, in the northern Chihuahuan Desert (US), grasslands shifted into shrublands dominated by Creosote Bush (*Larrea tridentata*) during a prolonged drought combined with overgrazing, but the recovery of grass productivity did not occur in subsequent wet years (Bestelmeyer et al., 2011). Results also suggest the possibility of crossing critical thresholds for irreversible degradation (i.e. 20 per cent plant cover in Gao et al., 2011).

Long legacy effects are consistent with the existence of hysteresis in drylands. For example, palaeoclimatic legacies, e.g., from the Last Glacial Maximum, influence soil biodiversity (Delgado-Baquerizo et al., 2017), function (Ye et al., 2019) and forest distribution (Guirado et al., 2022). For example, drylands with a wetter past now have greater levels of function and forest coverage than what would be expected for current climatic conditions (Ye et al., 2019).

The reversibility of ecological transitions in drylands is challenging because plant growth rate is strongly limited by water scarcity and local disturbances. However, it is noteworthy that fast vegetation recovery during rainy periods has been observed at local and regional scales (Holmgren et al,.2006a, 2013). Studies have also found recovery of drylands to strong grazing pressure even at low cover levels in case of favourable weather conditions (Bestelmeyer et al., 2013). Coupling passive and active restoration of drylands to favourable climate swings can open windows of opportunity for dryland recovery (Holmgren and Scheffer 2001, Holmgren et al., 2006b, Sitters et al., 2012).

Timescale for transitions are about weeks to months for tree heat and grazing, months to decades for shrub encroachment Bestelmeyer et al., 2011; Tabares et al., 2019 and abrupt vegetation loss due to droughts Berdugo et al., 2022), and a few decades for the desertification of the Sahara (Shanahan et al., 2015; Claussen et al., 2017; Hopcroft and Valdes 2021; Claussen et al., 1999).

Assessment and knowledge gaps

Dynamical evidence of tipping points in drylands is challenging to find due to the slow dynamics of these ecosystems. Altogether, the knowledge of past transitions shows that relatively rapid changes have occurred in drylands, in particular in terms of vegetation cover, species composition and soil communities, leading to important changes for biodiversity and ecosystem functioning. Further, evidence from positive/amplifying feedbacks between different components of ecosystems, thresholds values in stressors (aridity, fire frequency, grazing) and hysteresis (lack of recovery) suggests the likelihood of future recurrence. We assess that dryland ecosystems can feature local to landscape-scale tipping points towards land degradation (medium confidence) with climate and land use change.

Core ecological questions remain, mainly on the mechanisms by which abruptness appears in drylands. We need long-term dynamical records. This is in particular true for soils; which is very relevant given that several thresholds involve soil transformations (particularly soil fertility losses). This lack of evidence in soils is even more difficult to address given that soils are themselves a slow component in an already slow ecosystem type and, unlike vegetation, can not be assessed with remote sensing. Quantification of the thresholds for herbivory pressure, fire frequency, and logging along aridity gradients is also necessary. Crucially, we need to improve our description and incorporation of social-ecological feedbacks in drylands (Reynolds et al., 2007). Indeed, dryland ecosystem transitions are associated with important social pressures and livelihood dependency, especially in developing countries, making social-ecological feedbacks critical to understand (see Section 2; Walker et al., 2004; Reynolds et al., 2007).

Several biotic mechanisms (e.g. local negative plant-patch feedbacks – Mayor et al., 2019) that confer resilience to dryland ecosystems are still not sufficiently explored, such as plant plasticity or adaptability to drought. Some mechanisms might be able to counteract abrupt changes; for example CO_2 fertilisation may confer higher water use efficiency to plants, thus opposing stress caused by lack of water (Zhu et al., 2016) and possibly counteracting aridification (Peñuelas et al., 2017; Zhang et al., 2022). Also, we can refine our understanding of windows of opportunity for restoration in drylands (e.g. taking advantage of temporarily favourable climatic conditions; Holmgren and Scheffer 2001; Holmgren et al., 2006b; Sitters et al., 2012; Walker and Salt 2012).

1.3.2.6 Freshwater ecosystems

The scientific content of this chapter is closely based on the following scientific manuscript: Hessen et al., (in review) Lake ecosystem tipping points and climate feedbacks, Earth System Dynamics Discussion.

Freshwater bodies such as lakes are common across most biomes, forming unique and sometimes isolated ecosystems (Figure 1.3.12). In natural sciences, the hysteretic behaviour of lakes (Scheffer et al., 2007) has informed the concept of tipping points at the ecosystem level, leading to the development of the alternative stable states theory in shallow lakes (Scheffer et al., 1993; Carpenter et al., 1999; Carpenter 2005). They represent archetypal case studies for how tipping points relate to theories of ecological stability and resilience that can underpin preventative management approaches (Andersen et al., 2009; Spears et al., 2017). Despite this, significant uncertainty remains on the geographical extent of tipping points in lakes and the wider relevance for the Earth's climate system.

Lakes are also good examples of social-ecological systems, with their ecological dynamics closely intertwined with the socio-economic dynamics of surrounding populations who often depend on them for key ecosystem services and adaptively respond to changes in lake condition (Martin et al., 2020). Given the global vulnerability of freshwaters and the pervasive nature of major pressures acting upon them (e.g. nutrient pollution and climate change), tipping points in these systems could have significant societal impacts, including on human and environmental health, food production and climate regulation. The capacity to detect discontinuous ecosystem responses to pressure changes in natural systems has been challenged (e.g. Hillebrand et al., 2020). Nevertheless, there are several studies that have reported real tipping points, i.e. shifts from one stable state to another in small shallow lakes (the most common lake type globally, Messager et al., 2016).

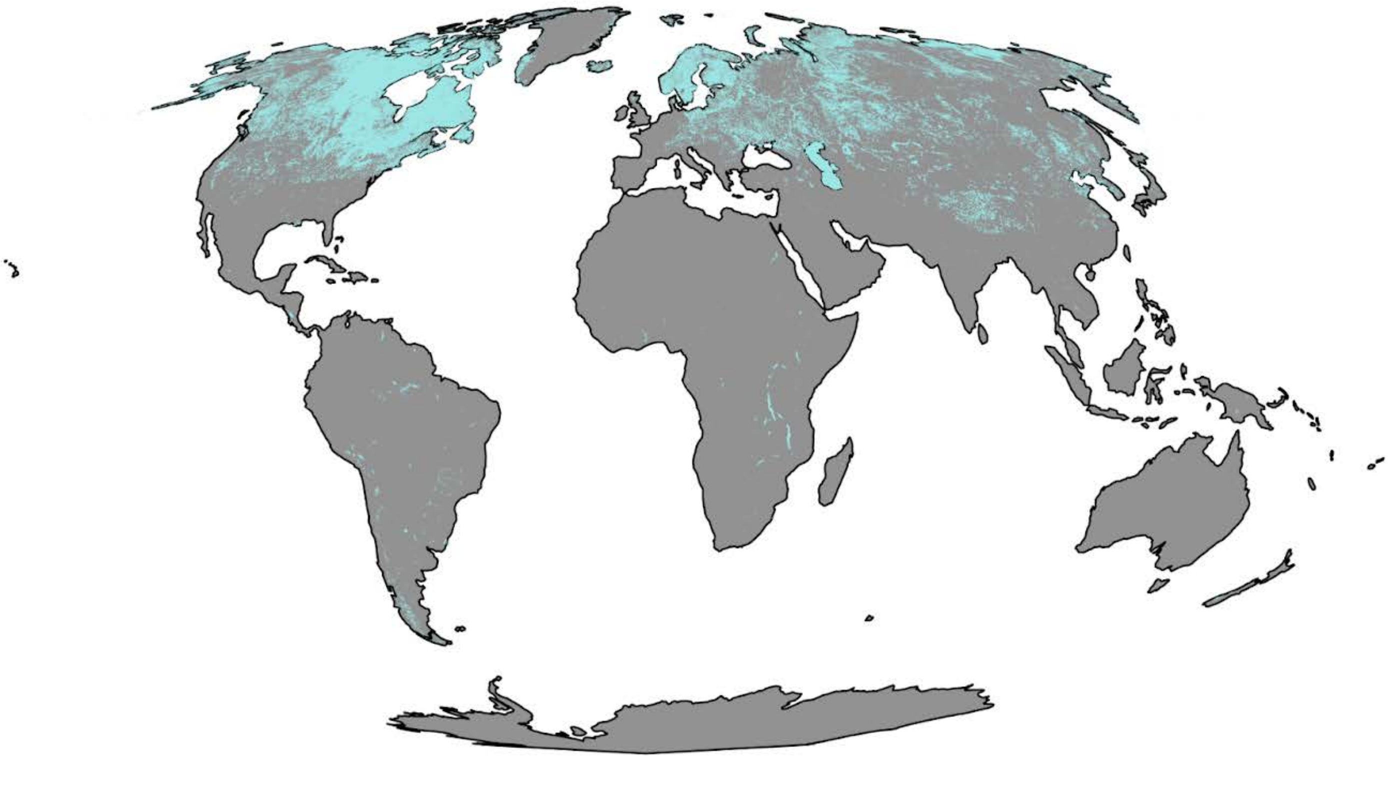


Figure 1.3.12: Top: map showing global distribution of lakes (light blue) (source: (Keith et al., 2022). Middle left: eutrophic urban lake receiving high organic matter loading leading to elevated CH_4 emissions, Bellandur Lake, Bengaluru City, India (photo: Laurence Carvalho). Middle right: boreal, brown water lake with deepwater anoxia and high emissions of CO_2 and CH_4 (photo: D.O. Hessen). Bottom left: Arctic pond at Svalbard, recently formed by permafrost thaw below Zeppelin mountain (photo: D.O. Hessen). Bottom right: thermokarst lakes in Yukon Flats, Alaska (photo: Sebastian Westermann).

Empirical analyses, process modelling and experimental studies are advanced for shallow lakes providing a good understanding of ecosystem behaviours around tipping points, typically starting with positive/amplifying feedback loops, then entering a runaway phase before finally the tipping point brings the system into a different stable state (Nes et al., 2016). For example, the well documented increase of phosphorus (P) loading across European lakes in the last century (e.g. from agricultural and waste water pollution) has uncovered critical loading thresholds beyond which lakes can shift rapidly from a clear water, macrophyte rich state to a turbid, phytoplankton rich state (Scheffer et al., 2001; Jeppesen et al., 2005; Tátrai et al., 2009), and vice versa when nutrient loading decreases.

Adding to such well-described and mechanistically well-understood changes, there is a wide range of local or single lake shifts that may be categorised as tipping points. The question remains as to whether tipping points are merely isolated phenomena in single lakes, or specific types of lakes, or whether they manifest, or will in the future, across geographically distinct populations of lakes experiencing similar environmental change, with the potential for regional or global extent (Figures 1.3.12 and 1.3.13).

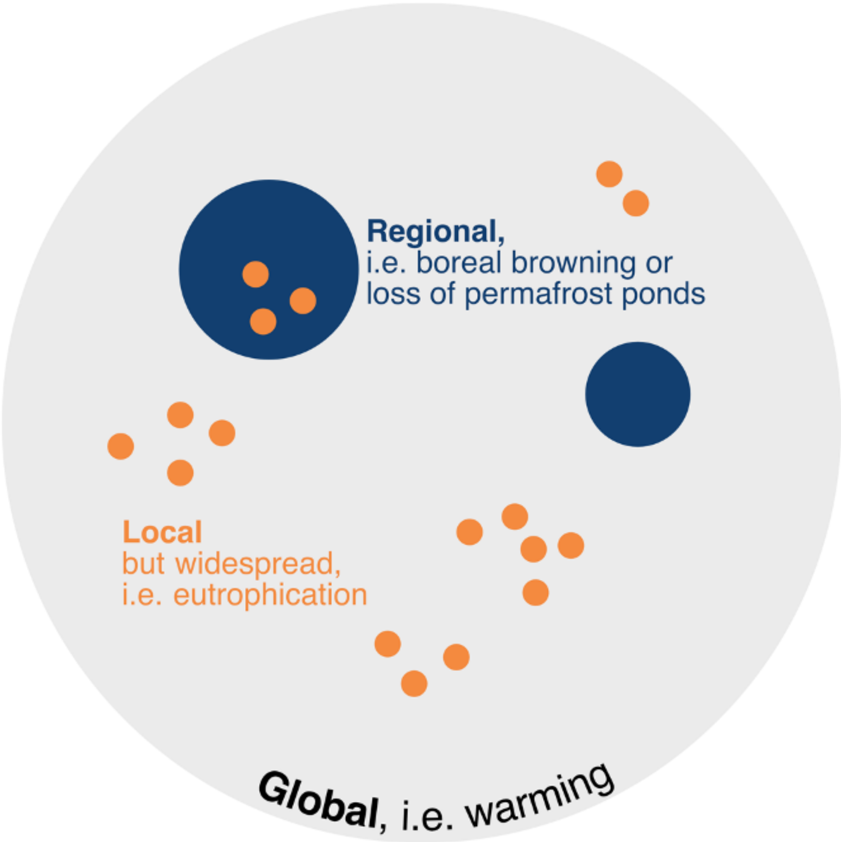


Fig. 1.3.13: Impacts at levels that may qualify for tipping points at relevant scales. Regional or biome-wise, effects could be loss of ponds and lakes due to permafrost thaw and/or increased loadings of DOM in the boreal biome or salinisation. Also, local but widespread changes such as anthropogenic eutrophication of lakes in populated areas would have large-scale impacts. Lakes worldwide show a warming trend, hence a global impact. Source: (Hessen et al., 2023, in review).

It is well established that lakes are sensitive to the effects of climate change, including warming and changes in precipitation and storminess (Meerhoff et al., 2022). Emerging evidence suggests that they may also play an important role in climate regulation, through both the emission of greenhouse gases (predominantly methane – Downing et al., 2021) and carbon burial (Anderson et al., 2020). It is therefore relevant to consider the extent to which potential tipping points may drive, or be driven by, climate change, leading to higher-level feedbacks to the Earth's climate system. In this context we will constrain the discussion to potential tipping points that are more generic, at least with some regional or biome-wise impact, and that could feedback to the climate, while not necessarily being driven or triggered by climate change per se.

Here, we adhere to tipping points as defined in this report (and matching Nes et al., 2016). Based on this we discuss candidate tipping points in freshwaters (Table 1.3.2), focusing on lakes and ponds, with the potential for global or at least regional or biome-scale relevance.

Evidence for tipping dynamics

Eutrophication-driven anoxia and internal P-loading

The mobilisation of P from sediments, a process known as internal loading (Sondergaard et al., 2001), is well described and plays a key role in hysteresis in preventing lakes recovering from human-driven eutrophication (Boström et al., 1982; Jeppesen et al., 1991; Spears and Steinman 2020).

The process may be enhanced by lake warming, and there are feedbacks to climate since water anoxia and internal P-loading (which features the actual tipping point) could offset CO_2-fixation by increased release of GHGs. Consequent changes in biota also strengthen hysteresis (Brabrand et al., 1990), not least when cyanobacterial blooms develop. The phenomenon is local but widespread, and likely to increase as a result of global warming (Meerhoff et al., 2022). Increases in precipitation, and high-intensity rainfall events, are also expected to significantly increase runoff of P from agricultural catchments to surface freshwaters (Ockenden et al., 2017), further promoting eutrophication and its manifestations. Warming increases stratification and thermal stability promoting anoxia (Maberly et al., 2020; Woolway et al., 2020), internal fertilisation and increased GHG emissions. In addition to anoxia, there are other feedback mechanisms for lake eutrophication tipping points, such as the macrophyte-nutrient-algae-turbidity and macrophyte-zooplankton/fish-algae-turbidity loops (Wang et al., 2022). Shifts in trophic cascades, i.e. a top-down control of zooplankton and reduced grazing on phytoplankton, could also help drive eutrophication (Carpenter et al., 1985; Carpenter and Kitchell 1988). However, feedback to the climate is primarily related to anoxia.

Increased loading of DOM and anoxia

Increased export of terrestrially derived dissolved organic matter (DOM) to lakes and rivers in boreal regions ("browning") is a widespread phenomenon partly linked to reduced acidification, but also driven by land use changes (notably afforestation) and climate change (CO_2-fertilisation of forests, warming and hydrology) (de Wit et al., 2016; Creed et al., 2018; Monteith et al., 2023). Wide-scale regime shifts in boreal lakes caused by increased loadings of DOM can promote a prolonged and more intensified stratification period (implications summarised above, described for DOM by Spears et al., 2017), amplified by warming. Increased terrestrial DOM loadings intensify net heterotrophy in the systems (i.e. through increased light attenuation and increased access to organic carbon) (Karlsson et al., 2009; Thrane et al., 2014; Horppila et al., 2023). While at present the thresholds around these effects have not been well constrained, the impacts may be significant at the global scale for GHG emissions (Tranvik et al., 2009) and regionally for coastal productivity (Opdal et al., 2019)

Both eutrophication and browning are to some extent driven by climate change, and warming of lakes will promote the effects by increasing thermal stratification, promoting anoxia which again promotes internal loadings of phosphorus, leading in some cases to self-sustaining change (i.e. tipping). Increased release of GHGs will serve as another feedback to the climate (Fig. 1.3.14).

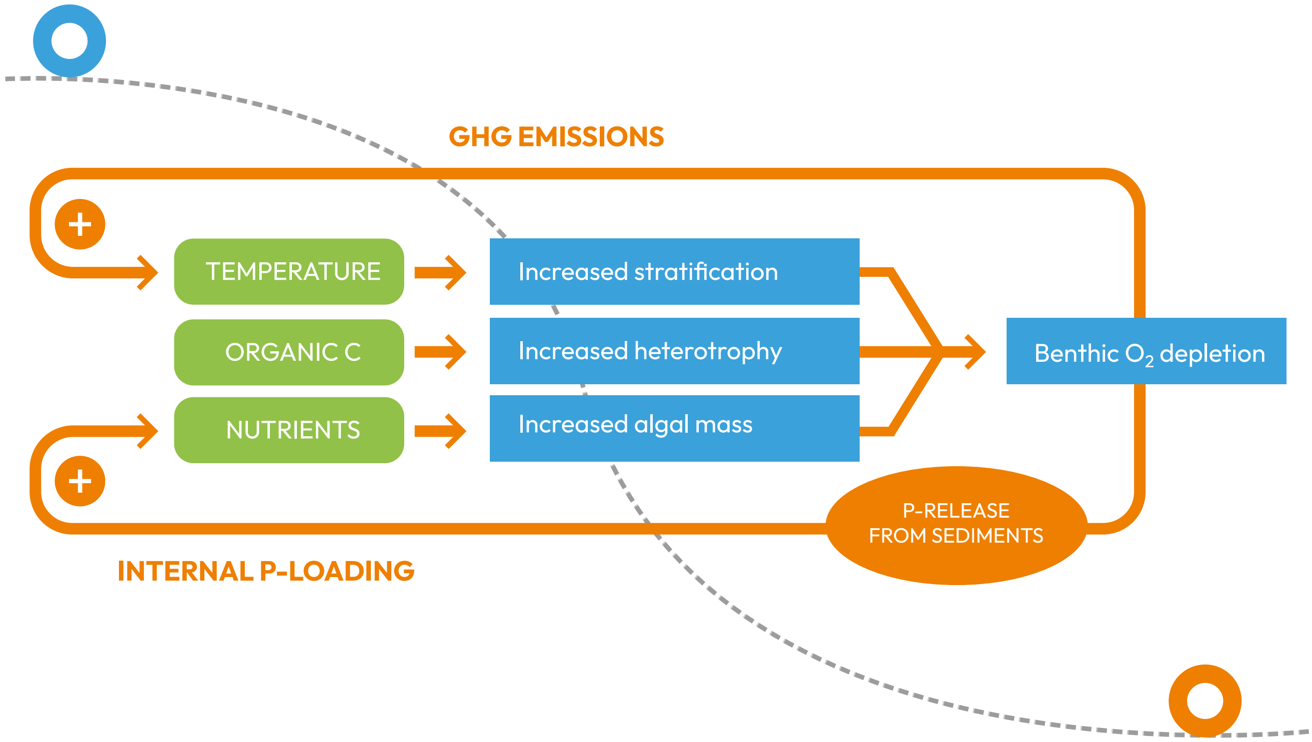


Figure 1.3.14: The interactive role of eutrophication, DOM-export (browning) and warming on lakes. Separately or combined they promote benthic O_2-depletions which cause an internal feedback by P-loading from sediments and a climate feedback via release of greenhouse gases. The potential shift between states (blue to red circle) is indicated. Adapted from: (Hessen et al., 2023, in review).

Disappearance/appearance of waterbodies

A global reduction in lake water storage (Yao et al., 2023) and climate-related creation or, more frequently, disappearance, of water bodies is a large-scale concern (Woolway et al., 2022). For example, current and future permafrost thaw and glacier melting can both create new and drain old waterbodies, providing a strong link to the fate of the cryosphere (Smith et al., 2005; Olefeldt et al., 2021). Such small but numerous waterbodies over vast areas in the high Arctic may also serve as major conduits of greenhouse gases and historical soil carbon stocks to the atmosphere (Laurion et al., 2010) and play an important role in mediating nutrient delivery to the polar oceans (Emmerton et al., 2008), potentially affecting global productivity (Terhaar et al., 2021).

Despite the scale considered here, the extent of open water globally is relatively easy to quantify using remote sensing, and loss of waterbodies can be predicted from water balance and thresholds for permafrost thaw with high confidence. However, while representing a binary shift between two states, driven by climate, this should not be classified as tipping events as in most cases no self-sustaining feedback is involved. Lake appearance or disappearance can be driven by cryosphere tipping points though – for example, thermokarst lake formation or abrupt drainage due to permafrost thaw (Turetsky et al., 2020; Teufel and Sushama, 2019) (see Chapter 1.2) – and in such cases the lake forms part of a coupled thermokarst system capable of tipping.

Switch from N to P-limitation

Regions receiving increased nitrogen (N) deposition may shift from prevailing P- to N-limitation (Elser et al., 2009). Conversely, increased N-loss by denitrification, eventually associated with increased internal P-loading, may shift systems from P to N-limitation (Weyhenmeyer et al., 2007). Changes in N- versus P-limitation of productivity are associated with changes in community structure, both for the phytoplankton and macrophyte communities, which could involve ecological tipping points. However, while the switch between N and P-limitation represents a binary switch with ecological consequences, it is not itself classified as a tipping point according to our criteria, as self-sustaining feedbacks have not been identified. There is currently weak evidence for this shift's impact on climate feedbacks.

Salinisation

Salinisation is a prevalent threat to freshwater rivers, lakes and wetlands and is caused by a range of anthropogenic actions including water extraction, pollution and climate change (Herbert et al., 2015). It has severe consequences for aquatic communities (Short et al., 2016, Cunillera-Montcusí et al., 2022) with salinity thresholds likely strongly impacted by other stressors – including eutrophication (Kaijser et al., 2019). Salinisation has a strong societal impact, particularly related to domestic and agricultural water supply in arid and semi-arid regions (Williams et al., 1999). Salinisation tends to decrease CH_4 emissions (Herbert et al., 2015) and, in that sense, is a negative/damping feedback with respect to climate change. Salinisation may induce ecological regime shifts, for example leading to microbial mat dominance (Sim et al., 2006), and results in some hysteresis, with salinised sediments remaining salty also after the system is flushed with fresh water (Van Dijk et al., 2019), but is not in itself driven by self-sustaining feedbacks.

Spread of invasive species

Freshwaters are especially vulnerable to species loss and population declines as well as species invasions due to their isolation. Substantial ecosystem changes by reinforcing interactions between invasive species and alternative stable states (i.e. macrophyte – aquatic plant – *versus* phytoplankton dominance, as described above) may occur (Reynolds and Aldridge 2021). The spread of several invasive species can be facilitated by climate change (Rahel and Olden, 2008) and may have some self-sustaining properties. Such changes could thus drive a regime shift for a given system, but in most cases are hypothetically reversible if the original driver (the invasive species) were removed. Species invasion is hard to predict and difficult to quantify, despite the risk of species ingress as ranges expand with climate change.

Assessment and knowledge gaps

Table 1.3.2: Candidate tipping events from the literature with potential to occur at local to regional scales, their association with climate change, and whether tipping points and hysteresis have been associated with them. Brackets indicate higher uncertainty. Bold entries represent categories that qualify as tipping points in this context, while the others are either simply binary shifts between states, threshold effects, or similar.

Type of event	Local	Regional	Climate driver	Climate feedback	Tipping event	Hysteresis
Eutrophication-driven anoxia and internal P-loading	**x**		**x**	**x**	**x**	**x**
Increased loadings of DOM		**x**	**x**	**x**	**x**	**(x)**
Disappearance/ appearance of waterbodies		x	x	x	(x) (linked to cryosphere tipping)	(x)
Switch between N and P limitation		x	x	(x)		
Salinisation		x	x	x		(x)
Spread of invasive species	x	(x)	(x)			(x)

Abrupt changes driven by warming, eutrophication or increased loadings of organic matter, leading to changes in the production to respiration ratio (i.e. systems shifting from net autotrophic to net heterotrophic), and/or onset of bottom-water anoxia have clear tipping dynamics (high confidence) and strong feedback to the climate via GHG emissions (Meerhoff et al., 2022) (Table 1.3.2). Whether the widespread effect of increased loading of organic matter (browning) in boreal lakes can drive tipping points is more of a knowledge gap, yet the feedback of lake browning to climate through increased GHG emissions is evident.

Loss of waterbodies residing on permafrost or suffering negative water balance and eventually complete disappearance represents a binary shift, which has major ecological consequences (Woolway et al., 2022) but is not considered a tipping event *sensu stricto*. The same holds for other types of binary shifts, threshold effects or local changes. The role of warming as a catalyst on the changes driven by eutrophication and browning is a critical knowledge gap. Quantification of GHG release from lakes represents major feedbacks to climate, and to quantify the impact of eutrophication, browning and warming in this context should have high priority.

1.3.2.7 Coastal ecosystems

In this section we consider ecosystems bordering the land and ocean, covering the 'littoral' intertidal and subtidal zones. These zones include some of the most biodiverse and human-depended ecosystems on Earth, despite occupying globally tiny areas: warm-water coral reefs, mangrove forests and seagrass meadows. However, all face increasing pressures from increasingly frequent climate change-induced extremes compounded by habitat destruction, pollution and sea level rise.

Warm-water coral reefs

Warm-water coral reefs span the Earth's tropical and subtropical ocean, and are estimated to support over half a billion people for their livelihoods and over a quarter of marine species for part of their lifecycle (Wilkinson et al., 2004; Plaisance et al., 2011) (Figure 1.3.15). They can cross a threshold of ecosystem collapse when they cease to have sufficient cover (typically ~10 per cent) and diversity of hard corals to support the wide diversity of species taxa and ecological interactions typical of a coral reef (Bland et al., 2018; Darling et al,.2019; Sheppard et al,.2020; Perry et al,.2013; Vercelloni et al., 2020). Coral reef collapse is an ecological phenomenon at local scales; here we explore where localised coral reef collapse aggregates to the scale of regions, potentially irreversibly, and potentially to a global scale.

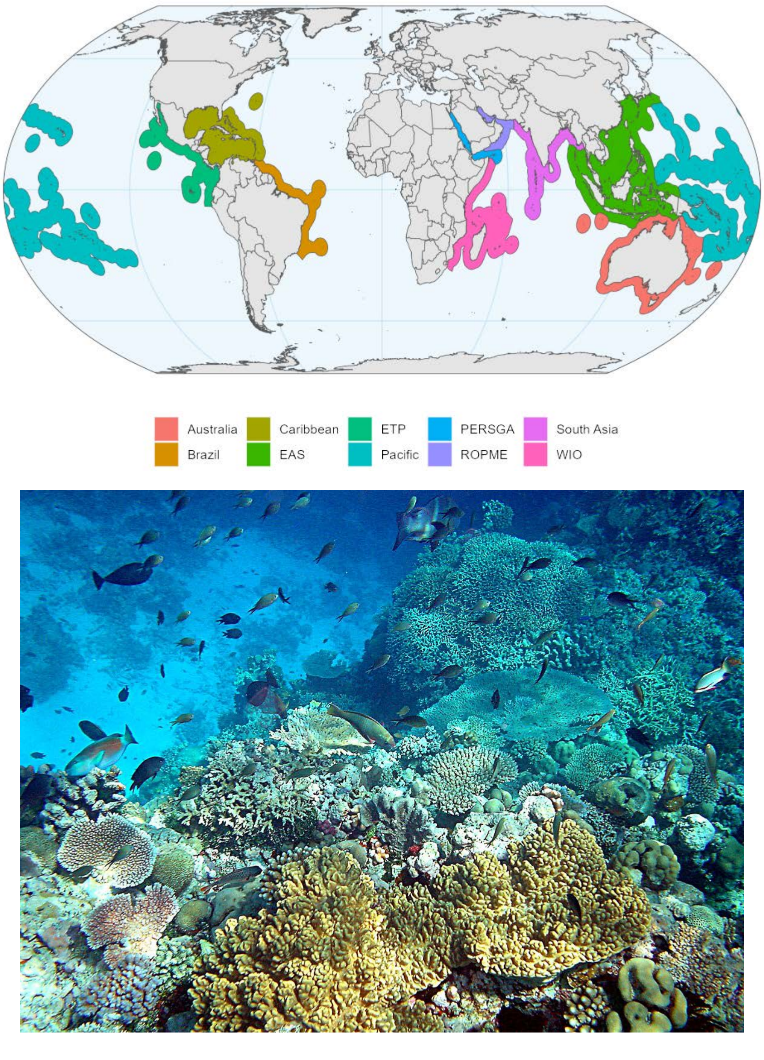


Figure 1.3.15: Global distribution of warm water coral reefs and key reef regions (top). ETP is the Eastern Tropical Pacific, PERSGA is the area included within the Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden, ROPME is the sea area surrounded by the eight Member States of the Regional Organisation for the Protection of the Marine Environment, and WIO is the Western Indian Ocean. A coral reef ecosystem in Papua New Guinea in 2003 (bottom). Credit: (Souter et al., 2021) and (top), Brocken Inaglory via Wikimedia (bottom).

Thermal stress, driven by increasingly warmer oceans and superimposed El Niño extreme events, is the primary driver of regional-scale mortality of hard corals (Hughes et al., 2017; Houk et al., 2020). Coral 'bleaching' occurs when thermal stress causes corals to expel the symbiotic algae that provides them with food (resulting in a characteristic loss of colour), and can result in death if it occurs frequently enough to prevent recovery (Hughes et al., 2018a, 2018b, Obura et al., 2022).

However, a wide variety of interacting and synergistic threats co-occur (e.g. ocean acidification, overfishing, pollution, invertebrate predators and sea level rise), generally lowering the thermal threshold for bleaching and/or mortality, bringing forward timing of collapse, or even surpassing thermal stress in local importance (Ban et al., 2013; Edmunds et al., 2014; Darling et al., 2019; Cramer et al., 2020; Dixon et al., 2022; Setter et al., 2022). Coral mortality may play out over weeks to a few months (for e.g. thermal stress-induced bleaching, for example), or years (for chronic threats such as diseases and land-based impacts), but prolonged failure to recover over a decade or more is necessary to qualify a coral reef as 'collapsed'.

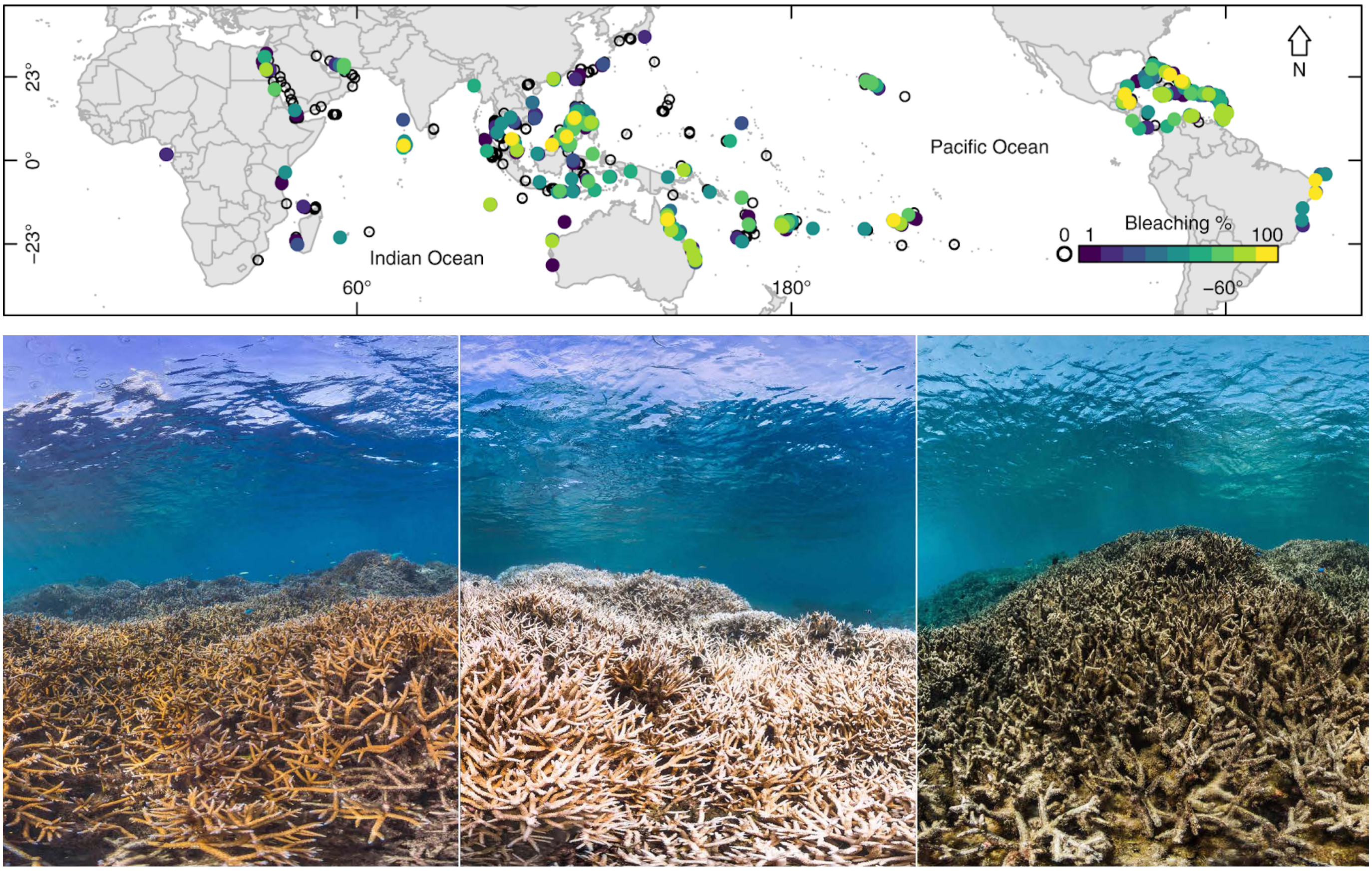


Figure 1.3.16: Map of recent coral reef bleaching distribution (as a percentage of the coral assemblage bleached at surveys from 1998 to 2017, with white circles indicating no bleaching. and coloured circles from 1% (blue) to 100% bleaching (yellow)) (top). Photos showing impact of coral bleaching in American Samoa before (left), during (middle), and after (right) the 2015 bleaching event (bottom). Credit: (top) (Sully et al., 2019), (bottom) from The Ocean Agency.

Localised coral responses to increasing stressor magnitude and intensity are now aggregating at scales exceeding 1,000km and manifesting as regional die-offs (e.g. western and central Indian Ocean, Great Barrier Reef, Mesoamerican Reefs) (Le Nohaïc et al.,2017; Amir, 2022; Muñiz-Castillo et al., 2019; Obura et al., 2022), with most reef regions having experienced multiple mass coral bleaching and die-off events (Darling et al., 2019; Cramer et al., 2020) (Figure 1.3.16). Around 50 per cent of global coral reefs are estimated to have been lost over the past 50-150 years (IPBES 2019), with estimated loss of 16 per cent in 1998 (Wilkinson et al., 1999) and measured loss of 14 per cent from 2009-2018 (Souter et al., 2020), but with high variance among regions.

Projected loss of coral reefs has been estimated in varied ways. Dominant projections are of 70-90 per cent loss of coral reefs at 1.5°C and ~99 per cent at 2°C warming (Cooley et al., 2022). The average year for projected global annual severe bleaching under SSP2-4.5 (a trajectory close to current projections) is 2045, which is delayed 30 years if corals can adapt to an additional 1°C of warming (UNEP 2020). A shift occurs from 84 per cent of reefs globally having 'good' thermal regimes in 1986-2019 to 0.2 per cent in 2100 at projections of 1.5°C, and 0 per cent at 2°C warming (Dixon et al., 2022). Finally, the proportion of reefs facing 'unsuitable conditions' increases from 44 per cent in 2005 to, under worst case scenarios, 100 per cent by 2055 under any one of several stressors, but by 2035 for cumulative stressors (Setter et al., 2022). Continued ocean warming over several decades (due to lagged ocean heat uptake) and sea level rise over centuries to millennia (due to thermal expansion and ice sheet melt, see 1.2.3) mean some reefs and other coastal ecosystems (see also Mangroves and Seagrassees) may be committed to eventually passing tipping thresholds even if emissions ceased soon (Abrams et al,. accepted).

Evidence for tipping dynamics

Failure to recover from mass mortality shows evidence of having crossed a threshold for recovery, which we address for scales above approximately 1,000km, to regional and global scales. A key question is if coral reef decline globally is just an aggregate of regional events, so a linear/chronic decline process (Souter et al., 2021), or if there may be a global tipping point.

Observations on coral reef tipping points include the following:

- The first reported global bleaching event in 1998 was associated with atmospheric warming of ~0.6°C (corresponding to c. 350 ppm CO_2) with a strong El Niño on top (Veron et al., 2009), past which more frequent, intense and widespread coral bleaching and mortality has occurred.
- A very high risk of impact to corals was assessed by the IPCC as global mean warming levels crossed around 1.2°C (IPCC SR1.5 2018).
- Thermal bleaching tipping points are already being passed in the majority of coral reef regions (Cooley et al., 2022 – see Figure 1.3.17).
- The risk of ecosystem collapse is already predicted at high levels in all coral reef regions assessed. The MesoAmerican Barrier Reef is Endangered (Bland et al., 2018) and Western Indian Ocean coral reefs are Vulnerable to collapse, with two thirds of subsidiary ecoregions being Endangered or Critically Endangered due to projected warming (Obura et al., 2022).

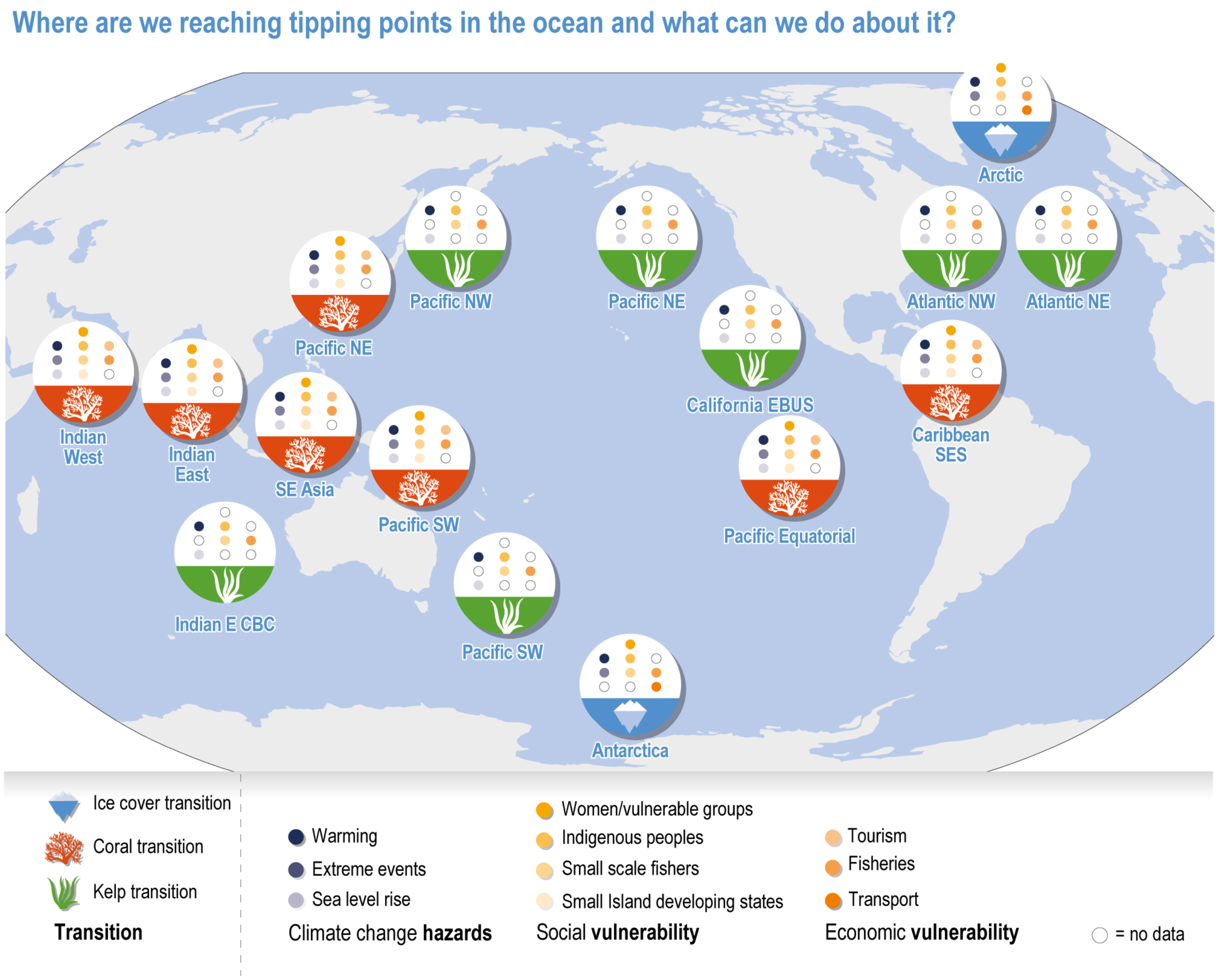


Figure 1.3.17: Tipping points have been passed in many ocean ecosystems, including coral reefs, kelp forests, and those associated with sea ice, with diverse socio-economic implications. [From FAQ3.3.1 in (Cooley et al,. 2022).

Elevated summer ocean heat maxima (over 1-2°C above site-specific individual coral acclimation thresholds) for weeks to months, and larger acute temperature spikes for several days, cause severe coral bleaching and mass mortality. Mass-mortality bleaching thresholds have been proposed at eight "Degree Heating Weeks" (a measure of how long and how much ocean temperatures are above normal) which is likely by ~2°C global warming (McWhorter et al., 2021), or at two bleaching events per decade (likely by ~1.5°C) (Frieler et al., 2013). Mass coral mortality repeated more than twice per decade and over hundreds to thousands of kilometres and larger, is increasingly recognised as giving insufficient time for recovery of impacted populations, and of ecological interactions (Hughes et al., 2018a, 2018b, Obura et al., 2022). However, estimating globally consistent warming thresholds is challenging given variation from individual corals to species and across all spatial scales in acclimation and adaptation ability. Other stressors reduce the ability of corals to resist thermal stress, thus bringing down tipping thresholds.

Increasing frequency and intensity of regional-scale coral mortality events past 1°C warming are suggestive that these coral reef regions have already passed regional bleaching tipping points (Cooley et al., 2022). The potential for thermal refuges for corals under likely future scenarios is doubtful (Beyer et al., 2018; Dixon et al., 2022; Setter et al., 2022) as very few or no reef areas are projected to remain below tipping thresholds of key stressors. The existence of putative refuges at greater depths (Bongaerts and Smith 2019) or higher latitudes (Yamano et al., 2011; Setter et al., 2022) are not strongly supported by recent work (Hoegh-Guldberg et al., 2017; Cooley et al., 2022). Ecological and biogeographical (spatial) positive/amplifying feedback loops prevent local recovery of coral reefs and promote expansion of reef collapses from local to regional scales when surviving corals and coral patches become too spatially separated for successful reproduction of adults, and supply of larvae from surviving to damaged reefs (Hock et al., 2017).

Coral reef decline does not substantially feedback to the climate system on policy-relevant timescales. However, localised surface cooling may arise through increased low level cloud albedo induced by sulphur compounds released by reef metabolism. Consequently, extensive coral die-offs could amplify local warming (Jackson et al., 2020).

Assessment and knowledge gaps

Warm-water coral reefs have localised tipping points (high confidence) and are now experiencing regionally clustered tipping points (high confidence). Based on the evidence collected here, we suggest that the critical threshold of 1.5°C (range 1-2°C) (Armstrong McKay et al., 2022) should be adjusted, narrowing and lowering the range to 1-1.5°C, with a middle estimate of 1.2°C, marked by the multi-year global coral reef bleaching events of 2015-2017 (Cooley et al., 2022; Hoegh-Guldberg et al., 2018; Dixon et al., 2022; Setter et al., 2022). The co-occurence of additional synergistic drivers also support lowering the critical threshold (Willcock et al., 2023) and there is evidence of accelerating collapses at increasing spatial scales (Cooper et al., 2020).

The combined effects of long-term warming, sea level rise, ocean acidification and other stressors bears more investigation to identify the lower critical threshold for the coral reef tipping point. The potential for coral adaptation to warming is a critical but poorly known factor, and subject to high levels of variation locally. The potential effectiveness of restoration for coral reefs at scale, and with enhanced capacity to resist future threats, are both currently poor. The effect of climate migration on coral recovery is not known, with potentially positive effects at higher latitude (with in-migration), but negative at lower latitudes (with out-migration, but no replacement; Herbert-Read et al., 2023).

Mangroves and seagrasses

Mangroves and seagrasses play vital roles in coastal societies and economies. They provide fundamental and hard-to-substitute ecosystem services such as support to fisheries, nutrient cycling, coastal protection and sediment trapping (Malik et al., 2015; Nordlund et al., 2016; Menéndez et al., 2020; Nabilah Ruslan et al., 2022; doAmaral-Camara et al., 2023, James et al., 2023). Located between the sea and the land, their unique dual nature exposes mangroves and seagrasses to climate drivers that arise in both systems (Lovelock et al., 2017a; Duke et al., 2017a, 2019), making them particularly vulnerable to climate change (Duke et al., 2022). Recent attention has focused on their climate mitigation services ('blue carbon') linked to their high productivities and long-term (millennia) storage of organic matter in their sediments, which positions them among the most dense carbon sinks on Earth (Donato et al., 2011; Alongi et al., 2016; Macreadie et al., 2021; Serrano et al., 2021).

While they occupy small areas (c. 140,000 sq km and uncertain c. 266,562 sq km for mangroves and seagrasses respectively in 2020; Bunting et al., 2022; McKenzie et al., 2020; Figure 1.3.18 and 1.3.19), they store up to 12.3 GtC and 3.8 GtC respectively (Macreadie et al., 2021). These ecosystems are natural sinks of CO_2, but when degraded they can release CO_2, NO_2 and CH_4, adding to the emissions of the estuaries they are embedded in (Rosentreter et al., 2022). Emissions derive from carbon stored long-term in sediments, which cannot be recovered in a lifespan and is therefore additional to the current atmospheric balance (Lovelock et al., 2017b; Schorn et al., 2021; Romero-Uribe et al., 2022).

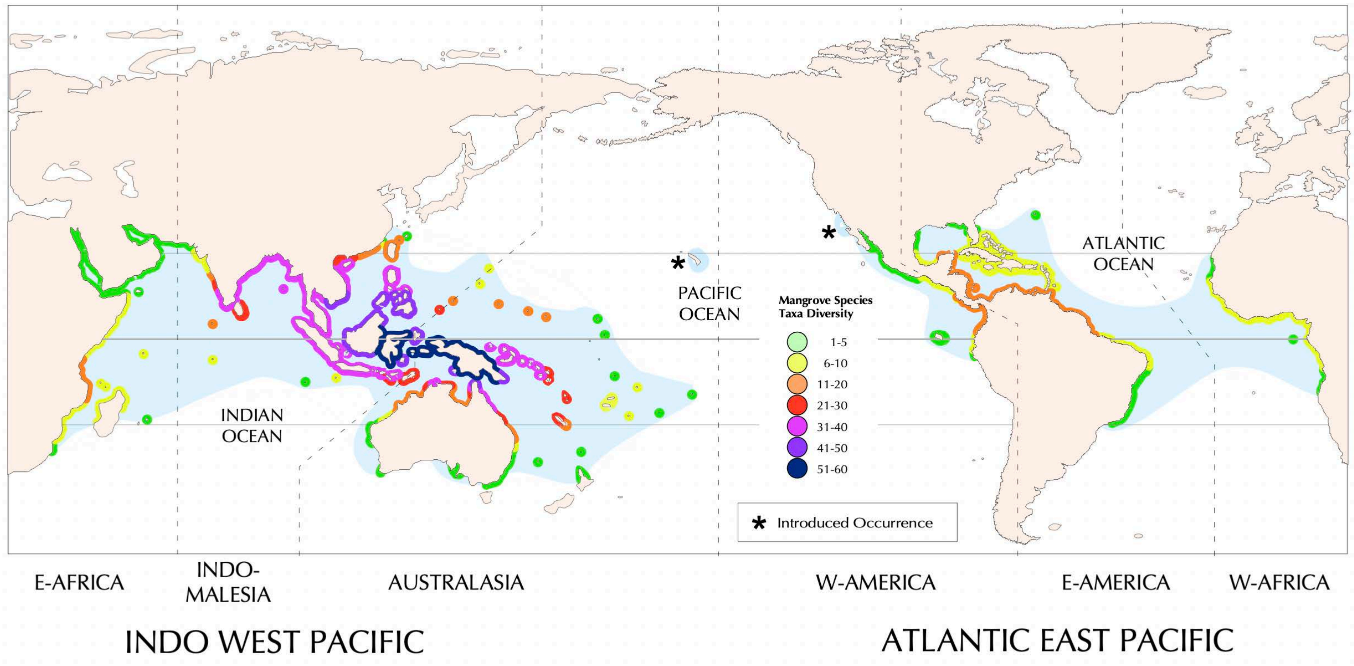


Figure 1.3.18: Upper panel: floristic distribution of mangroves in the world, with a marked diversity in the Wallacea region (Indo Pacific). Lower panel: white mangrove (*Laguncularia racemosa*) from Yucatan, showing the intricacy of mangrove roots, and their service as fish habitat, coastal protection against storms and sediment trapping. Source: (Duke et al., 2017) (top) and Jorge Herrera, CINVESTAV (bottom).

Mangroves and seagrasses are historically among the most human-threatened ecosystems in the world (Valiela et al., 2001; Waycott et al., 2009), with 35-50 per cent of mangroves' original cover now lost, mainly to aquaculture and agriculture (Richards and Friess, 2016, Goldberg et al., 2020; Hagger et al., 2022), while other factors including nutrient overload, invasive species, and ocean warming have led to a 19-30 per cent decrease of the original seagrass surveyed area (Waycott et al., 2009; Dunic et al., 2021).

In spite of this, the magnitude of their past and current feedback to global warming remains uncertain (Rosentreter et al., 2022). Under current rates of deforestation, estimates of global mangrove emissions by the end of the century range between 0.24 to 0.34 Gg CO_2e if foregone soil carbon sequestration is also included (Adame et al., 2021), which is comparable to the European Union's emissions in 2022. Southeast and South Asia (West Coral Triangle, Sunda Shelf and the Bay of Bengal) are projected to lead the emissions, followed by the Caribbean (Tropical Northwest Atlantic), the Andaman coast (West Myanmar), and northern Brazil (Adame et al., 2021).

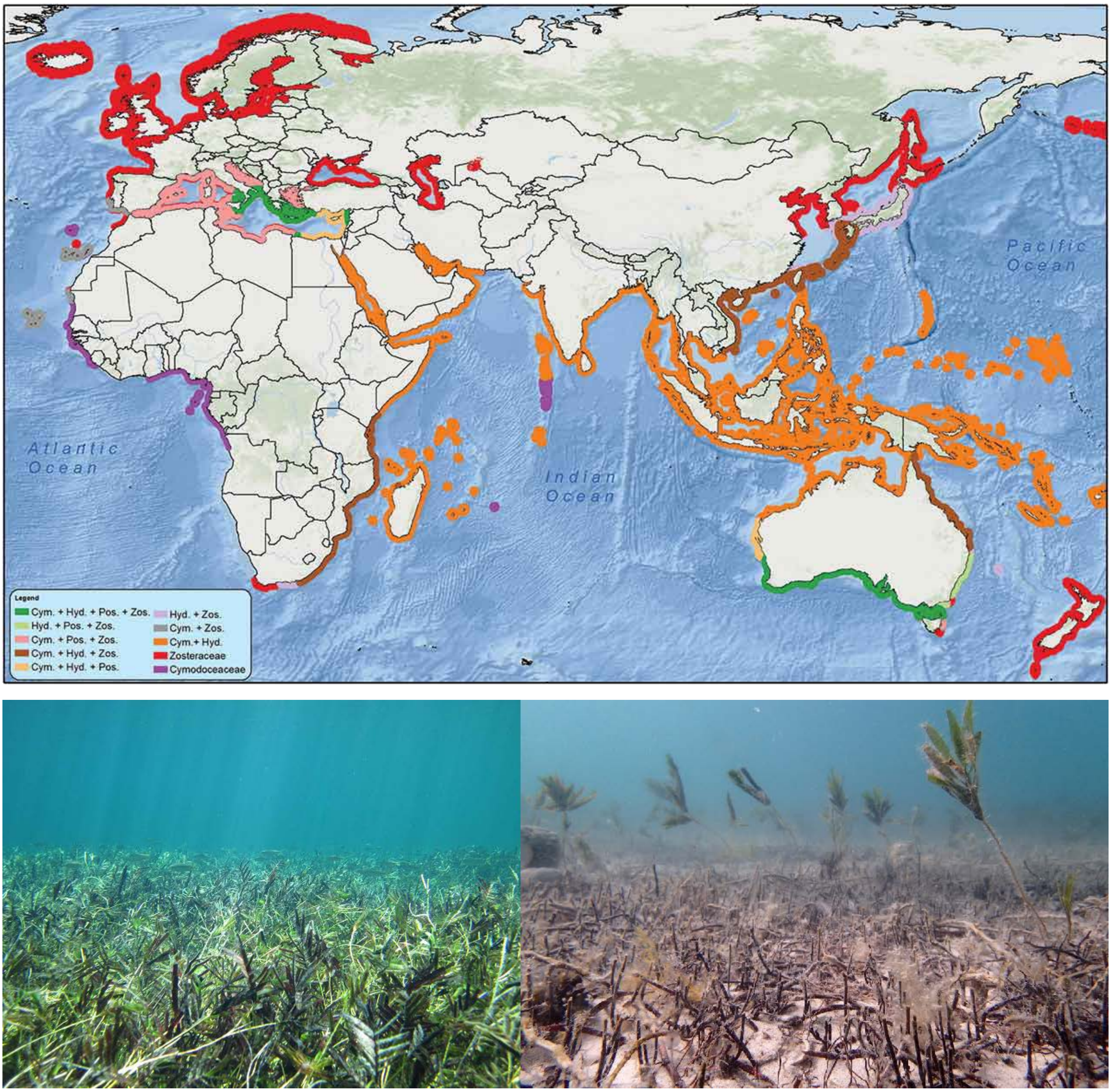


Figure 1.3.19: Upper panel: global distribution of seagrasses. Lower panel: Shark Bay temperate seagrass (*Amphibolis antarctica*) before the 2011 heatwave and after (2013). Revisits from 2012 to 2014 verify poor recovery of A. antarctica, and the slow expansion of the tropical seagrass *Halodule uninervis*, in sites with no recovery (30% of cover three years later). Source: IUCN, map created by T. Bakirman. Seagrass die-off: credit goes to the Shark Bay Ecosystem Research Project and (Nowicki et al., 2017).

Evidence for tipping dynamics

In spite of major historical habitat loss and degradation, there are not yet generalised signs of irreversible global transitions of mangroves towards alternative states such as tidal flats, and the remaining systems have so far retained large-scale stability in the tropics. Bistability is, however, observed in northern subtropical distributions with mangrove encroachment over tidal marshes where freezing events are now rarer (Feller et al., 2017; Hesterberg et al., 2022). Observational data also suggests rainfall-induced bistability of mangroves and salt marshes (Duke et al., 2019).

Scarce global monitoring prevents robust analyses of seagrass trends, but transitions (>50 sq km) towards unvegetated sediments have intensified in many coastal regions in the last two decades (e.g. Europe, Australia, US, Caribbean) (Waycott et al., 2009; Carr et al., 2012; Arias-Ortiz et al., 2018; Duarte et al., 2018; Kendrick et al., 2019; Cooley et al., 2022; MacLeod et al., 2023) (Fig 1.3.19). For temperate regions, bistability and tropicalisation of temperate seagrass species are observed in edge-of-range meadows, with uncertain stability trends (Bartenfelder et al., 2022). For tropical seagrasses, local resilience after disturbance has been observed when enough time and reduced pressures apply (MacLeod et al., 2023).

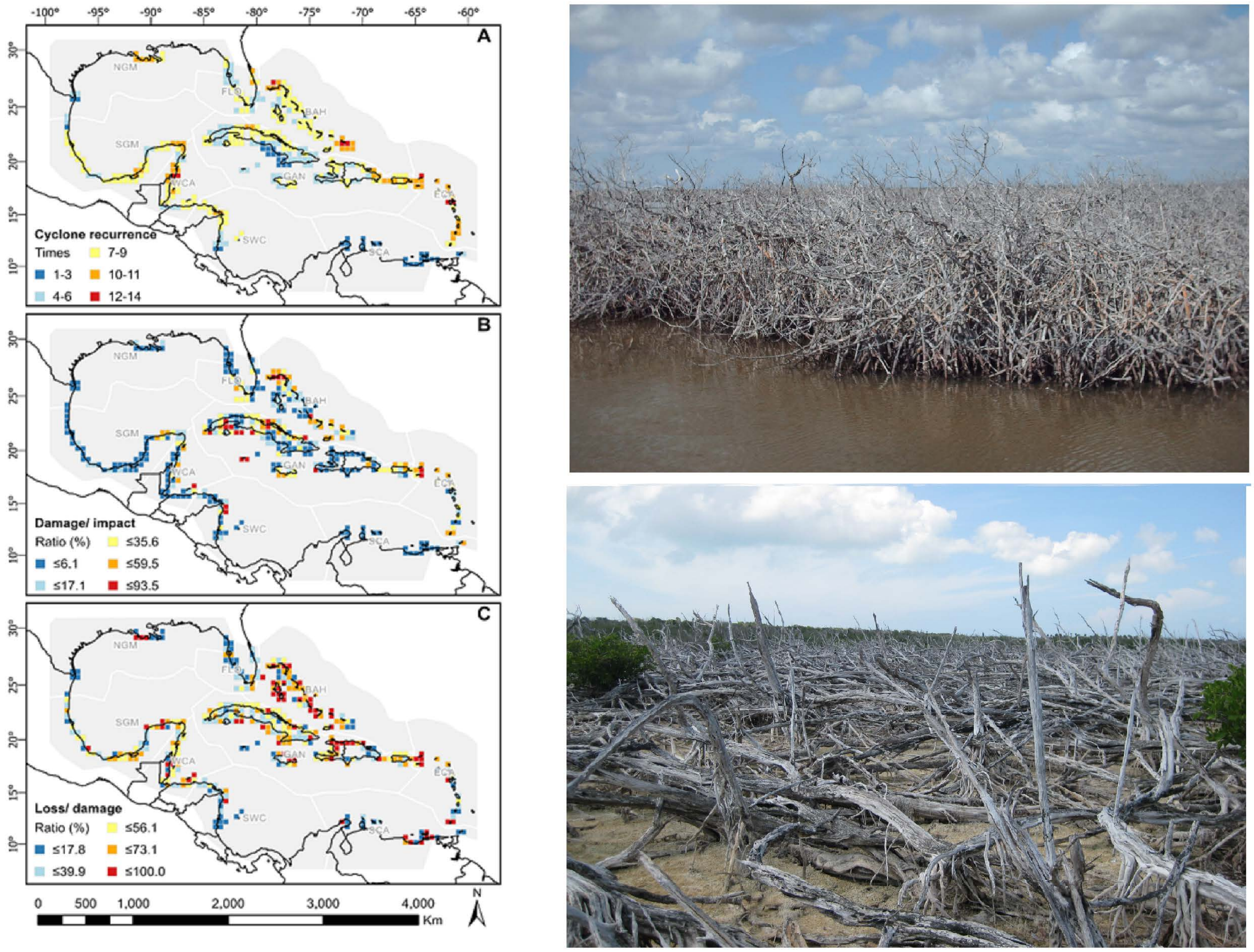


Figure 1.3.20: Left panel presents (A) the recurrence of tropical cyclones (from tropical storms to hurricanes category 5) in different subregions of the North Atlantic Basin (Caribbean, Gulf of Mexico, Mesoamerica), (B) percentage of pixels hit by a tropical cyclone where mangroves show damage six months after the pass of the storm (vulnerability), and (C) percentage of pixels that showed damage after a storm that do not show signal of recovery one year after being damaged (resilience). Right panel includes photos from mangroves hit by hurricanes in Yucatan. Sources: (Amaral et al., 2023) (left panel), Jorge Herrera, CINVESTAV (right panel).

While the resilience of these systems (particularly mangroves) does not yet seem compromised at the global scale, there is increasing evidence of region-dependent declines in resilience for both seagrasses (Dunic et al., 2021; Turschwell et al., 2021) and mangroves (Bergstrom et al., 2021, Friess et al., 2022; Amaral et al., 2023, Duke et al., 2023 in press). These responses relate to:

i) An increased exposure to more frequent and intense extreme events such as hazardous cyclonic activity (Figure 1.3.20), more frequent and intense El Niño (Figure 1.3.21) and marine heatwaves (Fig 1.3.19), which add to the long existing human pressures (nutrient overloads, land use changes, sedimentation rates, etc) and to the long-term environmental impacts that promote mangrove and seagrass mortality (including sea level rise, ocean acidification, ocean/atmosphere warming, regional drought, salinity, hypoxia, diseases and invasive species) (Waycott et al., 2009; Krauss et al., 2014; Lovelock et al,.2015; Feller et al., 2017; Duke et al., 2021; Friess et al., 2022; MacLeod et al., 2023).

ii) Shortened recovery times below re-establishment needs. Post-disturbance recovery has been reported to take ca. 10-20 years depending on the ecosystem service considered (Lugo 1980; Jimenez et al., 1985; MacLeod et al., 2023), with mangrove recovery taking c. 20 years (more on arid climates), and c.10 years for seagrasses. A decade has been considered the absolute minimum successful re-establishment time for both systems, if pre-disturbance conditions (hydrological stability and seed sources) were retained (Lugo 1980; Teutli-Hernandez et al., 2020, Duke et al., 2023 in press; MacLeod et al., 2023). Revisiting times are currently below these thresholds in many regions,

iii) Unprecedented increases in compound extreme events that precede, succeed, or coincide in time and space and amplify ecosystem responses (Allen et al., 2021). Along this line, magnified mangrove mortality due to drought-hurricane duos has already been reported in the Caribbean (Taillie et al., 2020; Amaral et al., 2023).

iv) Exposure to multivariable extreme pressures (Fig 1.3.22). While models frequently focus on a few independent-forcing variables, in reality multiple amplifying, synergistic or antagonic effects occur among stressors. As an example, El Niño combines multiple variables such as heat, drought, flooding, more extreme oscillations in sea level (e.g. Taimasas in the Indo-Pacific), and marine heatwaves, whose combined interaction amplifies mangrove and seagrass mortality.

Decreasing resilience enhances damages in coastal habitats, including severe losses of biodiversity, collapse of regional fisheries and aquaculture, and reduced capacity of habitat-forming species to protect shorelines, preventing re-establishment (Cooley et al., 2022). These make mangroves and seagrasses likely candidates for regional tipping points, with major social and economic consequences.

Additionally, lagged ocean warming (over decades) and sea level rise (over centuries) mean coastal ecosystems will continue to face increasing pressure after atmospheric warming stabilises, meaning tipping can be committed decades before it is realised (see warm-water coral reefs above).

Figure 1.3.21: Mangrove die-off in physiologically stressed mangrove systems after intense El Niño-driven droughts (2015-2016, 2019) combined with other interacting stresses (prolonged ocean retreat in the Indo Pacific, previous eutrophication in the Bay of Panama, timber extraction, etc). a) El Niño 2015-2016 effects over Australia's Gulf of Carpentaria (8,000 hectares of affected mangroves), b) mangrove die-off in the Maldives has been reported in 11 islands since mid-2020, c) mangrove die-off in the Bay of Panama (Juan Diaz site) after the 2015-2016 El Niño on an eutrophic, rapidly sedimented and colonised site. Sources: Norman Duke (James Cook University), Steve Paton (STRI-Panama), Save Maldives Campaign and Neykurendhoo Island Council (2020).

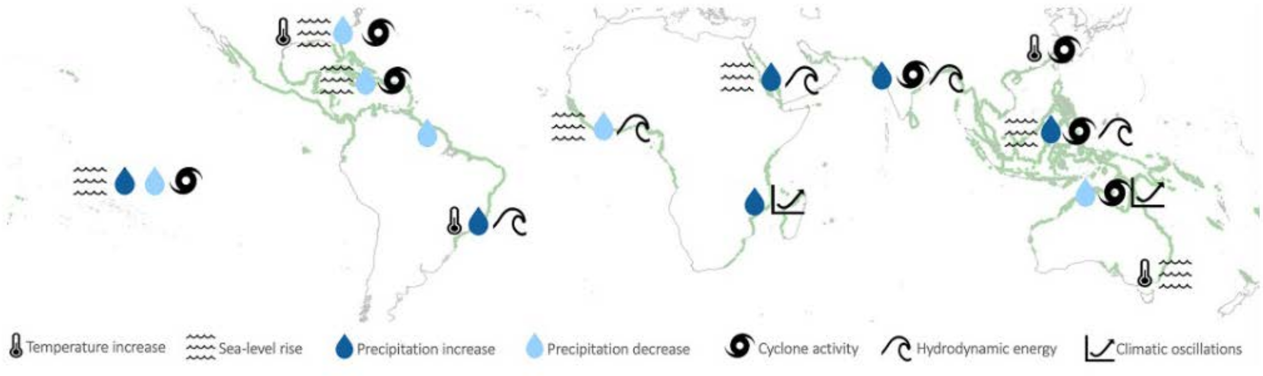


Figure 1.3.22. Regional differences in climate drivers (long-term trends and extreme events) leading to mangrove impacts. Combined with human and other environmental impacts, they are expected to lead to different regional tipping timings and degradation speeds. Source: (Friess et al., 2022).

On the potential tipping dynamics of coastal systems, the IPCC AR6 chapter on ocean and coastal ecosystems (Cooley et al., 2022) noted "irreversible phase shifts with global warming levels >1.5°C, making both systems at high risk this century even in <1.5°C scenarios that include periods of temperature overshoot beyond 1.5°C (high confidence). Mangroves, under SSP1-2.6, are expected to be unable to keep up with sea level rise by 2050, with ecological impacts escalating rapidly beyond 2050".

(Saintilan et al., 2020, 2023) found it very likely that mangroves were unable to initiate sustained accretion when relative sea level rise rates exceeded 6.1 (4-7) mm/year. This threshold is likely to be surpassed on low-latitude tropical coastlines within 3-5 decades under high-emissions scenarios (Sweet and Park 2014; Saintilan et al., 2020, 2023). For seagrasses, the IPCC AR6 (Cooley et al., 2022) projects contractions of temperate edge-ranges (e.g. ***Zostera costera*** seagrasses in the US would retract by 150-650km under RCP2.6 and RCP8.5, respectively and ***Posidonia oceanica*** in the Mediterranean Sea, which might lose as much as 75 per cent of their habitat by 2050 under RCP8.5 and become functionally extinct by 2100). Marine heat waves will escalate seagrass responses, with moderate responses to sea level rise (Cooley et al., 2022).

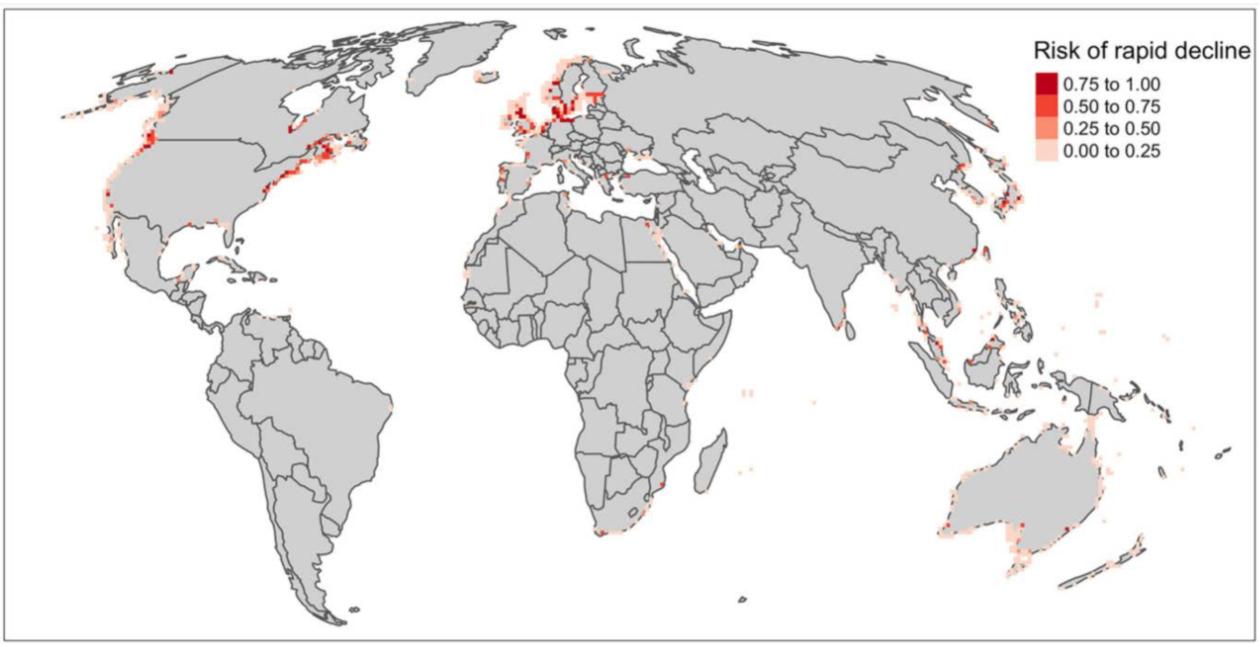


Fig 1.3.23: Rapidly declining trajectories of seagrass meadow extent (>25% loss from 2000 to 2010) predicted in 100×100 km grid cells. Sites are coloured by the probability of a site being ranked among the 10% of sites most likely to have a rapidly decreasing trajectory. Predictions were most strongly associated with high pressures from destructive demersal fishing and poor water quality. Source: (Turschwell et al., 2021).

Assessment and knowledge gaps

We conclude with medium confidence that, under current relative sea level rise projections, subsidence, expected increases in extreme events and coastal development (Cooley et al., 2022), tipping responses for mangroves are likely to be regionally visible by 2080 at temperature thresholds between 1.5-2°C (starting with physiologically stressed regions that host increasing extreme events – also medium confidence). Seagrasses are likely (medium confidence) to show region-dependent die-off responses earlier (by mid century) due to more intense and recurrent marine heatwaves, nutrient pollution and turbidity, at global temperature thresholds closer to 1.5°C (medium confidence).

We have high confidence that tipping responses will be region and site-dependent with diverse timings and degradation speeds. For mangroves, physiologically stressed regions such as arid or highly seasonal climates like the Middle East or the dry corridor of Central America, karstic systems such as the Caribbean, small islands, northern Australia, or the northern Coral Triangle are likely (medium confidence) to show tipping responses earlier than other regions such as the Indo-Pacific, South America or parts of the Indian Ocean, whose systems either have more species, are less exposed, or are less vulnerable to hazard exposure (e.g. there is more space for encroachment, or more refugia).

For seagrasses, temperate regions are predicted to be more vulnerable to tipping than warmer regions (Turschwell et al., 2021; Green et al., 2021; Cooley et al., 2022) (Fig. 1.3.23). Seagrasses in warm regions that are more exposed to water pollution, turbidity, extreme events (marine heat waves and cyclones), coastal development, salinity or invasive species are expected to tip earlier than seagrasses in other warm regions.

Compared to the IPCC AR6 report (Cooley et al., 2022), we highlight a higher confidence on the directional effects of storms on both mangroves and seagrasses towards regionally synchronous mortality (Carlson et al., 2012; Wilson et al., 2019; Taillie et al., 2020; Amaral et al., 2023; Duke et al., 2023 in press). Evidence also exists on decreased regional resilience in mangroves after cyclones (Amaral et al., 2023) and transitions to mudflat shifts in areas where storms combine with erosion co-stressors (Bhargava and Friess 2022). Similarly, warming responses in mangroves have a clearer directional trend, with extreme El Niño hot-droughts superimposed onto global warming and regional drought leading to well-known extended mangrove mortality in many regions (Jimenez et al., 1985), including recent reports of die-off in Australia (Duke et al., 2017a), Panama (Fig. 1.3.21) and the Maldives (Save Maldives Campaign and Neykurendhoo Island Council, 2020).

Current modelling does not yet properly cover extreme events or multiple drivers, nor their interactions (Cooley et al., 2022). These gaps are likely leading to an underestimation of their impacts on ecosystems and their long-term resilience thresholds. Resilience responses to enhanced stressors will be region- and site-dependent, but models still need data to properly represent key drivers per region and their interactions, as well as the thresholds of survival of regional ecosystems (Marba et al., 2022).

1.3.2.8. Marine ecosystems and environment

Climate change, pollution and overexploitation are affecting the marine environment at the physical, chemical and biological levels (e.g. Heinze et al., 2021; Jouffray et al., 2020; Bindoff et al., 2019). Pelagic marine ecosystems (defined as the water column from the surface ocean to the seafloor) as well as benthic marine ecosystems (defined as restricted on the seafloor) from the organism to the community level are changing at the same time as the ocean waters are becoming more warm, acidic and deoxygenated. In this section, we outline five potential tipping systems ranging from fisheries collapse and regime shifts in marine communities to ocean water hypoxia and the nonlinear weakening of parts of the ocean's biological pump (Figure 1.3.24).

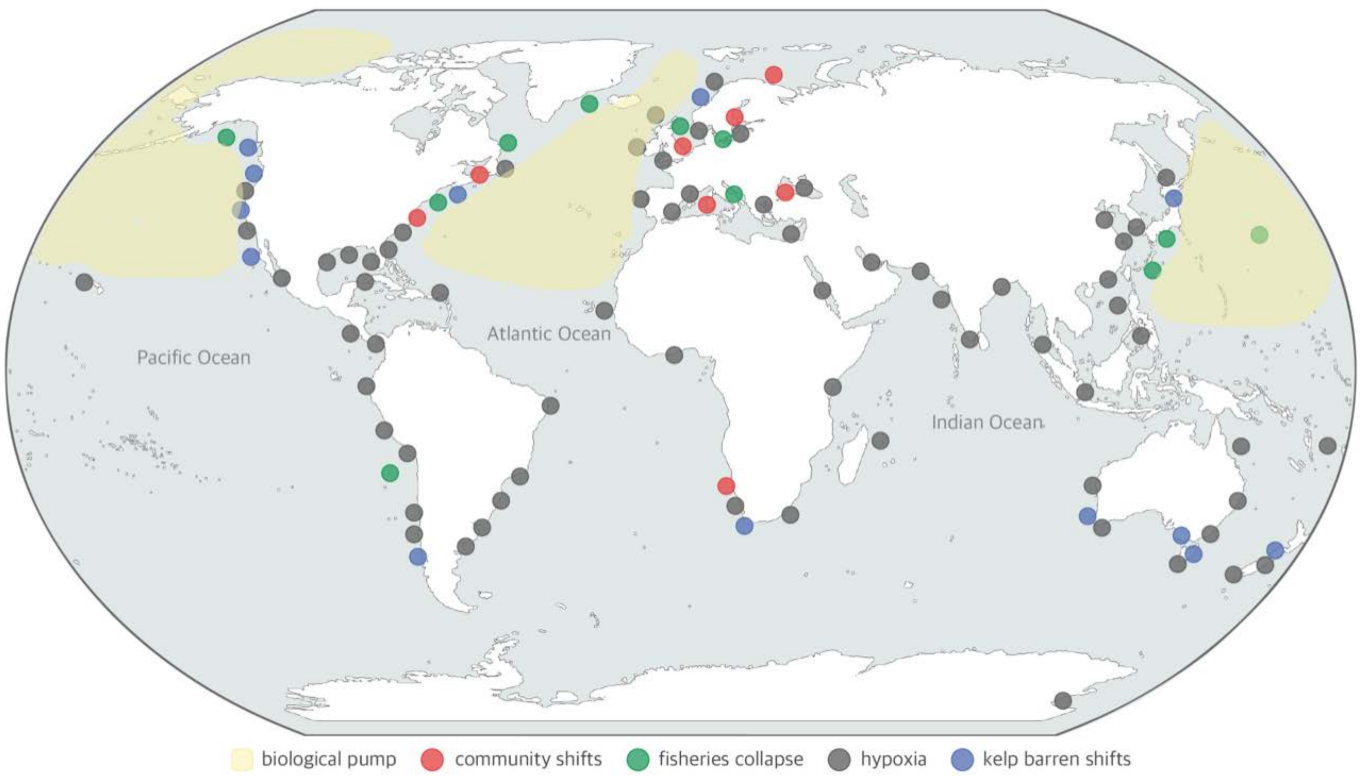


Figure 1.3.24: Locations of reported regime shifts and potential tipping points in the global marine environment. Redrawn and updated from (Blenckner and Niiranen, 2013).

Evidence for tipping dynamics

Fisheries collapse

Over the past decades many fisheries have collapsed primarily due to over-exploitation, but they are increasingly threatened by climate change.

Fish stocks are defined as management units of a species; thus one fish species can have multiple stocks (e.g. more than 20 stocks in the North Atlantic are assessed for Atlantic cod, *Gadus morhua*).

Figure 1.3.25: A school of fish: Credit: iStock.com/armiblue.

Among more than 200 exploited fish stocks, 23 per cent of the species showed at least one stock collapse (biomass below sustainable reference points) (Pinksy et al., 2011). Concerningly, 40 per cent of the collapsed stocks present different regimes of productivity (different relationships between fishing and biomass at different productivity stages) (Vert-pre et al,.2013) that potentially indicate the presence of regime shifts and hysteresis. But, while for some species there is clear evidence of regime shifts (Atlantic cod stocks), for others more studies are needed (Frank et al., 2016; Sguotti et al., 2019).

Fish stock collapses can be due to different feedback mechanisms. The collapse of a stock can induce food web changes (i.e. trophic cascades) that, by modifying the other species of the community and their interactions, can maintain the population at a low level through predation or competition. For instance, large predators such as Atlantic cod may be successful because of the 'cultivation effect': adult cod prey on the juveniles of forage fishes (small pelagic fish which are preyed on by larger predators) that are competitors or predators of juvenile cod. Once the collapse in the biomass of cod occurs, the predation on the forage fish is released and these species start to thrive. Forage fish then prey on juvenile or recruit cod, thus maintaining the population in a depleted state. Examples of this particular dynamic can be found in Newfoundland and also the Baltic Sea (Walters and Kitchell, 2001). Another possible mechanism of hysteresis is the so-called Allee effect, which takes place when recruitment of a population (the process by which new organisms are added to a population) is positively correlated with its biomass.

This means that a minimum population size is needed for the population to grow; otherwise it collapses. Thus, if biomass collapses, recruitment will also drastically decline, limiting the capacity of the population to recover. The Allee effect has been shown to be one of the possible hysteresis mechanisms of 13 stocks of Atlantic cod (Winter et al., 2023).

It is difficult to detect specific thresholds in fisheries in general, since every species and every stock within each species is impacted by different levels of the same driver and may experience different pressures. However, it has been shown that, for Atlantic cod stocks, the threshold was created by the combination of multiple drivers, especially warming and fishing (Sguotti et al., 2019; Beaugrand et al., 2022). Specific thresholds need to be detected for every stock.

Beaugrand et al., (2022) have shown that rebuilding cod stocks may depend upon the fishing-environment interaction. When the environment becomes unsuitable at the same time fish stocks collapse, rebuilding the stock may take time or even be impossible so long as adverse environmental conditions persist. This provides an explanation as to why, despite the fishing moratorium near Newfoundland, a partial recovery took more than two decades (DFO 2018). Long-living, slow-growing species might be more prone to irreversibility. For instance, 16 out of 19 Atlantic cod stocks present regime shift dynamics due to fishing and warming and their recovery is hindered by the presence of hysteresis (Sguotti et al., 2019; Möllmann et al., 2022., Frank et al., 2016).

Marine community shifts

Marine community shifts take place when abrupt changes cascade through several species or functional groups of an ecosystem, i.e. the change is not limited to a single species, as in a fish stock collapse, but can cascade all the way from top predators to phytoplankton (Figure 1.3.26).

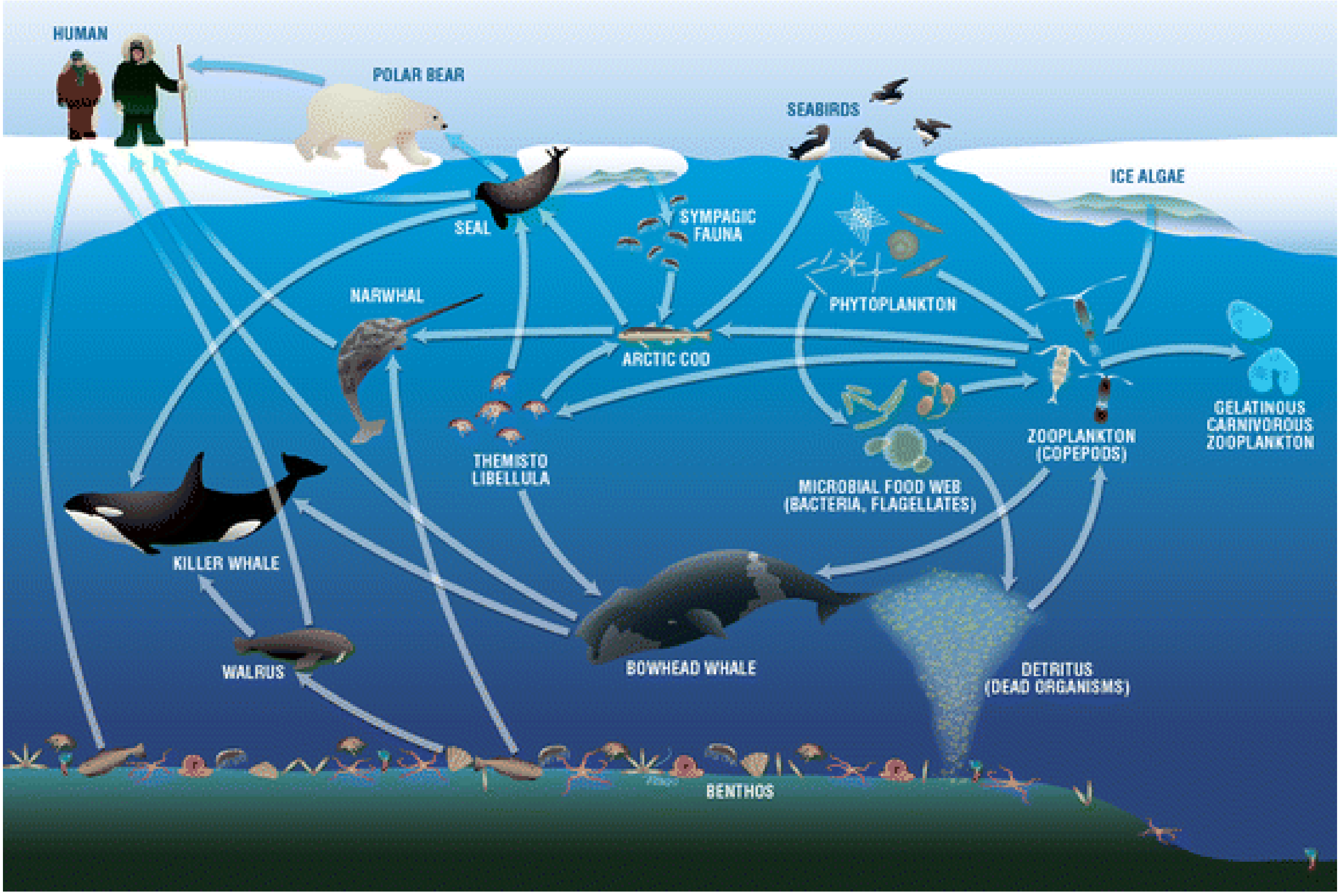


Figure 1.3.26: Schematic of a marine food web. Source: (Darnis et al., (2012).

Many community shifts have been reported in marine ecosystems (Conversi et al., 2015; Beaugrand et al., 2019; Möllmann et al., 2021; Ban et al., 2022; Sguotti et al., 2022). Some ecosystems have even experienced several marine community shifts, such as the Black Sea and Baltic Sea. In the Black Sea, the first major shift started in the end of 1960s with the overfishing of pelagic top predators, enabling surplus phytoplankton and jellyfish production during the following decades, and resulting in increased hypoxia (lack of oxygen necessary for life) followed by collapse of small pelagic fish and domination of jellyfish (Daskalov et al., 2017). In the Baltic Sea, the increased inflow of nutrients and organic matter resulted in the eutrophication of the main basins around the 1950s, enabling higher biological production, but also worsening hypoxia (Österblom et al.,(2007).

Community shifts related to tipping responses mostly occur when the system is controlled by a few key species through trophic cascade (Beaugrand et al., 2015; Daskalov et al., 2007, 2017). Trophic cascades can be environmentally induced or induced by anthropogenic pressures such as pollution or overfishing (Casini et al., 2009). The mechanisms at the origin of the apparent synchronicities among marine community shifts have been debated (Conversi et al., 2010a, Beaugrand 2015). Möllmann and Diekmann, (2012) suggested that multiple drivers, such as climate and overfishing, may interact in triggering ecosystem community shifts between alternative states. Reid and Beaugrand (2012) observed that, in many cases, the reported shifts coincided with major temporal changes seen in marine temperature anomalies. The interaction between climate-induced environmental changes and species' ecological niches (Beaugrand 2015; Beaugrand et al., 2019) may lead to a community shift. For such shifts, the existence of tipping is not needed as an explanation.

Another region of potential climate change-induced regime shifts is the Arctic Ocean. As summer sea ice declines, spring phytoplankton blooms are becoming possible, leading to Arctic ecosystems becoming more like the present North Atlantic and productivity increasing by 30-50 per cent (Yool et al., 2015). Warming and circulation changes can also lead to the spread of invasive species – for example in the Barents Sea and from the Pacific (Kelly et al., 2020; Neukermans et al., 2018; Oziel et al., 2020) (see 1.4.2.1). However, while these changes may trigger regime shifts, it is currently difficult to predict whether they will feature self-sustaining tipping dynamics.

Empirical thresholds for marine communities have been estimated in specific cases using ecosystem model-derived indicators of community status (e.g. Samhouri et al., 2010), but are in general challenging to identify. Evidence for irreversibility is anecdotal and case-specific. One example is shifts in the anchovy-sardine cycles (Schwartzlose et al., 1999) that occur worldwide. Such shifts appear to be triggered by changes in short and long-term climate conditions. In the Peruvian upwelling system, switches in climate cycles can thus correspond to tipping points for the community (Alheit and Niquen 2004; Chavez et al.,2003), with effects on the middle (decadal) to long (centuries) timescale (Salvatteci et al., 2018). Evidence for this system suggests that natural fluctuations and anthropogenic climate change may pose an increased risk of tipping toward irreversible changes to a community characterised by less desirable (from a social-ecological perspective) and less productive features (Salvatteci et al.,2022).

Kelp forests

Kelp forests are mostly coastal ecosystems dominated by dense populations of large brown macroalgae (Figure 1.3.27). In recent decades, a significant number of these forests have undergone devastating collapses, resulting in their transformation into desolate and unproductive communities, called barrens. These collapses are primarily driven by overgrazing by sea urchins (Ling et al., 2015). However, additional pressures, such as marine heatwaves (McPherson et al., 2021), nutrient concentration (Boada et al., 2017) and sedimentation (Foster and Schiel, 2010), also contribute to its formation.

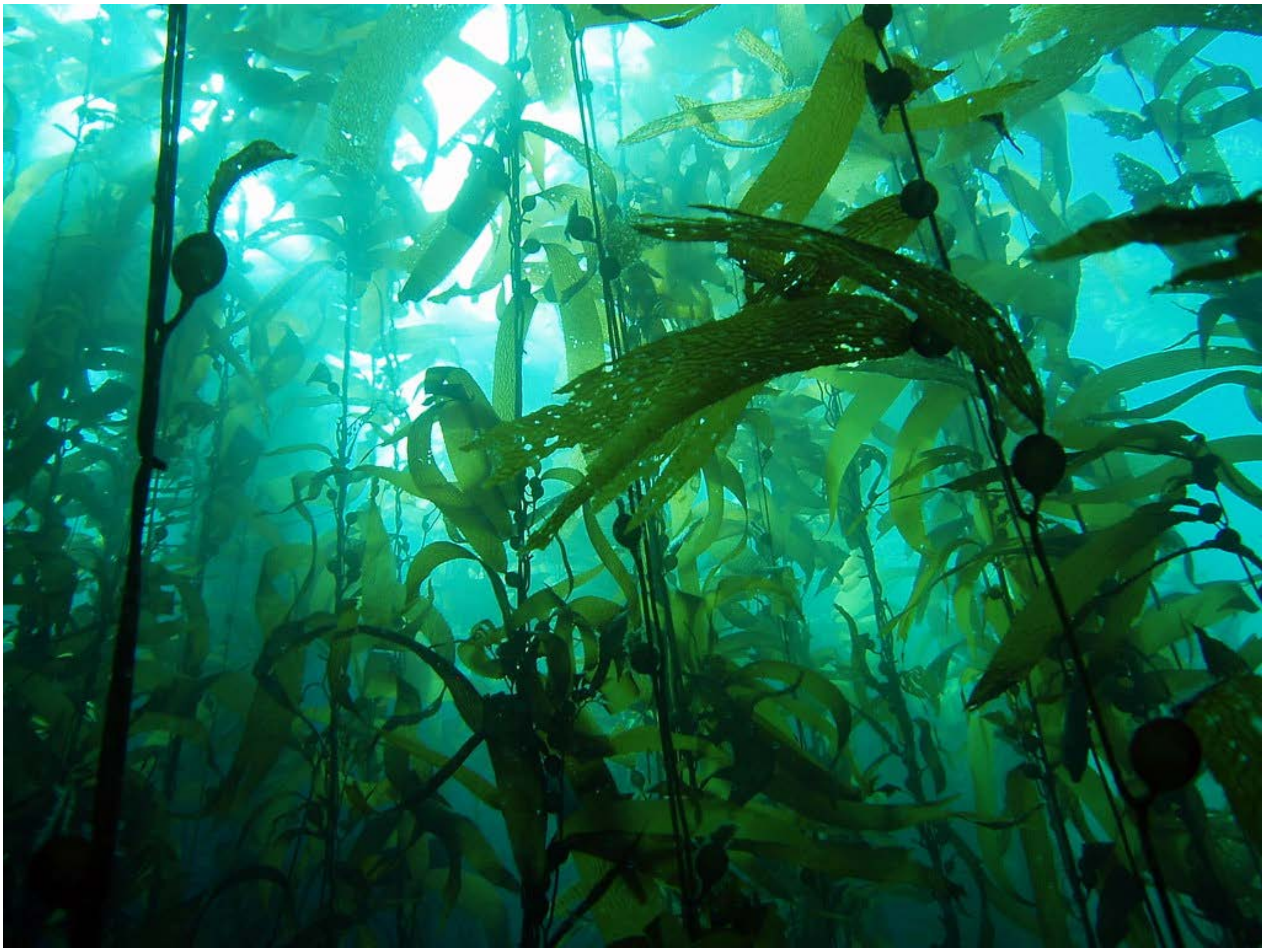


Figure 1.3.27: Kelp forest at Anacapa Island, California, 2010. Source: Dana Roeber Murray, flickr

Persistent, catastrophic regime shifts in coastal rocky communities transitioning between productive macroalgal beds and impoverished sea urchin barrens have been shown to occur worldwide (Ling et al., 2015). In many cases, such regime shifts exhibit nonlinear dynamics with hysteresis, where the transition shifts exhibit tipping points (Filbee-Dexter and Scheibling, 2018). Thresholds can be estimated empirically through a critical density of sea urchins (Ling et al., 2015), but such thresholds are influenced by biotic and abiotic factors.

Two feedbacks promote the stability of the barren state: processes that reduce kelp recruitment on barrens and processes that allow sea urchins to maintain high densities on barrens (Filbee-Dexter and Scheibling, 2018). For example, adult sea urchins seem to provide shelter and facilitate survival of urchin recruitment, offering a reinforcing mechanism. Similarly, barren conditions are kept open by intense grazing, reducing the chances of kelp recruitment.

Empirical studies have demonstrated the possibility of kelp forest recovery once sea urchin densities are limited (Smith and Tinker, 2022; Galloway et al., 2023). However, such recovery is influenced by abiotic factors such as marine heat waves, making kelp forest reversibility uncertain.

Biological carbon pump

The biological carbon pump (BCP) refers to the suite of processes that remove ~50 Gt of carbon annually from the atmosphere and into marine biomass, transferring ~10 per cent of this into the deep ocean (Carr et al., 2006; Westberry et al., 2008; Fu et al., 2016). Without this flux, atmospheric CO_2 would likely be ~200 ppm higher than the present-day concentration (Henson et al., 2022).

The largest component of the BCP, the gravitational pump, is driven by sinking of organic matter, mostly from dead plankton and detritus such as faecal pellets (Figure 1.3.28) (Nowicki et al., 2022). This part of the BCP is expected to decline with warming as a result of reduced mixing between warming surface and colder deep waters (thermal stratification) leading to reduced nutrient supplies for surface algae (i.e. phytoplankton), as well as warming favouring smaller plankton species that contribute less sinking matter (Armstrong McKay et al., 2021). However, there is no known mechanism that would enable this decline to become self-sustaining, with changes scaling quasi-linearly with emissions in models, and it is therefore not considered to show tipping-point behaviour (Armstrong McKay et al., 2022).

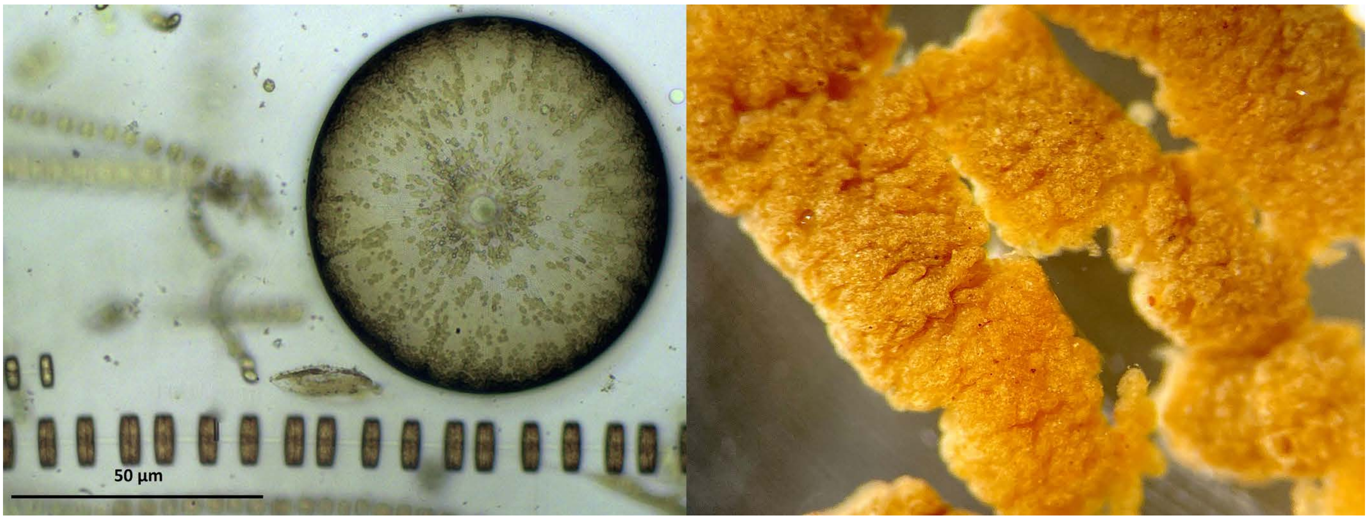


Figure 1.3.28: Left: the centric diatom *Coscinodiscus* sp. which is a large, lipid and carbohydrate-rich species that capitalises on peak nutrients during early spring. Image courtesy of Amanda Burson (British Antarctic Survey). Right: organic detritus produced by jellyfish from the subtropical South Atlantic, March 2023. Approximate width of pellets is 1.5mm. Image: Daniel Mayor on Instagram (accessed 2023).

A system that is more likely to show tipping-point behaviour is the seasonal lipid (fat) pump (SLP) (Jonasdottir et al., 2015). The SLP mainly occurs in high latitude oceans and is driven by the seasonal vertical migration of lipid-rich zooplankton (Figure 1.3.29) into the deep ocean, where they overwinter for ≥6 months, directly injecting carbon below the winter mixed layer.

A dramatic reduction in primary production via diatoms, for example, driven by changing nutrient supply patterns via increased stratification due to ocean warming, could result in zooplankton not consuming enough lipids to successfully overwinter and reproduce the following spring. Arresting the SLP would irreversibly change the ecological and biogeochemical functioning of high latitude ecosystems.

Figure 1.3.29: The marine copepod, *Calanus finmarchicus*, with its lipid sac outlined in red. Reproduced from (Mayor et al., (2020) and (Anderson et al., (2022).

Deep ocean warming will increase rates of respiration, meaning that lipid reserves may become exhausted before returning to the surface. This will interrupt recruitment and halt the SLP. The poleward migration of non-diapausing species (i.e. those that do not form an inactive life-form for parts of the year), as polar conditions ameliorate, could eventually mean that lipid-storing deep-diapausing zooplankton eventually disappear and the SLP collapse will be irreversible. However, the SLP was only described <10 years ago, and so our nascent understanding of its scale and complexity currently precludes the establishment of thresholds.

Other parts of the ocean biological pump could also result in nonlinear dynamics or tipping points. A recent paper found evidence that 'mixotrophs' – plankton that can both photosynthesise like algae and consume other plankton – can switch between a photosynthesis-dominant carbon sink state to a consumption-dominant carbon source state, with warming pushing them towards the latter and nutrient pollution making tipping dynamics more likely (Wieczynski et al., 2023). Mixotrophs are common in the ocean but their role in ocean and ecosystems and the biological pump is under-studied (Ward, 2019), making the impacts of these potential tipping dynamics unclear.

Marine oxygenation

Coastal hypoxia is a regime shift that occurs when dissolved oxygen in water diminishes below levels detrimental to marine life. As a consequence, one of their symptoms are 'dead zones', areas of the oceans where fish and many other marine organisms (particularly in benthic communities) migrate outwards or die due to low oxygen levels.

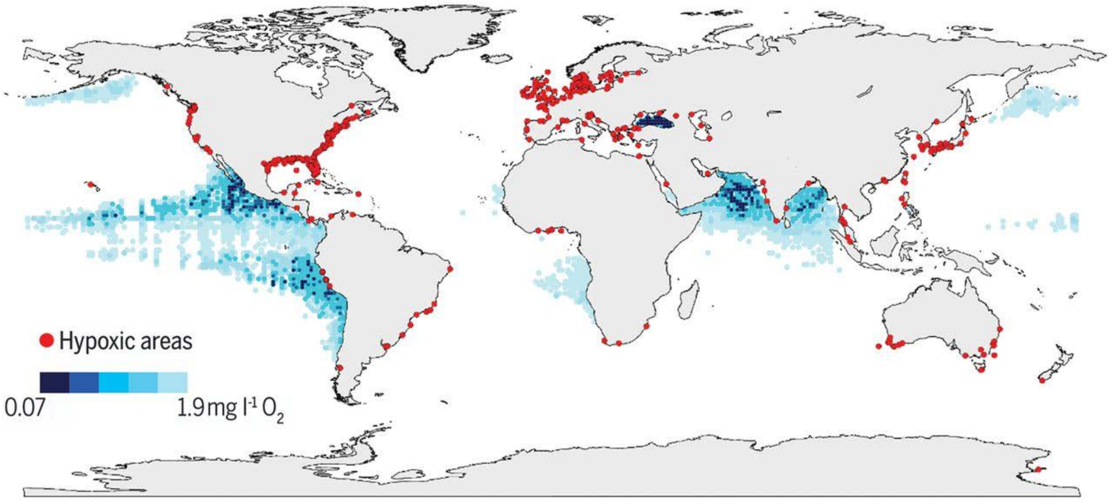


Figure 1.3.30: Map of known oceanic oxygen minimum zones (at 300m depth, blue) and coastal sites where anthropogenic nutrients have exacerbated or caused O_2 to decline to <2 mg/litre (red dots), becoming 'dead zones'. Source: (Breitburg et al., 2018).

While hypoxia is naturally occurring in some areas, hypoxic events have been increasing over the last few decades. A first global assessment of ocean deoxygenation documented over 300 cases mainly in the Atlantic coast of North America, the Caribbean, Mediterranean and Baltic seas (Diaz and Rosenberg, 2008). Subsequent assessments expanded to >500 case studies, from occasional hypoxic events to severe anoxia (Breitburg et al., 2018) (Figure 1.3.30).

The main mechanisms underlying coastal hypoxia are related to over-enrichment of nutrients like phosphorus and nitrogen coming from agricultural fertilisers, sewage or upwelling currents in the ocean. The latter are natural currents that bring nutrient-rich waters from the deep ocean to the surface, powering the primary producers (i.e. algae) and in turn productive food webs. In high-nutrient waters, algae can become over-abundant, consuming the available oxygen and causing the death of fish or other oxygen-dependent organisms. As they die, decomposers then further decrease available oxygen as they break down extra organic matter. Additional nutrients from fertiliser and sewage runoff on land is amplifying this process, increasing the number of hypoxic events and sites (Breitburg et al., 2018; Heinze et al., 2020).

At the same time, phosphorus can be released from sediment under low oxygen conditions, acting as a positive/amplifying feedback by further amplifying the growth of algae and the consumption of oxygen (Conley et al., 2002; Adhikari et al., 2015). Besides nutrients, climate change can exacerbate hypoxia by reducing oxygen solubility in water (Breitburg et al., 2018), and is projected to cause widespread deoxygenation over coming centuries to millennia via warming and enhanced land weathering delivering more phosphorus (Watson et al,.2017; Battaglia and Joos, 2018). Even if warming peaks and falls ('overshoot') Earth system models indicate that deoxygenation in the upper 1000 metres of the ocean is irreversible for multiple centuries (Santana-Falcon et al., 2023). Sea surface temperature can also change the strength of upwellings and thus the inflow of nutrients in coastal ecosystems.

Marine ecosystems with dissolved oxygen higher than >2 mL per litre sustain diverse ecological communities, and this level is considered normal (also known as 'normoxia'). Below this level the symptoms of hypoxia appear, including hypoxic events and dead zones. Anoxia occurs when levels of dissolved oxygen are below 0.5 mL per litre, which only a few microbial species are able to survive (Diaz and Rosenberg, 2008). Some dead zones and hypoxic events are reversible in scale of months to years. However, more and more areas are reported as chronically hypoxic, possibly irreversible in the timescale of ecosystem managers (centuries). Examples of severe hypoxia are dead zones in the Gulf of Mexico, central Baltic, Kattegat, Black Sea, and East China Sea (Breitburg et al., 2018).

Assessment and knowledge gaps

Table 1.3.3: Summary table of marine environment tipping points considered in this section.

System	Tipping system?	Timescale	Biophysical Impacts	Confidence	Gaps
Fisheries **[Small, fast-growing fish]**	No	Decades	Changes in entire trophic assemblage. A regime shift in one species could propagate the regime shift in many components of the ecosystem. Important especially in bottom-up and wasp-waist ecosystems.	Low confidence because too many different species	Need more coherent statistical approaches to identify tipping points and the presence of hysteresis. Also need more analyses on single species that look at tipping points in fisheries.
Fisheries **[Large, slow-growing fish]**	Depends on the stock	Decades	Changes in entire trophic assemblage. A regime shift in one species could propagate the regime shift in many components of the ecosystem. Especially important in top-down ecosystems.	Low confidence because too many different species and many different areas	Need more coherent statistical approaches to identify the tipping points and the presence of hysteresis. Also need more analyses on single species that look at tipping points in fisheries.
Fisheries [Cod]	Yes (in 16 out of 19 stocks)	Decades	Changes in the entire trophic assemblage, trophic cascade.	High confidence	In some cases there is the need to better understand feedbacks of hysteresis.
Community shifts	Yes	Decades	Changes in ecosystem function. structure and feedbacks that may affect how to best manage the system.	Low confidence - complexity from many different species and interacting drivers	Better understanding required on interplay of multiple drivers and species interactions. Tipping points difficult to identify and predict.
Kelp forests	Yes	Months to decades	Changes to community composition of fish and macroinvertebrates scaling up to trophic disassembly.	High confidence	Necessary to understand how key ecosystem properties, e.g. resilience or stability of kelp forests, evolve over the years.
Ocean hypoxia	Yes	Months/years to centuries. Reversible at surface, irreversible at depth for centuries to millennia	Major changes in ocean productivity, biodiversity and biogeochemical cycles.	Low confidence	Degree of self-sustaining change and hysteresis; influence of future climate change and nutrient use.
Biological pump [Seasonal Lipid Pump]	Potential, but uncertain	Decades	Major changes in trophic transfer, carbon sequestration and ocean biogeochemistry.	Low confidence	Better understanding of zooplankton physiology and its response to environmental change.

Table 1.3.3 summarises our assessment of tipping dynamics (with confidence levels) along with biophysical impacts, timescales and knowledge gaps for marine ecosystems. We have high confidence that cod fisheries and kelp forests can pass tipping points, low confidence that some other large-fish fisheries, marine communities and potentially the lipid pump could also tip, and medium confidence that marine hypoxia could feature tipping dynamics. Knowledge gaps include limited understanding of complex species and driver interactions, limited ability to detect and project marine tipping points in practice, and how ecosystem resilience can change over time.

1.3.3 Final remarks

In this chapter we have assessed evidence for tipping dynamics across the biosphere, finding that many ecosystem tipping points are possible. Compared to tipping points in the cryosphere (Chapter 1.2) and ocean/atmosphere circulations (Chapter 1.4), biosphere tipping points tend to feature more co-drivers, including habitat degradation and loss, direct exploitation and nutrient pollution with often complex interactions (IPBES, 2019). Along with strong spatial variability, this often makes ecosystem tipping thresholds and risks more difficult to assess. However, these complexities also provide opportunities for action to avert tipping.

While climate change is a common leading driver, requiring urgent global emissions phaseout, compared to the cryosphere or ocean circulation it is more possible to directly increase the resilience of some at-risk systems. Actions such as ecological restoration and inclusive conservation, adaptive management and improved governance can help protect biodiversity and bio-abundance and so help to maintain key stabilising feedbacks that can help counter tipping (see Chapter 3.2). Such restoration and regenerative land use practices would also help to draw down some carbon from the atmosphere, helping to slow climate change (Girardin et al., 2021; Rockström et al., 2021). Such 'nature-based solutions' would not be enough to stop climate change though, which can only be achieved with a rapid cessation of greenhouse gas emissions.

Most ecosystems considered in this chapter can also be considered social-ecological systems, with people living within, and being integral to, the dynamics of these systems (Folke et al., 2016, 2021). While in some heavily degraded ecosystems restoration might entail minimising human impacts, in most places actions like supporting sustainable livelihoods for local communities can better help promote both ecological restoration and support human wellbeing in a way that makes both more sustainable in the long term (IPBES, 2019). The rights of Indigenous peoples – whose territories cover more biodiverse area globally than officially protected areas (ICCA Consortium, 2021) – must be respected, and their knowledge recognised as critical. Many other societal shifts are also necessary to underpin ecological restoration, including transformative changes to the global food system and commodity consumption (which together are key drivers behind much habitat loss and pollution – IPBES, 2019).

From a research perspective, we have identified several critical areas where improved knowledge could help us better understand biosphere tipping dynamics. In particular, deep uncertainties exist around the relative strength of feedbacks controlling ecosystem tipping dynamics, such as the complex interactions between ecohydrological and fire feedbacks in forest, savanna and dryland biomes. The role of increasing extreme event frequency and intensity in reducing and overcoming ecological resilience is also critical for ecosystems such as coral reefs, mangroves and forests, but it is not well resolved in models. Plant adaptability and spatial variability are also not well represented in models, despite being key factors adding complexity to ecosystem tipping dynamics. More observations, experiments and improved models, and integrations across these, are all required to address these issues.

Observations from field and remote sensing can also help monitor and detect declining ecosystem resilience, as well as potential early warning signals (see Chapter 1.6). Greater data sharing and international collaboration would improve both monitoring and understanding. Lastly, co-designing research with researchers from across the natural and social sciences, Global South and North, and from multiple knowledge systems including Indigenous and traditional ecological knowledge is critical for fully understanding ecological dynamics and the potential for tipping.

1.4 Tipping points in ocean and atmosphere circulations

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Summary

This chapter assesses scientific evidence for tipping points across circulations in the ocean and atmosphere. The warming of oceans, modified wind patterns and increasing freshwater influx from melting ice hold the potential to disrupt established circulation patterns. We find evidence for tipping points in the Atlantic Meridional Overturning Circulation (AMOC), the North Atlantic Subpolar Gyre (SPG), and the Antarctic Overturning Circulation, which may collapse under warmer and 'fresher' (i.e. less salty) conditions.

A slowdown or collapse of these oceanic circulations would have far-reaching consequences for the rest of the climate system, such as shifts in the monsoons. There is evidence that this has happened in the past, having led to vastly different states of the Sahara following abrupt changes in the West African monsoon, which we also classify as a tipping system. Evidence about tipping of the monsoons over South America and Asia is limited, however large-scale deforestation or air pollution are considered as potential sources of destabilisation. Although theoretically possible, there is little indication for tipping points in tropical clouds or mid-latitude atmospheric circulations. Similarly, tipping towards a more extreme or persistent El Niño Southern Oscillation (ENSO) state is not sufficiently supported by models and observations.

While the thresholds for many of these systems are uncertain, tipping could be devastating for many millions of people. Stabilising climate (along with minimising other pressures, like aerosol pollution and ecosystem degradation) is critical for reducing the likelihood of reaching tipping points in the ocean-atmosphere system.

The scientific content of this chapter is based on the following manuscript: Loriani et al., Tipping points in ocean and atmosphere circulations. Earth System Dynamics (submitted).

Key messages

- There is evidence for tipping points in the overturning circulations in the Atlantic and the Southern ocean, as well as for the West African monsoon.
- Short observational records, potential model biases towards stability, and limited resolution of various important feedback processes in models leave uncertainties, making an assessment of potential tipping difficult.

Recommendations

- Prevent destabilisation of ocean and atmosphere circulations by urgent and ambitious reduction of greenhouse gas emissions and other pressures such as air pollution.
- Fill knowledge gaps and improve models to constrain projected impacts for the next decades and beyond. Reduce uncertainties. For example related to the resolution of small-scale processes and interaction of different systems.
- Invest in observations and palaeo reconstructions to detect early warning signs of tipping dynamics, and foster data sharing and international collaboration.

1.4.1 Introduction

The Earth's ocean and atmosphere form the flowing fluid parts of the Earth system that circulate around the planet. They drive the daily weather and climate patterns we see. On a global scale, the dominant circulations in the atmosphere are a consequence of regional differences in solar radiation (with poles less heated than the equator), Earth's rotation (redirecting winds) and thermodynamic properties (e.g. that warm air is less dense and rises).

Atmospheric circulation can be divided into several rotating cells: The 'Hadley cell' is formed either side of the equator by warm air rising near the equator (at the 'Intertropical Convergence Zone', or ITCZ) before sinking in both midlatitudes (at ~30° North or South). The midlatitude Ferrel cell sinks at mid latitudes and rises at high latitudes (~60° N or S), connecting to the polar cell rising at high latitudes and sinking at the poles. Diverted by Earth's rotation, surface winds tend to blow westwards (the 'easterly' trade winds) in the tropical cells, and eastwards ('westerlies') in the mid and high latitudes.

Over 70 per cent of the Earth's surface is covered by the global ocean, and is conventionally divided into the Atlantic, Indian, Pacific and Southern oceans. Ocean currents circulate water around the Earth as a result of pressure gradients driven by differences in temperature and salinity. This 'global thermohaline circulation', also known as the 'ocean conveyor belt', mixes the whole ocean over a roughly thousand-year timescale. Key components of this mechanism, connecting deep currents with those on the surface, are the sinking of cold and salty – therefore dense – water in polar regions as well as widespread 'upwelling'. The force exerted by atmospheric surface winds leads to basin-wide rotating 'gyres' of surface currents in the various ocean basins (Figure 1.4.1).

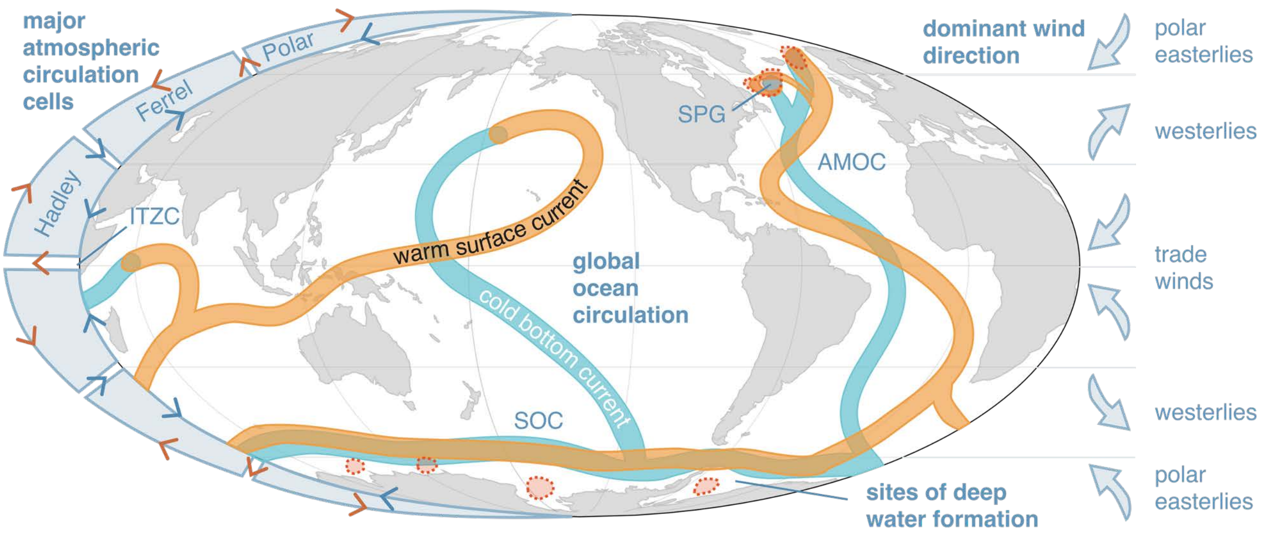

Figure 1.4.1: Atmospheric circulation cells, dominant wind directions, key ocean basins, surface currents and deep water formation sites. AMOC: Atlantic Meridional Overturning Circulation; SPG: Subpolar Gyre; SOC: Southern Ocean Circulation; ITCZ: Intertropical Convergence Zone.

Human-driven climate change is causing ongoing long-term changes in the ocean and atmosphere circulation. The effect of added greenhouse gases is to trap additional heat in the Earth system, driving atmospheric and ocean warming (with the latter accounting for more than 90 per cent of the heat trapped so far, (Fox-Kemper et al., 2021). There may also be changes in key circulation patterns, with increasing evidence that the Atlantic Meridional Overturning Circulation (AMOC) may be slowing (Dima and Lohmann 2010; Caesar et al., 2018; Rahmstorf et al,. 2015; Zhu et al., 2023). An extra seven per cent of water vapour can be held by the near-surface atmosphere with every degree of warming, leading to increasing precipitation in some regions (Zika et al, 2018). Evidence shows that heat extremes, heavy rainfall events and agricultural and ecological droughts are already increasing across every continent (IPCC 2021). As the ocean and atmosphere gradually warm, the range of natural variability around the baseline is shifting upwards, making formerly extreme events more common and formerly impossible events possible.

Evidence exists from geological records and model simulations that some of these circulation patterns could also feature tipping points, beyond which they may shift to a different state (Lenton et al,. 2008; Armstrong McKay et al. 2022; Wang et al,. 2023). Palaeorecords suggest deep water convection in the North Atlantic has abruptly shifted to a weaker or completely 'off' state during previous glacial cycles, with major climatic consequences – a pattern supported by some models (Böhm et al,. 2015; Iouville et al., 2021: Fox-Kemper et al., 2021). It has also been suggested that the Indian summer monsoon could shift to an alternative state as a result of aerosol emissions, counter to the general trend of monsoon strengthening with warming (Levermann et al. 2009; Doblas-Reyes et al., 2021), and as potential shifts in circulations in the southern hemisphere to El Niño-like mean conditions have also been proposed (Fedorov et al, 2006).

1.4.2 Current state of knowledge on ocean and atmosphere circulation tipping points

In this section, we assess available scientific literature on tipping points in ocean and atmosphere circulations. To this end, we focus on the following systems: ocean circulations in the Atlantic and the Southern Ocean; monsoons over West Africa, India and South America; tropical clouds and circulations; El Niño southern oscillation; and mid-latitude atmospheric circulations.

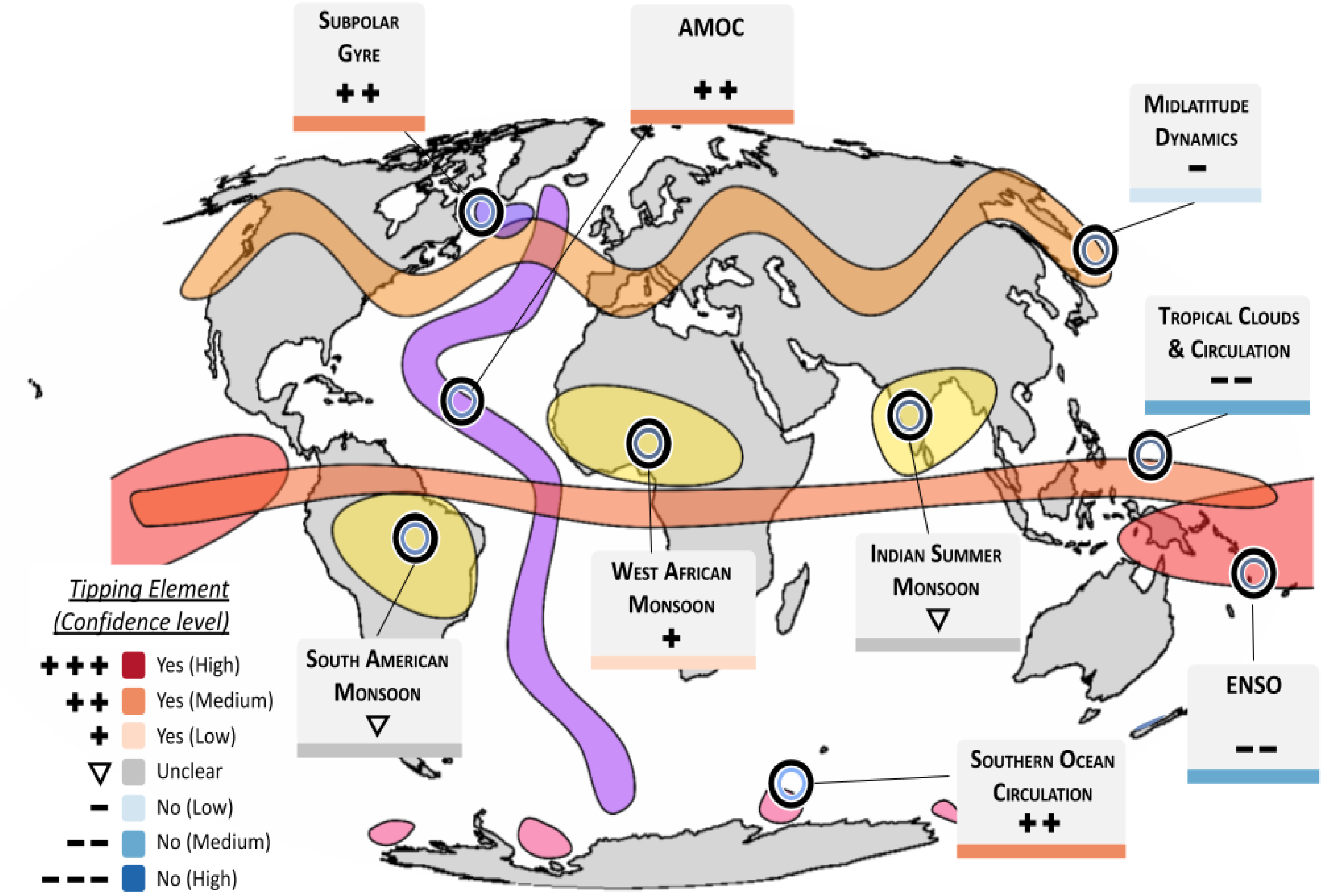

Figure 1.4.2: Potential tipping systems in ocean and atmosphere circulations considered in this chapter.

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.

Table 1.4.1: Summary of evidence for tipping dynamics, key drivers, and biophysical impacts in each system considered in this chapter

Key: +++ Yes (high confidence), **++** Yes (medium confidence), **+** Yes (low confidence), **- - -** No (high confidence), **- -** No (medium confidence), **-** No (low confidence)

Primary drivers are bolded, DC: Direct Climate driver (via direct impact of emissions on radiative forcing); **CA:** Climate-Associated driver (including second-order & related effects of climate change); **NC:** Non-Climate driver. Drivers can enhance **(↗)** the tipping process or counter it **(↘)**

System	Key drivers	Key biophysical impacts *(see S2 for societal impacts)*	Key feedbacks	Abrupt / large rate change?	Critical threshold(s)?	Irreversible? (timescale)	Tipping system?
Ocean overturning circulation							
Atlantic Meridional Overturning Circulation (AMOC) Shutdown/collapse	• **DC: ocean warming (↗)** • **DC: precipitation increase (↗)** • **CA: Greenland ice sheet meltwater increase (↗)** • **CA: Arctic river discharge increase (↗)** • CA: sea ice extent & thickness decrease (↗) • DC: regional aerosol forcing increase (↘) • CA: regional ocean circulation changes (?)	• Cooling over Northern Hemisphere (up to 10°C over W/N Europe) • Change in precipitation and weather patterns over Europe • Change in location and strength of rainfall in all tropical regions • Reduced efficiency of global carbon sink, and ocean acidification • Reduced support for primary production in Atlantic oceans • Deoxygenation in the North Atlantic • Change in sea level in the North Atlantic • Modification of sea ice and arctic permafrost distribution • Change in winter storminess • Reduced land productivity in Atlantic bordering regions • Increased wetland in some tropical areas and associated methane emission • Change in rainforest response in drying regions	• **Salt-advection (↗)** • Sea ice melting (↗) • Heat transport (↘) • Temperature (↗) • Surface heat flux (↗) • Collapse of convection in the Labrador and Irminger Seas (↗)	Feedback-dependent: Century (basin-wide salt advection feedback), Few decades (North Atlantic salt-advection feedback), < few decades (sudden increase in seaice cover in all convective regions)	**Salinity change/ freshwater/AMOC strength** Thresholds likely path-dependent (depending on rate and spatial pattern)	++ (centuries)	++
North Atlantic Subpolar Gyre (SPG) Collapse		• Increase in summer heat waves frequency • Collapse of the North Atlantic spring bloom and the Atlantic marine primary productivity • Increase in regional ocean acidification • Regional long-term oxygen decline • Impact on marine ecosystems in the tropics and subtropics		Years to few decades	**Salinity change/ freshwater** Global warming 1.1-3.8°C	++ (decades)	++
Southern Ocean circulation Antarctic Overturning Collapse / Rapid continental shelf warming	• **DC: ocean warming (↗)** • **CA: Antarctic ice sheet meltwater increase (↗)** • CA: wind trends (↗) • CA: Sea ice formation (↗) • DC: precipitation increase (↗)	• Modification of Earth's global energy balance, timing of reaching 2°C global warming • Reduced efficiency of global carbon sink • Change in global heat storage • Reduced support for primary production in world's oceans • Drying of Southern Hemisphere • Wetting of Northern Hemisphere • Modification of regional albedo, shelf water temperatures • Potential feedback to further ice shelf melt	• Density-stratification (↗) • Meltwater-warming (↗)	++ (AABW formation & abyssal overturning shutdown within decades)	Salinity change/freshwater	++ (cavity warming reversion would need 20th-century atmospheric conditions + reduced meltwater input)	++

System	Key drivers	Key biophysical impacts *(see S2 for societal impacts)*	Key feedbacks	Abrupt / large rate change?	Critical threshold(s)?	Irreversible? (timescale)	Tipping system?
Atmosphere: Monsoons							
Indian summer monsoon (ISM) Collapse / Shift to low-precipitation state	• NC: increased summer insolation (↘) • DC: increased water vapour in atmosphere (↘) • CA: Indian Ocean Dipole events (?) • CA: ENSO change (?) • CA: North Atlantic cold SST (↗) • DC: aerosol loading (↗) • CA: Indian Ocean warming (↗) • CA: low cloud reduction (↘)	• **Massive change in precipitation** • Change in tropical and subtropical climates • Biodiversity loss and ecosystem degradation	• Moisture-advection (↘)	Decades to centuries	Regional AOD level over Indian subcontinent (>0.25) Interhemispheric AOD difference (>0.15) AMOC slowdown (unknown threshold)	Uncertain; likely decades to centuries	**unknown**
West African monsoon (WAM) Collapse or abrupt strengthening	• DC: increased water vapour in atmosphere (↗) • NC: increased summer insolation (↘) • NC: land-cover change (↗) • CA: desertification (↗) • CA: AMOC slowdown (↗) • CA: regional SST variations (?) • CA: High latitude cooling (↗) • CA/NC: regional soil moisture variation (?) • CA/NC: regional vegetation variation (?) • NC: dust emissions (?)	• **Massive change in precipitation** • Change in tropical and subtropical climates • Biodiversity loss and ecosystem degradation	• Vegetation-albedo (↗)	Decades to centuries	Insolation changes in the Northern Hemisphere summers and surface albedo changes (unknown threshold) Interhemispheric asymmetry in AOD (>0.15) AMOC slowdown (unknown threshold)	Decades to centuries	**+**
South American Monsoon (SAM)	• DC: increased water vapour in atmosphere (↗) • NA: increased summer insolation (↘) • CA: AMOC slowdown (↗) • NC: Amazon deforestation (↗)	• **Massive change in precipitation** • Change in tropical and subtropical climates • Biodiversity loss and ecosystem degradation	• Vegetation-moisture (?)	Decades	Interhemispheric asymmetry in AOD (>0.15) Extent of Amazon deforestation (30-50%) AMOC slowdown (unknown threshold)	Uncertain; likely decades to centuries	**unknown**
Atmosphere: Planetary circulations							
Tropical clouds, circulation and climate sensitivity Shift to different large-scale configuration	• **DC: atmospheric warming (↗)** • **DC: ocean warming (↗)**	• Massive alteration of hydrology in many regions • Impact on ambient atmospheric-oceanic phenomena such as ENSO • Strong intensification of global climate change	• Cloud-moisture-radiation (↗)	Unknown	Unknown	Unknown	- -

System	Key drivers	Key biophysical impacts *(see S2 for societal impacts)*	Key feedbacks	Abrupt / large rate change?	Critical threshold(s)?	Irreversible? (timescale)	Tipping system?
El Niño Southern Oscillation (ENSO) Shift to more extreme or persistent state	• **DC: east vs west Pacific warming (↗)** • **DC: increased water vapour in atmosphere (↗)** • DC: weaker trade winds (↗) • CA: MJO strengthening (↗)	• Temporary trade wind collapse during El Niño phase • Increase in global mean surface temperatures during El Niño phase • Modification of global atmospheric circulation • Modification of worldwide patterns of weather variability	• Bjerknes (↗) (SST-tradewinds-ocean thermocline)	No evidence (gradual)	No evidence (gradual)	No evidence	- -
Mid-latitude atmospheric dynamics Shift to wavy-jet state / more frequent or extreme planetary waves or blocks	• CA: AMOC slowdown (↗) • CA: Midlatitude flow weakening (↗) • DC: Arctic amplification (↗)	• More persistent and slower moving weather patterns • Increase in extreme events on Northern hemisphere	• Debated: Waviness quasi-resonance (↗)	No evidence	Potentially waviness threshold, beyond which quasi-resonance kicks in	No evidence	-

1.4.2.1 Atlantic circulation

Atlantic Meridional Overturning Circulation (AMOC)

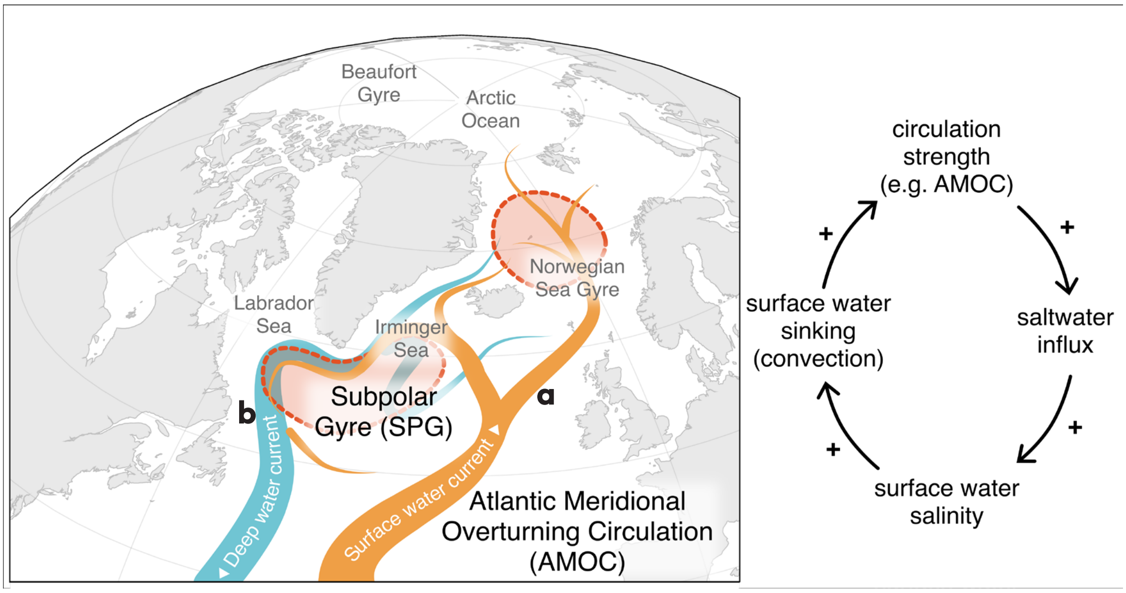

Figure 1.4.3: Overview over the major oceanic circulation systems in the North Atlantic. **a** The surface currents (orange pathways) are connected to deep ocean currents (blue) through sites where dense (cold, salty) water sinks, driving the overturning circulation (pink shading). **b** One critical feedback is the salt-advection feedback, in which the circulation strength determines how well the convection works, which in turn benefits the circulation.

The Atlantic Meridional Overturning Circulation

The Atlantic Meridional Overturning Circulation (AMOC) refers to a three-dimensional circulation present in the Atlantic (Figure 1.4.3a) whereby warm upper ocean waters ('upper branch') move northward from the tip of Southern Africa to the northern North Atlantic, where they cool, sink and return southwards as cold deep waters ('lower branch'). The AMOC moves heat from the South to the North Atlantic, helping to maintain the mild climate of western and northern Europe. Thereby it shapes the climate of the whole Earth, influencing, for example, the 1-2°C temperature difference between the Northern and Southern hemispheres, and the location and strength of rainfall across all tropical regions (Buckley and Marshall, 2016; Feulner et al., 2013; Marshall et al., 2014).

Fresh, warm water is less dense than cold, salty water. In the future, surface waters in the northern North Atlantic may become less dense. This will make it harder for the water in that region to sink, which will disrupt the connection between the upper and lower branches of the AMOC, causing it to weaken significantly or even collapse completely. Therefore, we need to monitor the processes which tend to warm and freshen the upper ocean at high latitudes. AMOC strength has only been observed directly since 2004 (Srokosz and Bryden, 2013), with more uncertain reconstructions based on observations such as surface temperature, which extend back in time before 2004 ('observational proxies'), or from palaeoclimate archives such as ocean sediment cores which extend back to prehistoric times ('palaeoclimate proxies') (Caesar et al,. 2018, 2021; Moffa-Sánchez et al., 2019). The lack of a sufficiently long observational record is a major issue for robust understanding of the AMOC.

The North Atlantic Ocean is freshening at subpolar latitudes (50-65°N), most strongly in the upper 100m, and warming, most strongly between 100-500 m water depth (IPCC, 2021). Both trends act to reduce AMOC strength. Greenland Ice Sheet melt is accelerating and releasing extra fresh water into the North Atlantic (Shepherd et al., 2020). In addition, Arctic sea ice is reducing in surface extent and thickness (Serreze and Meier, 2019) and overall Arctic river discharge is increasing (Druckenmiller et al., 2021), adding fresh water to the Arctic continental shelves and the high Arctic, and this riverine fresh water is potentially leaking into the North Atlantic from the Arctic. The North Atlantic is a region of high variability on interannual to decadal timescales (Boer 2000) and therefore subject to substantial climatic perturbations with the potential to trigger any underlying instability if a tipping point is approached.

Limited direct observations of AMOC strength make current trends uncertain, but there are some signs of ongoing weakening. Observational and palaeoclimate proxies suggest the AMOC may have weakened by around 15 per cent over the past 50 years (Caesar et al,. 2018) and may be at its weakest in 1,000 years (Caesar et al., 2021). However, the proxy data used in these studies have large uncertainties, and some other reconstructions show little evidence of decline (Moffa-Sanchez et al., 2019; Kilbourne et al., 2022). It is therefore difficult to confidently discern potential recent trends from natural variability, due to disagreement between published studies (Bonnet et al,. 2021; Latif et al., 2022; versus Qasmi, 2022).

The IPCC's most recent assessment is that the AMOC has weakened relative to 1850-1900, but with low confidence due to disagreement among reconstructions (Moffa-Sanchez et al., 2019; Kilbourne et al., 2022) and models (Fox-Kemper et al., 2021). For the future, the IPCC projects that it is very likely that the AMOC will decline in the 21st century (however with low confidence on timings and magnitude) (Figure 1.4.4a).

There is medium confidence (about 5 on a scale of 1 to 10) that a collapse would not happen before 2100, though a collapse is judged to be as likely as not by 2300. Hence the possibility of an AMOC collapse within the next century is very much left open by the latest IPCC report.

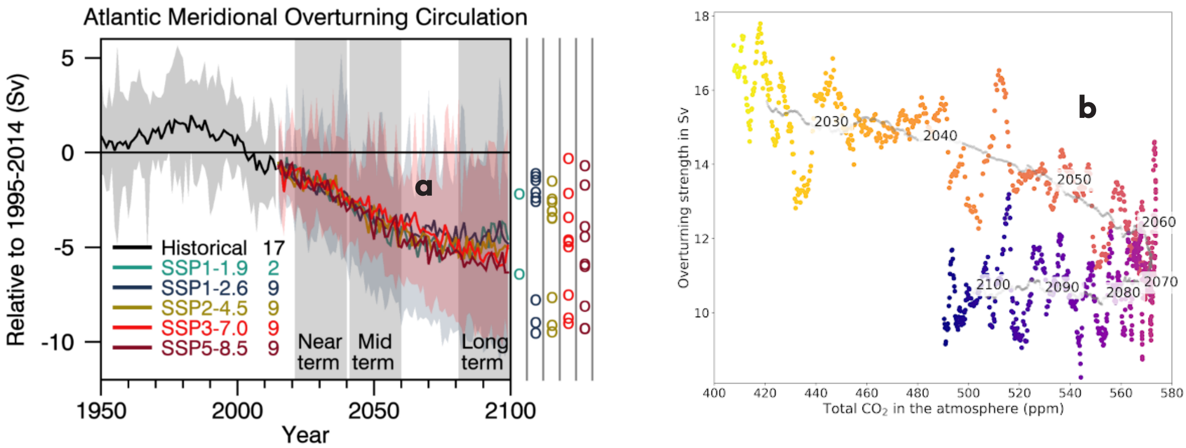

Figure 1.4.4: AMOC in CMIP models. **a** CMIP6 models showing gradual weakening of the AMOC during the 21st Century under all emission scenarios. Credit: Lee et al., 2021 l . **b** CMIP6 overshoot experiments (using UKESM; Jones et al. 2020) showing hysteresis - different states of the AMOC (vertical axis) for the same atmospheric CO² concentration (horizontal axis). Possible causes are delayed or nonlinear response to forcing or possibly bistability of AMOC. The AMOC strength is measured in 'Sverdrups' (Sv; i.e. a flow of 1 million cubic metres per second); colours from yellow to blue show model years from 2015 to 2100 respectively.

Evidence for tipping dynamics

The AMOC has been proposed as a 'global core' tipping system of the climate system with medium confidence by Armstrong McKay et al., (2022). Palaeorecords indicate it has abruptly switched between stronger and weaker modes during recent glacial cycles (Figure 1.4.5).

Most of the time (including the warm Holocene of the past 12,000 years) the AMOC is in a strong, warm mode, but during peak glacials it sometimes shifted to a weak, cold mode instead (Böhm et al., 2014). It also occasionally collapsed entirely to an 'off' mode during 'Heinrich' events, in which iceberg outbursts from the North American Laurentide Ice Sheet temporarily blocked Atlantic overturning for several centuries.

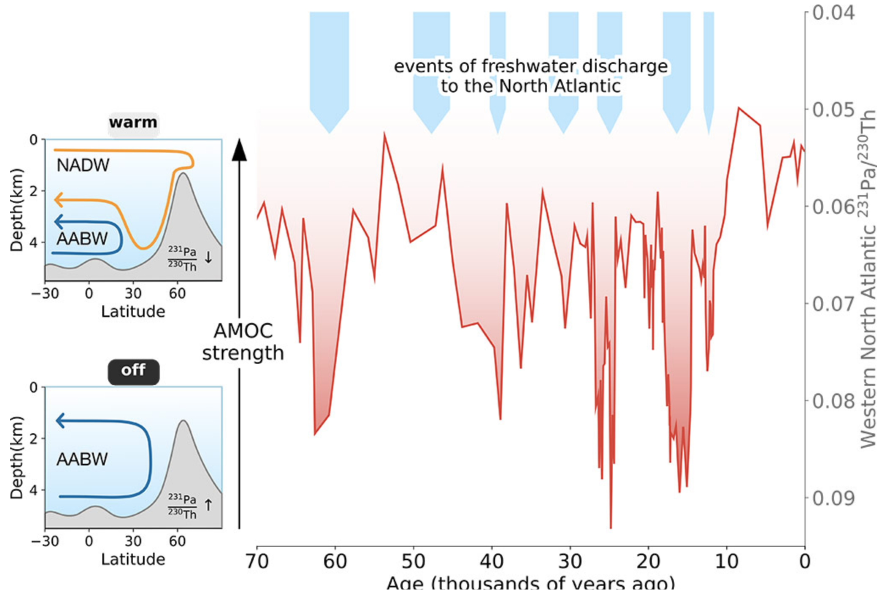

Figure 1.4.5: Different AMOC modes and palaeo-evidence.The diagrams on the left show two AMOC modes as indicated by sedimentary $^{231}Pa/^{230}Th$ in palaeorecords. NADW: North Atlantic Deep Water; AABW: Antarctic Bottom Water, adapted from Böhm et al., 2015. The timeline shows AMOC slowdown events during the last 70,000 years as recorded by sedimentary $^{231}Pa/^{230}Th$ data (McManus et al., 2004; Böhm et al., 2015) from the Western North Atlantic (Bermuda Rise, ca. 34°N). Sedimentary $^{231}Pa/^{230}Th$ from the Bermuda Rise is a proxy for AMOC strength that assesses the southward flowing North Atlantic Deep Water between ca. 3,500 and 4,500m water depth. The top of the panel marks the timing of past major events of freshwater discharge to the high latitudes of the North Atlantic that decreased AMOC strength (Sarnthein et al., 2001; Carlson et al., 2013; Sanchez Goñi and Harrison, 2010). The red shading highlights past AMOC slowdown events. There is also evidence of AMOC shifts during the last interglacial period, 116,000-128,000 years ago (Galaasen et al., 2014).

In two previous censuses of climate model projections, a shut-down of the AMOC over many decades was observed in a small minority of simulations (Drijfhout et al., 2015; Sgubin et al., 2017). This shut-down was preceded by decreases in subpolar surface air and ocean temperature and increased sea ice cover. Ultimately, deep mixing ceased to occur, destroying the connection between the surface and the deep ocean. There are, however, concerns that the AMOC may be too stable in CMIP-type climate models (Mecking et al., 2017; Liu et al., 2017), which suggests the CMIP multimodel ensembles may underestimate the likelihood of AMOC collapse (Fox-Kemper et al., 2021).

Some recent studies have suggested that 'early warning signals' indicating destabilisation (see Chapter 1.6) can be detected in reconstructed 'fingerprints' of AMOC strength over the 20th Century (Boers, 2021), and if a tipping point is assumed then the collapse threshold could be reached during the 21st Century (Ditlevsen & Ditlevsen, 2023). These studies used observational proxies for temperature and salinity from the Northeastern subpolar North Atlantic, which are used as indirect AMOC fingerprints rather than direct measurements of AMOC strength. This gives long enough data to analyse for early warning signals, but using indirect proxies adds uncertainty. The model used by Ditlevsen & Ditlevsen (2023) to project collapse is also highly simplified with a tipping point assumed, and does not take into account the low-frequency variability of the AMOC, nor the presence of external forcings such as increasing greenhouse gases. So while signals in this dataset are consistent with approaching a tipping point, there are substantial uncertainties with this methodology (see also Michel et al., 2023 highlighting potential false warnings). Further potential early warning signals have been found from analysis of Northern Hemisphere palaeoproxies (Michel et al., 2022). Despite the caveats mentioned above, these results amount to a serious warning that the AMOC might be en route to tipping. However, the claim that we might expect tipping in a few decades is – in the view of the present authors – not substantiated enough.

AMOC stability is strongly linked to the 'salt-advection feedback' (Stommel, 1961, see Figure 1.4.3b). The AMOC imports salt into the Atlantic and transports it from the South Atlantic to the northern North Atlantic. If the AMOC weakens then less salt is transported to the northern North Atlantic, the surface waters freshen, which inhibits sinking, and the AMOC weakens further. The AMOC collapses seen in models (Drijfhout et al., 2015; Sgubin et al., 2017) were driven by this salt-advection feedback. However, the strength of this feedback, and the timescale over which it operates are governed by processes whose effects are quite uncertain. Although Figure 1.4.3a shows typical pathways of surface and deep water through the Atlantic, these are an average picture over many decades. Individual water parcels may get caught up in basin-scale surface or deep recirculations, smaller-scale eddies and meandering currents. There is no definitive evidence though from models or observations that these systematically impact the salt advection feedback.

Additionally, changes in the AMOC have other impacts on salinity – for instance through affecting evaporation and precipitation patterns (Jackson., 2013; Weijer et al., 2019). These other feedbacks can temporarily mask, and may even overcome, the salt advection feedback, potentially changing the stability of the AMOC (Jackson, 2013; Gent, 2018). It is difficult to characterise these processes and feedbacks from observations alone due to insufficient data coverage both in time and space, so we are dependent on numerical models. However, many studies have used reduced complexity models, which may not capture all the potential feedbacks, and even the current generation of climate models have quite low spatial resolution and do not well characterise narrow currents, eddies and processes such as horizontal and vertical mixing (Swingedouw et al,. 2022).

Armstrong McKay et al. (2022) estimated with low confidence a global warming threshold for AMOC collapse of ~4°C (1.4-8°C). In our view, the range is a better indication of the uncertainty in the different model responses rather than a relationship to global warming, as the likelihood is probably less dependent on temperature, but strongly depends on salinity changes and the strength of opposing feedbacks on the freshwater budget. Studies with climate models have found that adding freshwater can cause the AMOC to collapse and not recover in some models. Since many climate models might be biased towards stability, however, these studies use an unphysically large amount of freshwater to explore the sensitivity (Jackson et al., 2023). Although adding freshwater causes a collapse, they show the threshold is dependent on the strength of the AMOC and deep convection, rather than on the amount of freshwater added (Jackson and Wood, 2018; Jackson et al, 2023). AMOC collapse may also be more sensitive to the rate of freshwater forcing than the total magnitude (Lohmann & Ditlevsen, 2021).

Hysteresis and bistability both refer to systems which can adopt one of two or more states for the same external forcing, such as CO_2 concentration (see Figure 1.4.4b and Glossary; Boucher et al., 2012). Commonly, this is explored by approaching the same external conditions with different trajectories in model simulations, e.g. increasing and reversing the forcing to study reversibility. Bistability involving a full collapse of the AMOC by artificially flooding the North Atlantic with freshwater has been demonstrated (or strongly implied) in theoretical models (Stommel, 1961) and climate models of reduced complexity (Rahmstorf et al., 2005; Hawkins et al., 2011). These types of numerical experiments study bistability through forcings that change slowly enough for the system to equilibrate, typically requiring long simulations and thus coarse model resolution for reasonable computational performance. In more complex models it is not possible to conduct experiments for long enough to demonstrate bistability or hysteresis, however weak states have been shown to be stable for at least 100 years in about half of a test group of CMIP6-type models (Jackson et al., 2023) and in a high-resolution ocean-atmosphere coupled climate model (Mecking et al., 2016). A recent study finds AMOC tipping in a CMIP-type model in response to gradually increasing freshwater release in the North Atlantic (Van Westen et al., 2023). AMOC bistability is model-dependent though, controlled by the balance of the positive and negative feedbacks that determine the salinity of the subpolar North Atlantic. It is not yet understood why the bistability occurs in some models and not others (Jackson et al., 2023). However, as previously mentioned, there is evidence that the present generation of climate models is too stable due to model biases in the distribution of ocean salinity (Liu et al., 2017; Mecking et al., 2017).

Not only is it difficult to prove system bistability, the complexity of the system and interaction with multiple drivers make it hard to assess collapse thresholds. It may be that realistic freshwater input is not sufficient to cause the transition, or that changing CO² alters the underlying system stability, thus increasing the critical freshwater threshold (Wood et al., 2019). Nevertheless, overshoot scenarios, where the CO_2 trend is assumed to reverse at some point in the future, provide some useful information about reversibility of the AMOC on human timescales. Figure 1.4.4b shows how the AMOC changes in the UKESM climate model under an overshoot emission scenario exceeding and returning to 500 ppm. Even if CO² concentrations return to 500 ppm by 2100 the AMOC is still only 77 per cent of the strength it was in 2050 also at 500 ppm. Although the AMOC does not collapse in this model, it seems unlikely that it will recover its former strength on human timescales.

The timescale of AMOC tipping was estimated by Armstrong McKay et al., (2022) to be 15-300 years, however this range is very dependent on the strength of the freshwater forcing applied in experiments, which in many cases is unrealistically large as compared to projected melting of the Greenland Ice Sheet and increase in precipitation and river runoff. Moreover, the assessment is also potentially impacted by the models being unrealistically stable. With a realistic forcing scenario, the timescale will depend on the feedbacks. A basin-wide salt advection feedback may have a century timescale, while if it is preceded by a local North Atlantic salt advection feedback it may be reduced to a few decades. Even faster timescales are possible when deep mixing is capped off by sudden increases in sea ice cover in all convective regions (Rahmstorf et al., 2001; Kuhlbrodt et al., 2001).

AMOC collapse would lead to cooling over most of the Northern Hemisphere, particularly strong (up to 10°C relative to preindustrial) over Western and Northern Europe. In addition, a southward shift of the Intertropical Convergence Zone would occur, impacting monsoon systems globally and causing large changes in storminess and rainfall patterns (Jackson et al., 2015). A collapse of the AMOC would influence sea level rise along the boundaries of the North Atlantic, modify Arctic sea ice and permafrost distribution (Schwinger et al., 2022; Bulgin et al., 2023), reduce oceanic carbon uptake (Rhein et al., 2017) and potentially lead to ocean deoxygenation (Kwiatkowski et al., 2020) and severe disruption of marine ecosystems (including changes in the North Atlantic Subpolar Gyre, see below), impacting North Atlantic fish stocks. See Chapter 2.2 for more discussion on impacts.

Assessment and knowledge gaps

Although the AMOC does not always behave like a tipping system in many ocean/climate models, palaeoceanographic evidence strongly points to its capability for tipping or at least to shift to another state that can be quasi-stable for many centuries (Figure 1.4.5). Tipping is also suggested in a recent study of several CMIP6 models (Jackson et al., 2023) and in another study which found that removing model salinity biases strongly increased the likelihood of tipping (Liu et al., 2017). This does not necessarily mean that tipping is likely in a future climate, since some of these scenarios specified unrealistic inputs of freshwater or GHG emissions. Nonetheless, although the likelihood for collapse is considered small compared to the likelihood of AMOC decline, the potential impacts of AMOC tipping make it an important risk to consider in framing mitigation targets, for instance.

The latest AR6 assessment states that we have only medium confidence that an AMOC collapse will not happen before 2100 (Fox-Kemper et al., 2021). This uncertainty is due to models having strong ocean salinity biases, absence of meltwater release from the Greenland Ice Sheet in climate change scenarios, and the possible impact of eddies and other unresolved ocean processes on freshwater pathways. However, a recent study with the PAGES2K database of climate reconstructions of the past 2,000 years suggests, using statistical methods based on dynamical systems theory, that we may be close to an AMOC tipping point (Michel et al., 2022), as do the studies of Boers (2021) and Ditlevsen and Ditlevsen (2023) cited above. AR6 also concluded that reported recent weakening in both historical model simulations and observation-based reconstructions of the AMOC have low confidence. Direct AMOC observations have not been made for long enough to separate a long-term weakening from short-term variability. Another recent study suggests that we will need to wait until at least 2028 to obtain a robust statistical signal of AMOC weakening (Lobelle et al,. 2020). Thus, the coming years will be crucial for detection of an AMOC weakening potentially leading to longer-term instability.

There are substantial uncertainties around how the AMOC evolves over long timescales, because of a lack of direct observations. More palaeo-reconstructions of AMOC strength, ocean surface temperature, and other AMOC-related properties with high temporal resolution, using appropriate proxies and careful chronological control performed for key past periods (e.g. last millennium, millennial-scale climate change events, previous interglacials), hold great potential to improve our understanding about the AMOC as a tipping point. Other open issues are to: (i) reconcile disagreements between palaeo-reconstructions and model simulations, and (ii) develop improved metrics for creating historical reconstructions and monitoring the AMOC.

Current climate models suffer from imperfect representation of some important processes (such as eddies and mixing) and from biases which can impact the AMOC response to forcings. Hence we need to assess how important these issues are for representing AMOC stability, in particular, to understand how different feedbacks vary across models and are affected by modelling deficiencies. Given these issues, a robust assessment of the likelihood of an AMOC collapse is difficult, but based on the evidence presented, we assess that the AMOC features tipping dynamics with medium confidence. One potential way forward, given these uncertainties, is in developing observable precursors to a collapse that could be monitored.

North Atlantic Subpolar Gyre (SPG)

The North Atlantic Subpolar Gyre (SPG) is an oceanic cyclonic (counter-clockwise in the northern hemisphere) flow to the south of Greenland (Figure 1.4.6). It is linked to a site of deep ocean convection in the Labrador-Irminger Seas, i.e. sinking of the subsurface ocean waters to great depths, contributing to the AMOC (Figures 1.4.3, 1.4.6-7).

There are indications for change in the SPG, as observations show that Labrador Sea Water (LSW) formed during oceanic deep convection events after 2014 was less dense than the LSW formed between 1987 and 1994 (Yashayaev and Loder, 2016), potentially influencing the AMOC. Moreover, the observed 'warming hole' over the North Atlantic can be explained by AMOC slowdown (Drijfhout et al., 2012; Caesar et al., 2018; also see AMOC above) and has also been linked to SPG weakening in CMIP6 models (Sgubin et al., 2017; Swingedouw et al., 2021). In these models, a collapse of the oceanic convection causes a localised North Atlantic regional surface air temperature drop of ~2-3°C. This cooling moderates warming over north-west Europe and eastern Canada in global warming scenarios, although it is smaller and less widespread than that associated with AMOC collapse.

A northward-shift of the atmospheric jet stream, which is predicted to take place with SPG weakening, means more weather extremes in Europe (which may be linked to the unusual cooling and heat waves in recent years) (Osman et al., 2021) and southward shift of the intertropical convergence zone (ITCZ, see Figure 1.4.1) (Sgubin et al,. 2017; Swingedouw et al,. 2021). These changes in the physical system may trigger changes in ecosystems with detrimental consequences for the North Atlantic spring bloom and overall Atlantic marine primary productivity. Neither of these return to the preindustrial state even if emissions reverse by 2100 in models for clarity (Yool et al., 2015; Heinze et al., 2023). This would impose a strong impact on fisheries and biodiversity, with wide societal implications (see Section 2). Last but not least, a transition between two SPG stable states has been suggested to explain the onset of the so-called 'Little Ice Age' in which colder conditions prevailed in Europe during the 16th-19th centuries (Lehner et al., 2013; Michel et al., 2022).

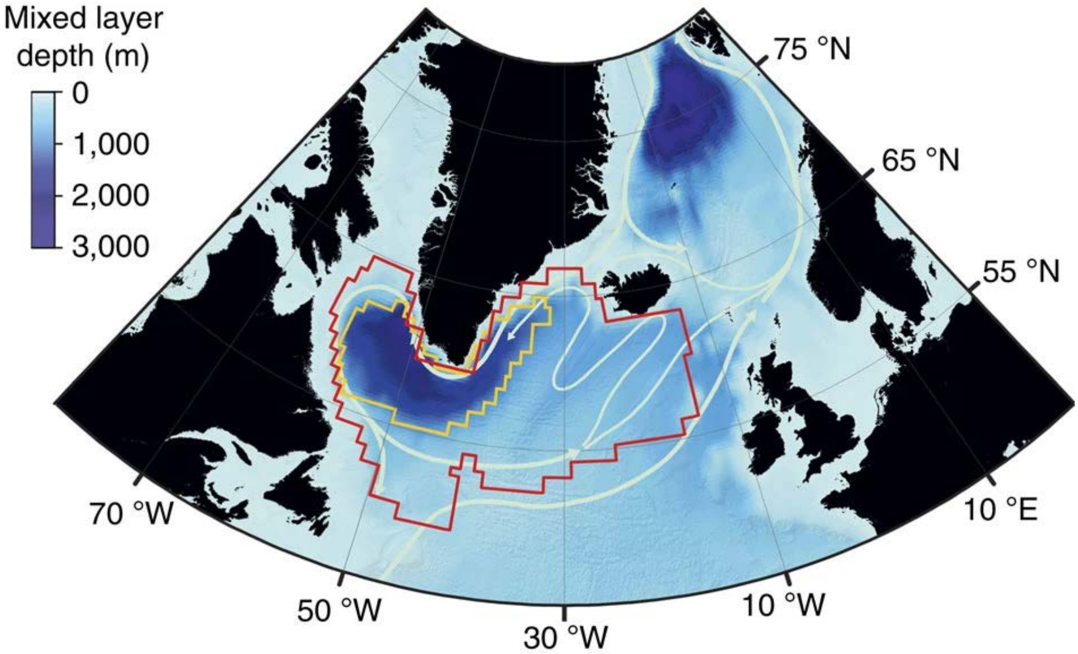

Figure 1.4.6: Map showing the maximum ocean mixing depth in the North Atlantic (light to dark blue), showing deep water convection sites driving the AMOC and SPG east and south of Greenland respectively (with the Labrador-Irminger Seas convection area bordered by yellow). The pale arrows show surface water currents, with the anti-clockwise subpolar gyre occurring within the red bordered area. Credit: Sgubin et al,. (2017).

Ventilation of LSW is accompanied by an uptake of oxygen. Starting in 2014, the convection in the Labrador Sea became more intense and reached depths of 1,500m and below. Consequently, oxygen in LSW is in general increased, but this increase did not penetrate the densest part of this water mass (Rhein et al., 2017). The oxygen concentrations in the deepest part of the LSW (around 2,000m) have decreased in the formation region and along the main export pathways (southward and eastward crossing the Mid-Atlantic Ridge) for more than 20 years. Most of the oxygen from the export of newly formed LSW has been consumed north of the equator (Koelling et al., 2022), and the long-term oxygen decline along the southward LSW pathway might have impacts on ecosystems in the tropics and subtropics over longer timescales (e.g., Heinze et al., 2023).

The potential shutting-down of winter convection in the Labrador Sea (see Figure 1.4.7a,b and Swingedouw et al., 2021) will also stop the production of Labrador Slope Water (LSLW). This water is next to the Labrador Sea continental slope and is lighter and less deep than LSW. It contributes to AMOC and the Gulf Stream and can influence variability of the Atlantic climate system overall (New et al., 2021). The LSLW is rich in nutrients and oxygen too, thereby affecting the ecosystems on the North American continental shelf and shelf slope (e.g. Claret et al., 2018) and might affect tropical and subtropical marine ecosystems on a timescale of several decades. Furthermore, the SPG takes up large amounts of atmospheric carbon and exports it to the deep ocean (Henson et al., 2022).

Shallowing of the SPG (Sgubin et al., 2017; Swingedouw et al., 2021) would directly increase regional CO_2 uptake but negatively impact marine biology, for instance threatening the habitat of cold-water corals in the area due to higher acidity with more CO_2 dissolved in the water (Fröb et al., 2019; Fontela et al., 2020; García-Ibáñez et al., 2021). Weakening or collapse of the SPG would reduce the amount of carbon-depleted intermediate water being upwelled and newly carbon-enriched water being convected, reducing export of anthropogenic CO^2 to the deep ocean (Halloran et al. 2015; Ridge & McKinley 2021), which in turn might lead to an increase of atmospheric CO^2 concentration in the long term (Schmittner et al. 2007). Declining SPG strength may also be reducing the currently high phytoplankton productivity in this area (Osman et al., 2019; Henson et al. 2022), reducing the amount of biologically fixed carbon to deeper water too.

Changes in the overall Atlantic ocean circulation (AMOC and SPG) can impact the spread of Atlantic water into the Arctic and affect marine ecosystems there. Summer sea ice decline reduces light limitation, rendering Arctic ecosystems more similar to the present North Atlantic (Yool et al., 2015). Increased seasonal phytoplankton blooms will deplete nutrients in the ocean, but increased inputs from rivers and coastal erosion can alleviate this, with Arctic primary production (i.e. the turnover photosynthesising plankton biomass) projected to increase by about 30-50 per cent in this century. Invasive species can also extend further into the Arctic habitat due to warming and current changes, e.g. in the Barents Sea and from the Pacific (Kelly et al., 2020; Neukermans et al., 2018; Oziel et al., 2020; Terhaar et al., 2021) (see also Chapter 1.3).

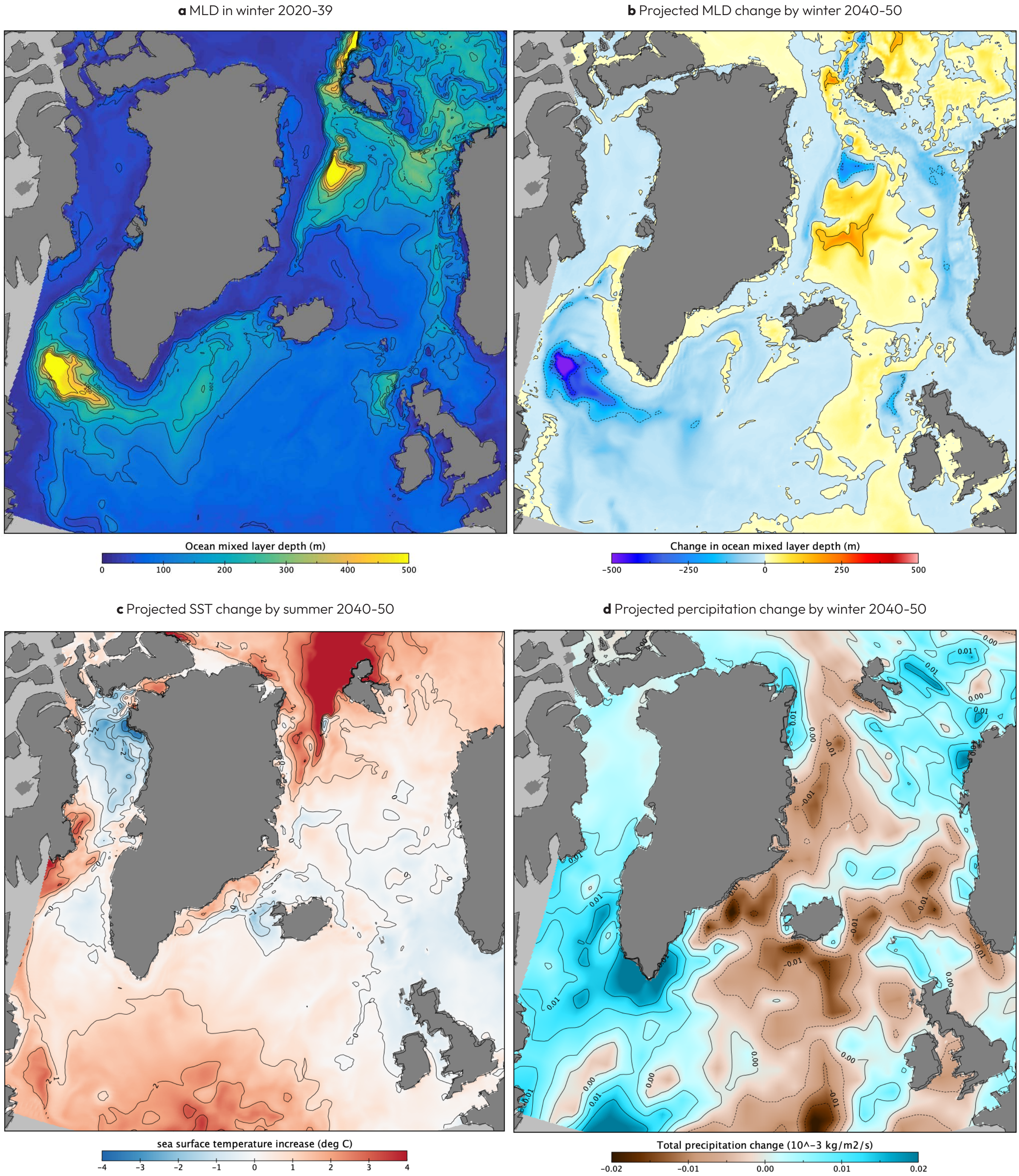

Figure 1.4.7: a Winter ocean mixed layer depth (MLD) as indicator of ocean convection in winter 2020-30 (January-March). **b** Changes in projected MLD by winter 2040-50. **c** Change in summer sea surface temperature (SST) and **d** winter total atmospheric precipitation, respectively, projected by winter 2040-50. NEMO-MEDUSA 1/4 degree high resolution model results using ssp370 CMIP6 scenario 2015-2099. High-resolution simulations are courtesy of Drs Andrew Coward, Andrew Yool, Katya Popova and Stephen Kelly, National Oceanography Centre, UK. Also see Swingedouw et al., (2021) for the IPCC CMIP6 model results.

In the North Atlantic, the AMOC can be defined as north-going warm 'limb' and saline upper waters and south-going, colder, denser deep water 'limb' (Frajka-Williams et al., 2019). In contrast, in the Subpolar North Atlantic and the SPG, the AMOC features a third 'limb' of a cold, fresh western boundary current with the origin in the Arctic Ocean and Nordic Seas (Bacon et al., 2023). This is likely linked with the deep convection and winter oceanic mixing in the Labrador, Irminger and Iceland seas, injecting waters into the deep, southward-flowing limb of the AMOC (Bower et al,. 2019). Changes in SPG circulation are associated with the shallowing of the oceanic mixed layer and convection (Figure 1.4.7a,b) in the SPG and link the predicted future weakening of the North Atlantic subtropical gyre and a strengthening of the Nordic Seas gyre, pointing to the influences of the upstream changes in the Arctic on the North Atlantic (Swingedouw et al., 2021).

Evidence for tipping dynamics

Potential convection instability in the Labrador and Irminger Seas and the wider SPG is believed to be linked to lightening of the upper ocean waters due to reduced salinity (e,g., due to increased precipitation, Figure 1.4.7d), thus increasing 'stratification' – i.e. reduced mixing between layers of the water column. Warming (Figure 1.4.7c) also plays a role and could contribute to convection collapse (Armstrong McKay et al., 2022). Freshening and warming make surface waters more buoyant and thus harder to sink, which, beyond a threshold, can abruptly propel a self-sustained convection collapse (Drijfhout et al,. 2015; Sgubin et al., 2017). This process can result in two alternative stable SPG states (Levermann and Born, 2007), with or without deep convection (Armstrong McKay et al., 2022). Similar to the AMOC, SPG stability is also strongly linked to the salt-advection feedback. When the SPG is 'on', it brings dense salty waters from the North Atlantic drift into the Irminger and Labrador Seas, allowing deep sinking and convection to occur (Born & Stocker, 2014; Born et al., 2016). When convection decreases due to stratification, the SPG weakens, less salty North Atlantic water flows eastwards, and the convection is further weakened, which eventually leads to convection collapse in some models. SPG collapse leads to cooling across the SPG region, and so will impact marine biology and bordering regions.

A freshwater anomaly is currently building up in the Beaufort gyre – a pile-up of fresh water at the surface of the Beaufort Sea in the Arctic – due to increased input from rivers, sea ice and snow melting as well as the prevailing clockwise (anticyclonic in the northern hemisphere) winds over the sea (Haine, et al., 2015; Regan et al., 2019; Kelly et al., 2020).

There is a considerable risk that this freshwater excess might flush into the SPG, disrupting the AMOC (Zhang et al,. 2021). The most recent changes in Beaufort gyre size and circulation (Lin et al,. 2023) suggest flushing might occur very soon or has already started. The SPG system has recently experienced its largest freshening for the last 120 years in its eastern side due to changes in the atmospheric circulation (Holliday et al,. 2020). In contrast, so far there is only limited evidence of Arctic freshwater fluxes impacting freshwater accumulation in the Labrador Sea (Florindo-Lopez et al., 2020). An increased freshwater input into SPG water mass formation regions from melting of Greenland's glaciers can also inhibit deep water formation and reduce the SPG and AMOC (Dukhovskoy et al., 2021).

Although SPG changes are apparently linked to the AMOC the SPG collapse can occur much faster than AMOC collapse, on the timescale of only a few decades (Armstrong McKay et al., 2022). Armstrong McKay et al. (2022) estimated global warming threshold of ~1.8°C (1.1 to 3.8°C) for the SPG collapse (high confidence) based on climate models from CMIP5 and CMIP6. Abrupt future SPG collapse is diverse in the CMIP6 models, occurring as early as the 2040s (~1 to 2°C) but in only a subset of models. However, as these models better represent some key processes, the chance of SPG collapse is estimated at 36-44 per cent (Sgubin et al., 2017; Swingedouw et al., 2021).

Assessment and knowledge gaps

Similar to Armstrong McKay et al,. (2022), the SPG is classified as a tipping system with medium confidence. A global warming threshold for tipping that could be passed within the next few decades, and an estimated tipping timescale of years to a few decades, raise reasons for concern. Furthermore, cessation of deep water production from other sources in the Labrador and Nordic Seas and the Arctic could also present other potential tipping points in the future North Atlantic (Sgubin et al., 2017).

1.4.2.2 Southern Ocean circulation

Two main tipping points in the Southern Ocean have been discussed in the past, which both could have large and global climate consequences. The first is the slowdown and collapse of the Antarctic Overturning Circulation; the second is the abrupt change in ocean circulation on the Antarctic continental shelf, leading to suddenly rising ocean temperature in contact with the Antarctic ice shelves fringing the ice sheet.

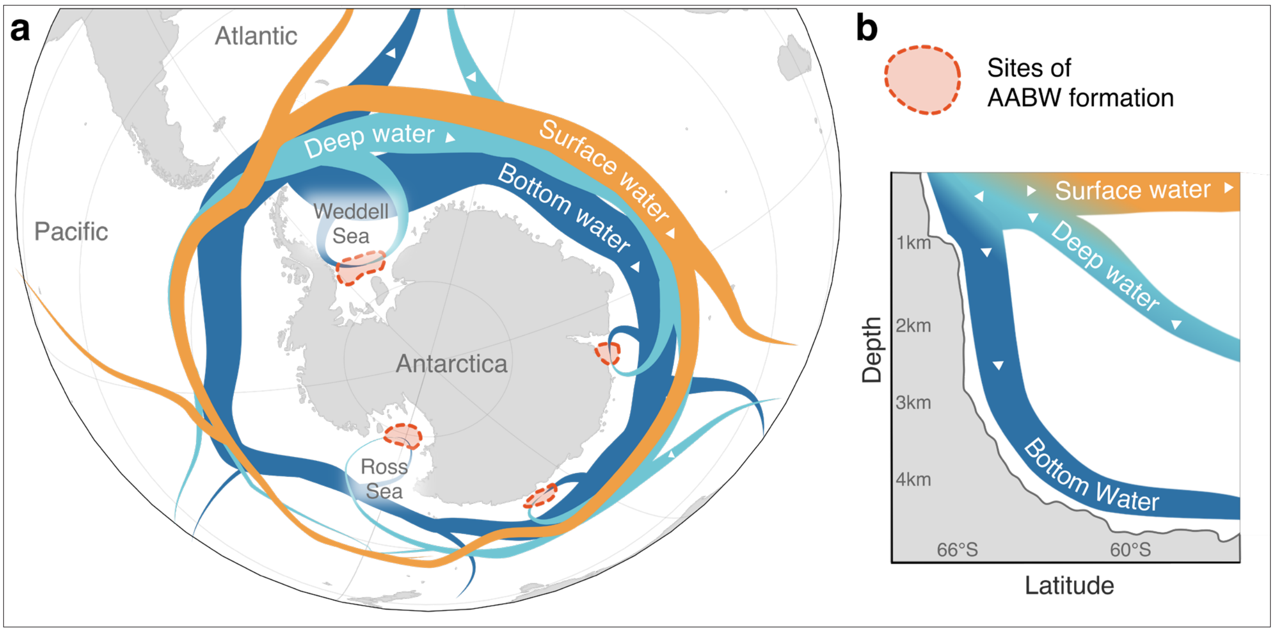

Figure 1.4.8: Circulations and potential tipping systems in the Southern Ocean. Adapted from Li, et al (2023) and IPCC SROCC Fig CB7.1

Along with the AMOC, the Antarctic overturing circulation constitutes the second branch of the global ocean overturning circulation linking the surface to the deep ocean (Figures 1.4.1 and 1.4.8), forming Antarctic bottom water (AABW) through sinking of the shelf waters around the Antarctic continent. A key mechanism is brine rejection from sea-ice formation: very salty water that is left behind when ocean water freezes, which causes the ambient liquid water to become heavier and sink. This is maintained by offshore winds blowing away from the Antarctic continent, pushing sea ice away from the coast and forming areas of open water (so-called polynyas) supporting brine rejection. The formation of AABW sustains the operation of the lower branch of the Antarctic overturning circulation (Figure 1.4.8 and Abernathey et al., 2016).

In contrast to our understanding of the AMOC, any changes related to the future of the Antarctic Overturning Circulation have remained at low or medium confidence due to a persistent lack of process understanding (Fox-Kemper et al., 2021; Heuzé et al., 2021; Purich and England 2023). However, evidence of its ongoing decline has escalated in recent years, both from observations (Gunn et al., 2023; Zhou et al., 2023; including record low sea ice extent in 2022-2023) and numerical models (Lago and England, 2019; Liu et al., 2022; Li et al, 2023), linked to the changes in melt water, wind trends, sea ice transport and water mass formation (Holland et al., 2012). (For the analysis of potential tipping in Antarctic sea ice, please see Chapter 1.2.)

Change or collapse in the Antarctic Overturning Circulation has the potential for widespread climate and ecosystem implications within this century. The Southern Ocean surface temperature is set by a delicate balance between ocean overturning strength, upper ocean stratification (the degree of mixing between ocean layers), and sea ice cover. The Antarctic Overturning circulation affects cloud feedbacks and has been shown to be a key regulator of Earth's global energy balance, so much so that it is the main control on the timing at which the 2°C global warming threshold will be reached for a given emission scenario (Bronsealer et al., 2018; Dong et al., 2022; Shin et al., 2023).

Reduced Antarctic overturning can also shift global precipitation patterns, resulting in drying of the Southern Hemisphere and wetting of the Northern Hemisphere (Bronsealer et al., 2018). Reduced Antarctic overturning also reduces the efficiency of the global ocean carbon sink, leaving more nutrient-rich water at the seafloor (Liu et al., 2022), and also affects global ocean heat storage (Li et al., 2023). Amplifying feedbacks to further shelf water warming and ice melt are also possible (Bronsealer et al., 2018; Purich and England, 2023; Li et al., 2023).

Evidence for tipping dynamics

Different generation climate models consistently project a slowing or collapse of the Antarctic overturning under a warming climate (Heuzé et al., 2015, 2021; Lago and England, 2019; Meredith et al., 2019; Fox-Kemper et al., 2021; Liu et al., 2022). However, our confidence in these models to assess change in Antarctic overturning is limited due to known limitations in the representation of dense water formation (Purich and England 2023). Limitations come also from the lack of representation of increased Antarctic ice sheet meltwater in most models (Fox-Kemper et al., 2021). Armstrong McKay et al., (2022) identified the Antarctic Overturning Circulation as a potential but uncertain tipping system in the climate system, but gaps in process understanding meant a threshold remained uncertain. They estimated it to be prone to collapse at a global warming level of 1.75-3°C based on Lago and England, (2019).

Specifically designed model experiments aiming to bridge some of these limitations, in combination with evidence from observed changes (Gunn et al., 2023; Purkey and Johnson, 2013), confirm that we are currently heading toward a decline and possible collapse of the Antarctic Overturning Circulation (Li et al., 2023, Zhou et al., 2023). The rapidity of this decline might even be underestimated, according to recent observations (Gunn et al., 2023). The sensitivity of the overturning to increases in upper ocean stratification is also consistent with palaeo evidence. Observations from marine sediments suggest that AABW formation was vulnerable to freshwater fluxes during past interglacials (Hayes et al., 2014; Huang et al., 2020; Turney et al., 2020) and that AABW formation was strongly reduced (Skinner et al., 2010; Gottschalk et al., 2016; Jaccard et al., 2016) or possibly totally curtailed (Huang et al., 2020) during the Last Glacial Maximum and earlier transient cold intervals.

Local water mass characteristics and associated circulation regimes on the Antarctic continental shelf are setting the rate of ice shelf melt rates in ice 'cavities', the regions of ocean water covered by floating ice shelves. Relatively warm water reaching the continental shelf in west Antarctica causes high basal melt rates with severe consequences for the ice shelf, ice sheet dynamics, and sea level rise (Naughten et al., 2023). In contrast, the largest ice shelf cavities in the Weddell and Ross Seas are not exposed to this relatively warm water, and consequently have melt rates orders of magnitude smaller than in West Antarctica. Despite this, the Weddell and Ross Sea ice shelf cavities have been shown to exhibit tipping behaviour (Hellmer et al., 2012; 2017; Siahaan et al., 2022). Models show that they are prone to sudden warming of their cavity under future climate change, dramatically increasing basal melting with important consequences for global sea level rise (Hellmer et al., 2012; 2017; Siahaan et al., 2022). Once tipped into a warm state, such cavities could be irreversibly maintained in such a state, even when forcing is reduced (Hellmer et al., 2017). However, it remains unclear what threshold would need to be crossed to tip those cavities from a cold to warm state, and it may only occur under extreme climate change scenarios.

Assessment and knowledge gaps

In summary, the combination of process-based understanding and observational, modelling and palaeoclimate evidence suggests that Antarctic Overturning Circulation will continue to decline in the 21st Century. There is increasing evidence for positive amplifying feedback loops that can lead to the collapse of the overturning, with widespread global climate and ecosystem consequences. Closely linked to this is a potential tipping in continental shelf water temperature, driven by amplifying meltwater feedbacks once a regional temperature threshold is crossed. We therefore classify the Southern Ocean Circulation as a tipping system with medium confidence. However, its potential tipping thresholds remain uncertain.

1.4.2.3 Monsoons

Monsoon circulations are large-scale seasonal changes in the direction and strength of prevailing winds driven by insolation (incoming solar radiation) and local temperature differences between land and ocean. Their dynamics are strongly influenced by the seasonal migration of the Intertropical Convergence Zone (ITCZ), the regional band in the tropics where the trade winds from the northern and southern hemisphere converge and rise as part of the tropical atmospheric overturning circulation (see Figure 1.4.1). The term 'monsoon' was historically associated with summer precipitation over South Asia; however, monsoon systems affect other parts of the globe such as East Asia, Africa, Australia and the Americas.

Historically, monsoons were seen as large-scale sea breeze circulations driven by land-sea heating differences due to seasonal changes in incoming solar radiation. Currently, a perspective of a global monsoon has emerged (Trenberth et al., 2000; Wang & Ding, 2008), where the monsoon systems are seen as interconnected and driven by localised seasonal and more extreme migrations of the ITCZ (Gadgil, 2018; Geen et al., 2020, and references within). Monsoon regions in the world experience heavy precipitation in the summer months, and the global monsoon system is an integral part of the global hydrological cycle, contributing ~31 per cent of total precipitation over the globe (Wang and Ding, 2008).

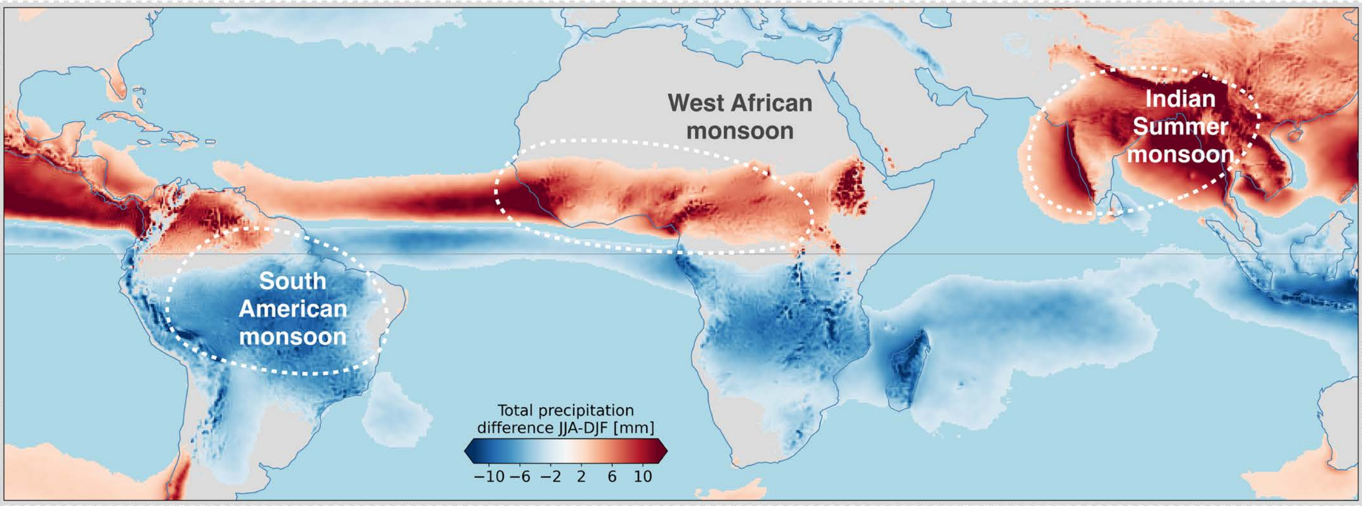

Figure 1.4.9: Monsoon systems. Shown is the total precipitation difference between Northern hemisphere summer (June-August, JJA) and winter months (December-February, DJF), highlighting the dominant precipitation patterns over South America (SAM), West Africa (WAM) and India (ISM). Generated using Copernicus Climate Change Service information (Hersbach et al., 2023), with monthly averages over 1980-2010.

There is a recent intensification trend in global monsoon precipitation, mainly due to enhanced northern hemisphere summer monsoon (Wang et al., 2012). It will likely continue in the future (high confidence, IPCC 2021, by ~1-3% per °C warming) because of increased water vapour related to warming driven by increased CO_2 in the atmosphere (Hsu et al., 2013; Lee and Wang, 2014; Chen et al., 2020; Ha et al., 2020; Wang et al., 2019); although a few studies conversely show that climate warming may lead to a weakened global monsoon circulation (Hsu et al., 2012, 2013). Climate simulations also project expansion of global monsoon domain areas with increasing CO_2 (Wang et al., 2020; Paik et al., 2023) and increased frequency of monsoon precipitation extremes in the 21st Century (Chevuturi et al., 2018; Ali et al., 2020; Ha et al., 2020; Katzenberger et al., 2021).

Monsoon precipitation is vital for agrarian populations and livelihoods in vast areas of South Asia, Africa and South America, and changes to it could expose almost two thirds of the global population to disastrous effects (Wang et al,. 2021). Hence it is crucial to understand the dynamics and potential nonlinear changes or tipping behaviour of monsoon systems under a changing climate. Here the 'tipping' of monsoon systems refers to a significant, feedback-driven shift in the precipitation state of the monsoon, with implications for the regional and global climate and ecosystems. In this discussion we assess if the major regional monsoon systems (West African, Indian and South American) show any evidence of nonlinear (tipping or abrupt) responses to climate forcings based on available literature.

Indian summer monsoon (ISM)

During the summer season over South Asia (June-September), winds from the south west carry large amounts of water vapour from the Indian Ocean to the Indian subcontinent and cause heavy precipitation in the region, providing ~80 per cent of the total annual precipitation (Figure 1.4.9). ISM precipitation shows considerable intra-seasonal, interannual and decadal variability, many times with precipitation extremes (leading to droughts, floods) during the season, and years and decades with above and below (in drought years) normal precipitation. Indian monsoon variability is strongly influenced by ocean-atmosphere interactions such as El Niño Southern Oscillation (ENSO, see Chapter 1.4.2.5), Indian Ocean Dipole events (irregular changes in the temperature gradients in the Indian Ocean, Cherchi et al., 2021; Chaudhary et al., 2021; Hrudya et al., 2021), and cooler temperatures in the North Atlantic (Borah et al., 2020).

ISM precipitation declined in the second half of the 20th Century, attributed mainly to human-driven aerosol loading (Bollasina et al., 2011) and strong Indian Ocean warming (Roxy et al., 2015). Recent studies (Jin and Wang, 2017) suggest it has revived since 2002, linked to enhanced warming over the Indian subcontinent due to reduced low clouds, resulting in an increased land-ocean thermal gradient. Future projections suggest increases in the ISM precipitation in future warming scenarios (by 5.3% per celsius of global warming, according to CMIP6 models, Katzenberger et al., 2021) and a longer monsoon duration (Ha et al., 2020).

Evidence for tipping dynamics

Many periods of abrupt ISM transitions have been identified in past monsoon records in association with high-latitude climate events (Schulz et al., 1998; Morrill et al., 2003) such as during Heinrich events (glacial outbursts that temporarily shut down the AMOC – see 1.4.2.1) (McManus et al., 2004; Stager et al., 2011), the Younger Dryas (a temporary return to more intense glacial conditions 12,900-11,700 years ago; (Cai et al., 2008; Carlson 2013), and several periods during the more recent Holocene (Gupta et al., 2003; Berkelhammer et al., 2012; Yan and Liu, 2019). However, the mechanisms of such abrupt transitions are not clearly understood. Efforts have been made to identify any Indian monsoon tipping mechanisms using simplified models (Zickfeld et. al., 2005; Levermann et al., 2009).

An internal feedback mechanism, a 'positive moisture advection feedback' (Zickfeld et. al., 2005; Levermann et al., 2009; Schewe et al., 2012), has been suggested as responsible for abrupt transitions simulated using these analytical models. In this feedback, the atmospheric temperature gradient between the land and cooler ocean in summer leads to the onshore transport of moist air (advection), which then rises, forms clouds and condenses into rain. The phase transition from vapour to liquid warms the surrounding air (through the release of latent heat, or 'diabatic heating'), increasing the land-ocean temperature gradient and sustaining this monsoon circulation. Any forcing that weakens this pressure gradient can therefore lead to monsoon destabilisation (Zickfeld et al., 2005). If monsoon winds weaken, advection and condensation reduce, and the threshold for a monsoon tipping is reached when the diabatic heating fails to balance the heat advection away from the region (Levermann et al., 2009).

Contrarily, follow-up studies (Boos and Storelvmo, 2016) challenge occurence of any tipping in these simplified models, and rule out any abrupt monsoon responses to human-driven forcings in the future, and instead attribute past monsoon shifts to rapid forcings or vegetation feedbacks. Simplified models omit key aspects and feedbacks in the monsoon system (specifically, static stability of the troposphere in the models that simulated the monsoon tipping, (Boos and Storelvmo, 2016; Kumar and Seshadri, 2022). Hence, more studies using models that represent the complexities of the monsoon and palaeoclimate data are required for a clearer picture on any non-linear changes in the monsoon system.

Apart from climate change, aerosols pose another significant human-driven pressure on the Earth system. Aerosols influence the Earth's radiative budget, climate and hydrological cycle by reflecting or absorbing solar radiation, changing the optical properties of clouds, and also by acting as cloud condensation nuclei. An increase in anthropogenic aerosols has been attributed as the major reason for the decline of Northern Hemispheric summer monsoon strength from the 1950s to 1980s (Cao et al., 2022), due to its dimming effect.

A large increase in regional aerosol loading over South and East Asia (>0.25 Aerosol Optical Depth, AOD, Steffen et al., 2015) could potentially switch the Asian regional monsoon systems to a drier state. Further, hemispheric asymmetries in the aerosol loading (>0.15 AOD, Rockström et al., 2023), due to volcanic eruptions, human sources or intentional geoengineering, could lead to hemispheric temperature asymmetries and changes in the location of the ITCZ, significantly disrupting regional monsoons over West Africa and South Asia (Haywood et al., 2013; Rockström et al., 2023; Richardson et al., 2023). However, there is no direct evidence of aerosols causing a tipping of the monsoon systems, and uncertainties in threshold estimates are large due to complex aerosol microphysics and aerosol-cloud interactions. Hence, systematic observational and modelling approaches would be needed to reduce the uncertainties, as well as additional assessments of interhemispheric asymmetries in the aerosol distribution.

Assessment and knowledge gaps

The ISM system was earlier classified as one of the Earth's tipping systems (Lenton et al., 2008), based on the threshold behaviour of the monsoon in the past and the moisture-advection feedback (Levermann et al., 2009), but this was refuted by later studies (Boos and Storelvmo, 2016; Seshadri, 2017). Most recently, Armstrong McKay et al,. (2022) categorise ISM as an "uncertain potential [climate] tipping element" as global warming is not likely to cause tipping behaviour directly in ISM precipitation.

Based on this current literature, the chances for ISM exhibiting a tipping behaviour towards a new low-precipitation state under climate change are uncertain, warranting extensive studies on the subject. However, potential tipping behaviour in the AMOC (see Chapter 1.4.2.1, 1.5.2.5, and relation to global monsoon described in West African monsoon below) or increase in the interhemispheric asymmetry of aerosol loading in the atmosphere beyond potential threshold levels could lead to large disruptions to monsoon systems. This could cause calamitous effects on millions of people in the monsoon regions, even in the absence of tipping.

West African monsoon (WAM)

The West African monsoon (WAM) controls hydroclimatic conditions, vegetation and mineral-dust emissions of northern tropical and subtropical Africa, up to the dry Sahel region at the southern edge of the Sahara Desert (**Figure 1.4.9**). The strength of the monsoon shows large variations over a range of timescales from interannual to decadal and longer. Albedo (reflectivity of the Earth's surface) changes caused by human-driven land-cover changes and desertification (Charney et al., 1975; Charney, 1975; Otterman, 1974) can affect rainfall: a less vegetated surface with higher albedo increases radiative loss, thereby reducing temperature and suppressing the rising and condensation of moist air into rainfall (i.e. convective precipitation). Variations of sea surface temperatures (SSTs) in different oceanic basins can also drive interannual and decadal variability in WAM precipitation (Rodríguez-Fonseca et al., 2015). Other major factors that affect WAM variability are land surface variability such as variations in soil moisture (Giannini et al., 2013; Zeng et al., 1999), vegetation (Charney et al., 1975; Kucharski et al., 2013; Otterman, 1974; Wang et al., 2004; Xue, 1997), high-latitude cooling (Collins et al., 2017) and dust emissions (Konare et al., 2008; Solmon et al., 2008; Zhao et al., 2011).

Evidence for tipping dynamics

Palaeoclimate records underscore dramatic variations of the WAM in the more distant past, such as the periodic expansion of vegetation into the Sahara Desert during the so-called 'African humid periods' (AHPs) and linked to the emergence of ancient cultures along the Nile. Another example is the drought 200-300 years ago, which caused the water level of Lake Bosumtwi in Ghana to fall by almost four times as much as it did during the drought of the 1970s and 1980s. Large past variations of the WAM, such as those during the AHPs, raise the question of whether present-day anthropogenic global warming could have potentially significant impacts on the WAM. Although the nature and magnitude of radiative forcing were different during the AHPs than they are now (i.e. an external change in insolation due to orbital forcing versus an internal change from increased greenhouse gases), the fact that the AHPs occurred under a globally warmer climate than the pre-industrial period invites questions.

Some palaeoclimate archives show WAM precipitation changes that took place over several centuries (deMenocal et al., 2000; McGee et al., 2013), i.e. an order of magnitude faster than the orbital forcing. However, others show a much more gradual change (e.g. Kröpelin et al., 2008) with a time-varying withdrawal of the WAM from North to South following the insolation changes (Shanahan et al., 2015). Because of geographic variability of the African landscape and African monsoon circulation, abrupt changes can occur in several, but not all, regions at different times during the transition from the humid to arid climate (Dallmeyer et al., 2021).

By inducing latitudinal movements of the ITCZ, change in the AMOC is considered to play a role in shifts of global monsoon systems. Palaeoclimate evidence suggests that glacial meltwater-induced weakening of the AMOC during Heinrich events in the last glacial period led to abrupt Asian and African monsoon weakening (Mohtadi et al., 2014; Mohtadi et al., 2016). Similarly, the Younger Dryas led to a cool and dry state over Northern Hemisphere tropical monsoon regions. North Atlantic fresh water-hosing simulations using climate models (Lewis et al., 2010; Pausata et al., 2011; Kageyama et al., 2013) confirm these shifts in ITCZ can occur as a result of substantial glacial meltwater release. These influences of AMOC on the monsoon systems have also been studied in the context of the South American monsoon (see below). Hence, a collapse of AMOC (see Chapter 1.4.2.1) has the potential to cause disruptions to the regional monsoon systems and other tropical precipitation systems over Asia, Africa and South America (Gupta et al., 2003; IPCC 2021).

Assessment and knowledge gaps

Abrupt changes in one region can be induced by abrupt changes in others, a process sometimes referred to as 'induced tipping'. The AHP transition of the Sahara was slow with respect to timescales of individual humans and local ecosystems, but regionally rapid with respect to changes in the driver. Based on the record of large past variations of WAM precipitation patterns (including collapse), and the existence of positive amplifying feedbacks, we classify WAM as a tipping system with low confidence. This is in line with previous assessments (Armstrong McKay et al., 2022), in which a lower tipping threshold of 2°C global warming was estimated but attributed low confidence due to limited model resolution of vegetation shifts, and model disagreements in future trends. The timescale of abrupt shifts is estimated to range from decades as observed in CMIP5 models (Drijfhout et al., 2015) to centuries based on palaeorecords (Hopcroft and Valdes, 2021; Shanahan et al.; 2015). Potential additional destabilisation through AMOC weakening and atmospheric aerosol loading, and the far-reaching implications of WAM tipping, call for intensified research efforts on this system.

South American monsoon (SAM)

The South American monsoon (SAM) system is characterised by strong seasonality in precipitation, even though it does not show a reversal of low-level winds like in the Asian monsoon (Zhou and Lau, 1998; Vera et al., 2006; Liebmann and Mechoso, 2011; Carvalho et al., 2012). Studies are relatively few compared to the Asian and African monsoon systems, as it was not classified as a monsoon system until a couple of decades ago (Zhou and Lau, 1998).

A mature SAM system (from December to February) shows features such as enhanced northeastern trade winds, increased land-ocean thermal gradient and the development of an active convective zone (the South Atlantic Convergence Zone) (Figure 1.4.9; Zhou and Lau, 1998). The SAM system affects vast areas of tropical South America all the way to southern Brazil, and provides more than 50 per cent of the annual precipitation to these regions (Vera et al., 2006) including most of the Amazon rainforest. SAM precipitation varies from interannual to orbital timescales (Chiessi et al., 2009; Liebmann and Mechoso, 2011; Carvalho and Cavalcanti, 2016; Hou et al., 2020).

The influence of anthropogenic climate change on the SAM precipitation is ambiguous (Douville et al., 2021), and many CMIP5/CMIP6 models are noted for their poor representation of SAM precipitation (Jones and Carvalho, 2013; Douville et al., 2021). IPCC AR6 finds high confidence in delayed onset of the SAM precipitation since the 1970s associated with climate change, which could worsen with increased CO_2 levels (Douville et al., 2021). However, the projected future change in total SAM precipitation is uncertain, as the models show low agreement on the projections (Douville et al., 2021).

Evidence for tipping dynamics

Orbital timescale changes (i.e. over tens of thousands of years) in SAM precipitation seem to be largely controlled by changes in insolation and respond linearly to it (Cruz et al., 2005; Hou et al., 2020). Millennial-scale changes (i.e. over thousands of years) in the SAM are thought to be associated with variations in strength of the AMOC, as described for the West African monsoon above. In particular, palaeo evidence indicates that an increase in South American precipitation to the south of the equator followed weakening of the AMOC related to Heinrich events (Mulitza et al., 2017; Campos et al., 2019). Similarly, meltwater flux from the Laurentide Ice Sheet during the Younger Dryas may have led to a warm and wet state over tropical South America to the south of the equator (McManus et al., 2004; Broecker et al., 2010; Venancio et al., 2020; Brovkin et al., 2021). Earth system model projections of AMOC collapse impacts on the tropical rainfall in South America are model-dependent, but generally find a reduction in rainfall over northern South America and an increase over the southern Amazon (Bellomo et al., 2023; Nian et al., 2023; Orihuela-Pinto et al., 2022; Liu et al., 2020: see 1.5.2.4).

Further, deforestation over 30-50 per cent of the Amazon rainforest led to a tipping point in the SAM system in one model (Boers et al., 2017), causing precipitation reductions of up to 40 per cent in non-forested parts of the western Amazon. This reduction is caused by the breakdown of a positive amplifying feedback mechanism that involves latent heat of condensation over the Amazon rainforest due to transpiration (i.e. water lost from plants) and water vapour transport from the Atlantic. Reduced transpiration due to deforestation can no longer sufficiently provide water vapour to sustain the latent heat required, thereby reducing the inflow of oceanic water vapour, and leading to a monsoon tipping in this model (Boers et al., 2017). (see 1.3.2.1 for more on Amazon dieback)

Assessment and knowledge gaps

A combination of climate change and deforestation could lead to substantial changes in the SAM system, affecting many millions of people. Additionally, a decrease in AMOC strength could potentially trigger major changes in tropical South American precipitation (see 1.5.2.4). However, the current scarcity of research in the subject limits our ability to fully understand and assess the tipping potential of the system, and we classify the possibility of SAM tipping to be uncertain.

1.4.2.4 Tropical clouds, circulation and climate sensitivity

Clouds play an important role in the climate system, as they contribute to the regulation of Earth's energy budget linked to the amount of solar radiation trapped or reflected back to space (Figure 1.4.10). In general, high, thin clouds at several kilometres altitude have a two-fold warming effect on the climate: They have a high transmissivity for shortwave radiation (incoming sunlight) and low emissivity for longwave radiation (heat), meaning they allow most of the sunlight to reach the surface but block some of the heat escaping to space. In contrast, low, thick clouds reflect more sunlight, and also have a high emissivity for long-wave radiation, allowing more heat to escape, and so have a cooling effect. A changing climate, which causes changes in temperature, humidity and circulation patterns, affects the formation and dynamics of these clouds. This, in turn, can influence the climate and how much warming results from increased atmospheric CO_2 concentrations (i.e. 'climate sensitivity').

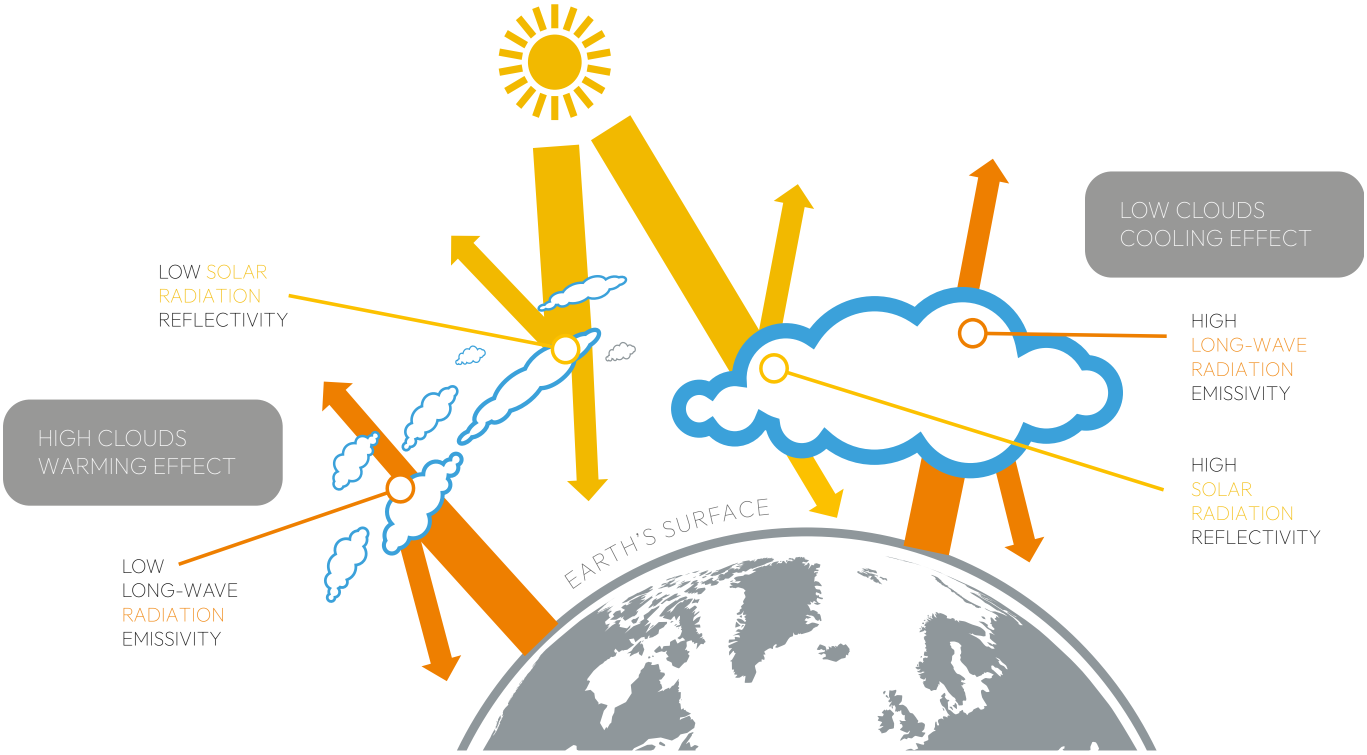

Figure 1.4.10: The role of clouds in regulating Earth's radiation budget.

Evidence for tipping dynamics

Literature on cloud-induced tipping points is very limited. Yet cloud-forming processes exhibit strong hysteresis on weather timescales. Indeed, a cloud droplet forms when water starts to stick to a particle after a certain level of humidity (in which a so-called hygroscopic aerosol particle crosses a humidity tipping point into an unstable condensational growth phase); and precipitation, once initiated, is a self-reinforcing cascade where larger particles fall faster and hence grow faster by collisions. Coupling of these micro-scale processes to atmospheric dynamics can lead to spontaneous and irreversible transitions at the intermediate mesoscale – in particular, the transition of shallow cloud layers from closed to open-cell geometries (honeycomb-like cloud patterns formed by convecting air) (Feingold et al., 2015) and self-aggregation of deep convection (Muller et al., 2022). Both of these significantly decrease cloud cover and albedo, potentially enabling climate interactions. Could further coupling out to planetary scales produce climate-relevant tipping behaviour? Complicating this question is the fact that cloud-related processes are not well represented in current climate models, limiting their ability to guide us.

The most-discussed possibility has been the extreme case of a global climate runaway. If the atmosphere became sufficiently opaque to infrared (i.e. if it became harder for longwave heat energy to escape due to overcast high cloud, very high humidity, or CFC-like greenhouse gases filling in spectral absorption windows), the planet could effectively lose its ability to cool to space, producing a Venus-like runaway. Although general circulation models (GCMs) and palaeoclimate evidence suggest climate sensitivity rises as climate warms (Sherwood et al., 2020), calculations show virtually no chance of runaway warming on Earth at current insolation levels (Leconte et al., 2013).

A more plausible scenario is unexpectedly strong global positive amplifying radiative feedback from clouds and high climate sensitivity. Although presumably reversible, this would be serious. With respect to high clouds, suggested missing feedbacks (due to novel microphysical or aggregation mechanisms) have generally been negative (e.g. Mauritsen and Stevens, 2015).

Low clouds are a greater concern: one recent study using a multiscale atmospheric model found a strong and growing positive amplifying feedback from rapid disappearance of these clouds (Schneider et al., 2019), highlighting the possibility of nonlinear cloud behaviour and surprises (Bloch-Johnson et al., 2015; Caballero and Huber, 2013). Although various observations generally weigh against high-end climate sensitivities above 4°C per CO_2 doubling, they cannot rule them out (Sherwood et al., 2020).

A final possibility is surprising reorganisations of tropospheric circulation (i.e. in the lowest layer of the atmosphere). Innovative atmospheric models (Caballero and Carlson, 2018; Seeley and Wordsworth 2021) and geologic evidence (Tziperman and Farrell, 2009; Caballero and Huber 2010) have suggested possible 'super-MJO' (the 'Madden-Julian Oscillation' being the dominant mode of 'intraseasonal' variability in the tropical Indo-Pacific, characterised by the eastward spread of enhanced or suppressed tropical rainfall lasting less than a season) and/or reorganisation of the tropical atmospheric circulation in a warmer climate due to cloud-circulation coupling. These scenarios are supported by little evidence, but if they did occur they could massively alter hydrology in many regions. Poor representation of tropical low clouds has also likely inhibited coupled model simulations of decadal variability or regional trends (Bellomo et al., 2014; Myers et al. 2018), raising the possibility that, even if clouds cannot drive tipping points, they might amplify other tipping points in ways that are missing from current models.

Assessment and knowledge gaps

In summary, concern about cloud-driven tipping points is relatively low. Cloud feedbacks will, however, likely affect the strength of climate responses, including for many tipping points. For example, they could potentially amplify variability, and current models may not be capturing this well. High climate sensitivity from strongly positive cloud feedbacks also cannot be ruled out.

1.4.2.5 El Niño-Southern Oscillation (ENSO)

The El Niño-Southern Oscillation (ENSO) is the dominant interannual mode of variability in Earth's climate. It originates in the tropical Pacific, where it affects sea surface temperatures (SST), trade winds, rainfall and many other climate variables. El Niño events typically happen every three to five years (hence the term 'interannual'). The tropical Pacific average climate is characterised by a strong east-west gradient along the equator of about 5-6°C, with warmer SSTs in the west and colder SSTs in the east maintained by easterly Pacific trade winds. During El Niño – the warm phase of this oscillation – this gradient weakens, while during La Niña – its cold phase – it intensifies (schematically depicted in Fig 1.4.11a). Both phases of this oscillation have far-reaching impacts on global climate and weather patterns, ecosystems and human health (e.g. McPhaden et al,. 2020).

The impacts of ENSO become especially pronounced during the strongest events, often referred to as extreme El Niños, defined as events with SST anomalies above a chosen threshold (for example 2 standard deviations as in Heede and Fedorov 2023a) (Fig. 1.4.11b). At their peak, these events can eliminate the east-west ocean temperature gradient along the equator, leading to a temporary collapse of the trade winds. Additionally, an extreme El Niño causes an increase in global mean surface temperature of up to 0.25°C (Hu and Fedorov 2017), contributing to the prevalence of heat waves around the globe. While only a few El Niño events reach large magnitudes, the global impacts of these events result in billions of dollars in damage (Callahan and Mankin 2023).

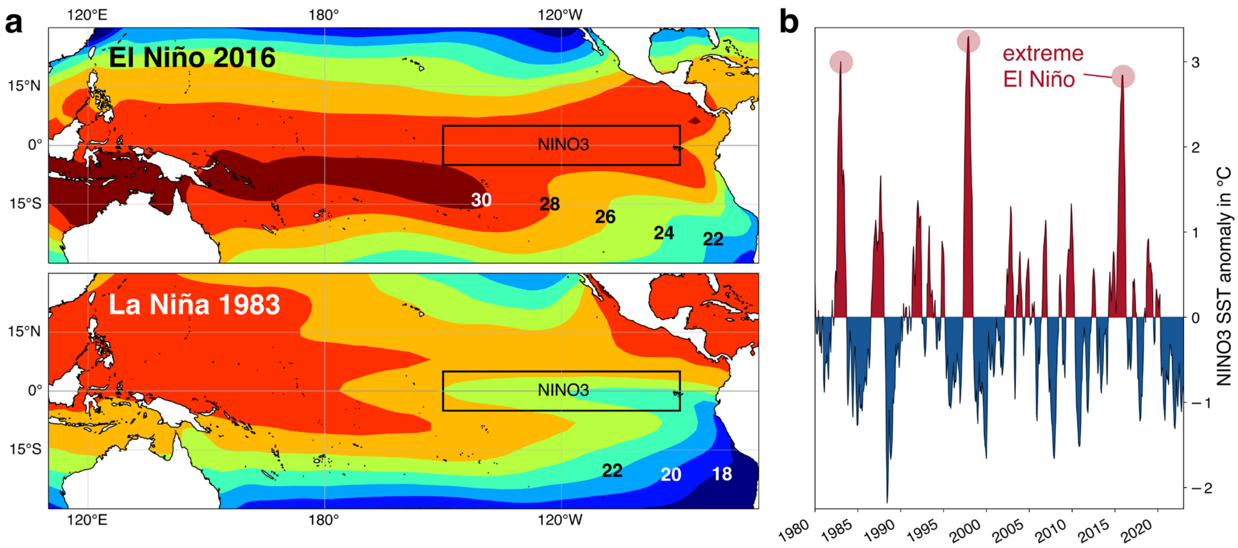

Figure 1.4.11: ENSO warm and cold phases and observational record. a Examples of strong El Niño (top) and La Niña (bottom) events seen in the tropical Pacific surface temperature (SST) distribution, with characteristic strong and weak SST gradient along the equator, respectively. **b** ENSO record since the 1980s. Note the three extreme events of the past four decades (1982, 1997 and 2015) and the weakening of ENSO variability between years 2000 and 2015. Temperature is averaged for the NINO3 region (5°C-5°N, 150°W-90°W) in the eastern equatorial Pacific. Based on NOAA Extended Reconstructed SST V5 data (Huang et al., 2017).

As this report was being written, a new El Niño event was announced (WMO, 2023), and will likely reach peak strength around the time of its publication in December 2023. At the time of writing, it is projected to be a 'strong' event, reaching ~2°C relative to neutral (CPC/NCEP/NWS, 2023).

Evidence for tipping dynamics

Extensive research conducted since the 1980s has significantly advanced our understanding of the physics behind El Niño, leading to improved predictive capabilities of climate models (L'Heureux et al., 2017). ENSO is now recognised as a large-scale, irregular, internal oscillatory mode of variability within the tropical climate system, influenced by atmospheric noise (Timmermann et al., 2018). The spatial pattern of ENSO is determined by ocean-atmosphere feedbacks, while its timescale is determined by ocean dynamics. In particular, it is a sequence of self-reinforcing feedbacks between SSTs, changes in zonal surface winds, equatorial upwelling and ocean thermocline depth that promotes the growth of El Niño anomalies (i.e. Bjerknes feedbacks, McPhaden et al,. 2020).

Coral-based proxy data indicate that the amplitude and frequency of ENSO events has gradually increased during the Holocene (Grothe et al., 2020; Lawman et al., 2022), possibly due to an increase in extreme El Niño events. All extreme El Niños in the observational record (1982, 1997 and 2015) occurred during the accelerated growth of global mean temperatures. This raises the question whether this trend is indicative of upcoming changes in the tropical Pacific to conditions with more frequent extreme El Niño events.

In the context of tipping points, the question arises: is there a critical threshold with an abrupt and/or irreversible transition to such a new state? Several recent studies (Cai et al,. 2018, 2022; Heede and Fedorov, 2023a) have indeed suggested that El Niño magnitude and impacts may intensify under global warming (**Figure 1.4.12**), even though there is still no model consensus on the systematic future change in ENSO, as IPCC AR6 and the results in **Figure 1.4.12** suggest.

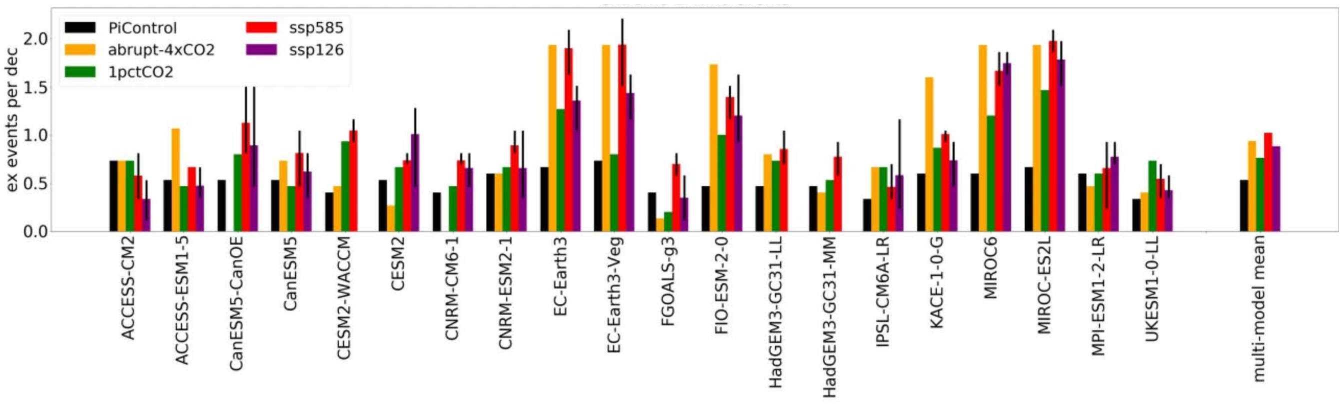

Figure 1.4.12: Overview of projected changes in extreme El Niño events in CMIP6 climate models. The bar chart shows the time-mean frequency of extreme El Niño events (the number of events per decade) for several idealised and more realistic global warming experiments (abrupt-4xCO2, 1pctCO2, SSP5-8.5 and SSP1-2.6) next to the pre-industrial Control simulation (piControl). From Heede and Fedorov, 2023a

It is projected that the eastern equatorial Pacific (EEP) will warm faster than the western part of the basin, leading to an EEP warming pattern or El Niño-like mean conditions, associated with weaker Pacific trade winds. Most climate model future projections exhibit this pattern (e.g. DiNezio et al,. 2009; Xie et al,. 2010; Heede and Fedorov 2021), and increased ENSO variability is prevalent in models that simulate stronger nonlinear (Bjerknes) feedbacks (Cai et al,. 2022). A recent comprehensive study of CMIP6 models and scenarios concluded that, although a common mechanism to explain a change in ENSO activity across models is missing, its increase under warming scenarios is robust (Heede and Fedorov, 2023a).

Furthermore, during the warm Pliocene epoch approximately 3-5 million years ago, when global surface temperatures were ~3°C above pre-industrial, the east-west SST gradient was indeed reduced (Wara et al,. 2005; Fedorov et al., 2006, 2013, 2015; Tierney et al., 2019). This state is often referred to as 'permanent El Niño-like' conditions, which does not indicate ENSO changes, but rather a consistent mean decrease in the east-west SST gradient. While debates on this topic are ongoing, estimates for this gradient reduction range from 1.5°C to 4°C, depending on the time interval, proxy data and the definition of this gradient.

Assessment and knowledge gaps

Therefore, there is a general expectation of a future reduction in the Pacific's east-west SST gradient by the end of the 21st Century. Together with other contributing factors, such as the strengthening of the MJO, the dominant intraseasonal mode in the tropical Indo-Pacific (Arnold et al., 2015; see 1.4.2.4), this reduction is expected to amplify ENSO (Heede and Fedorov, 2023a). Additionally, a warmer atmosphere can hold more water vapour, which could result in stronger precipitation and heating anomalies in the atmosphere, leading to greater remote impacts of El Niño events.

Consequently, the collective evidence implies an increase of El Niño magnitude and impacts under global warming. There is, however, insufficient indication for a critical transition associated with an abrupt or irreversible regime shift towards a new, more extreme or persistent, ENSO state, such that ENSO is considered with medium confidence not to be a tipping system (see also Armstrong McKay et al., 2022). However, it is well connected to other Earth system components (e.g. affecting tropical monsoon rainfall), thereby possibly playing a role in tipping cascades, linking different tipping elements via global teleconnections (see Chapter 1.5).

Notably, the projections of a future EEP warming pattern, weaker mean trade winds and stronger El Niño events contradict decadal trends in the tropical climate over the past 30 years or so. In fact, since the early 1990s, the Pacific trade winds have strengthened, and the eastern equatorial Pacific has become colder (e.g. Ma Zhou, 2016; Seager et al., 2022; Wills et al., 2022; Heede and Fedorov 2023b). Whether these trends reflect an ocean thermostat-like response to global warming, internal variability of the system, or both, remains an open question. Similarly, the magnitude of ENSO events has been generally weaker since the 2000s compared to the 1980s and 1990s (Fig. 1.4.11b; also Capotondi et al., 2015 or Fedorov et al., 2020).

Therefore, debates on the future of the tropical Pacific and ENSO revolve around the question of when the transition to a mean EEP pattern and weaker trade winds may occur, likely leading to a stronger El Niño and more frequent extreme events. Simulations with global climate models including strongly eddying ocean components (Wieners et al., 2019; Chang et al., 2020) and the currently developing 2023-2024 El Niño are expected to help reduce persistent model tropical biases in SST, precipitation and ocean thermocline, and to resolve some of the remaining issues.

1.4.2.6 Mid-latitude atmospheric dynamics

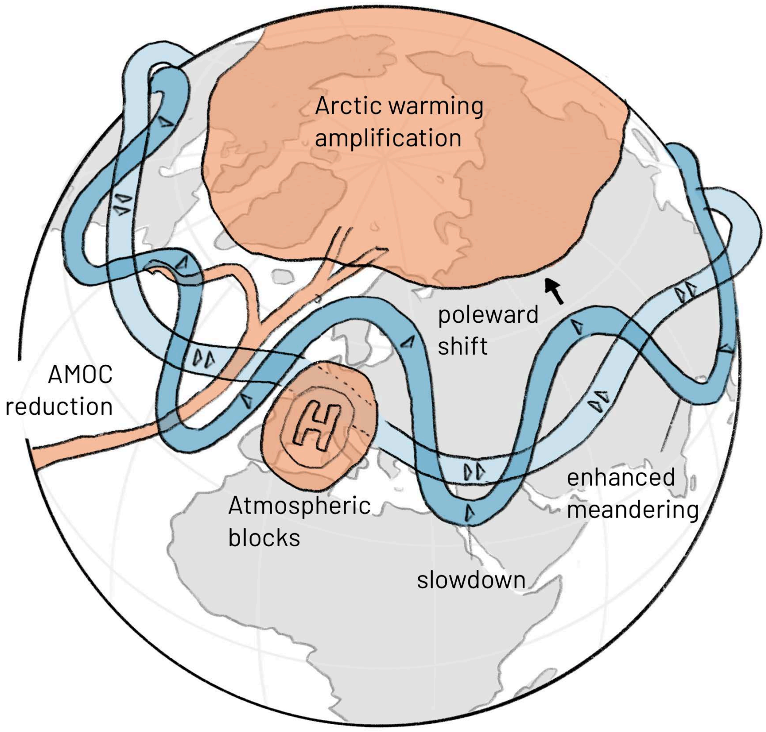

Figure 1.4.13: Potential changes in mid-latitude atmospheric circulations, exemplary for the Northern Hemisphere. Reduction of AMOC, atmospheric blocking events, Arctic warming and other drivers can modify the jet stream. Potential consequences are a northward shift, slowdown and enhanced meandering, related to increases in extreme weather phenomena.

Mid-latitude atmospheric circulation is characterised by a band of strong westerly winds (see Figure 1.4.1), with largest velocities at an altitude of 7-12km, forming the so-called northern polar 'jet-stream'. The jet serves as a separation of cold air masses at high-latitudes in the north from temperate air masses further south. Large meanders in the jet are referred to as planetary, or Rossby, waves. In most cases, these waves move over large distances and decline over timescales of a few days. When persisting for a prolonged time over the same location (referred to as 'quasi-stationary' waves) they can lead to high-impact climate extremes, including temperature extremes or heavy precipitation. An example is the record-breaking heatwave of 2021 in the North American Pacific Northwest (Bartusek et al., 2022).

Atmospheric features such as blocks (quasi-stationary high-pressure regions that divert, or 'block', the large-scale atmospheric flow on timescales of several days to weeks) are intimately linked to these persistent meanders in the jet. A widely discussed effect of climate change is a poleward shift of the mid-latitude jet, although this may be season and location-dependent (Oudar et al,. 2020), and smaller than previously thought (Curtis et al., 2020) (Figure 1.4.13).

Evidence for tipping dynamics

In climate models, the magnitude of the jet's shift strongly depends on the reduction of the AMOC (see Chapter 1.4.2.1). Models with a strong AMOC reduction in the future tend to project a much stronger poleward shift of the jet than models with a weaker AMOC reduction, making this the largest atmospheric circulation uncertainty in regional climate change projections (Bellomo et al., 2021).

Furthermore, it has been suggested that the mid-latitude flow might weaken, leading to more persistent and slower-moving weather patterns (Coumou et al., 2015; Kornhuber and Tamarin-Brodsky, 2021). A possible driver is Arctic amplification – namely the fact that the Arctic is warming more rapidly than the rest of the planet, partly driven by sea ice loss (see Chapter 1.2). This reduces the equator-pole temperature contrast, and could result in a weakening and enhanced meandering of the jet stream (Francis and Vavrus, 2015). While Arctic amplification is most evident during winter, such increase in waviness may also be occurring during the summer season (Coumou et al., 2018). However, evidence that the occurrence of large-amplitude atmospheric waves is increasing is debated (Screen and Simmonds, 2013; Blackport and Screen, 2020; Riboldi et al., 2020), and mechanisms which would reduce blocking in the future have also been proposed (Kennedy et al., 2016).

As part of this debate, it has been proposed that several weather extremes in recent decades were associated with a quasi-stationary, quasi-resonant wave pattern. This results from the interaction of climatological waves that are perpetually forced by orography (mountain geography) and land-sea contrasts with transient meanders of the jet stream (Petoukhov et al., 2013), given a set of favourable conditions (White et al., 2022). Petoukhov et al., (2013) also hypothesised that Arctic amplification and the associated weakened, wavier jet may provide increasingly favourable conditions for the occurrence of quasi-resonance. This can result in circulation features which accelerate regional extreme weather occurrence trends – for example, heatwave trends in Europe (Rousi et al., 2022), although the direction of causality is debated (Wirth and Polster, 2021). If recent extreme events are indeed associated with a resonance mechanism that only kicks in when the jet crosses a certain threshold in waviness, a tipping point might be involved. However, it is uncertain whether this would be associated with hysteresis and irreversibility or would just be a reversible, but abrupt, shift of the atmosphere towards enhanced large-amplitude mid-latitude waves.

More generally, there is no robust evidence that continued climate change and Arctic amplification will lead to a tipping towards a wavy-jet state, systematically higher amplitude and/or more frequent planetary waves, or blocks. Equally, there is no robust evidence that these hypothetical changes would be self-sustaining. Indeed, while a number of large changes in atmospheric dynamical features may occur under climate change, these are typically discussed as gradual changes, without explicit hysteresis or tipping behaviour. Similarly, there is no robust evidence pointing to tipping-like behaviour in the jet stream's latitudinal location, although gradual, long-term shifts may occur.

It should nonetheless be noted that atmospheric circulation responses to climate change are characterised by large model uncertainty and are possibly biased by the relatively low resolution of global climate models compared to, for example, weather-prediction models (Shepherd, 2019). In addition, some climate models show that tipping behaviour in atmospheric blocking, in the form of a self-sustaining, feedback-driven shift, is possible (Drijfhout et al., 2013).

Assessment and knowledge gaps

Although theoretically possible, there is thus no robust evidence for tipping point behaviour in mid-latitude atmospheric circulations in the near future. At the same time, a number of relevant physical processes are currently debated or ill-constrained. We thus evaluate, with low confidence, the mid-latitude atmosphere as not displaying tipping points.

The mid-latitude large-scale circulation itself may, though, still affect or be affected by tipping behaviour of other components of the Earth system to which it is coupled, such as the land surface, overturning ocean circulations (e.g., Orihuela-Pinto et al., 2022) or high-latitude cryosphere. Indeed, such interactions can lead to abrupt climate shifts. A recent example is the transition to hotter and drier conditions in inner East Asia, resulting from drier soils, a strengthened land-atmosphere coupling, and a contribution from large-scale circulation anomalies (Zhang et al., 2020). Furthermore, joint non-tipping changes in mid-latitude atmospheric dynamics, the associated surface climate, and other components of the Earth system, may lead to tipping point behaviour, for example in vegetation (Lloret and Batllori, 2021). This could in turn feed back onto the atmospheric circulation.

Due to such feedbacks and interactions between the atmospheric circulation and other components of the Earth system, and due to its role in weather and climate extremes, an improved understanding of the physical processes underlying changes in mid-latitude atmospheric dynamics under recent and future climate change appears pivotal in a tipping point context. Large model uncertainty in projecting abrupt regional atmospheric circulation changes conditioned by changes in the ocean, cryosphere or land surface would lend itself eminently for a storyline approach (Zappa and Shepherd, 2017). Tipping of atmospheric circulation, and associated weather extremes, would then be conditioned by threshold behaviour in other, connected systems.

Finally, we argue for the need to investigate whether recent, record-breaking weather extremes can be explained by the slowly changing likelihood distribution that belongs to the last decades, or whether they are signs of abruptly changing likelihood distributions. Such a shift in the distribution of extremes could be diagnosed using extreme value theory. Although a shift cannot be associated with a global tipping point, it would suggest that the extreme value distribution of (a) certain type(s) of extreme weather did witness regional tipping, whether or not reversible, in the sense of a large nonlinear change in response to a small and gradual change in forcing, potentially driven by self-sustaining feedbacks.

1.5 Climate tipping point interactions and cascades

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Summary

This chapter reviews interactions between climate tipping systems and assesses the potential risk of cascading effects. After a definition of tipping system interactions, we map out the current state of the literature on specific interactions between climate tipping systems that may be important for the overall stability of the climate system. For this, we gather evidence from model simulations, observations and conceptual understanding, as well as archetypal examples of palaeoclimate reconstructions where propagating transitions were potentially at play. This chapter concludes by identifying crucial knowledge gaps in tipping system interactions that should be resolved in order to improve risk assessments of cascading transitions under future climate change scenarios.

The scientific content of this chapter is closely based on the following scientific manuscript: Wunderling, N., von der Heydt, A. et al.: Climate tipping point interactions and cascades: A review, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2023-1576, 2023.

Key messages

- Tipping systems in the climate system are closely interacting, meaning a substantial change in one will have consequences for subsequently connected tipping systems.
- A majority of interactions between climate tipping systems are destabilising. While confirmation or rejection through future research is necessary, it seems plausible/possible that interactions between climate tipping systems destabilise the Earth system in addition to climate change effects on individual tipping systems.
- We are quickly approaching global warming thresholds where tipping system interactions become relevant, because multiple individual thresholds are being crossed.

Recommendations

- At least three approaches are needed to improve risk assessments for tipping cascades: (i) Time-series analysis of observations and palaeoclimate data, (ii) Earth system models designed for tipping system interactions, (iii) Risk analysis using large model ensembles.
- Palaeoclimate observations improve our understanding of tipping cascades, by studying past abrupt or transition events such as the Eocene-Oligocene Transition, Bølling-Allerød warm period.
- Besides direct interactions, additional indirect feedbacks (for example, via temperature) should be quantified in order to determine the risk for tipping cascades.

1.5.1 Introduction and definition

The tipping systems identified in the climate system generally operate not in isolation from each other, but connected either directly or mediated via changes in the overall climate (for example, global temperature) (Liu et al., 2023; Kriegler et al., 2009). Via such connections (see Figure. 1.5.1) tipping in one subsystem can therefore cause tipping in another, which we define as a tipping cascade (see Definition below) (Wunderling et al., 2021a; Klose et al., 2020; Dekker et al., 2018).

Definition:
Here we call the linkages between tipping systems and/or other nonlinear components as tipping interactions, which could have a stabilising or a destabilising effect. The most extreme case is the situation in which the tipping of element 'A' causes a subsequent tipping of element 'B'. In this report, we define a sequence of tipping events involving several nonlinear components of the Earth system as **tipping cascades** (Dekker et al., 2018; Wunderling et al., 2021a). These tipping cascades can come in various forms dependent on the ordering of tipping systems (e.g. Klose et al., 2021; Dekker et al., 2018). Eventually, a tipping cascade might result in a fundamental change in the Earth's equilibrium climate.

For example, disintegration of the Greenland Ice Sheet (GrIS) can lead to an abrupt shift in the Atlantic Meridional Overturning Circulation (AMOC), while an abrupt change in AMOC strength can lead to an intensification of the El Niño-Southern Oscillation (ENSO). Interactions between climate tipping systems could effectively lower the thresholds for triggering a tipping event as compared to those individual tipping systems in isolation (Wunderling et al., 2021a; Klose et al., 2020). Moreover, one or more tipping events could activate processes leading to additional CO_2 emissions into the atmosphere; permafrost thaw and forest dieback are typical examples of such additions of stored CO_2 into the atmosphere via positive amplifying feedbacks (Wunderling et al., 2020; Lenton et al., 2019; Steffen et al., 2018).

It is also conceivable that components of the Earth system, though not necessarily tipping systems in themselves, could mediate or amplify tipping in other components, thereby creating larger-scale impacts. As a result, some of these nonlinear components are also taken into account in this chapter. A prominent example is Arctic summer sea ice cover, which is not expected to show tipping behaviour (Lee et al., 2021) (see 1.2.2.2), but can nevertheless trigger tipping events in the ocean-atmosphere-cryosphere system (Gildor and Tziperman, 2003). On the other hand, an abrupt transition in one tipping system may also stabilise other climate subsystems (Nian et al., 2023; Sinet et al., 2023) as is the case for a weakening AMOC decreasing local temperatures around Greenland (Jackson et al., 2015).

While most tipping systems that have been proposed so far are clearly regional (with some being large-scale), there are significant knowledge gaps with respect to their tipping probability, impact estimates and timescales, as well as their interactions. The potential of a tipping cascade that could lead to a global reorganisation of the climate system (Steffen et al., 2018; Hughes et al., 2013) remains therefore speculative. However, since multiple individual tipping point thresholds may be crossed during this century with ongoing global warming, and could lead to severe tipping system interactions and cascading transitions in the worst case, it is critical to review the current state of knowledge and reveal research gaps that need to be addressed (Armstrong McKay et al., 2022; Masson-Delmotte et al., 2021; Rocha et al., 2018).

1.5.2 Interactions between climate tipping systems and further nonlinear climate components

1.5.2.1 Interactions across scales in space and time

In this section, we lay out the current state of the scientific literature on the interaction processes between several tipping systems and some other nonlinear components of the Earth system. The summary is shown in Figures 1.5.1 and 1.5.3.

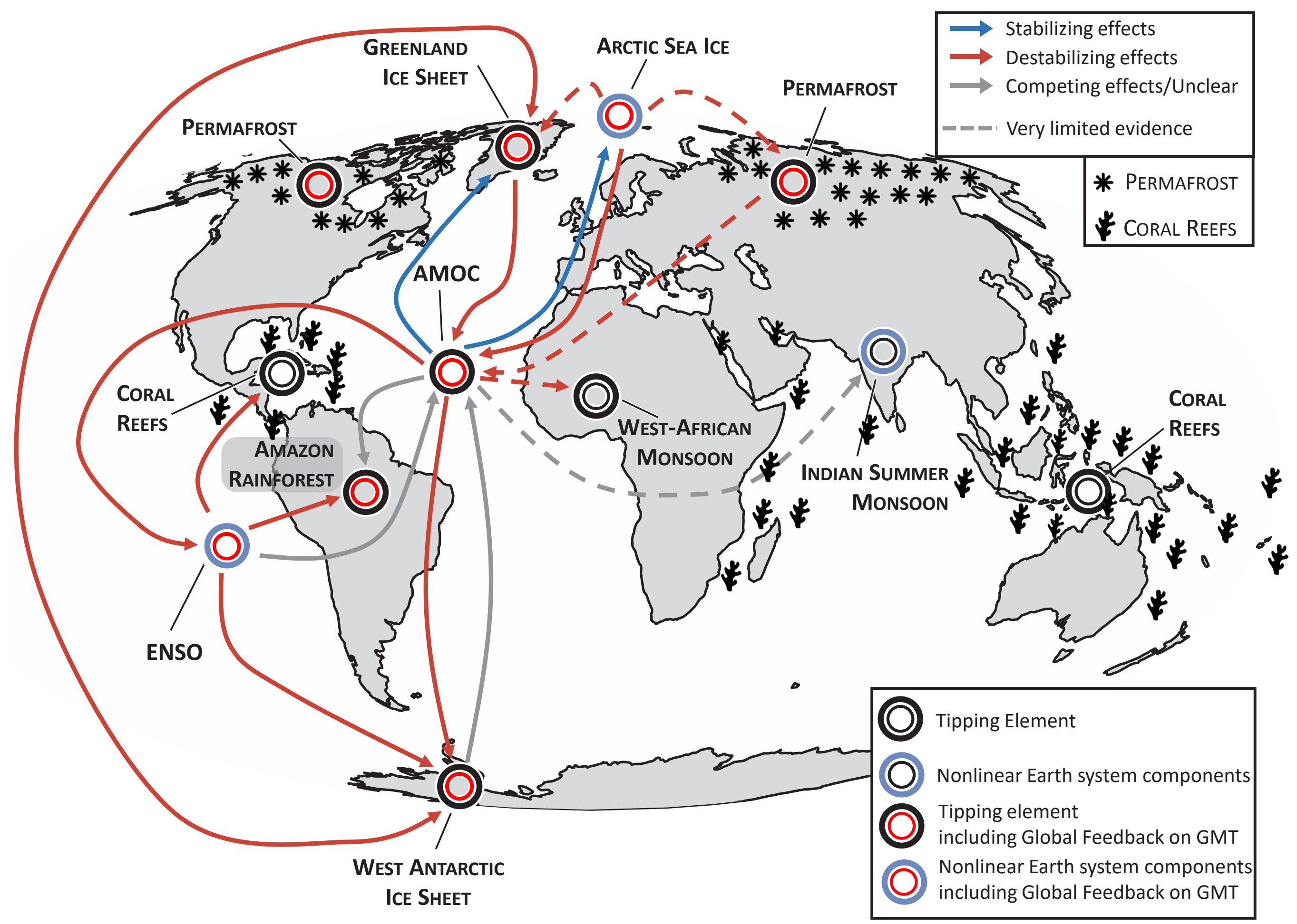

Figure 1.5.1: Interactions between established and more speculative tipping systems on a world map. All tipping systems discussed in this chapter are shown together with their potential connections. The causal interaction links can have stabilising (blue arrows), destabilising (red arrows), or unclear (grey arrows) effects. For some systems, it is speculative whether they are tipping systems on their own (such as ENSO or the Arctic sea ice) and they are denoted as such (blue outer ring) but they are included if they play an important role in mediating transitions towards (or from) core tipping systems. Tipping systems that exert a notable feedback on global mean temperature (GMT) when they tip are denoted by a red inner ring (for instance via albedo changes in case of a disintegration of the Greenland or West Antarctic ice sheets or Arctic sea ice, or via carbon release through tipping of permafrost or rainforests). This temperature feedback can be positive (i.e. amplifying warming, as likely for the permafrost, the Arctic sea ice, the Greenland and West Antarctic ice sheets, the Amazon rainforest and ENSO) or negative. Source: Wunderling and von der Heydt et al.

These systems are not isolated entities but interact across the entire globe (Figure 1.5.1). Not only do the interactions span global distances, but some tipping systems themselves can be of regional spatial scale (e.g. coral reefs or the GrIS), while others cover significant portions of the globe (e.g. the AMOC). Also, timescales differ vastly among the different climate tipping systems: some are considered fast tipping systems once the process has been initiated (in the order of years/decades to centuries, such as the Amazon rainforest and AMOC), while others are considered slow tipping systems (in the order of centuries to millennia, such as the GrIS).

These different spatial and temporal scales of the individual tipping systems are therefore also important for their interactions and are mapped out in Figure 1.5.2 (Rocha et al., 2018; Kriegler et al., 2009). The respective processes of the interactions can be found in Figure 1.5.3, alongside an estimation of the interaction direction and, if available, an estimation of their strength.

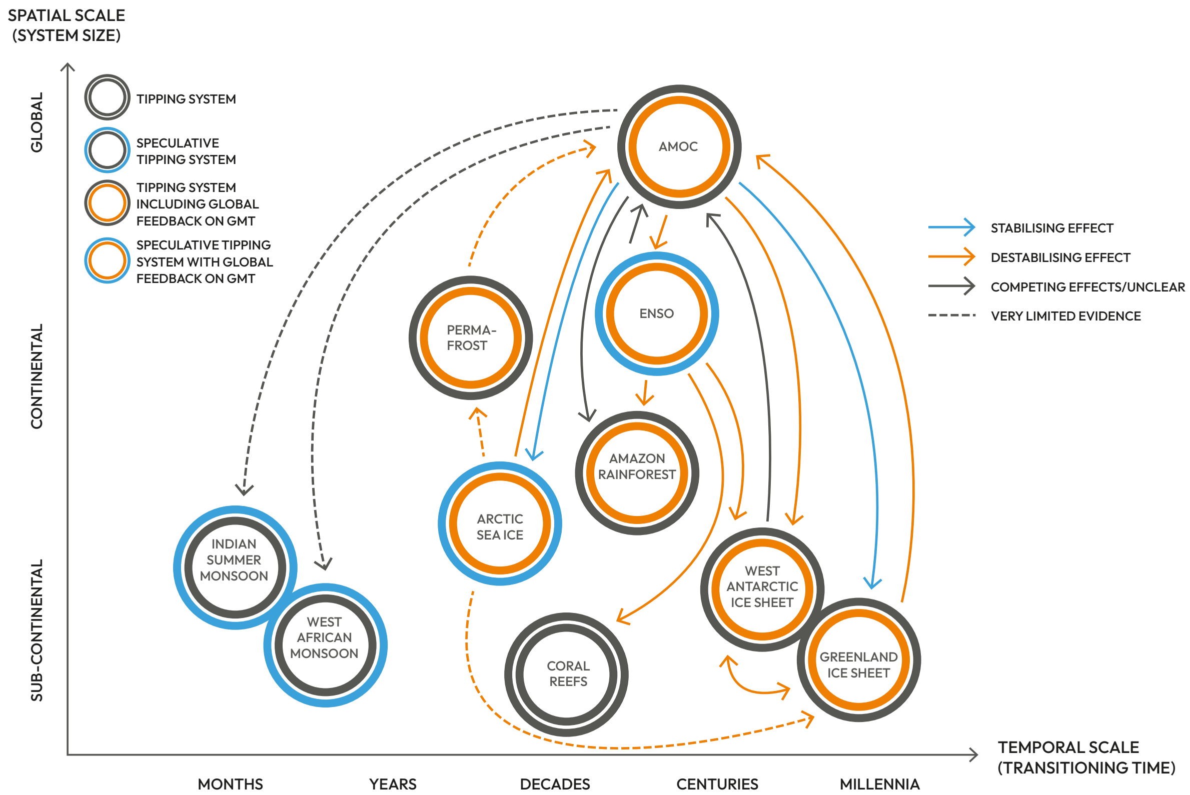

Figure 1.5.2: Interactions between tipping systems across scales in space and time. Temporal scales are transitioning times of a disintegrating tipping system from months up to millennia. Spatial scales denote the system size from sub-continental to (nearly) global scales. Transitioning times are taken from Armstrong McKay et al. (2022), and spatial scales from Winkelmann et al. (2022). The causal links can be stabilising (blue arrows), destabilising (red arrows), or unclear (grey arrows). Some tipping systems are particularly speculative (such as ENSO or the Arctic sea ice) and denoted as such (outer blue border). Tipping systems that exert a feedback on the global mean temperature (GMT) when they tip are shown with an inner red border. Adapted from: Wunderling and von der Heydt et al.

1.5.2.2 Interactions between ice sheets and the AMOC

The AMOC, Greenland Ice Sheet (GrIS), and West Antarctic Ice Sheet (WAIS) are key tipping systems and are threatened by increasing CO_2 emissions and temperatures (Armstrong McKay et al., 2022; Pörtner et al., 2019). Moreover, GrIS, AMOC, and WAIS interact on very different timescales, ranging from decades to multiple centuries. While some of those links might be stabilising, others are destabilising and would allow for the possibility of large-scale cascading events.

Greenland Ice Sheet to AMOC

The AMOC depends on the formation of dense, salty water in the high latitudes of the North Atlantic. As GrIS melting increases (1.2.2.1), the associated discharge of salt-free freshwater in the ocean will decrease surface water salinity and thereby density, inhibiting the formation of dense waters and weakening the circulation. As less salt is transported to the North Atlantic, the salt-advection feedback implies a self-sustained freshening of the high latitudes of the North Atlantic, which, in the worst case, can result in the collapse of the AMOC (1.4.2.1). On top of this classic positive/amplifying feedback, there exists a wide range of other feedbacks related to the AMOC, either negative (heat advection feedback) or positive (evaporation feedback).

An overall destabilising impact of GrIS melting on the AMOC is mostly consistent across models, where adding freshwater in the North Atlantic (Jackson and Wood, 2018; Mecking et al., 2016; Stouffer et al., 2007), also in combination with increasing CO_2 emissions (Bakker et al., 2016; Swingedouw et al., 2006), leads to a substantial weakening of the circulation. Importantly, in the case of AMOC collapse, some models suggest it does not recover within century timescales (Jackson and Wood, 2018; Mecking et al., 2016).

Note, however, that estimated melt rates of the GrIS are generally smaller than the amount of freshwater additions in models necessary to collapse the AMOC (Sinet et al., 2023, Jackson and Wood 2018), and it is currently a smaller contributor than increased Arctic precipitation.

West Antarctic Ice Sheet to AMOC

In the case of freshwater release in the Southern Hemisphere originating from West Antarctica, different opposing processes are at play that could affect the AMOC. These effects have been identified to act on different timescales and depend on the state of the circulation (Berk et al., 2021; Swingedouw et al., 2009). First, the weakening of Antarctic Bottom Water (AABW; see 1.4.2.2) formation might lead to enhancement of the AMOC through the so-called 'ocean bipolar seesaw'. This describes the tendency for opposing temperature changes in the Southern and Northern Hemisphere, with ocean bottom water changes in response to ice sheet melt in either hemisphere taking a long time to affect the other hemisphere.

Second, the increase in wind intensity over the Southern Hemisphere, related to an increase in sea ice cover, might also help to enhance the AMOC (Li et al., 2023; Swingedouw et al., 2008). Third, the release of freshwater in the Southern Ocean might eventually reach the North Atlantic on a longer timescale (centuries), possibly weakening the AMOC. As a result, the impact of a WAIS collapse on the AMOC is still unclear, as most models show either a slight weakening (e.g. Stouffer et al., 2007; Seidov et al., 2005) or a slight strengthening (e.g. Swingedouw et al., 2009) of the circulation. Notably, some studies also found that a sufficient freshwater release into the Southern Ocean allows for delaying an AMOC collapse (Sadai et al., 2020), or a recovery from it (Weaver et al., 2003).

AMOC to ice sheets

An AMOC collapse would decrease northward heat transport, leading to a substantial cooling of the Northern Hemisphere, and warming in the Southern Hemisphere (Pedro et al., 2018; Jackson et al., 2015; Stouffer et al., 2006). Cooling the high latitudes of the North Atlantic could stabilise the GrIS. Conversely, the related warming of the Southern Ocean represents a destabilising impact on the WAIS, being susceptible to these warmer ocean waters via the ice shelves and their buttressing effect on upstream ice flow (Favier et al., 2014; Joughin et al., 2014).

Direct interactions between Greenland and West Antarctic ice sheets via sea level.

It is known that an increase in sea level has an overall destabilising influence on marine-based sectors of ice sheets, possibly triggering or enhancing the retreat of their grounding line (Schoof, 2007; Weertman, 1974). In the case of ice sheet collapse, the induced sea level rise would vary locally depending on gravitational effects (with sea level falling near the former ice sheet as less water is attracted towards it), rotational effects, and mantle deformation (Kopp et al., 2010; Mitrovica et al., 2009). Overall, sea level rise is expected to negatively impact both the GrIS and WAIS, but more strongly the latter, where most of the bedrock lies well below sea level (Gomez et al., 2020).

1.5.2.3 Arctic sea ice interactions

Interactions between AMOC and Arctic sea ice

Changing Arctic sea ice cover can change AMOC strength in two main ways (Sévellec et al., 2017): First, it alters radiative heating and ocean-atmosphere heat loss via changing albedo. More precisely, as the Arctic sea ice area has substantially decreased over the past 40 years, especially during summer months (Masson-Delmotte et al., 2021), the open water fraction of the Arctic Ocean has increased and will continue to do so (Crawford et al., 2021). This has led to an increase in the absorption of solar radiation and to subsequent ocean warming, which can spread to ocean convection areas, affecting stratification and potentially weakening the AMOC. Second, the recent decrease in Arctic sea ice area together with ice loss from the GrIS has added freshwater to the Arctic Ocean. Although the trend in freshwater content has slowed during the past decade (Solomon et al., 2021), it could affect North Atlantic deep water formation and thus weaken the AMOC.

The AMOC can also affect Arctic sea ice via the transport of warm water to the North Atlantic Ocean, and subsequently to the Arctic Ocean via the Barents Sea Opening and Fram Strait. A weaker AMOC could result in lower ocean heat transport and increased Arctic sea ice area (Delworth et al., 2016). However, recent observations show that the ocean heat transport to the Arctic has increased, especially on the Atlantic side (Docquier and Koenigk, 2021; Polyakov et al., 2017; Onarheim et al., 2015; Årthun et al., 2012). Thus, the effect of a weaker AMOC may be merely to slow the pace of ongoing increases in ocean heat transport and the associated decrease in Arctic sea ice (Liu et al., 2020).

Effect of Arctic sea ice on the Greenland Ice Sheet and Arctic permafrost

Besides interacting with the AMOC, reduced Arctic sea ice cover could have a direct effect via regional warming on further high-latitude tipping systems such as the GrIS and Arctic permafrost (1.2.2.4). In the case of sustained Arctic summer sea ice loss, which may occur during the second half of this century (Niederdrenk et al., 2018) or sooner (Kim et al., 2023), additional warming levels are in the order of 0.3-0.5°C regionally over Greenland and the permafrost (Wunderling et al., 2020). Regional warming levels may be higher if Arctic winter sea ice also disappears under high-emission scenarios. Further, it has been found that regional Arctic sea ice loss has a limited effect for Greenland warming patterns and is mainly relevant for coastal parts of Greenland (Pedersen and Christensen, 2019).

At the same time, Arctic sea ice loss leads to increased coastal permafrost erosion (Hošeková et a., 2021; Casas-Prat and Wang, 2020; Grigoriev et al., 2019; Nielsen et al., 2020 and 2022). Abrupt changes in summer-autumn seaice retreat from the permafrost coast leads to an increase in waves, resulting in sudden increases in erosion rates (– about 50-160 per cent in the last 50 years (a two- to fourfold increase in hotspots in the Laptev and Beaufort Seas) (Irrgang et al., 2022). Thus, coastal permafrost collapse leads to a potential cascading risk of carbon releases locally to the Arctic ocean and the atmosphere of 0.0023–0.0042 GtC per year per degree celsius by the end of the century (Nielsen et al., 2022). The erosion causes changes in the shoreline, sediments, carbon, nutrients and contaminants in the coastal seas and offshore marine environment (Irrgang et al., 2022).

1.5.2.4 Effects of AMOC changes on the Amazon rainforest

The strength of the AMOC exerts a substantial influence on the climate of tropical South America – most importantly, on rainfall and its seasonal distribution (1.4.2.3). This in turn affects the state and stability of another potential tipping system in the Earth system: the Amazon rainforest.

The most important large-scale effect of the AMOC on Amazon rainfall works via the pattern of sea surface temperatures (SSTs) in the Atlantic, and the associated southward shifts of the Intertropical Convergence Zone (ITCZ) and the tropical rain belt. There is widespread agreement that a reduction or even collapse of the AMOC would lead to reduced SSTs in the North Atlantic and increased SSTs in the South Atlantic (Bellomo et al., 2023; Manabe and Stouffer, 1995). This southward shift would cause a substantial reduction in rainfall over northern South America, and an increase in rainfall over the southern Amazon rainforest as well as over northeastern Brazil, which is directly affected by the tropical rain belt (Jackson et al., 2015). Nevertheless, over the Amazon basin, rainfall change is uncertain and model-dependent (Ciemer et al., 2021; Swingedouw et al., 2013; Stouffer et al., 2006), resulting in a large uncertainty concerning the potential impact of AMOC weakening in the Amazon rainforest dieback.

Although different Earth system models have different biases in the location, shape and strength of the tropical rain belt, they generally agree on the AMOC collapse-induced increase in precipitation over the southern portion of the Amazon and northeastern Brazil (Bellomo et al., 2023; Nian et al., 2023; Orihuela-Pinto et al., 2022; Liu et al., 2020). Given that the forests in the southern half of the basin contribute mostly to the rainfall generation over the basin (Staal et al., 2018), one could speculate that this would lead to a stabilisation of the Amazon, given that a substantial fraction (24-70 per cent, Baudena et al., (2021) and references therein) of the rainfall of the basin is nonetheless produced by local moisture recycling. More generally, the full spectrum of rainforest stressors, including human-driven pressures such as land use changes driving deforestation, has to be taken into account when assessing AMOC effects over the Amazon rainforest (Lovejoy and Nobre, 2018).

1.5.2.5 Interactions between ENSO and tipping systems

The El Niño-Southern Oscillation (ENSO) is the most important mode of climate variability on interannual time scales, fundamentally affecting regional and global atmospheric and oceanic circulation (McPhaden et al., 2006). The response to climate change of ENSO itself is still debated, mainly because there are multiple (positive and negative) feedback processes in the tropical Pacific ocean-atmosphere system, whose relative strengths determine the response of ENSO variability (Timmermann et al., 2018; Cai et al., 2015; see 1.4.2.5).

Further, recent studies disagree about the future frequency of El Niño phases under global warming (Cai et al., 2021; Wengel et al., 2021). Although it is debated or even unlikely whether ENSO should be considered a tipping system in itself (Armstrong McKay et al., 2022), it exerts important effects on other tipping systems (for example, tropical monsoon rainfall). Through its global 'teleconnections' (i.e. links between widely separated climate phenomena), ENSO has the potential to influence multiple Earth system components including the AMOC, Amazon rainforest, WAIS, warm water coral reefs and tropical monsoon systems.

Interactions between ENSO and AMOC

Various physical mechanisms have been discussed to explain how a decline or complete shutdown of the AMOC could affect ENSO. An AMOC decline typically leads to cooling in North Atlantic surface temperatures, which affects the global atmospheric circulation, including the trade winds in the tropical Pacific. Therefore, many complex climate models project that AMOC decline leads to an intensification of northeasterly trade winds and a southward shift of the ITCZ, eventually leading to an intensification of ENSO amplitude through nonlinear interactions (Timmermann et al., 2007).

While the response of the trade winds and ITCZ to AMOC decline seems to be relatively robust within different climate models, the response in ENSO magnitude or frequency is much more model-dependent and thus uncertain. It should be noted that most complex climate models still exhibit severe biases in tropical temperature patterns, partly caused by not properly resolved oceanic processes (Wengel et al., 2021), which complicates the understanding of the fate of ENSO under global warming and AMOC changes.

The reversed pathway – i.e. ENSO impacting the AMOC – depends on several atmosphere-ocean processes which may not be adequately resolved in current state-of-the-art models. A relatively robust teleconnection exists between the El Niño phase and the North Atlantic Oscillation (NAO) (Ayarzagüena et al., 2018; Brönnimann et al., 2007). The relationship between the AMOC and the NAO in Earth system models depends on the subpolar North Atlantic background state; the AMOC is less sensitive in models that have extensive sea ice cover in the North Atlantic, while in models with less sea ice cover, the background upper ocean stratification largely determines how sensitively the AMOC reacts (Kim et al., 2023). As for ENSO, unbiased representation of the North Atlantic average state represents a significant challenge for state-of-the-art Earth system models, in part due to insufficient resolution of intermediate mesoscale ocean eddies.

Influences of ENSO on the Amazon rainforest

The frequency and amplitude of ENSO variability have changed on decadal to centennial timescales in the past (Cobb et al., 2013). In recent years, extreme El Niño events combined with global warming have become increasingly associated with unprecedented extreme drought and heat stress across the Amazon basin (Jiménez-Muñoz et al., 2016), leading to increases in tree mortality, fire and dieback (Nobre et al., 2016). Imposing the surface temperature pattern of a typical El Niño event in a global atmosphere-vegetation model suggests increased drought and warming in the Amazon (Duque-Villegas et al., 2019), which could enhance rainforest dieback (1.3.2.1) and transition regions of the Amazon rainforest from carbon sinks sources.

The destabilising effects from ENSO towards the Amazon rainforest are compounded by direct climate change effects and land use change and deforestation, often mediated by intensifying fires (1.5.2.4). Parts of the Amazon rainforest undergoing degradation and drying have already turned from a net carbon sink to a carbon source (Gatti et al., 2021). Further, it remains uncertain whetherthe vast Amazon rainforest would tip in its entirety or only partially, as it may have multiple intermediate stable states. In such a scenario, only specific areas in the rainforest margins might transition into degraded land (Rietkerk et al., 2021; Bastiaansen et al., 2020).

Influences of ENSO on the WAIS

Recent significant surface melt events on West Antarctica were associated with strong El Niño phases (Scott et al., 2019; Nicolas et al., 2017). It has been proposed that these melt events were caused by atmospheric blocking, eventually leading to warm air temperature anomalies over West Antarctica that pass the melt point of parts of the ice sheet (Scott et al., 2019). Using reanalysis data, satellite observations and hindcasting methods, strong indications have been found that the Ross and Amundsen Sea Embayment regions are most affected by El Niño phases (Scott et al., 2019; Deb et al., 2018).

Taken together, this adds to a growing body of literature that indicates a disintegration of the WAIS, especially along the Ross-Amundsen sector, would be favoured by strong El Niño phases, and tipping risks may increase if El Niño phases would become more frequent or intense under ongoing climate change (Cai et al., 2021; Wang et al., 2017; Cai et al., 2014; 1.4.2.5). This may be concerning in particular because the Amundsen region is where the most vulnerable glaciers of the WAIS are located, such as the Pine Island and Thwaites glaciers (Favier et al., 2014; Joughin et al., 2014).

Influences of ENSO on warm-water coral reefs

ENSO drives abnormally high SSTs (and seasonal summer heat waves), which are superimposed on already warming oceans. Anomalous heat destabilises corals, resulting in severe bleaching and mortality across multiple coral species on spatial scales exceeding thousands of kilometres (1.3.2.7). While ENSO is geographically modulated by other ocean dipoles (e.g. North Atlantic Oscillation, Indian Ocean dipole) (Houk et al., 2020; Krawczyk et al., 2020; Zhang et al., 2017), the Pacific signal is dominant and El Niño warm phases have been related to global episodes of extreme heat stress since the 1970s (1979/1980, 1997/98 and 2014-2017, for example) (Krawczyk et al., 2020; Muñiz-Castillo et al., 2019; Lough et al., 2018; Le Nohaïc et al., 2017).

As global warming progresses and oceans become significantly warmer, the incidence of mass bleaching can occur more frequently even without El Niño warm phases (Veron et al., 2009), with warmer conditions compared to three decades ago (McGowan and Theobald, 2023; Muñiz-Castillo et al., 2019). The global recurrence of bleaching has reduced to an average of six years (Hughes et al., 2018) – sooner than expected from climate models and satellite-based sea temperatures. While recovery from repeated bleaching events has been observed (Palacio-Castro et al., 2023; Obura et al., 2018), the proposed global mean warming thresholds of 1.5°C and 2°C would result in widespread reef die-off (70-90 and 90-00 per cent respectively loss of coral reefs globally) (Lough et al., 2018; Schleussner et al., 2016; Frieler et al., 2013), and lower thresholds of 1.0-1.5°C are argued for in this report (1.3.2.7).

Effects of AMOC and ENSO changes on tropical monsoon systems

Future climate projections show a weakening of the AMOC, which can be substantial in its impact on the regional and global climate (Pörtner et al., 2019; see 1.4.2.1). Indeed, model simulations of freshwater addition (via 'hosing experiments') in the North Atlantic show a clear southward shift of the ITCZ in response to the AMOC weakening and a decrease in northward oceanic heat transport (Defrance et al., 2017; Swingedouw et al., 2013; Stouffer et al., 2006). This shift of the ITCZ impacts the various monsoon systems worldwide (Chemison et al., 2022), as is also visible in palaeorecords (Sun et al., 2012).

For example, palaeo-reconstructions of a Heinrich event (a massive iceberg release causing further cooling in the North Atlantic region, 1.5.3.2) of the penultimate deglaciation between 135,000 and 130,000 years ago have been compiled, suggesting an increase in Indian summer monsoon rainfall (Nilsson-Kerr et al., 2019), but a subsequent reduction of the length of the monsoon rain season (e.g. Wassenburg et al., 2021). Summarised, a reduction of the AMOC strength, subsequent cooling of the Northern Hemisphere and southward shifts the ITCZ (Chemke et al., 2022) affect spatial rainfall patterns and amount of rainfall in the Northern Hemisphere semi-arid and tropical monsoon regions of West Africa and India/Asia.

An AMOC weakening has also been shown to strengthen the Indo-Pacific Walker circulation via cooling of the equatorial Pacific and warming of the Southern Hemisphere/Antarctic climate on a multi-decadal timescale (Orihuela-Pinto et al., 2022). The observed potential AMOC weakening during the last multiple decades might be partially affected by interannual ocean-atmosphere interactions, such as ENSO. These superimposed effects, operating across timescales, alter relationships between the ENSO and tropical monsoon systems and, thereby, regional rainfall patterns in a warmer climate (Mahendra et al., 2021; Pandey et al., 2020). For example, while the linear relationship between ENSO and the Indian summer monsoon rainfall has weakened, the ENSO-West African monsoon relationship has increased in recent decades (Srivastava et al., 2019).

However, ENSO and AMOC effects on tropical monsoon systems are still highly uncertain and should be further constrained using palaeoclimate reconstructions and Earth system models (see 1.4.2.3 for more on monsoon tipping).

1.5.2.6 Effects of permafrost thaw on the global hydrological cycle

Permafrost regions have accumulated substantial amounts of ice in their soils. With ground ice melting away in a warmer climate, permafrost landscapes experience abrupt thaw processes (1.2.2.4) and drastic hydrological changes, which are not fully understood yet. Hence, uncertainty exists about whether high-latitude regions might become wetter or drier in the future. They could turn into a wetter and cooler state with many freshwater systems and lakes, which support increasing land-atmosphere moisture recycling and cloud cover, reducing ground temperatures; or a drier state as newly formed lakes could drain, with less moisture recycling supporting less cloud cover and a warmer surface (Nitzbon et al., 2020; Liljedahl et al., 2016).

Which parts of the Arctic will be wetter or drier in the future is uncertain, but the differences between the potential Arctic hydroclimatic futures could be very pronounced. As recently shown by de Vrese et al. (2023), the drier and warmer permafrost state would lead to less sea ice, a reduced pole-to-equator temperature gradient, and a weaker AMOC. The drier Arctic state also shifts the position of the ITCZ, which results in higher precipitation in the Sahel region and potentially also in the Amazon rainforest. Increased forest and vegetation cover in these regions would be the consequence (de Vrese et al., 2023). Therefore, shifts in permafrost hydrology could affect climate tipping systems far beyond Arctic boundaries.

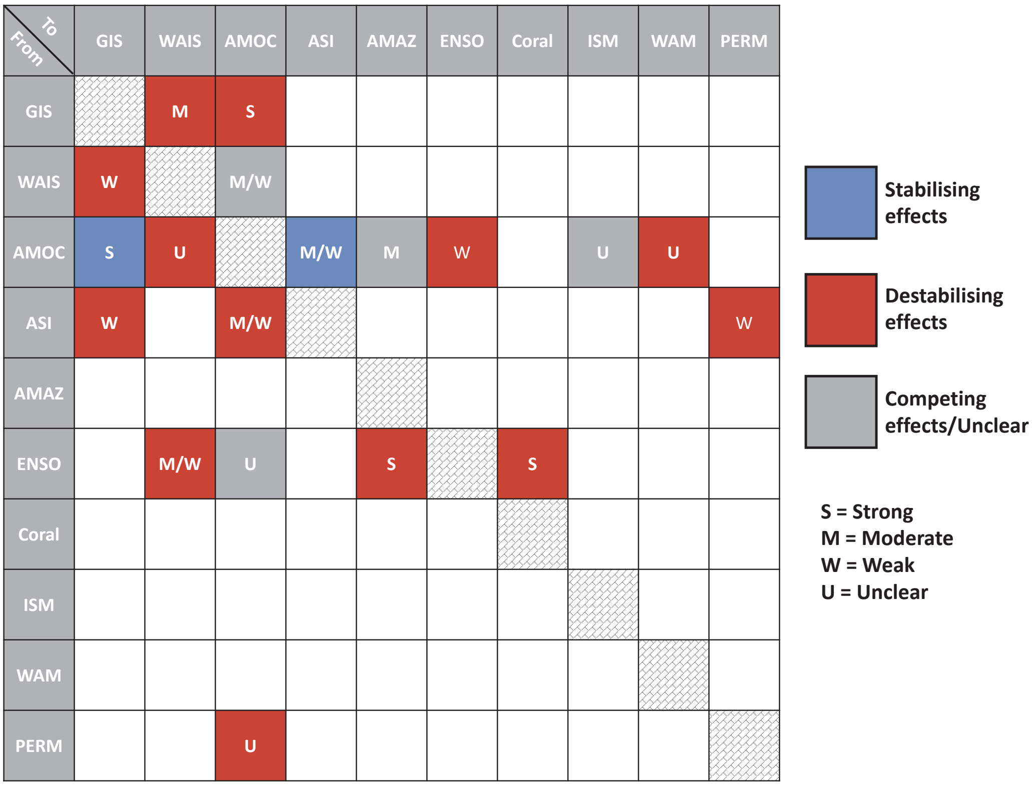

Figure 1.5.3: Matrix of links between elements (tipping systems and other nonlinear components) discussed in this chapter (see also Figs. 1 and 2). Columns denote the element from which the interaction originates, rows denote the tipping system to which element the interaction is pointing. We separate three different types of effects: A stabilising effect (blue box), a destabilising link (red box) and an unclear or competing link (grey box). White boxes denote no (or an unknown) link. Based on the recent literature, the strengths of the links are grouped into four groups: Strong (S), Moderate (M), Weak (W), and Unclear if a strength estimate is lacking (U). Abbreviations of the elements stand for: GrIS = Greenland Ice Sheet, WAIS = West Antarctic Ice Sheet, AMOC = Atlantic Meridional Overturning Circulation, ASI = Arctic Sea Ice, AMAZ = Amazon rainforest, ENSO = El Niño-Southern Oscillation, Coral = Coral reefs, ISM = Indian summer monsoon, WAM = West African monsoon, PERM = Permafrost. More details on each of the links can be found in Table 1 of the accompanying scientific review paper Wunderling and von der Heydt et al, from which this figure is adapted from.

1.5.3 Archetypal examples of interactions between tipping systems from a palaeoclimate perspective

1.5.3.1 Interactions in the distant past: the Eocene-Oligocene Transition

The formation of a continent-scale ice sheet on Antarctica during the 'Eocene-Oligocene Transition' about 34 million years ago is known as Earth's Greenhouse-Icehouse Transition. Following a cooling over tens of millions of years during the warm 'Eocene' period (c. 56 to 34 million years ago), this shift to a new cooler climate state in the 'Oligocene' period (c. 34 to 23 million years ago) would have been visible from space, as Antarctic forests were replaced by a blanket of ice and seawater receded from the continents, changing the shapes of coastlines worldwide. The climate transition had global consequences for Earth's flora and fauna, both in the oceans and on land (Hutchinson et al., 2020; Coxall et al., 2005).

This climate transition has been identified as a possible palaeoclimate example of cascading tipping points in the Earth system (Dekker et al., 2018; Tigchelaar et al., 2011). Examples of climate tipping systems in this case consist of the global ocean circulatory system, the Antarctic ice sheet, polar sea ice, monsoon systems and tropical forests. In a conceptual model, the first part of the Eocene-Oligocene Transition is attributed to a major transition in global ocean circulation, while the second phase reflects the subsequent blanketing of Antarctica with a thick ice sheet (Tigchelaar et al., 2011). The glaciation of Antarctica also produced a sea level fall of several tens of metres, causing shallow seaways to recede, turning many marine regions into continental habitats (Toumoulin et al., 2022; Lear et al., 2008), see Figure 1.5.4.

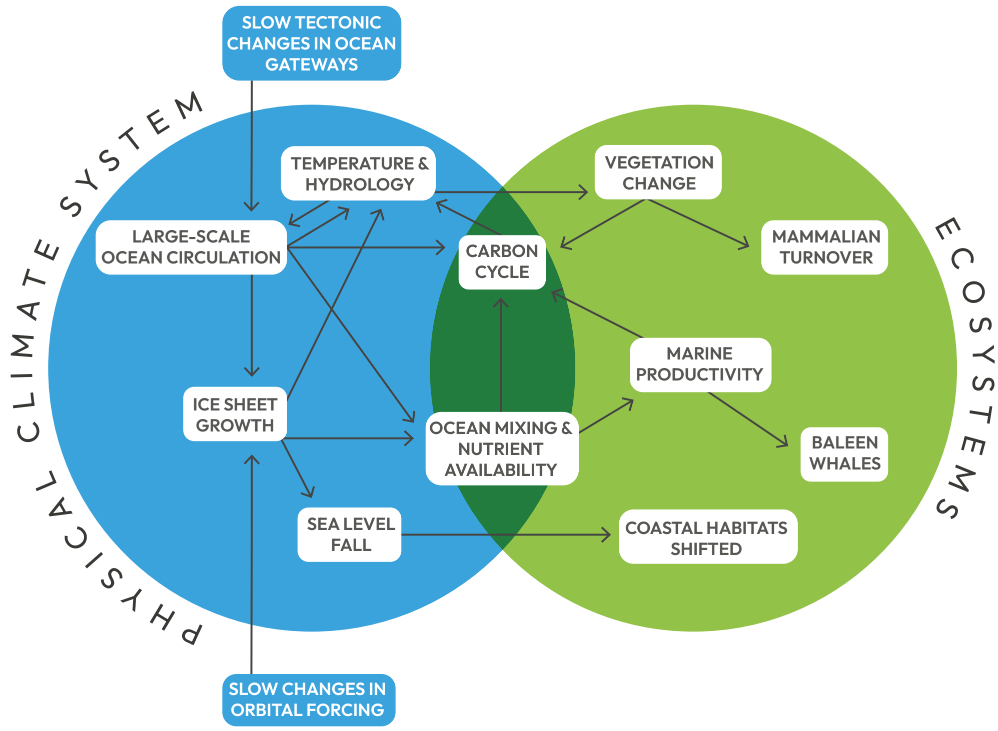

Figure 1.5.4: Conceptual linkages between changes in the Earth system associated with the Eocene-Oligocene Transition, 34 million years ago. External drivers were the slow changes in ocean gateways caused by tectonic plate movement, and slow changes in Earth's orbital configuration. The interactions and feedbacks within the Earth system act on different timescales, which makes the complete sequence of events complicated, but overall these processes resulted in Earth's Greenhouse-Icehouse Transition. There is a large uncertainty in all links portrayed. Adapted from: Wunderling and von der Heydt et al.

Ocean circulation

The global ocean circulatory system was showing tentative signs of change a few million years before the climate transition, likely caused by changing ocean gateways in the north Atlantic (Coxall et al., 2018). Isotope measurements suggest that a precursor to North Atlantic Deep Water reached the southern hemisphere close to the Eocene-Oligocene Transition, perhaps signalling the first onset of AMOC (Via and Thomas, 2006), but the exact timing remains uncertain.

Biosphere

Biomes in Earth's greenhouse state reflect warmer and wetter conditions than the icehouse state of the early Oligocene, but many of these seemed to have changed gradually as climate cooled in the Eocene, making it difficult to identify vegetation tipping systems following the glaciation of Antarctica (Hutchinson et al., 2020). The mammal fossil record, which is coupled to vegetation through diet, suggests more acute changes in the early Oligocene.

The Grand Coupure ('The Big Break'), is a long-known mammal extinction/origination event around the Eocene-Oligocene Transition, involving large-scale migrations of Asian mammals into Europe (Hooker et al., 2004). Thought to signal a combination of changing climate and floral changes, this abrupt faunal turnover might reflect the crossing of ecosystem tipping points caused by the crossing of a climate tipping point: a climate-biosphere tipping cascade.

In summary, Earth's Greenhouse-Icehouse Transition was likely associated with a range of interactions between components of the Earth system that are debated as potential tipping systems. Determining the extent to which these reflect a cascading series will require a major data-modelling effort, with improved correlations between marine and terrestrial records, and better constraints on the rate and magnitude of change within a range of tipping systems.

1.5.3.2 Interactions during and since the last glacial period

Here, we discuss three important palaeoclimate candidates for tipping interactions during and since the last glacial period.

Dansgaard-Oeschger events

Rapid, decadal-timescale Northern Hemisphere warming transitions known as 'Dansgaard-Oeschger' (D/O) events (Figure 1.5.5) occurred repeatedly during glacial periods throughout much of the late Pleistocene prior to the Holocene (Ganopolski and Rahmstorf, 2001). In general, these events consist of an abrupt (in the order of decades) warming from glacial to interglacial conditions, followed by gradual cooling over the course of hundreds to a few thousand years, before a rapid transition back to cold glacial conditions.

Evidence from Greenland ice cores and North Atlantic sediment records suggest that the abrupt cooling transitions were systematically preceded and possibly triggered by more gradual cooling across the high-latitude Northern Hemisphere (NGRIP project partners, 2004; Barker et al., 2015). The abrupt transitions from glacial to interglacial conditions were also preceded by more gradual changes elsewhere (for example, increasing Antarctic and deep ocean temperatures and decreasing dustiness; Barker and Knorr (2007)), leading to the idea that both types of transitions may be predictable to some extent (Lohmann, 2019; Barker and Knorr, 2016). Each event was also paired with rapid changes in ocean circulation, terrestrial hydroclimate, atmospheric composition and ocean oxygenation. The occurrence and interactions among many subsystems that show abrupt changes make it plausible then to consider it a cascade, and that such cascades are a common feature of late-Pleistocene climate variability.

During the abrupt warming phases of D/O cycles, an abrupt decrease of Arctic and North Atlantic sea ice cover likely contributed to the onset of convection and a rapid resurgence of a much weaker, and potentially even collapsed, AMOC (Gildor and Tziperman, 2003; Li et al., 2010: see 1.4.2.1). D/O-type changes in coupled climate models also feature a rapid disappearance of sea ice that precedes the abrupt AMOC strengthening (Vettoretti and Peltier, 2016; Zhang et al., 2014). Thus, the D/O warming events may potentially comprise a tipping cascade (Lohmann and Ditlevsen, 2021). However, such a cascading interaction may depend on the background climate state (i.e. only possible during glacial conditions), and it is unclear whether North Atlantic sea ice cover during the last glacial period can be considered a tipping system.

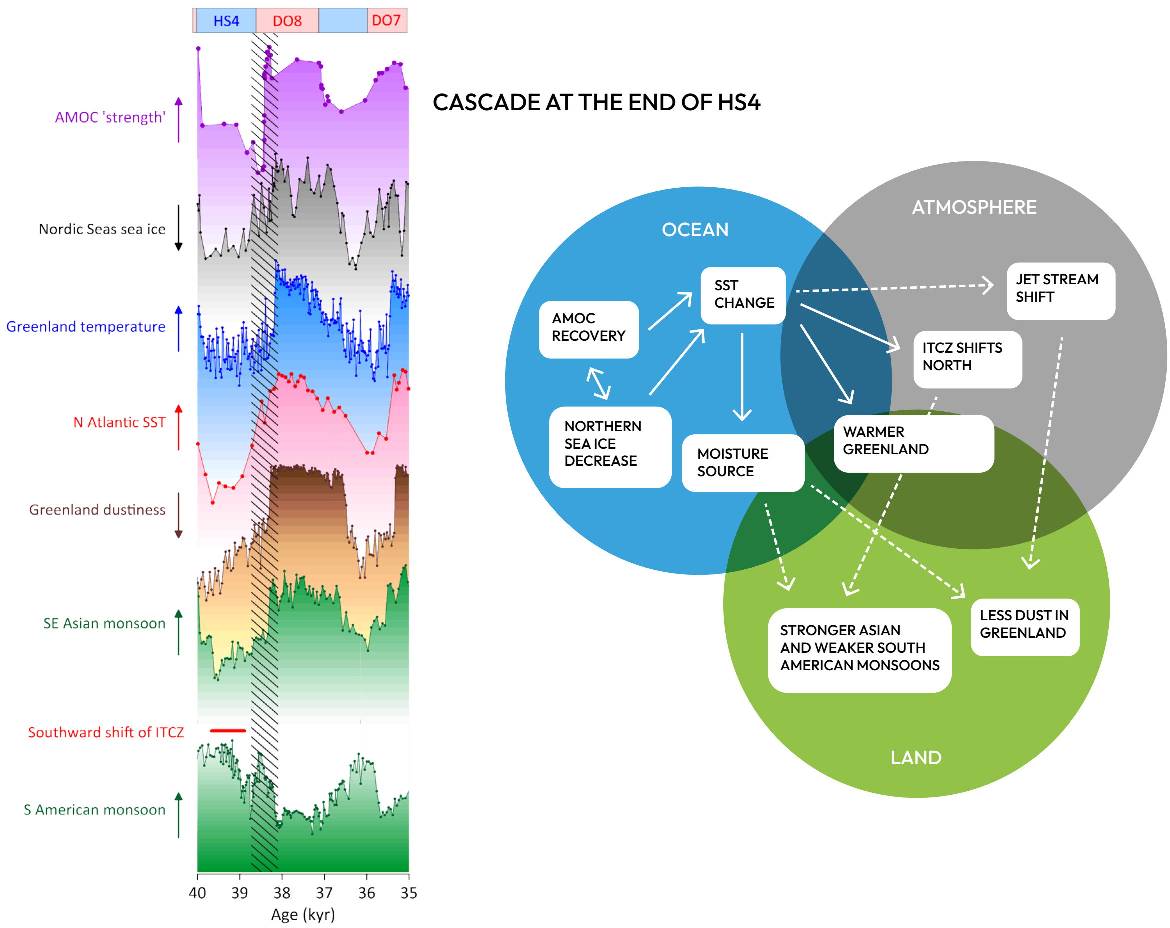

Figure 1.5.5: Interactions at the end of the Heinrich event 'Heinrich Stadial 4' (HS4). (a) Climate proxy indices spanning the transition from HS4 into Dansgaard-Oeschger (D/O) event 8 (time goes from left to right). From top to bottom: AMOC strength (Henry et al., 2016), Norwegian Sea ice cover (Sadatzki et al., 2020), Greenland temperature (North Greenland Ice Core Project members (NGRIP), 2004), North Atlantic SST (Martrat et al., 2007), Dust accumulation in Greenland (Ruth et al., 2007), Asian monsoon intensity (Cheng et al., 2016), South American monsoon intensity (Kanner et al., 2012). Horizontal red bar indicates period when ITCZ assumed a more southerly position (Wang et al., 2004). Hatched region spans the transition from HS4 to D/O8 and represents an estimate of the relative age uncertainty among the records shown (i.e. it is generally not possible to tell which changes occurred earlier or later within the overall sequence). Vertical arrows indicate the sense of increase for each parameter. (b) Interactions between ocean, atmosphere, and land during the end of HS4. Links with higher uncertainty are denoted by dashed arrows. Adapted from: Wunderling and von der Heydt et al.

Bølling-Allerød

Towards the end of the last 'ice age' glacial period, a very prominent climate event is recorded in numerous geological archives. The Bølling-Allerød (B/A) started 14,700 years ago with abrupt warming in the Northern Hemisphere (with temperature increase in Greenland by 10-14°C over a few years) in response to a reinvigoration of the AMOC (McManus et al., 2004) and lasted until 12,900 years ago. The B/A is an example of pronounced interactions between Earth system components and cascading impacts in the Earth system (Brovkin et al., 2021), potentially similar to a last D/O event during the ongoing deglaciation.

At the onset of the B/A, atmospheric CO_2 and CH_4 concentrations rapidly increased over a few decades (Marcott et al., 2014) in response to abrupt Northern Hemisphere warming and permafrost thaw (Köhler et al., 2014) and moisture changes (Kleinen et al., 2023). This was followed by fast changes in precipitation (e.g. Zhang et al., 2017) and vegetation composition (Novello et al., 2017; Fletcher et al., 2010). The trigger for the rapid amplification of ocean circulation and the associated abrupt impacts at the B/A transition has been a focus of debate, with opinions divided between an essentially linear response to the (possibly abrupt) cessation of freshwater forcing (Liu et al., 2009) versus a non-linear response to more gradual forcing (i.e. a tipping point – Barker and Knorr (2021); Knorr and Lohmann (2007); Chiessi et al. (2008)).

Heinrich events

While the exact causes and mechanisms of the B/A transition and D/O events are still under debate, Heinrich events are better understood. They occurred during some of the cold glacial phases mentioned above and were associated with major reorganisation of ocean circulation in the North Atlantic (for a review, see Clement and Peterson (2008)). During Heinrich events, large masses of ice were released from the Laurentide Ice Sheet, which at that point covered most of northern North America, leading to a dramatic freshening of the North Atlantic Ocean and enhanced suppression of deep-water formation and the AMOC (Henry et al., 2016). They can be understood as a phenomenon involving two tipping systems – the Laurentide Ice Sheet and the AMOC (referred to as 'binge/purge oscillator' – MacAyeal (1993)).

Heinrich events provide some, albeit not fully consistent, insights into the response of the Amazon rainforest to reductions in rainfall, and therefore shed some light on its resilience. Using isotopes from sediments, savanna intrusions into the Amazon rainforest have been found during repeated Heinrich events (Häggi et al., 2017). These intrusions occurred in northern Amazonia (Zular et al., 2019; Häggi et al., 2017) and validate the suggested decrease in precipitation over that region in response to AMOC weakening (Campos et al., 2019; see 1.4.2.3). While further palaeoclimate evidence showed that large parts of the Amazon rainforest were stable even when precipitation was relatively low (Kukla et al., 2021; Prado et al., 2013), in the present climate it is unclear how additional effects from deforestation (Zemp et al., 2017), future climate change (Wunderling et al., 2022) and increasing chances of fires (Drüke et al., 2023) will affect the stability of the rainforest in the future (1.3.2.1).

1.5.4 Interactions between tipping systems and planetary-scale cascades

Assembling the individual links mentioned in the sections before gives rise to the possibility of domino effect-style tipping cascades involving more than two elements. The likelihood of such domino effects clearly depends on the strengths of interactions between the tipping systems. These could lead to large changes at the regional and even planetary scale. A plausible palaeoclimate example are D/O events (section 1.5.3.2).

While unlikely, a major concern regarding the future may be that a cascade involving several tipping systems and feedbacks could lock the Earth system on a pathway towards a 'hothouse' state, with conditions resembling that of the mid-Miocene or even Eocene (around 4-5°C warmer, and sea level 10-60m higher compared to pre-industrial Holocene) (Burke et al., 2018; Steffen et al., 2018). Feedbacks that affect global temperature via albedo changes (through ice sheet or sea ice loss) and additional CO_2 and CH_4 emissions (through e.g. permafrost thawing or methane hydrates release) may lead to additional warming on medium to long timescales (Wunderling et al., 2020; Steffen et al., 2018). In a worst case (and unlikely) scenario, it has been speculated that a regional breakup of stratocumulus decks at atmospheric CO_2 levels above 1,200ppm could translate into a large-scale temperature feedback leading to a warming of roughly 8°C (Schneider et al., 2019; see 1.4.2.4).

Timescales are crucial when discussing hothouse scenarios. A potential hothouse state in the next few centuries seems implausible in light of the current state of research. For example, in climate projections up to 2100, CMIP6 models show no evidence of nonlinear responses on the global scale. Instead, they show a near-linear dependence of global mean temperature on cumulative CO_2 emissions (Masson-Delmotte et al., 2021). Similarly, in a recent assessment, it is concluded that a tipping cascade with large temperature feedbacks over the next couple of centuries remains unlikely and that, while the combined effect of tipping systems on temperature is significant for those timescales, it is secondary to the choice of anthropogenic emissions trajectory (Wang et al., 2023).

However, this does not completely rule out the possibility of a hothouse scenario in the longer term. Indeed, tipping events are not necessarily abrupt on human timescales. Positive/amplifying feedbacks could have negligible impacts by 2100, for example on global mean temperature and sea level rise, but still influence Earth system trajectories on a timescale of thousands of years (Kemp et al., 2022; Lenton et al., 2019; Steffen et al., 2018). Overall, this calls for experiments across the model complexity hierarchy. Earth system models of intermediate complexity in particular, and atmosphere-ocean general circulation models at coarse spatial resolution, offer an interesting trade-off as they include representations of most tipping systems while still allowing for long-term simulations.

Finally, spatial scales and patterns are relevant when it comes to risks of hothouse scenarios. Most examples of tipping cascades from palaeoclimate suggest that, while impacts are clearly global (e.g. greenhouse-icehouse transition, D/O events), the spatial expression of climate change (weather extremes, precipitation, seasonality) can vary greatly across the globe. Nevertheless, for societies, such cascades can be as dangerous as a global hothouse scenario, as are tipping cascades that do not lead to a hothouse but lock in other major harmful impacts such as a 'wethouse' scenario of tens of metres of sea level rise.

1.5.5 Final remarks

As anthropogenic global warming continues, tipping systems are at risk of crossing critical thresholds (Armstrong McKay et al., 2022). Several assessments have investigated the risk of crossing critical thresholds of individual tipping systems, whereas interactions between tipping systems are only more recently taken into account, mostly by conceptual models (e.g. Sinet et al., 2023; Wunderling et al., 2023b; Dekker et al., 2018).

Based on the current state of the literature, we conclude that tipping systems interact across scales in space and time (see Figure. 1.5.1 and 1.5.2), spanning from subcontinental to nearly planetary spatial scales and timescales from sub-yearly up to thousands of years. We find that many of the discussed interactions between tipping systems are of a destabilising nature (Figure 1.5.3), implying the possibility of cascading transitions under global warming. Of the 19 discussed interactions, 12 are assessed as destabilising, two are stabilising, and five are unclear (see Figure 1.5.1). Assessing the overall stability of the Earth system, and the possibility of a chain of nonlinear transitions, will however require more detailed assessments of their interactions, strengths, timescales and climate state-dependence.

While there is increasing research on individual thresholds of climate tipping systems, substantial uncertainties prevail in the existence and strength of many links between tipping systems. In order to decrease such uncertainties, we propose three possible ways forward:

(i) Observation-based approaches: Satellite observations, reanalysis and palaeoclimate datasets may be evaluated using correlation measures (Liu et al., 2023), or advanced methods of inferring causality (e.g. Runge et al., 2019; Kretschmer et al., 2016; Runge et al., 2015). In-situ monitoring is also very important for most of the tipping systems as well, and in particular for the biosphere (see Chapters 1.3 and 1.6).

(ii) Earth system model-based approaches: With recent progress, Earth system models of full or intermediate complexity could be used to evaluate interactions between climate tipping systems in detail at the process level, and quantify their interactions using specifically designed experiments (see Chapters 1.2, 1.3, and 1.4).

(iii) Risk analysis approaches: Since relevant parameter and structural uncertainties are large within Earth system models, analysing model ensembles with a considerable number of ensemble members is very helpful in order to comprehensively propagate uncertainties for risk assessments (Daron and Stainforth, 2013; Stainforth et al., 2007; Murphy et al., 2004).

(iv) Finally, all three approaches above have their limitations, and could probably benefit from direct expert input. Therefore, expert elicitation exercises on tipping system interactions remains of high value to update and move beyond early investigations of this kind (Kriegler et al., 2009).

To summarise, the approaches above (and likely more) are required to obtain more reliable estimates of the existential risks potentially posed by tipping events or even cascades (Kemp et al., 2022; Jehn et al., 2021). They could be used to inform an emulator model for tipping risks, taking into account properties of individual tipping systems as well as their interactions. In addition, there also exist large uncertainties, not only among the known interactions as discussed above, but also because not all interactions are known or quantified (i.e. known unknowns versus unknown unknowns).

Further, in certain systems there are forcings of non-climatic origin that could interact with climate change and lead to tipping, and thus to interactions and possibly cascades with other systems. For instance, land use change and specifically deforestation are threatening the Amazon and decreasing its resilience to climate change (e.g. Staal et al., 2020; Boulton et al., 2022) (1.3.2.1). Lastly, systems do not necessarily tip fully in one go, but can also have stable intermediate states (such as through the formation of spatial patterns). This has mostly been reported in ecological systems, but is not limited to them (Rietkerk et al., 2021; Bastiaansen et al., 2020).

Taken together, assessing and quantifying tipping system interactions better has great potential to advance suitable risk analysis methodologies for climate tipping points and cascades, especially because it is clear that tipping systems are not isolated systems. The relevance for developing such risk analysis tools to assess tipping events and cascades is clear given the potential for existential risks and long-term irreversible changes (Kemp et al., 2022).

1.6 Early warning signals of Earth system tipping points

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Summary

This chapter focuses on the methods used to predict the movement of parts of the Earth system towards tipping points. It begins by introducing the theory of critical slowing down (CSD), a general phenomenon of slowing recovery from perturbations that happens in many systems being forced slowly towards a tipping point. Then, it describes the various methods that can be used to estimate the occurrence of CSD and the approach of a tipping point, beginning with methods based on changes over time in the system, spatial changes, or changes in network structure, up to more advanced modelling techniques, including AI.

These 'early warning signals' (EWS) can be used on data from a number of different sources, be these models, field experiments or remotely sensed data from satellites. The chapter considers various case studies that use real-world observations, to show how these methods are being used to predict losses in resilience in these systems. Finally, it explores limitations and potential solutions in the field of EWS, looking ahead to advances in data availability and what this could mean for predicting the movement towards tipping in these systems in the future.

Key messages

- Early warning signals can be used to detect the potential movement of Earth's systems towards tipping points.
- The central western Greenland Ice Sheet, Atlantic Meridional Overturning Circulation, and Amazon rainforest all show evidence of loss of resilience consistent with moving towards tipping points.

Recommendations

- EWS can provide an indication of a tipping point approaching, and should be taken as a chance to prevent it from happening.
- Results from models need to be leveraged to identify which specific variables are most likely to display EWS as tipping points approach, so that these can be monitored with empirical data.
- Further investigation is required to explore the utility of machine learning for EWS and to detect the drivers of conventional EWS.
- Openly available datasets from on-the-ground sensors and measurements as well as remote sensing products provide an avenue for this EWS detection, however careful consideration is required to ascertain which variables are most appropriate and the limitations of existing remote sensing data.
- Future work should look to design remote sensing studies and data acquisition strategies that minimise the potential for biassing EWS such that false indications occur.

1.6.1 Theory and methods of early warning signals

While tipping points are often abrupt, rapid and irreversible, and may come as a surprise after only modest and smooth changes beforehand, they are not always unpredictable. Given their potential for disruption, there have been numerous attempts to identify when a system may be losing resilience and approaching a tipping point. These approaches, often called EWS, rely on monitoring the changes in the underlying behaviour of these systems across time and/or space prior to a transition. While these indicators are well grounded in theory, there are limitations to consider when transferring them to real-world systems.

Here, we introduce the theory of **critical slowing down** – the phenomenon that allows most of the EWS detailed here to be used. We then go into detail about the various methods used to predict the movement towards tipping points. These concepts are illustrated with real-world case studies from targeted climate and ecological systems. Finally, we explore some limitations of these methods, some potential solutions, and look ahead to potential future research in this field.

1.6.1.1 Theory of critical slowing down

The majority of studies on early warnings of Earth system tipping points are based on searching for evidence of CSD. Essentially, if a system is forced towards a tipping point, the state it currently occupies starts to lose its stability as the restoring feedbacks that 'pull' the system back to that state after it is perturbed start to weaken. If the system is forced sufficiently slowly that it can remain close to steady state, this causes the system to respond more sluggishly to short-term perturbations, and thus 'slow down' (Wissel, 1984).

Figure 1.6.1 shows this concept visually using the 'ball in potential well' analogy. When the system is more stable (represented by the well with steeper sides) recovery from any given perturbation is faster (the ball returns faster). A system closer to tipping (represented by a shallower well) has a slower recovery from the same perturbation (the ball takes longer to return). Eventually, the restoring feedbacks of the system become so weak at a tipping point that the stability of the initial state is lost, and the system moves to a new stable state. Before that point a random disturbance may cause the system to exit its initial state early.

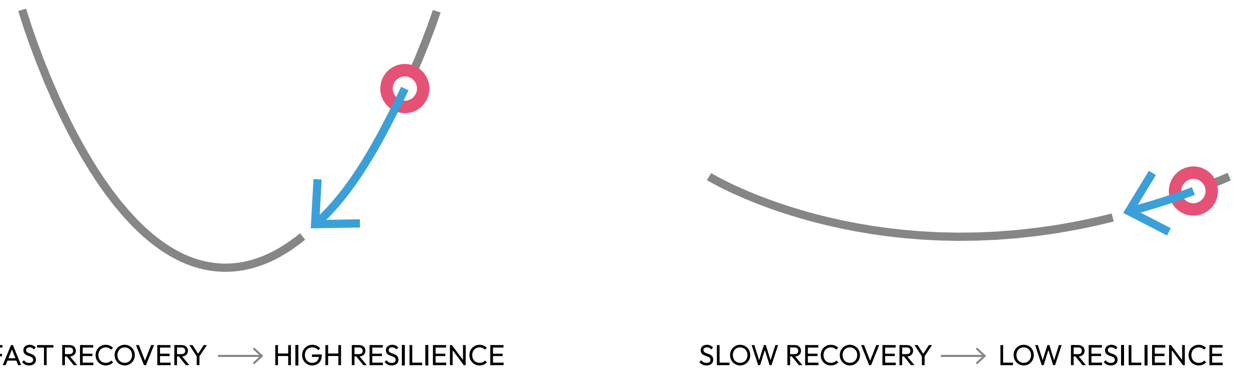

Figure 1.6.1: Using the 'ball in the well' analogy to compare a system that is (left) far from tipping, and (right) close to tipping. The system that is further away from tipping recovers faster from perturbations, the steeper sides of the well describing the stronger restoring feedbacks of the system. Close to tipping, the sides of the well are shallower, such that the system will take long to return from the same perturbation as the restoring feedbacks are weaker. Adapted from: Dakos et al. (2023).

The occurrence of CSD prior to a critical transition has been identified across numerous domains (Kubo, 1966; Kawasaki, 1966; Ferrell, 1970; Wissel, 1984; Dakos et al., 2023). In most cases, it mathematically involves the leading 'eigenvalue' of the system (which describes the strength of damping negative feedback) approaching 0 from below. However, in reality we typically do not have the equations that govern the system's dynamics, and as such have to estimate the occurrence of CSD with methods detailed in this chapter.

1.6.1.2 Temporal methods

One way to detect CSD is to measure the rate at which a system returns to its initial state following known disturbances. A resilient system with strong restoring feedbacks will return to its initial state faster than one which is near to a tipping point (Wissel, 1984). However, this method requires the occurrence of well-defined perturbations, as well as clear knowledge of when the equilibrium state of the system has been reached again, neither of which are always clearly defined in the real world. Hence statistical techniques are often used to detect CSD behaviour in the form of resilience loss of a system (resilience defined in this chapter as the ability to return to the equilibrium state) prior to a tipping point.

As a system approaches a tipping point and its recovery slows down, the system at each time step *t* is more correlated to the previous timestep, *t-1* (as shown in Figure 1.6.2). This can be measured with 'lag-1 autocorrelation' (or AR(1)) which measures a system's self-similarity through time, and tends towards 1 as a system experiences CSD prior to tipping to a different state (Scheffer et al., 2009); Visually, this can be viewed by observing a scatterplot of a section of the time series data of the system against the same section of time series lagged by one time point (Figure 1.6.2). When the system is far from tipping (left column Figure. 1.6.2), there is no relationship between the system now and with itself at the previous time step (i.e. low AR(1)). As the system approaches the tipping point, CSD means that there is a stronger correlation between the system now and with itself at the previous time step (and thus a higher AR(1)). Larger deviations in the red section of the time series can be seen, further showing this slowing down and increase in AR(1).

Similarly, as resilience is lost, a given perturbation will cause a greater movement of the 'ball' from Figure 1.6.1, meaning the variability (measured as 'variance') of the system is expected to increase. The system can sample more of its 'state space' (all the possible states the system can be in) due to the shallower well (Scheffer et al., 2009). Theory shows that because of CSD, AR(1) and variance should increase together in a characteristic fashion where their ratio remains constant. Hence an increase in both variance and AR(1) should be sought for robustness. However, there are other factors which can lead to a change in variance, such as a change in the variance of the system's external forcing (Ditlevsen and Johnson, 2010).

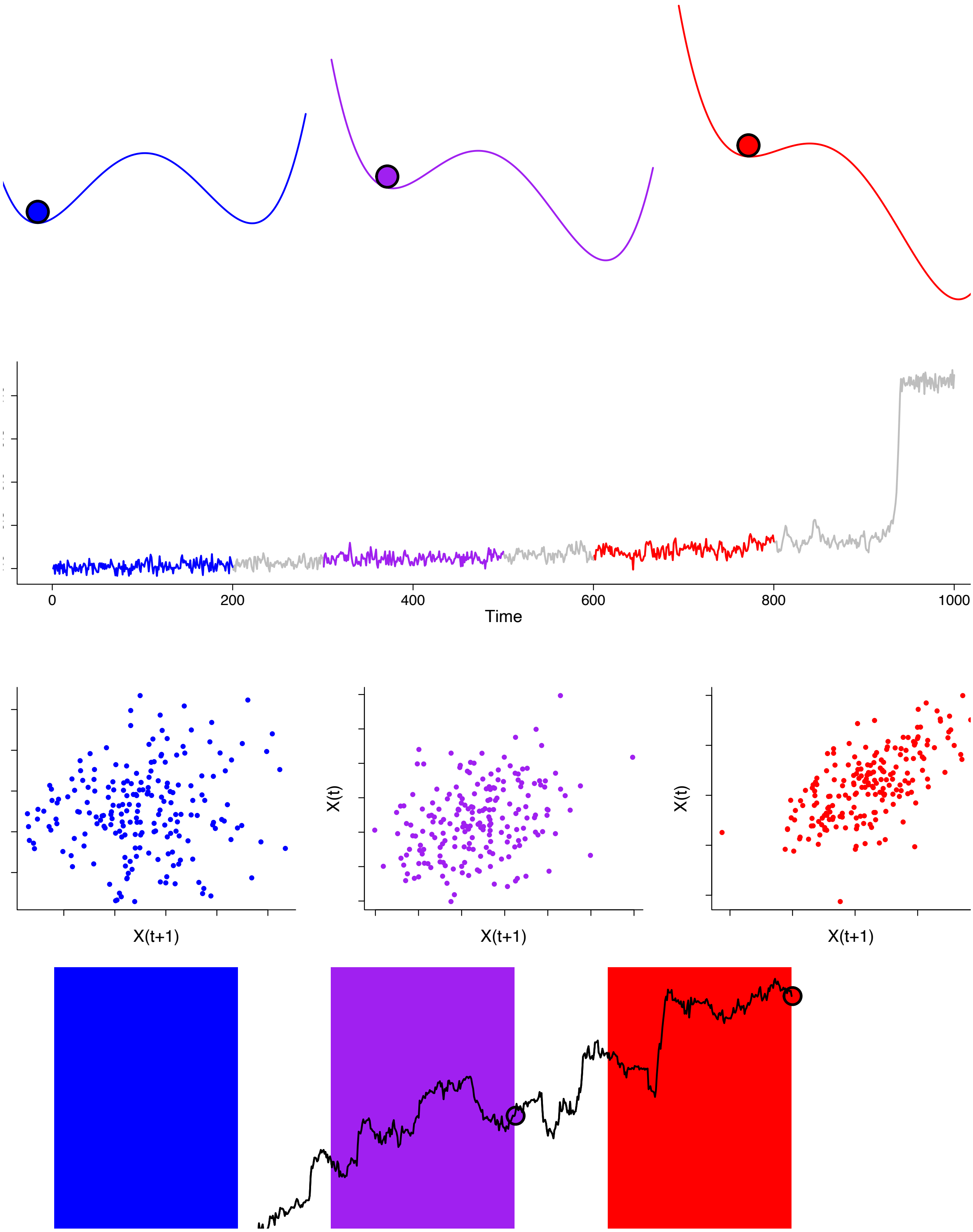

Figure 1.6.2: A comparison of the lag-1 autocorrelation (AR(1)) for a system that is far from tipping (blue), getting close to tipping (purple), and close to tipping (red). As the systems represented by the time series data approaches tipping (top row), there is no correlation between the time series and itself at the previous time point in the blue part of the time series, far from tipping. However, closer to tipping, in the purple and then red regions of the time series, there are correlations and thus higher AR(1) values. In the time series itself there are clear deviations towards the end compared to the beginning, suggesting CSD is occurring as the tipping point approaches. The EWS are calculated on a moving window (coloured regions in bottom plot). Here, AR(1) is shown at the end of the window used to calculate it, with examples shown as coloured points to match those windows on the detrended time series. Adapted from: Dakos et al. (2023).

For these time-based measures to be robust they require the time series data of the system to be stationary (i.e. the data's statistical properties do not depend on the time at which the data is observed). Multiple methods exist for removing non-stationarity, typically by detrending the time series (i.e. subtracting any trends). The EWS is then calculated on this detrended time series on a short section that shifts one time point at a time before recalculating (a 'moving window') (Figure. 1.6.2).

In our example tipping point, as the current steady state of the system is losing resilience and the probability to shift to an alternative state increases, the distribution of states of the system is expected to become increasingly skewed toward the alternative state (because of the increasing asymmetry of the potential well, see (Figure. 1.6.2). This can be quantified by the 'skewness' of the system, again measured on a moving window as described above. A change in skewness itself is not linked to CSD, but can be used as an EWS. 'Flickering' may also be observed before a tipping point, where sufficient noise can push a system temporarily into an alternative state before returning to the original with increasing likelihood as the system is approaching tipping (Wang et al., 2012; Dakos et al., 2013).

Once an EWS indicator has been calculated across a time series dataset, its tendency can be measured to determine if there is a movement towards tipping. Kendall's tau correlation coefficient is a common way to estimate trends. It is 1 if the time series of the indicator is always increasing (every value in the time series is higher than all of the previous values), -1 if it is always decreasing, and 0 if there is no overall trend. The significance of this trend can be calculated using null models that resample the time series such that the statistical properties of the system are maintained (e.g. mean and overall variance) but the memory of the system, such as changes in AR(1) and variance over time, are destroyed (Dakos et al., 2008). From these, the significance or p-value of an observed trend can be calculated. In practice, different detrending techniques and window lengths are used to test the robustness of EWS.

Particularly for temporal methods, there is a need to carefully consider the different timescales of the system. For EWS to work, a slow external forcing should move the system towards tipping, while faster 'noise' processes push the system away from equilibrium in either direction (noise can be thought of as short-term weather events in the climate system). This allows us to measure the return rate and other indicators on a time series from the system as it is monitored somewhere in between these timescales. The indicators may fail if, for example, the system is forced too fast towards tipping. This is further detailed in the Limitations section (1.6.1.6).

1.6.1.3 Spatial methods

Spatial analogues of the time-based EWS above exist too, allowing spatial information about a system within a single time step to be used. This can be considered as a space-for-time substitution, and eliminates the need for enough long-term data to have a moving window to measure AR(1) or variance on.

As a system approaches a tipping point, responding more sluggishly to external perturbations and sampling more of the state space, it is expected that there will be higher spatial autocorrelation and variance (Kéfi et al., 2014). This can be calculated, for instance, by Moran's I (Kéfi et al., 2014) and spatial variance (Guttal and Jayaprakash, 2009). The change in skewness observed in time series data also has a spatially analogous statistic (Guttal and Jayaprakash, 2009), noting again that this is not specifically related to CSD.

Some ecosystems have a clear self-organised spatial structure (e.g. drylands, peatlands, salt marshes, mussel beds; Rietkerk and van de Koppel, 2008). The emergence of such spatial patterns is thought to increase their resilience (Von Hardenberg et al., 2001), and could even allow them to evade tipping points altogether (Rietkerk et al., 2021). The size and shape of these patterns have been shown to change in a consistent way along stress gradients and have been suggested to be good candidate indicators of ecosystem degradation (Von Hardenberg et al., 2001; Rietkerk et al., 2002; Kéfi et al., 2007).

One of the most studied examples is the case of dryland ecosystems, where changes in the shape of the patch size distribution could inform us about the stress experienced by the ecosystem (Kéfi et al., 2007). As the stress level increases, the larger vegetation patches in the system fragment into smaller ones, which leads to a change in the shape of the patch size distribution from power law-like to a truncated power law (Kéfi et al., 2011). A number of metrics can be used to quantify the shape of the patch size distribution, such as the parameters of the best fit (e.g. the slope of the power law fit), the size of the largest patch in the system, or the power law range (Kéfi et al., 2014; Berdugo et al., 2017). We note that the use of spatial EWS is also dependent on some knowledge about the underlying system's spatial feedbacks (Villa Martín et al., 2015).

1.6.1.4 Network methods

Another way to monitor resilience loss in systems is to conceive of them as a network. In a spatial system, this would involve edges connecting neighbouring points. This framework can be applied to other, non-spatial, systems which are not necessarily linked in space but through other variables.

Multivariate systems (i.e. systems with multiple measurable variables) can pose problems for early warning signals. For instance, two different variables may give conflicting information, or obscure a clear signal (Boerlijst et al., 2013; Weinans et al., 2021). Multivariate systems relevant for climate science include examples such as interaction networks with different plant or animal species, or spatial systems where every grid cell can be represented as a variable in the system or a node in the network (Tsonis and Roebber, 2004; Donges et al., 2009).

Changes in network structure can show an approaching tipping point and have been observed in some systems, including climate (Lu et al., 2021) and lake systems (Wang et al., 2019). More generally, monitoring structural changes properties (e.g. connectivity, node centrality) in network systems (i.e. a network of interacting components, such as spatially connected sites, interacting actors, or species in a community (Mayfield et al., 2020; Cavaliere et al., 2016; Yin et al., 2016) can be used for EWS. Alternatively, correlations in time between components in multivariate systems has been used to construct an interaction network and analyse its structural properties (Tirabassi et al., 2014).

Once the nodes – or variables – are chosen, there are a number of ways the analysis can proceed. One such method evaluates network statistics. To create a network, the method calculates if the correlation between each set of two nodes is above a predetermined threshold and, if it is, connects the two nodes with an edge (a network connection). If this analysis is repeated on a moving window (measuring the correlation between two variables on a moving window like the temporal EWS), changes in the network topology (i.e. the arrangement of node connections) over time can be used as EWS. For instance, as the system moves towards a tipping point, the network will display a higher number of connections between nodes and an increase in variance in connections (Kuehn et al., 2013).

Unlike spatial methods, which examine a 'snapshot' of the system at a given time, these methods require the use of a time window to measure the changing structure on, and thus reasonably complete time series are needed. Another possible disadvantage is that, in some networks, the edges do not necessarily have a physical foundation (Ebert-Uphoff and Deng, 2012). Recent research explores a complementary approach where causal links are calculated instead of correlation links and the strength of the causal link works as the indicator of resilience (Nowack et al., 2020; Setty et al., 2023).

Alternatively, 'dimension reduction' techniques can capture overall network dynamics into a representative statistic. For instance, Principal Component Analysis (often referred to as 'Empirical Orthogonal Functions' (EOF) in climate science) can be used on a time series to get directions of change (Held and Kleinen, 2004; Weinans et al., 2019), although these linear projections may eliminate existing tipping points so care must be taken. It can often be used in spatial systems to detect the leading mode of variability over a region, such as a climate index like the Pacific Decadal Oscillation (Mantua and Hare, 2002). Next, data can be projected onto the leading principal component, effectively yielding a univariate (i.e. single variable) time series on which time-based univariate EWS can be calculated (Held and Kleinen, 2004; Bathiany et al., 2013; Boulton and Lenton, 2015).

From a network point of view, this analysis does not make any a priori assumptions about the interactions between the different network nodes, and is therefore quite flexible in its use. However, it requires large amounts of high-quality data to yield accurate results. The underlying assumption is that, as the system approaches the tipping point, the dynamics become more correlated, leading to a high explained variance of a PCA and clear directionality in the dynamics (Lever et al., 2020).

1.6.1.5 Model methods

As well as statistical and network methods that look for changing dynamics in a system, more complex methods can predict movement towards tipping points. One example is a generalised model approach, which integrates knowledge about the system into models and may allow us to estimate, for example, changes in the leading eigenvalue of the system once small model assumptions have been made (Lade and Gross, 2012). System-specific indicators can also be derived where understanding about processes in the system can help us to assess its resilience in novel ways (Boulton et al., 2013).

Machine learning (ML) techniques are now being applied to tipping point prediction. The documented success of neural networks for time series classification problems has inspired the development of similar ML methods specifically for EWS detection. There is a natural synergy to this approach in that the same CSD phenomena manifest across a wide range of systems approaching critical transitions, so the notoriously data-intensive task of training a neural network can be accomplished using plentiful synthetic data and still produce a result which can be applied to observational data (which is often more scarce and harder to label).

Deep learning models (which combine convolutional neural network layers with recurrent Long Short-Term Memory modules) have shown promise for EWS detection, outperforming methods using traditional statistical indicators (variance, AR(1), etc.) on a variety of test cases both real and simulated (Bury et al., 2021; Deb et. al., 2021). Furthermore, these models have exhibited success in inferring the *type* of oncoming bifurcation from observed pre-transition dynamics, and have performed well on rapid transitions in simple spatial models that evolve over time (Dylewsky et al., 2023).

Other ML techniques can also tell us something about how far systems are from tipping. For example, the 'random forest' method could be used to determine the factors that determine the AR(1) value in different areas of vegetation, and thus how close to tipping these areas could be, based on driving variables (Forzieri et al., 2022). Combining traditional EWS and ML techniques could provide some of the best prospects for monitoring systems that may be approaching tipping.

1.6.1.6 Limitations

There are some limitations to the EWS methods detailed here. These include, but are not limited to, availability of data used to monitor the systems, and the properties of the system assumed to be able to measure the EWS, such as the presence of a tipping point and the underlying timescales of the system.

Most importantly, it is worth noting that, for EWS to be used appropriately as an early warning of a tipping point, we require prior independent evidence that the system in question can actually exhibit tipping behaviour, as opposed to losing resilience with no tipping point or alternative state for the system to tip to. This evidence could come from established theory, models, or palaeo data. A subset of EWS can be used to monitor resilience in systems where a tipping is not necessarily expected, however these are not discussed here.

To make a robust assessment with EWS of a system, there is a requirement for high-quality data. Temporal EWS require a complete time series dataset which is sufficiently long to capture the relevant timescale of the system; infilling missing data points (which can be common in observational records) can interfere with the EWS, while shorter time series may not accurately detect changes in resilience.

Even with suitable amounts of data, there are inherent limitations associated with EWS. While theoretically, AR(1) should equal 1 when a system reaches a tipping point, these realworld systems are exposed to noise and can tip prior to this. Furthermore, the act of detrending the time series in the process calculating EWS changes the absolute value of AR(1). This means that, while EWS might tell us when a system is losing resilience, without a sufficiently dense dataset and knowledge about internal dynamics of the system, they cannot usually give a measure of the distance to a tipping point. However, robustly checking the tendency of these indicators (such as Kendall's tau) while varying the detrending technique and window length used to calculate the indicator on can provide useful information on the movement towards tipping.

Usually, it is assumed that a system approaching a tipping point is forced slowly towards it, and forced on shorter timescales by perturbations (which can be thought of as like weather in climate systems). It is generally assumed that this short-term noise is independent and identically distributed with a mean (average) of zero. This is unlikely to be the case in reality, with climate systems experiencing extreme weather events, for example, which are likely becoming more prevalent with the changing climate. Furthermore, extreme weather events would also increase the variance of the short-term noise over time, which also hampers the ability to use EWS indicators. To tackle this, we propose measuring EWS on the drivers themselves (e.g. on rainfall for vegetation systems) to check if changes in autocorrelation and variance in these are related to those found in the system being monitored.

Remote sensing products from satellite observations are a great resource of generally freely available data for using EWS on, and can enable complementary analyses to on-the-ground measurements of things that cannot be measured from space. They provide long records of climate systems, allowing us to create a long enough EWS indicator from which to get reliable results. However, due to sensor degradation and upgrades, it can be challenging to get a long time series from a single sensor, and products are often created from combined data sources. This can interfere with the EWS that we have described here, particularly AR(1) and variance, if this merging changes the signal-to-noise ratio (SNR) over time.

Newer sensors will measure with greater accuracy, increasing the SNR and in turn 'erroneously' increasing the AR(1) as far as an EWS is concerned, and a decrease in variance would also be expected. Anticorrelation between these two measures can show this is happening, whereas theory dictates that we should see an increase in both for a true EWS. In addition, newer remote sensors will also present shorter revisit times, as well as improved spatial resolutions, imposing the need to carefully consider the way data from different sensors are combined to produce long time series. Recently, we have become more aware of the effects of merging sensors and can prepare our analysis of these accordingly (Smith et al., 2023), such as only using data from a single sensor (Blaschke et al., 2023).

As well as questions around data availability and noise behaviour, the inherent timescale of the system being studied can hinder our ability to predict tipping points. While tipping is by definition a fast process, for slower-moving systems like the AMOC, the tipping event occurs over decades and it could therefore be difficult to detect the tipping point using EWS. Another example of this is the Amazon rainforest, where there is a slow decadal response of the forest based on climate change (1.3.2.1). It could take decades for dieback to occur even under a constant climate, such that a tipping point could be passed long before it is observed.

Part of the assumptions made around the occurrence of these EWS is that the system will approach a 'bifurcation' (a mathematically specific and common form of tipping point), rather than alternate forms of tipping. Alternatives include noise-induced tipping, where a system is shifted outside its stable state by a 'stochastic' (i.e. random) forcing, or rate-induced tipping, whereby a parameter changes too rapidly for the system to stay in the stable state (Ashwin et al., 2012). Rate-induced tipping can show some EWS (Ritchie and Sieber, 2016), such as threshold exceedance (detailed further in Chapter 2.5), while noise-induced tipping is generally unpredictable. For example, if the system is perturbed by something like an extreme weather event (e.g. a drought in the Amazon rainforest) such that it causes tipping by pushing the system past the ability for restoring feedbacks to return the system back to the previous state, CSD will not occur. However, bifurcation tipping and noise-induced tipping can be linked, whereby a system losing resilience approaching a bifurcation is more likely to be pushed to an alternate state by noise.

A related problem that may hamper EWS detection is that of cascading tipping points (see Chapter 1.5), where a tipping point in one system has a knock-on effect on another system, causing that to also tip. This can make it difficult for EWS to detect these tipping points, especially if the cascade causes instantaneous tipping points (a 'joint cascade') or happens soon after the first system tips (a 'domino cascade') (Klose et al., 2021).

Box 1.6.1: Use of early warning signals beyond climate and ecological systems

The EWS detailed here are not limited to use in climate and ecological systems; a recent study identified their use in other fields such as health, social systems and physical sciences (Dakos et al., 2023). Their utility in other domains is considered in later chapters in this report, specifically Chapter 2.5 - '*Early warnings of tipping points in socio-economic systems*' and Chapter 4.5 - '*Detecting "early opportunity indicators" for positive tipping points*'. Particular EWS of note which are used in these chapters include:

Lag-1 autocorrelation (AR(1)) – estimating critical slowing down (CSD), AR(1) in expected to increase as the restoring feedbacks of the system degrade such that the system slows and can be thought of as 'today is becoming more like yesterday'.

Variance – increases in variance are also expected due to CSD, as the system is able to sample more of the state space with weakened restoring feedbacks.

Skewness – not caused by CSD, skewness is expected to change as the potential well of the system changes shape, such that deviations or events become more pronounced towards the direction of tipping.

Full details of the indicators can be found in the relevant sections.

1.6.2 Case studies of empirically measured EWS

The EWS proposed above have been searched for in a number of real-world cases, using data from sources ranging from remotely sensed products from satellites to growth layers in marine bivalve shells.

A systematic review of academic papers that mention phrases associated with 'early warning' and 'tipping point', which we further filter based on using empirical data only, yields 229 studies, of which 33 are associated with the climate (Dakos et al., 2023); 22 of these climate studies find positive EWS, 1 negative, 9 mixed (from calculating EWS on different records and having conflicting results) and 1 inconclusive. These climate studies are further subsetted into palaeoclimate (12 total, 9 positive, 1 mixed, 1 negative), cryosphere (6 total, 3 positive, 2 mixed, 1 inconclusive), weather (3 total, 2 positive, 1 mixed), and modern climate, including AMOC collapse, El Niño, and monsoons, etc (12 total, 8 positive, 4 mixed). Overall, the most commonly used EWS are temporal AR(1) (17) and temporal variance (17 also, 13 of these using both together). Further details can be found in Dakos et al. (2023), and discussion of EWS beyond climate and ecological systems in Box 1.6.1.

Figure 1.6.3 below shows which climate systems have had studies searching for EWS of potential tipping points using empirical data. Below we detail some of these case studies specifically. We discuss where models suggest we may see EWS of climate tipping points and cases where empirical data has shown a loss of resilience in these systems. However, not all potential tipping points in the climate system have shown EWS in empirical data. In many cases this is due to observations being unavailable or the records being too short to see a significant movement towards tipping using EWS.

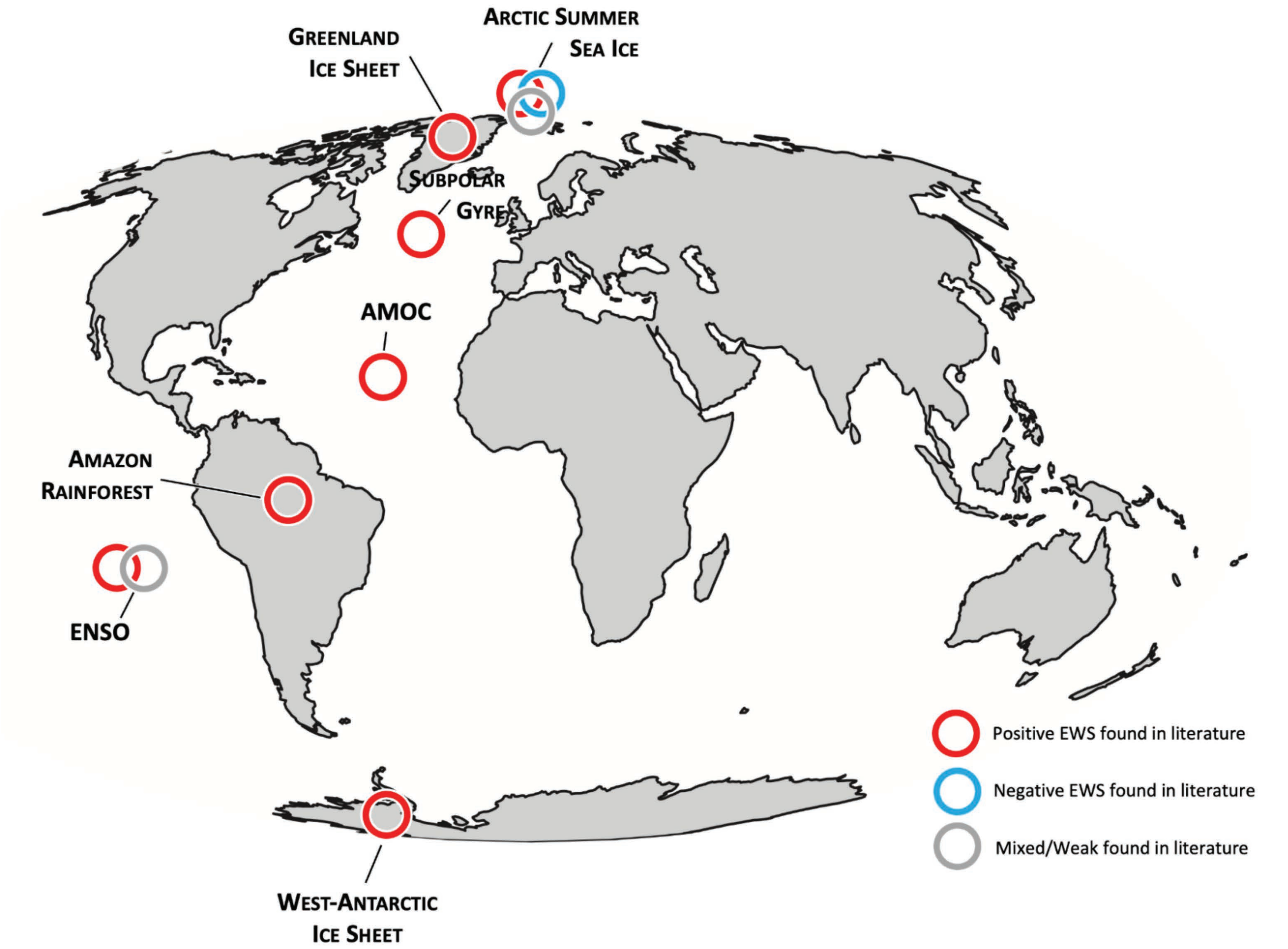

Figure 1.6.3: Map of studies that use empirical data to look for early warning signals (EWS) of tipping points in climate systems, and if they found evidence of EWS (red circles), no evidence (blue circles), or the evidence was unclear (grey circles). Specifically, these studies use real-world observations rather than being restricted to modelling studies.

1.6.2.1 Cryosphere: Ice sheets and sea ice

Ice sheets

Tipping points in the Greenland and West Antarctic ice sheets are detailed in Chapter 1.2, and several studies have looked for EWS. In West Antarctica, Rosier et al. (2021) searched for EWS for marine ice sheet instability on the Pine Island Glacier, identifying changes in recovery time and looking at the variance of the system state in a model. The EWS were applied to model output and successfully used to pinpoint tipping points. They find the tipping point that leads to total collapse of the glacier occurs at a +1.2°C ocean temperature increase, relative to initial conditions.

In Greenland, Boers and Rypdal (2021) found significant increases in variance and autocorrelation in detrended ice core-derived melt records from the central-western part of the Greenland Ice Sheet (GrIS), suggesting that this part of the ice sheet might be close to a tipping point. While they rule out that these EWS are directly caused by changes in temperature or precipitation, the exact mechanisms leading to the observed signs of stability decline remain unclear. The melt-elevation feedback (Levermann and Winkelmann, 2016) acts mostly on timescales longer than what can be captured by the data used by Boers and Rypdal (2021), so other positive/amplifying feedbacks related to much shorter timescales likely dominate.

As mentioned by Boers and Rypdal (2021) these include the melt-albedo feedback, related to snowline migration and albedo reductions once the uppermost, white firn layer has melted and the darker grey ice is exposed (Ryan et al., 2019), as well as thinning of outlet glaciers, which accelerates the ice flow upstream (Aschwanden et al., 2019).

Sea ice

Arctic sea ice loss has previously been proposed as a potential tipping system, but in this report both summer and winter sea ice loss are categorised as unlikely to feature tipping thresholds beyond which feedback-driven self-sustaining loss occurs, with other factors driving abrupt losses (1.2.2.2). In simplified models, however, Merryfield et al. (2008) found increasing variance and AR(1) in sea ice area before abrupt summer loss in a single column, two-season model. In another single-column model with a continuous seasonal cycle (Eisenman and Wettlaufer, 2009), Moon and Wettlaufer (2011) found that the destabilising ice-albedo feedback leads to CSD before the loss of winter sea ice.

While these results are apparently in agreement with expectations from simple dynamical systems, Arctic sea ice is an example of how additional caveats can obscure EWS, leading to 'false alarms'. Although attempts have been made using empirical data (Livina and Lenton, 2013), using total Arctic sea ice area as a variable could lead to misleading EWS, due to the different amounts of area masked by the continents in different climates (Goose et al., 2009; Eisenman, 2010). Moreover, several nonlinear feedbacks can dominate the recovery time and obscure CSD far from tipping; once ice gets thinner, its heat conductivity decreases, making its response to atmospheric temperature anomalies much faster (Thorndike et al., 1975). Also, a warmer Arctic means a longer period of open water after summer sea ice loss, which introduces a longer timescale. This effect is independent of the nonlinearity of the winter sea ice loss, and could cause EWS false alarms (Wagner and Eisenman, 2015; Bathiany et al., 2016a).

Alternative EWS which can also work in seasonal systems where the balance of feedbacks can change during the year (Moon and Wettlaufer, 2011) include measuring the amplitude and phase lag relative to the forcing (Williamson et al., 2016). Also, there are indications that abrupt loss of winter sea ice are still possible, but could potentially be predicted on the basis of the homogeneity in the ice-thickness distribution (Bathiany et al., 2016b; see 1.2.2.2).

1.6.2.2 Biosphere: Amazon rainforest dieback

Amazon dieback as a tipping point is observed in some modelled climate change scenarios (1.3.2.1). One such study shows that temporal EWS, such as increases in AR(1) and variance, are not necessarily good indicators of Amazon dieback in a number of HadCM3 GCM runs (Boulton et al., 2013). This is most likely because the Amazon is forced too fast and non-linearly for these statistical measures to work. Because of this, a system-specific indicator was suggested, looking at the sensitivity of ecosystem productivity anomalies to temperature changes, and then as a real-world measurable signal, the sensitivity of atmospheric CO_2 anomalies to these temperature anomalies. Both of these indicators worked well across the ensemble of runs.

Further work observes an increase in drying in the Amazon region across the recent CMIP6 model suite (Ritchie et al., 2022). An increase in the sensitivity of the temperature seasonal cycle amplitude to global warming is observed to be more prominent in locations that subsequently experience abrupt dieback shifts. The increasing sensitivity of the temperature seasonal cycle amplitude to global warming, therefore, has the potential to be used as a system-specific EWS for future dieback in the Amazon rainforest (Parry et al., 2022).

Real-world observational data has shown different results regarding the generic indicators discussed in this chapter, particularly the use of vegetation optical depth (VOD), a remotely sensed product that is strongly correlated with the amount of water content in the trees. Using this, increases in AR(1) and variance particularly since the early 2000s have shown a loss of resilience in the Amazon rainforest (Boulton et al., 2022). Using this same dataset, while modelling the water recycling network across the region (1.3.2.1), a network approach shows similar losses of resilience (Blaschke et al., 2023).

1.6.2.3 Ocean: Atlantic Meridional Overturning Circulation (AMOC)

The AMOC system has been identified as having the potential to collapse from its current strong state. One potential cause of this tipping point is the increased freshwater influx from a mix of increased precipitation and ice melt due to climate change (more detail on the mechanisms and likelihood given in 1.4.2.1).

EWS of AMOC collapse (Boulton et al., 2014) have been detected in a fully coupled climate model that was forced with a linearly increasing freshwater flux (Hawkins et al., 2011) – specifically increases in temporal AR(1) and variance in the strength of the overturning circulation. Furthermore, circulation strength at different latitudes are tested in this model, allowing the possibility to see where EWS may work best in the real world. A significant detection of the movement towards tipping could be seen up to 250 years in advance after 550 years of monitoring.

Direct measurements such as sea surface temperature and salinity across the Atlantic ocean can provide a real-world fingerprint of current AMOC strength. A recent study identified potential EWS of AMOC collapse using these measurements. In eight such indices, increases in AR(1) and variance are found over the last century and suggest that the AMOC could be approaching a tipping point to its weaker circulation mode (Boers, 2021). When extrapolated, these EWS of AMOC collapse give an indication of a mid-21st Century AMOC tipping point (Ditlevsen and Ditlevsen, 2023), although considerable uncertainty remains around these timelines (Ben-Yami et al., 2023; see 1.4.2.1).

Proxy records, such as bivalve shell increments, can provide an opportunity to measure early warning indicators prior to historical transitions. Recent work using three bivalve records has found that the North Atlantic Subpolar Gyre, a subsystem of the AMOC, destabilised prior to the transition into the Little Ice Age in the 14th century, with measurable EWS of AR(1) and variance prior to this transition (Arellano-Nava et al., 2022).

1.6.3 Recommendations and looking ahead

As detailed in this chapter, EWS can provide a way of detecting whether a system may be losing resilience and approaching a tipping point. This requires two elements: models to provide an indication of where tipping points and preceding EWS may be identified, and appropriate empirical data from the system (often remotely sensed) on which to calculate EWS. Future work in this field should be centred around this approach, and should aim to further our understanding of if (and when) a system may have a tipping point and increase the availability of tailored remote sensing products for empirically measuring these EWS.

1.6.3.1 Increasing data availability

Over the last decade, remote sensing data has gained greater prominence in assessing the possibility of climate and ecological tipping points (Dakos et al., 2023). This is linked to the increasing amount of open access data and the computational capacity to analyse it. Some datasets have been available since ~1972, thus giving us approximately 50 years of time series data to analyse. This provides users a long enough record from which to get statistically significant EWS (bearing in mind issues around merging data from new sensors; 1.6.1.6), and as such should be utilised as much as possible.

The use of remote sensed products can contribute in two different, and complementary, ways to detect EWS: direct and derived measurements. The use of direct observables, or low-level products, requires an advanced knowledge of the acquisition system to control and account for parameters that may affect the extraction of EWS in terms of the data's Signal-to-Noise ratio. Additionally, one could consider the use of derived measurements, or high-level products, which correspond to physical variables calculated from the aforementioned low-level products, such as NDVI ('normalised difference vegetation index') as a measure of vegetation greenness. These datasets can be more usable, but their second-order nature can present a source of uncertainty that may hinder the extraction of EWS. Nevertheless, both low- and high-level remote sensed data and products are considered in the extraction of domain-specific variables, such as climate, (Bojinski et al., 2014), ocean (Miloslavich et al., 2018) and biodiversity variables (Pereira et al., 2013).

The benefits of these growing and openly available remote sensing datasets are clear: new sensors are able to provide data with improved spatial resolutions (in the order of metres for optical and radar sensors) across very large areas, thus making possible improved analysis of both temporal and spatial EWS.

1.6.3.2 Models and EWS of tipping points

Earth system models can provide information on where to look for temporal and spatial EWS with empirical data, as well as to help determine what processes are most appropriate to monitor.

Systematic efforts to identify tipping points in Earth system models, such as the new Tipping Point Model Intercomparison Project (TipMip), will help to catalogue which variables we should focus on for different tipping points. For example, examining simulated sea surface height, temperature and salinity data prior to modelled abrupt shifts in the subpolar gyre, while incorporating known uncertainties in remote sensing, could determine which remotely sensed data are most informative and where additional monitoring could add value.

The unprecedented amount of Earth observation data originating from remote sensing systems, field measurements and simulated data, coupled with innovative Earth system models and cutting-edge computing, has made possible the concept of an Earth 'digital twin' that can be studied in detail. This concept will allow us to explore the different components of the Earth system and natural and human-induced changes to identify EWS.

1.6.3.3 Applications of AI for predicting tipping points

As alluded to earlier in this chapter, Artificial intelligence (AI), and in particular deep learning, is beginning to play an important role in tipping point prediction and EWS. With a wealth of data available now monitoring these systems, we can truly start to use these techniques alongside traditional EWS to attempt to fully understand Earth system tipping points. In addition to generic EWS derived from AI, we can conceive of system-specific AI-based EWS which are trained on models of specific climate tipping points. Eventually this might enable accurate prediction of critical thresholds in climate variables that would cause tipping, so that we can better predict when they would occur.

1.6.4 Final remarks

The EWS methods described in this chapter could be invaluable in understanding how climate and ecological systems are moving towards tipping points. A variety of different data types can be used to monitor the changing resilience of these systems, whether this be temporal, spatial, or more complex data. While many studies use models to test EWS, a number of studies already make use of real-world observations to do this. However, advances in machine learning techniques, in addition to longer and higher spatial resolution remote sensing products, can improve results. With these, we will be able to better determine with higher statistical accuracy if there are losses of resilience in systems, and in more systems than have been analysed so far.

1.7 Earth System Tipping Points Synthesis

In this chapter we present the key messages and knowledge gaps from this section on Earth system tipping points (ESTPs).

1.7.1 Key messages

Several key messages emerge from this section. Firstly, there is **considerable evidence for tipping points existing in many parts of the Earth system** (see Table 1.7.1 for summary). Several tipping points are likely in the cryosphere, at a large scale in ice sheets and on a more local scale in permafrost and glaciers. In the biosphere, evidence for regime shifts and tipping points exist in many ecosystems such as in tropical forests, savannas, drylands, lakes, coral reefs and fisheries, and are often spatially complex. Tipping points in ocean circulation and monsoons are also likely to exist, but the proximity of their thresholds are subject to high uncertainty. In contrast, some other suggested ESTPs have been assessed as unlikely in this report, including for Arctic sea ice, global-scale permafrost or glacier tipping, some types of lake ecosystem tipping, tropical clouds and climate sensitivity, and the El Niño–Southern Oscillation (ENSO).

Secondly, we know that **we could already be very close to some Earth system tipping points**. Several cryosphere tipping points cannot be ruled out at 1.5°C of global warming, which will be reached even with aggressive mitigation. These tipping points become likely beyond the 2°C of warming that the Paris Agreement commits countries to stay well below, but which current policies are likely to substantially overshoot (Climate Action Tracker, 2022; Meinshausen et al., 2022; IEA, 2023). In the biosphere, deforestation in the Amazon combined with climate change-induced drying could lead to regional dieback, some drylands are close to degradation tipping points, and coral reef die-off is already occurring in many regions. In the North Atlantic Ocean, convection in the Labrador and Irminger Seas could collapse within Paris Agreement warming levels of well below 2°C, with severe impacts across the North Atlantic region. Early warning signals indicate that several systems, such as parts of the Greenland Ice Sheet, Atlantic meridional overturning circulation (AMOC) and the Amazon rainforest may be losing resilience, which could mean their tipping points are approaching (but exactly when is uncertain).

Thirdly, **complex and sometimes uncertain interactions between tipping drivers, components of the Earth system and key feedbacks make tipping dynamics difficult to assess for some systems.** For example, parts of the Amazon rainforest could die back as a result of climate change-driven drying as well as direct deforestation and degradation, but while their combination makes tipping likely sooner, the thresholds for the combined effect of these processes is difficult to estimate. For many of the systems considered, key feedbacks and processes that could be involved in tipping are not well understood and so are either represented simplistically or left out of models (such as fire feedbacks, land use change, and spatial variability in the Amazon), making future projections more uncertain. Short observational records for some systems make early warning signals less reliable as well. Many tipping systems closely interact through the climate, and evidence – particularly from palaeorecords – suggests that most interactions mean one system tipping it tends to destabilise connected systems. Model limitations mean there are large uncertainties around these potential tipping cascades, but as warming approaches the levels where some key tipping points become likely, the possibility of cascades is a growing risk that requires new approaches to assess.

Together, this evidence provides strong motivation for both rapidly reducing human-driven pressures on the Earth system, from eliminating greenhouse gas emissions (GHG) and deforestation to increasing social-ecological resilience (see Section 3) and preparing adaptation plans for the societal impacts of Earth system tipping points (see Section 2) should some tipping points occur despite mitigation efforts.

Importantly, our assessment does not suggest that crossing major tipping points could lead to runaway warming, with mitigation to prevent further tipping points being worthwhile even if some tipping points are reached. Equally, uncertainties around tipping point thresholds and interactions makes mitigation even more critical, as we cannot rule out tipping happening sooner than we currently expect.

1.7.2 Recommendations

Our section presents clear implications, as well as multiple research and institutional avenues for improving our understanding of Earth system tipping points.

Firstly and most importantly, **reduction of human-driven pressures on the Earth system is critical in order to prevent destabilisation of the Earth's tipping systems**. In particular, most ESTPs considered in this section feature climate change as a key driver, and as such urgent and ambitious action to reduce GHG emissions to zero would reduce the chance of passing these tipping points. Many ESTPs in the biosphere are also driven by habitat loss and pollution – for example, deforestation and degradation in tropical forests or nutrient pollution in lakes and coastal ecosystems. Reducing these pressures would make climate-driven tipping less likely, as would efforts to bolster ecological resilience in these systems through restoration, legal protection and supporting sustainable livelihoods.

Secondly, **key knowledge gaps can be addressed through improved observations and models of varying complexity**. Despite our growing understanding of key Earth system feedbacks and interactions, some are currently not well represented in many computer models. As a result, tipping dynamics and interactions between tipping systems are less likely to emerge in model simulations, making comprehensive risk assessments difficult. To this end, it is necessary to better understand key feedbacks and interactions and resolve them in models, for example processes like marine ice cliff instabilities, feedbacks between meltwater and ocean circulations, small-scale mixing processes in ocean and atmosphere, and interactions between ecohydrological and fire feedbacks or spatial variability in the biosphere. These shortcomings can be systematically explored in tailored model intercomparison projects (MIPs), which are an established cornerstone of climate assessments. Insights from such modelling initiatives, together with palaeo evidence, observations and conceptual understanding of natural processes, can help guide the development of simpler models. Since their reduced complexity allows them to be run more often, they can help better understand uncertainties, for example around tipping point interactions, and can support interim risk analyses, together with expert elicitations.

Thirdly, **improved palaeo reconstructions and observational data are key, both for developing better models and determining what systems may be at most risk**. Remote sensing from space has allowed for global monitoring of vegetation cover over the last few decades, while in the ocean the RAPID array has allowed AMOC strength to be monitored for the past 20 years. However, these datasets are not yet long enough to be sure whether trends or early warnings they are detecting are outside of their natural ranges, while many parts of the ocean and biosphere have low observational coverage (in particular in the Global South). Continued and expanded observations would help improve and extend this coverage, while developing novel and improved early warning techniques could help mine this data to detect declining resilience and potential early warning signals. Of equal importance is the improvement of palaeo reconstructions, which in many cases has demonstrated that different systems have tipped in the past, including many ice sheets and the AMOC. As the observational period reaches back only a few decades, palaeorecords are essential to extend our observations into the past, to improve our understanding of the tipping systems and potentially provide critical information needed for early warning. International data sharing and collaboration is also vital for improving monitoring of ESTPs, as is improving coverage in under-represented areas such as Africa and Asia.

Finally, it is clear that multiple different approaches are needed to understand the complexities of Earth system tipping points. As a result, integrating and co-designing research across natural and social sciences as well as other knowledge systems, including Indigenous and traditional ecological knowledge, can help better understand the drivers, dynamics and impacts of tipping in the Earth system.

Table 1.7.1: Summary of key drivers, biophysical impacts and confidence in tipping dynamics for each system considered in Section 1.

Primary drivers, impacts and tipping systems are bolded. DC: Direct Climate driver (via direct impact of emissions on temperature/precipitation); **CA:** Climate-Associated driver (including second-order and associated effects of climate change); **NC:** Non-Climate driver; drivers can enhance (↗) the tipping process or counter it (↘).

Tipping point key: +++ Yes (high confidence), **++** Yes (medium confidence), **+** Yes (low confidence), **- - -** No (high confidence), **- -** No (medium confidence), **-** No (low confidence), ? unclear.

System (and proposed tipping point)	Key drivers	Key biophysical impacts *(see S2 for societal impacts)*	Evidence for tipping dynamics? *(+ yes, - no, ? uncertain)*
Cryosphere			
Ice Sheets (collapse)	**DC: atmospheric warming (↗)** **DC: ocean warming and circulation changes** (↗ GrIS, WAIS, EASBs / ↘ GrIS) DC: precipitation increase (↘) DC: black carbon deposition (↗) CA: sea ice decline (↗) CA: atmospheric circulation (?)	**Sea-level rise resulting in global loss of coastal land over centuries to millennia** Disruption of global ocean circulation Substantial shifts in atmospheric circulation patterns New ecosystems on exposed land	**+++ Greenland** **+++ West Antarctica** **+++ Marine basins East Antarctica** **++ Non-marine East Antarctica**
Sea Ice (loss)	**DC: atmospheric warming (↗)** DC: atmospheric circulation shifts (↗/↘) DC: ocean warming (↗) DC: ocean circulation shifts (↗/↘) DC: black carbon deposition (↗) DC: storminess increase (↗) CA: ocean stratification increase (↘)	**Regional warming (polar amplification)** Ecosystem disruption Impacts on ocean circulation Impacts on atmospheric circulations Increased evaporation	- - - Arctic summer - - Arctic winter - Barents Sea ? Southern Ocean
Glaciers (retreat)	**DC: atmospheric warming (↗)** DC: deposition of dust, black carbon etc. (albedo) (↗) DC: reduced snow (input and albedo) (↗) DC: local thermokarst (↗)	**Water supply decline** Ecosystem disruption (e.g. wetlands, water chemistry) Increase in number and size of glacier lakes Increase in slope instabilities Transition from glacial to paraglacial landscapes Sea-level rise	**++ (regional)** - - (global)
Permafrost (thaw)	**DC: atmospheric warming (↗)** **DC: ocean warming (subsea, ↗)** CA: vegetation change (increase: albedo ↗, increase summer shading ↘; vice versa for dieback) CA: wildfire intensity increase (↗) CA: precipitation (rain extremes, snow cover albedo ↗) CA: sea ice loss (subsea, ↗) CA: water pressure reduction (subsea, ↗)	**Greenhouse gas emissions** Landscape disruption Ecosystem disruption	**++ land (regional)** **- -** land/subsea (global, 10s-100s years)

System (and proposed tipping point)	Key drivers	Key biophysical impacts *(see S2 for societal impacts)*	Evidence for tipping dynamics? *(+ yes, - no, ? uncertain)*
Biosphere			
Tropical Forests (dieback)	**DC: atmospheric warming (↗)** **NC: deforestation/degradation (↗)** **DC: drying (↗)** **CA: increasing fire frequency/intensity (↗)** DC: heatwaves (↗) CA: ENSO intensification (e,g, Amazon, SE Asia, ↗) CA: AMOC/SPG weakening/collapse (e.g. Amazon, ↗) CA: terrestrial greening (↘, declining)	**Biodiversity loss** **Regional rainfall reduction (e.g. from Amazon dieback across Amazon Basin and Southern Cone)** Carbon emissions (amplifying global warming) Remote impacts on rainfall patterns all over the planet	**+++ (Amazon, local)** **++ (partial dieback/regional)** **+ (full dieback/continental)** **+? (SE Asia, local)** **- - (regional)**
Boreal Forests (dieback / expansion)	**DC: drying (↗)** **CA: fire frequency/intensity increase (↗)** **DC: atmospheric warming (↗)** **CA: permafrost thaw (↗)** **CA: insect outbreaks (↗)** NC: deforestation and degradation (↗) DC: heatwaves (↗) CA: terrestrial greening (↘) CA: vegetation albedo (↗) CA: sea ice albedo decline (↗) DC: precipitation changes (?)	**Biodiversity loss** Carbon emissions (amplifying global warming) from southern dieback, carbon drawdown (reducing global warming) from northern expansion Complex regional biogeophysical effects on warming - dieback = higher albedo (cooling) but less evaporative cooling (warming) and vice versa for expansion	**++ Southern dieback (partial/regional), + (continental)** **+ Northern Expansion (partial/regional)**
Temperate Forests (dieback)	**DC: atmospheric warming (↗)** **DC: droughts (↗)** **DC: heatwaves (↗)** CA: insect outbreaks (↗) CA: windthrow (↗) NC: deforestation and degradation (↗) CA: fire frequency increase (↗) NC: fragmentation (↗)	**Biodiversity loss** Carbon emissions (amplifying global warming) Regional warming in summer due to less evaporative cooling, less cloud cover Less atmospheric water supply Less groundwater recharge	? (partial / regional)
Savannas and Grasslands (regime shifts)	**NC: fire suppression (↗)** **NC: overgrazing (↗)** DC: increased precipitation intensity (↗) CA: terrestrial greening (↗) NC: afforestation (↗) CA: regional circulation changes (e.g. Sahel) (↗)	**Biodiversity loss** Greater groundwater depletion (with shrub encroachment) Nutrient cycle disruption Reduced fires (with shrub encroachment)	**++ (local to landscape),** ? (regional)

System (and proposed tipping point)	Key drivers	Key biophysical impacts *(see S2 for societal impacts)*	Evidence for tipping dynamics? *(+ yes, - no, ? uncertain)*
Drylands (regime shifts)	**DC: drying (↗)** **DC: atmospheric warming (↗)** **NC: land use intensification (↗)** DC: extreme events (heatwaves, floods) (↗) DC: increased rainfall variability (↗) CA: terrestrial greening (↘) CA: insect outbreaks (↗) CA: invasive species (↗)	**Biodiversity loss** Aridification/desertification Groundwater depletion (with encroachment) Regional rainfall changes Shift in species composition (e.g. shrub encroachment)	**++ (local to landscape), + (regional)**
Freshwater / Lakes (regime shifts)	**NC: nutrient pollution (↗)** **CA: terrestrial greening (↗)** **NC: afforestation (↗)** DC: atmospheric warming (↗) DC: precipitation changes (↗) CA: permafrost thaw-related thermokarst formation/ drainage (↗) CA: glacier lake formation/drainage (↗) DC: drought (↗) CA: warming-driven species range expansion (↗) CA: water use intensification (↗) NC: human-mediated species introduction (↗)	**Biodiversity loss** **Water quality decline** Increased GHG emissions from most (reduced for salinisation)	**+++ (eutrophication- driven anoxia , widespread localised)** **++ (DOM loading, widespread localised in boreal)** - (lake (dis)appearance, widespread localised in tundra) - (N to P-limitation switch, localised in high N-deposition regions) - (salinisation, localised in arid regions)) - (invasive species, widespread localised)
Coastal - warm-water coral reefs (die-off)	**DC: ocean warming (↗)** **DC: marine heatwaves (↗)** **CA: disease spread (↗)** CA: ocean acidification (↗) NC: water pollution (nutrient / sediment) (↗) NC: disruption (ships, over-harvesting) (↗) CA: disease spread (↗) CA: invasive species (↗) DC: storm intensity (↗) CA: sea level rise (↗)	**Biodiversity loss (ecosystem collapse, ~25% marine species have life stages dependent on coral reefs)** Loss of commercial and artisanal fisheries, and other sectors Coastal protection loss	**+++ (localised).** **+++ (regionally clustered)**
Coastal - mangroves and seagrass meadows (die-off)	**DC: increased climate extremes (e.g. tropical cyclones, marine heatwaves, El Niño intensity, droughts) (↗)** **NC: habitat loss (agri/aquaculture) and degradation (fishing damage) (↗)** **CA: sea level rise (esp. mangroves, ↗)** **NC: nutrient pollution (↗)** **NC: shoreline change (erosion, sedimentation) (↗)** DC: ocean warming (seagrass, ↗) CA: disease spread (seagrass, ↗) NC: invasive species (seagrass, ↗)	**Biodiversity loss** **Loss of coastal protection** Loss of carbon sink/increased GHG emissions Loss of water quality Sediment salinisation Subsidence Enhanced sediment sulphide and methane releases Hypoxia (seagrasses) Reduced nutrient recycling	**++ (mangroves, regional)** **++ (seagrasses, regional)**

System (and proposed tipping point)	Key drivers	Key biophysical impacts *(see S2 for societal impacts)*	Evidence for tipping dynamics? *(+ yes, – no, ? uncertain)*
Marine ecosystems and environment (regime shifts)	**NC: over-exploitation (↗)** **DC: ocean warming (↗)** **NC: water pollution (nutrients/sediment) (↗)** NC: habitat loss (↗) DC: marine heatwaves (↗)	**Keystone species collapse** **Trophic cascades** **Regime shifts** Changes to carbon sequestration Impacts on ocean biogeochemistry Major changes in ocean productivity, biodiversity and biogeochemical cycles	**+++ (cod fisheries, regional)** **+ (large fish fisheries, regional)** - (small fish fisheries, regional) **+ (marine communities, local)** **+++ (kelp forests, local)** ? (lipid pump, regional) - - (gravitational pump, regional)) **+ (marine hypoxia , ? (regional to global)**
Ocean/Atmosphere Circulation			
Ocean overturning (collapse)	**DC: ocean warming (↗)** **DC: precipitation increase (↗)** **CA: ice sheet meltwater increase (SO ↗, primary in the future for AMOC/SPG)** **CA: river discharge increase (AMOC/SPG ↗)** CA: sea ice extent and thickness decrease (↗) DC: regional aerosol forcing increase (↘) CA: regional ocean circulation changes (?) CA: wind trends (SO,↗) CA: sea ice formation (SO, ↗)	**Cooling, change in precipitation and weather over Northern Hemisphere** **Change in location and strength of rainfall in all tropical regions** Reduced efficiency of global carbon sink, and ocean acidification Deoxygenation in the North Atlantic Change in sea level in the North Atlantic Modification of sea ice and arctic permafrost distribution Change in winter storminess Reduced land productivity in Atlantic bordering regions Increased wetland in some tropical areas and associated methane emission Change in rainforest response in drying regions Modification of Earth's global energy balance, timing of reaching 2°C global warming Reduced efficiency of global carbon sink Change in global heat storage Reduced support for primary production in world's oceans Drying of Southern Hemisphere Wetting of Northern Hemisphere Modification of regional albedo, shelf water temperatures Increase in summer heat waves frequency Collapse of the North Atlantic spring bloom and the Atlantic marine primary productivity Increase in regional ocean acidification Regional long-term oxygen decline Impact on marine ecosystems in the tropics and subtropics.	**++ (AMOC)** **++ (Subpolar Gyre)** **++ (Southern Ocean)**

System (and proposed tipping point)	Key drivers	Key biophysical impacts *(see S2 for societal impacts)*	Evidence for tipping dynamics? *(+ yes, - no, ? uncertain)*
Monsoons (collapse / abrupt strengthening)	**DC: increased water vapour in atmosphere (ISM ↘, WAM/ SAM ↗)** **NC: increased summer insolation (↘)** **DC/NC: increased aerosols, dust (↗, ?)** NC: land-cover change, e.g. deforestation (↗) CA: desertification (↗) CA: regional SST variations (?) CA/NC: regional soil moisture/veg. variation (?) CA: ENSO/Indian Ocean Dipole change (?) CA: AMOC slowdown (SAM, WAM ↗) CA: low cloud reduction (ISM ↘) CA: ocean warming (ISM ↗)	**Massive change in precipitation** Change in tropical and subtropical climates Biodiversity loss and ecosystem degradation	**+ (West African monsoon)** ? (Indian Summer monsoon) ? (South American monsoon)
Tropical clouds and circulation (reorganisation)	**DC: atmospheric warming (↗)** DC: ocean warming (↗)	Massive alteration of hydrology in many regions Impact on ambient atmospheric phenomena such as ENSO Strong intensification of global climate change	- -
ENSO (more extreme or permanent)	**DC: East vs west Pacific warming (↗)** **DC: increased water vapour in atmosphere (↗)** DC: weaker trade winds (↗) CA: MJO strengthening (↗)	Temporary trade wind collapse during El Niño phase Increase in global mean surface temperatures during El Niño phase Modification of global atmospheric circulation Modification of worldwide patterns of weather variability	- -
Mid-latitude (shift to wavy-jet)	**CA: AMOC slowdown (↗)** **CA: Mid-latitude flow weakening (↗)** **DC: Arctic amplification (↗)**	More persistent and slower-moving weather patterns Increase in extreme events on Northern hemisphere	-

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Section 2

Tipping point impacts

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Section summary

Earth system destabilisation and tipping points can have far-reaching and catastrophic consequences across various critical sectors. Assessments of climate change often overlook the consequences of climate tipping points, with national evaluations lacking in-depth quantitative analysis and relying on expert opinions. These tipping points, including permafrost thaw and forest dieback, can lead to localised effects through land surface changes and regional climate alterations, as well as global impacts through shifts in atmospheric and oceanic circulations. Such changes carry the potential for severe impacts on people and ecosystems, including major impacts on water, food, energy security, health, communities and economies.

Climate change, especially if compounded by Earth system destabilisation, has the potential to set off negative social tipping points that would lead to catastrophic impacts for human societies. Such tipping points could encompass a breakdown in social cohesion known as anomie, manifesting as a loss of shared values and norms. This, in turn, could foster radicalisation and polarisation, driving societies ideologically further apart. Destabilisation caused by environmental shifts could lead to societies tipping into anomie, radicalisation, widespread displacement of populations, conflict over limited resources, and economic instability.

Negative social tipping points could reinforce each other in domino-like cascades, creating systemic risk, amplifying impacts and potentially accelerating climate change. These social tipping points and cascades mean the future will not adhere to 'business as usual'; rather, it will be defined by either constructive mitigation and adaptation to climate change or negative social change impeding the realisation of sustainable futures.

Confidence in many impacts is presently low, due to the lack of systematic assessments and the difficulty of forecasting social change. Investments are urgently needed to better understand potential impacts and negative social tipping, anticipate them through early warning systems, and develop actions to mitigate them.

Key messages

- Earth system tipping points have the potential for major, severe impacts on people and biodiversity.
- Negative social tipping points triggered by climate change could have catastrophic impacts on human societies.
- Negative social tipping points could cascade to create systemic risk.
- Early warning signals can be used to anticipate impact tipping points.

Recommendations

- Improved assessments of the impacts of Earth system tipping points and negative social tipping points are urgently needed.
- Assessment of the interactions of impact tipping points and possible cascades should be improved.
- Invest in early warning of both Earth system tipping points and negative social tipping points, in order to provide increased opportunity to pre-emptively adapt and reduce vulnerability to their impacts.

2.1 Tipping point impacts

Introduction

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A separate glossary of the terms ***in bold*** *is included as an appendix.*

In Section 1 of this report, we examined the unsettling possibility of negative tipping points in the Earth system, where vital components that regulate the Earth's climate, such as the cryosphere, biosphere, oceans and atmosphere, can abruptly shift. But the impacts of negative climate tipping points are not confined to isolated environmental disruptions: they have consequences for human societies.

In Section 2, we shift the spotlight to these human impacts. We first unpack the impacts of the negative Earth system tipping points on human societies (Chapter 2.2), then explore how Earth system destabilisation could trigger 'negative' tipping points in human societies (Chapter 2.3). When these thresholds are met, they can trigger cascading effects across systems that might also impact the Earth system (Chapter 2.4). Finally, we give a summary of the potential to implement early warning systems for tipping points (Chapter 2.5). Governance to limit tipping points risks is dealt with in Section 3, while 'positive' societal tipping points, where societies transform to respond to the threats of climate and environmental change, are dealt with in Section 4.

The concepts of 'negative social tipping points' and 'systemic risk' are crucial to understanding this section. **Negative tipping points** are those that are predominantly harmful for humans and the natural systems we depend upon. Here, the word 'negative' is used in the value-based sense, not in the mathematical sense. **Negative social tipping points**, therefore, describe critical junctures within societies where small changes in biophysical drivers lead to 'negative' social, economic, or political change. For example, conflict tipping over into violence in the Lake Chad basin has likely partly been triggered by the shrinking lake.

These tipping points can have different drivers. We limit our scope to negative social tipping points driven by change in the Earth system, while acknowledging that social drivers also contribute to enabling these tipping points. We acknowledge that 'negative' is a value judgement, as one person's negative outcome may be another's positive outcome, but in the most general sense, we consider a change to be negative when it is predominantly damaging for humans and the natural systems we depend upon. The repercussions of such tipping points extend far beyond their immediate contexts, impacting essential aspects of human wellbeing such as health (physical and mental), human security, and provisioning of other ecosystem services.

As societies grapple with the dual challenges of Earth system and social tipping points, the concept of **systemic risk** has gained prominence (Juhola et al., 2022; Kemp et al., 2022; Centeno et al., 2015). This refers to a critical aspect of complex systems where the functioning of an entire system is compromised due to the interactions among its components (Sillmann et al., 2022). The idea is that the failure of one component can trigger a chain reaction of failures in other components, propagating the negative effects across the system, leading to widespread and often unforeseen consequences across the entire system. This can occur not only within a single system but also across different systems and sectors (e.g. ecosystems, health, infrastructure and the food sector) via the movements of people, goods, capital and information within and across boundaries (e.g. regions, countries and continents).

The main insights of each chapter are as follows. Chapter 2.2 assesses the impacts on people of the Earth system tipping points introduced in Section 1. These impacts have received relatively little, and uneven, assessment, with most existing assessments (such as the IPCC reports) focusing on the impacts of linear climate change**.** The chapter examines potential impacts of Earth system tipping points from two perspectives. First, it considers the impacts that may arise from a selection of Earth system tipping points. For example, tipping of ice sheets will amplify sea level rise, potentially exposing half a billion people to coastal flooding annually. Collapse of the AMOC would impact temperatures, precipitation and sea level worldwide. Permafrost thaw and Amazon dieback would affect water supply, built infrastructure, ecosystems and food supply in the affected areas, in addition to their global impacts via amplifying global warming through carbon release. Second, the chapter looks at specific impact sectors, including water security, food security, energy security, health, ecosystems, communities and economies, and considers how each could be affected.

Chapter 2.3 demonstrates that climate change, potentially compounded by Earth system tipping points, could trigger negative social tipping points including eroded social cohesion, forced displacement, amplified polarisation, and security and financial destabilisation. These could also further accelerate climate change, including Earth system tipping, by undermining cooperation, resilience and response capacity.

Negative social tipping points herald the end of 'business as usual': human societies face a stark choice between an increasing risk of damaging, negative social tipping points or acting to accelerate positive change that mitigates Earth system tipping points and the risks they pose (Section 4).

Just as Earth system tipping points could trigger each other like a series of dominoes (Section 1, Chapter 1.6), Chapter 2.4 shows that negative societal and ecological tipping points could themselves form cascades. This is a key source of systemic risk that could amplify the impacts of global changes, including Earth system tipping points, on humans. These tipping cascades are not unidirectional: disruptions in social systems can, in turn, alter how communities affect climatic and ecological changes (see Figure, 2.3.1). For example, conflict in the Lake Chad Basin has led to breakdown in governance of the region's water resources and fisheries, leading to further degradation of those resources. This highlights how disruption in one domain can amplify disruption in others, underscoring the significance of these cross-sector interactions.

Amid the potential for negative social tipping points, the importance of early warning signals (EWS) emerges as an opportunity to enable proactive resilience. Anticipating the onset of tipping points, whether environmental or societal, may help decision makers avert or mitigate catastrophic outcomes. The concept of EWS for climate tipping points has been introduced in Section 1 (Chapter 1.5). Chapter 2.5 shows how similar methods can be used to anticipate negative social tipping points. However, the application of EWS methods to social-ecological systems differs from that to the physical Earth system due to their distinct characteristics and dynamics, presenting unique challenges. Specifically, human-influenced systems often involve a mix of social, economic and ecological components, making them inherently heterogeneous; human systems can exhibit abrupt changes on shorter timescales due to societal, economic or policy changes; and data availability in social-ecological systems can vary widely, with relevant data coming from mixed sources such as social media, economic reports, ecological surveys and remote sensing technologies.

To illustrate tipping point impacts, we give examples from different regions throughout Section 2. These examples highlight the diversity of tangible impacts on humans of tipping points in the coupled Earth-human system. We outline the impacts across systems and sectors. Our assessments are based on both empirical and modelling evidence. Together the evidence presented in this section provides strong motivation to swiftly act to minimise the risks associated with crossing Earth system destabilisation and tipping points including the negative impacts associated with them.

Further assessments of impacts of Earth system tipping points and negative social tipping points are urgently needed. Impacts of Earth system tipping points have received little attention in climate assessments and risks of negative social tipping points and their cascades have received almost no systematic analysis prior to this report. Our analysis of them is largely qualitative and case-based due to the limited available research. Given the catastrophic risks that negative Earth system and social tipping points pose for humans, substantial investment is needed to understand these risks, anticipate them with early warning signals, and govern them where possible.

2.2 Assessing impacts of Earth system tipping points on human societies

Authors: Richard Betts, James G. Dyke, Elizabeth Fuller, Laura Jackson, Laurie Laybourn, Norman J. Steinert, Yangyang Xu

Summary

Assessments of climate change effects on humans and ecosystems have previously included only limited information on the consequences of climate tipping points. While some national evaluations have touched on tipping point implications, assessment has been largely qualitative, with minimal quantitative analysis. Understanding and quantification of impacts of tipping points is recognised as a significant knowledge gap, and improving the research base in this area is essential for climate risks to be fully evaluated.

This chapter examines the current knowledge of Earth system tipping point impacts on people, exploring the evidence on impacts from individual tipping points, and assessing specific sectors and their vulnerability to these tipping points. Localised effects arise when climate tipping points, such as permafrost thaw and forest dieback, are crossed. These effects stem from land surface changes and alterations in regional climates and weather extremes. Global impacts manifest through large-scale shifts in atmospheric and oceanic circulations, altering global warming rates and sea level rise. Oceanic dynamics, like collapse of the AMOC, can reshape regional climates and cause widespread shifts in temperature and precipitation patterns. Similarly, cryospheric tipping points, such as marine ice cliff collapse, have the potential to accelerate sea level rise, affecting flooding hazards like coastal inundation. Biosphere tipping points, such as Amazon dieback, intensify greenhouse gas concentrations, hastening global warming and its associated extreme weather events, regional climate shifts and sea level rise.

All these have the potential to impact the security of water, food and energy, human health, ecosystem services, communities and economies. The body of evidence varies across tipping points and sectors, but the implications for profound impacts across all areas of human society are clear.

Key messages

- Earth system tipping points have the potential for severe impacts on people and biodiversity.
- Amazon dieback, ice sheet collapse, permafrost thawing and AMOC collapse are the most-studied tipping points for impacts, each having the potential for impacts on water, food and energy security, health, ecosystem services, communities and economies.
- Amazon dieback could put 6 million people at risk of extreme heat stress and cause US$1-3.5 trillion economic damages.
- Antarctic ice sheet instability leading to a potential sea level rise of 2 metres by 2100 would expose 480 million people to annual coastal flooding events.
- Permafrost thawing already damages property and infrastructure; 70% of current infrastructure in permafrost regions is in areas with high potential for thaw by 2050.
- An AMOC collapse would disrupt regional climates worldwide, substantially reducing vegetation and crop productivity across large areas of the world, with profound implications for food security.

Recommendations

- Improved assessments of the impacts of Earth system tipping points are urgently needed.
- Existing international, national and local risk assessments and adaptation plans should give deeper consideration to the implications of Earth system tipping points through the systematic use of available Earth system models, impact models and storylines of tipping point scenarios.
- Risk assessments should include the implications of tipping points for both the likelihood of more severe impacts and the uncertainties in possible outcomes, with consequent challenges for effective adaptation planning.
- Improved interdisciplinary collaboration between natural and social scientists is needed to ensure adequate representation of risk when assessing the economic impacts of crossing Earth system tipping points.
- Assessments should go beyond economic damages to broader human, social and cultural impacts of crossing Earth system tipping points, starting with food and water security; effects on infrastructure, housing and 'loss of place'; health and liveability; movement of people, capital and material; cognitive and emotional impacts; cultural and identity changes; and international relations, etc.

2.2.1 Introduction

Earth system tipping points have the potential for major impacts on human societies by altering or magnifying the regional and global consequences of anthropogenic climate change (Figure 2.2.1). Regional and local impacts may occur as a result of passing tipping points such as permafrost thaw and forest dieback, some related directly to impacts on the land surface and others due to effects on regional climates and weather extremes. Global impacts may occur via large-scale alterations to atmospheric and ocean circulations, and also potentially by altering the rate and magnitude of global warming and/or sea level rise.

Tipping points in the coupled ocean and/or atmosphere dynamics, such as shutdown of the Atlantic Meridional Overturning Circulation (AMOC), could have substantial influences on regional climates which are opposite to those expected without tipping – e.g. local cooling instead of warming. For tipping points that accelerate global warming and/or sea level rise, the impact relative to 'non-tipping' climate change projections would be to bring forward the timing of the hazard relative to levels of vulnerability, exposure and adaptation, potentially increasing the overall impact if there has been less time for societies to adapt. Passing tipping points in the cryosphere such as marine ice cliff collapse could lead to acceleration of sea level rise and/or commitment to greater long-term rise, both of which would affect the timing of increases in flooding hazards such as coastal inundation and storm surges. Biogeochemical tipping points such as Amazon forest die-back and permafrost thaw could potentially accelerate the increase in greenhouse gas concentrations in the atmosphere and hence accelerate global warming, leading to more rapid changes in the frequency or magnitude of extreme weather events, faster shifts in regional climates and more rapid sea level rise.

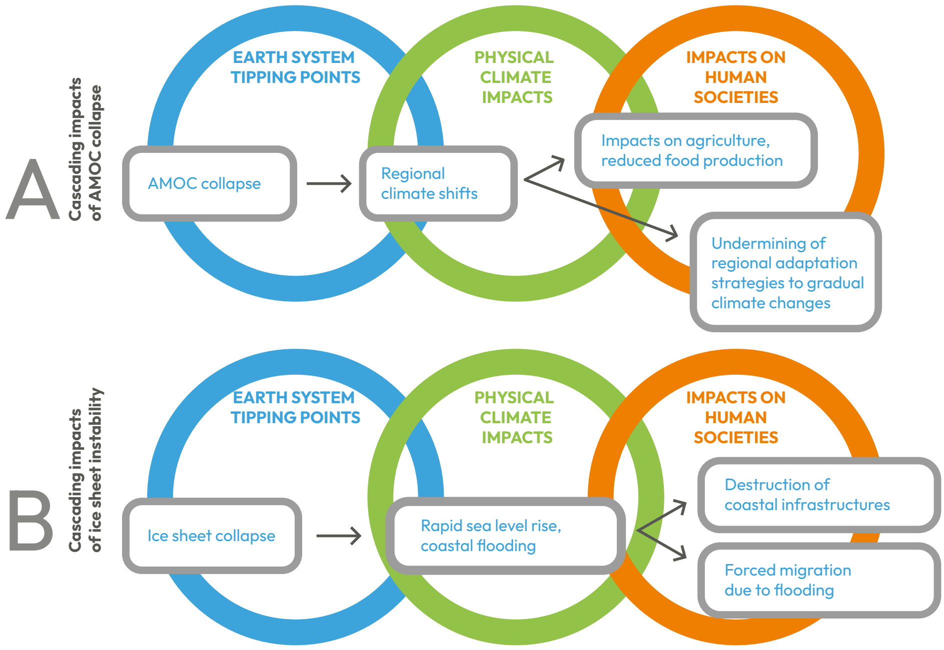

Figure 2.2.1: Selected impact pathways of negative Earth system tipping points. a) Cascading impacts of AMOC collapse, b) cascading impacts of ice sheet instability.

So far, systematic assessments of the impacts of climate change on people and ecosystems presented in policy-relevant reports such as those of the Intergovernmental Panel on Climate Change (IPCC) and Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) have generally included little information on the implications for human societies of passing tipping points in the Earth system. This is also true of broader economic modelling of climate damages. While some national climate assessments, such as the UK's third National Climate Change Risk Assessment (CCRA3) have included some consideration of the implications of tipping points (Hanlon et al., 2021), this has so far been limited in extent and often qualitative in nature. Quantification of the potential impacts of climate system tipping points is therefore widely recognised as a major knowledge gap.

This section will assess the current state of knowledge of the impacts and risks to people and ecosystems from specific Earth system tipping points, in comparison with projections that do not consider tipping points. Where possible, we draw on existing literature for this. Where literature does not yet exist, we use process understanding and expert judgement to assess how future projected impacts may change as a result of passing different tipping points.

We examine the potential impacts of Earth system tipping points from two perspectives. First, we consider the impacts that may arise from a selection of individual Earth system tipping points, grouped into cryosphere, biosphere and ocean-atmosphere circulation tipping points. Second, we consider specific impact sectors and discuss how each could be affected by individual climate system tipping points and, where information is available, by combinations of tipping points.

2.2.2 Impacts of cryosphere tipping points

2.2.2.1 Ice sheets

The most widespread physical impact of changes in ice sheets is rising sea levels. Sea level rise contributions from ice sheets in the present day represent around 1.45 mm of sea level rise per year (IMBIE Team, 2018). Under future climate change, the proportion of contribution coming from ice sheets will increase. However, typical modelling approaches struggle to accurately represent ice sheet dynamics, leading many studies to underestimate projections of sea level rise (Siegert et al., 2020).

Reconstructing past ice-sheet change and sea level rise can provide an analogue for sea level rise under tipping points. Around 125,000 years ago, when it was around 1°C warmer than today, it is estimated that global sea levels were around 6-9m higher than present (Dutton et al., 2015). Periods of very rapid sea level change have previously occurred, potentially up to 4m per century. These 'melt-water pulses' are thought to have occurred during periods of ice sheet collapse (International Cryosphere Climate Initiative, 2023).

Today, modelling estimates that total loss of the Greenland Ice Sheet (GrIS) could lead to a total of 7.5m additional sea level rise (Morlighem et al., 2017). While the Antarctic Ice Sheet is much larger, and has a greater sea level potential, the East Antarctic Ice Sheet is more stable and less susceptible to tipping elements. However, much of the West Antarctic Ice (WAIS) Sheet is grounded below sea level, making it more susceptible to processes associated with large-scale ice loss. The estimated possible contributions from the WAIS are around 5m of sea level rise (Pan et al., 2021). While complete loss of all ice sheets is highly unlikely, significant losses from the WAIS and GrIS could be triggered at relatively low levels of warming (1.5-3°C). Ice sheets respond relatively slowly to change, meaning substantial mass loss would likely occur over thousands of years, if triggered (Armstrong McKay et al., 2022).

Using 'structured expert judgement' (SEJ) in the IPCC 6th Assessment Report, Fox-Kemper et al., (2021) explore a 'high-end storyline' of ice sheet loss under a high-emissions scenario to complement standard modelling approaches. The storyline explores substantial contributions from Greenland and the Antarctic to sea level rise (including MICI and MISI, although it does not require both). This is a qualitative approach, and describes how projections of high sea level rise should not be ruled out. Fox-Kemper's projections show up to 2.3m rise by 2100 (95th percentile, SSP5-8.5) and, while they are low-confidence, this storylines approach shows they cannot be discounted, based on process-based understanding of possible tipping points within the cryosphere. Passing ice-sheet tipping points accelerates the rate of sea level rise and dramatically increases the magnitude of impacts (Armstrong McKay et al., 2022). Acceleration of melting ice sheets cannot be reversed or stopped on the timescales of millennia. Exploring such high-end scenarios is important for adaptation approaches where there are low risk tolerances, such as the construction of nuclear power sites at coastal locations.

Rising sea levels have the most immediate and significant impact upon coastal communities, with numerous detrimental consequences (Figure 2.2.2). Around 10 per cent of the global population live within 10m of sea level worldwide, with most of the world's megacities located within coastal areas (Neumann et al., 2015). This low-elevation coastal zone (LECZ) also generates around 14 per cent of the world GDP (Kummu et al., 2016). The inundation of coastal regions would lead to flooding of cities, damage to costly infrastructure, and even the complete loss of low-lying nations such as the Marshall Islands. Inundation of coastal regions would also impact natural systems, in turn resulting in negative impacts for fishing, agriculture, tourism and other ecosystem-based services. Such changes might force migration and would result in severe economic damages.

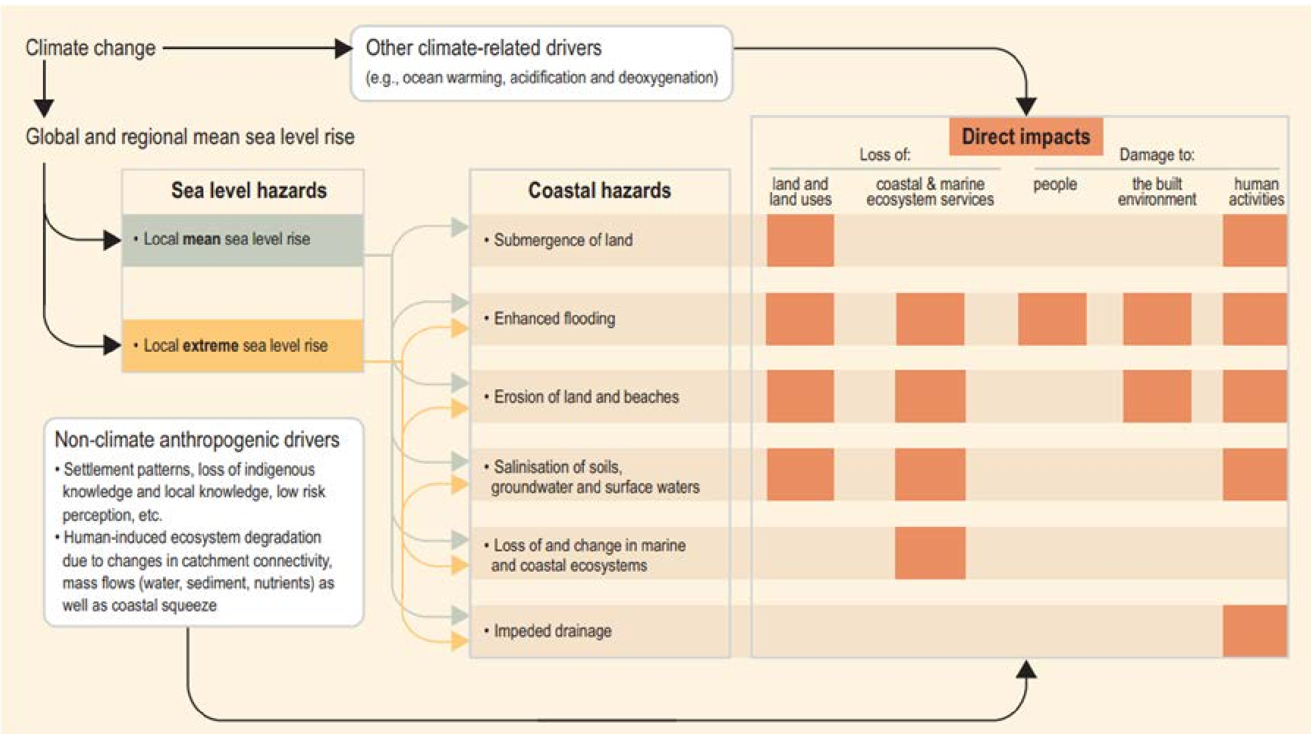

Figure 2.2.2. Cascading impacts of rising sea levels across systems, reproduced from Oppenheimer et al., 2019. Sea level rise and consequent impacts could be accelerated by crossing tipping points in ice sheets or the AMOC.

Under 1.5°C global warming by 2100, (Rockström et al., 2023) project that as many as 170 million people could be exposed to sea level rise. Population exposure increases significantly to 500 million over the long term (multi-century sea level rise), based on no adaptation and static population dynamics (Figure 2.2.3). One study estimates that, in a case of Antarctic instability (where sea level rise reaches over 2m by the end of the century, in line with the 'high-end storyline' presented in the IPCC 6th Assessment Report (Fox-Kemper et al., 2021) a total of 480 million people (based on current population dynamics) would be vulnerable to an annual coastal flood event by 2100 (Kulp and Strauss, 2019).

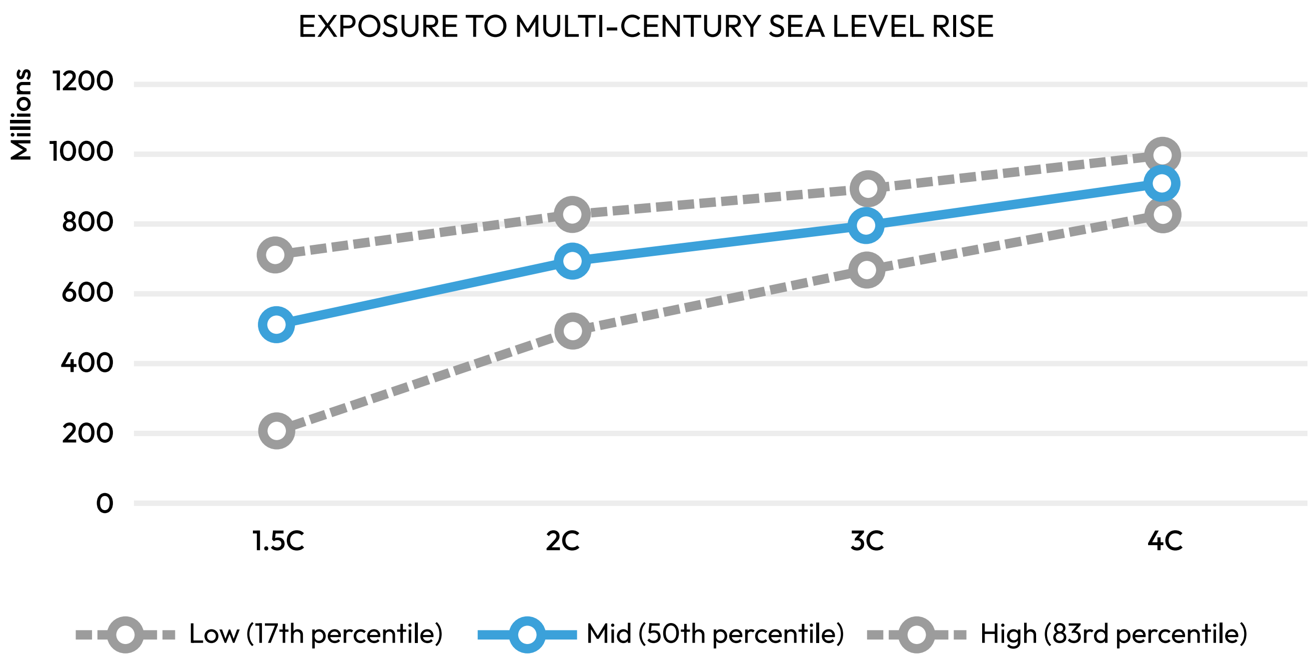

Figure 2.2.3. Projected number of people exposed to multi-centennial sea level rise including the impacts of cryosphere tipping points under a global mean temperature rise stabilised at 1.5°C, 2°C, 3°C and 4°C global warming, with population at 2010 levels Data source (Rockström et al., 2023).

Bangladesh, India, Indonesia and the Philippines are projected to experience the highest increases in populations living within the flood risk zone, increasing vulnerability in the nations. Such changes threaten populations and may result in displacement, with migration putting pressures on inland areas and cascading impacts across systems (Hauer et al., 2017).

The loss of atoll island nations is one of the most well-known examples of impacts from ongoing sea level rise (Oppenheimer et al., 2019) and begs many legal questions, including whether the loss of a nation results in 'statelessness', as well as having implications for access to resources such as maritime fishing zones, upon which communities depend (Hauer et al., 2020; Vidas et al., 2015).

The effectiveness of adaptation options under rising sea level, and the ability to adapt, remains a knowledge gap (Magnan et al., 2022). Limits to adaptation action will be reached in many different types of coastal environments within this century, even before tipping points are considered. It is suggested that 1m of global sea level rise would present challenges to adaptation approaches (O'Neill et al., 2017), leading to significant questions about our ability to adapt to high-end scenarios of sea level rise triggered by passing tipping points (see further discussion in Chapter 3.3).

2.2.2.2 Sea ice

Sea ice hosts unique ecosystems and plays a central role in marine life, influencing marine organisms and food webs by impacting on the penetration of light into the ocean and supplies of nutrients and organic matter (Cooley et al., 2022). Ongoing reductions in Arctic sea ice due to rising temperatures can therefore be expected to have direct impacts on biodiversity in the Arctic ocean. Moreover, reductions in sea ice cover in the Arctic lead to increased temperatures in the region due to decreased surface albedo, especially in summer when ice extent is at its annual low and daylight hours are long. This ice-albedo feedback is a key reason for the regional warming in the Arctic being four times the global rate of warming over the last four decades (Rantanen et al., 2022), contributing to the impacts of rising temperatures on ecosystems in the region and also potentially influencing climate change impacts at global scales by increasing the net energy imbalance of the planet. Reductions in summer sea ice have economic implications by opening routes for shipping and increasing access for fossil fuel extraction and export (Challinor and Benton, 2021), as well as mineral extraction. Arctic warming also has the potential to impact the jet stream and hence affect regional climates beyond its borders, although the current and future impacts of this remain uncertain (Barnes and Screen, 2015).

2.2.2.3 Permafrost

As a consequence of global warming and human-induced climate change, the thawing of permafrost not only contributes to global greenhouse gas (GHG) emissions and warming, but also poses substantial risks to both local ecosystems and human communities in affected regions (Figure 2.2.4). Permafrost thaw interacts with various climatic and human factors at a regional level, leading to significant alterations in geomorphology, hydrology and ecosystems (due to thermokarst and hillslope failures), thaw dynamic succession, biomes (e.g. plant communities influencing carbon balance), biogeochemical fluxes, tundra plant and animal ecology, and the functioning of lake, river and coastal marine ecosystems (Schuur and Mack, 2018; Vincent et al., 2017, Knapp & Trainor, 2015). The hydrological dynamics of affected areas are also disrupted, impacting water availability and quality. These alterations, in turn, have cascading effects on the frequency and magnitude of natural disasters such as floods, landslides and coastal erosion.

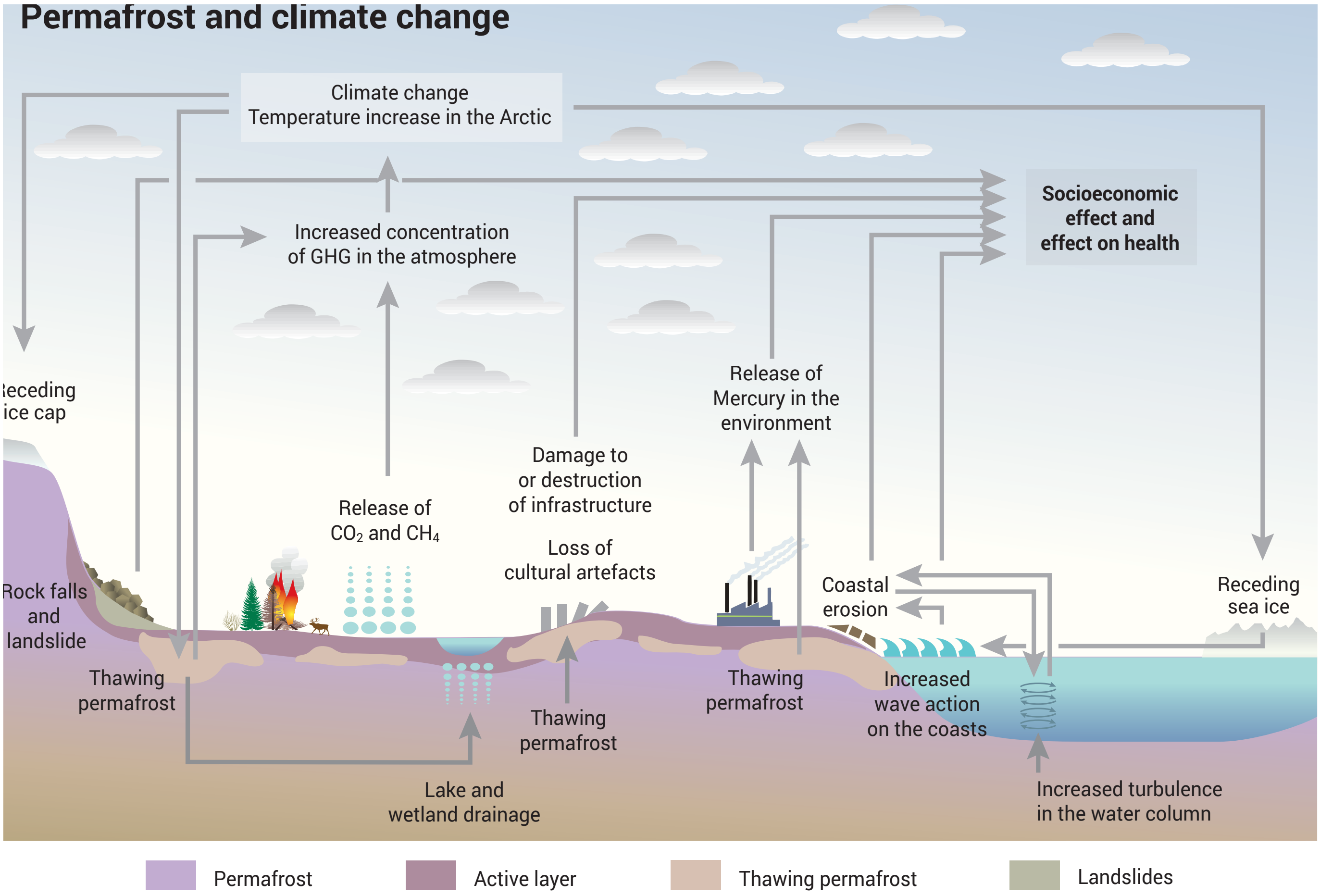

Figure 2.2.4: Permafrost changes under climate change and subsequent effects on environment and society (https://www.grida.no/resources/13348). Credit to Riccardo Pravettoni and Philippe Rekacewicz.

Regions with boreal forests and tundra biomes located above permafrost areas are experiencing pronounced changes in vegetation and ecosystems. While the tundra is showing signs of overall greening, boreal forests are facing regional browning, indicating significant shifts in plant and animal communities (Higgins et al., 2023, Myers-Smith et al., 2020). Such changes may affect the range and abundance of ecologically important species, including those in freshwater ecosystems. The consequences of these ecological transformations extend to the wellbeing of local communities, whose livelihoods and cultural heritage are intimately tied to the health of the surrounding environment. Further, the presence of vegetation above permafrost employs various mechanisms to protect permafrost from the effects of atmospheric conditions, serving as insulation for permafrost that has not adjusted to the present climate (Nitzbon et al., 2023). Alterations in this vegetation can impact the thermal conditions of permafrost (Loranty et al., 2011). Specifically, warming in northern regions can alter vegetation patterns, leading to an expansion of taller shrubs and trees. This increased vegetation cover can insulate underlying permafrost and cause it to warm. The resulting thaw and subsidence of permafrost promotes further shrub growth, creating a positive feedback loop, opening the door to potential self-sustaining and tipping point dynamics in response to a warming climate.

Considering the cold winters and short, cool summers, the presence of permafrost affects the availability of arable land and the growing season for crops, making agriculture challenging. While climate-driven northward expansion of agriculture increasingly provides new food sources, little is known about the effectiveness, feasibility and risks in cultivation-permafrost interactions (Ward Jones et al., 2022). Indigenous communities in permafrost regions therefore often rely on traditional knowledge and practices that are deeply rooted in their culture and are essential for their food security. They depend on the availability of natural resources such as fish and plants. Access to these resources and the ability to store them long-term in permanently frozen cellars may be impacted by environmental changes in permafrost regions (Maslakov et al., 2022). Increasingly, traditional diets transition to a diet from industrial store-bought food, which can significantly impact human health (Loring and Gerlach, 2009). Thawing permafrost also releases contaminants, including mercury, into the environment (Schäfer et al., 2020). This negatively impacts water quality in Arctic rivers and lakes, leading to potential risks to human health through contaminated food chains and drinking water sources.

Beyond its ecological consequences, permafrost thaw has significant implications for the infrastructure built on permafrost soil. As the ground becomes unstable, buildings, roads, pipelines, water facilities, and communication systems are damaged (Hjort et al., 2022; Hjort et al., 2018) and hazardous substances mobilised (Langer et al., 2023; Miner et al., 2021). Up to 80 per cent of infrastructure elements show substantial infrastructure damage and 70 per cent of current infrastructure in the permafrost domain is in areas with high potential for thaw by 2050 (Hjort et al., 2022).

Thus, permafrost thaw is a complex and multifaceted issue with global, regional and local ramifications. It not only contributes to global climate change but also poses considerable risks to ecosystems, human health and infrastructure in affected areas, posing substantial challenges for economic development and human activities and necessitating adaptation strategies and long-term planning. However, there is hope that mitigating global warming and limiting temperature rise to below 2°C would significantly reduce the impacts of permafrost thaw on infrastructure in permafrost areas. This highlights the urgency of adopting comprehensive climate change mitigation measures to protect both the environment and human communities in vulnerable regions.

The permafrost-carbon feedback, as a major part of the global carbon cycle, has long been proposed as a feedback loop that accelerates climate change. The potential for permafrost carbon emissions to alter the rate and magnitude of global warming is still uncertain (due to missing model representation and lack of observations) and likely to be too small to be self-perpetuating (Deutloff et al., 2023; Nitzbon et al., 2023; Wang et al., ; 2023Schäfer et al., 2014) (see section 1.2). Therefore, large-scale carbon release from permafrost thaw can be considered a threshold-free process (Nitzbon et al., 2023 ; Hugelius et al., 2020; Chadburn et al., 2017; Schuur et al., 2015). However, permafrost carbon can significantly contribute to the carbon budget of specific warming targets or scenarios, specifically those aiming for low warming levels, such as those more likely to prevent tipping of other elements (Schuur et al., 2022 ; Natali et al., 2021; Gasser et al., 2018). Thus, biogeochemical feedback of permafrost has the potential to influence socioeconomic conditions. More importantly, any changes today commit us to long-term impacts (McGuire et al., 2018). At the local scale, rapid permafrost thaw can have severe consequences on a number of services to humans as well as to global society across four domains of ecosystem services: provisioning, regulating, supporting, and cultural (Schuur and Mack, 2018).

Communicating a 'threshold' for permafrost that indicates a 'safe zone' is misleading, as every tenth of a degree of global warming leads to significant impacts in permafrost-dominated landscapes (Schuur et al., 2022).

2.2.3 Impacts of biosphere tipping points

2.2.3.1 Amazon dieback

The potential for a tipping point in the Amazon – also known as 'Amazon dieback' - relates to the close coupling between the land ecosystem and the atmosphere, with the rainforest playing an important role in maintaining precipitation (and hence soil moisture) at levels sufficient to support rainforest (Betts, 1999). There is recycling of rainfall from eastern to western part of the Amazon basin (Zemp et al., 2017), so loss of forest in the east could exert further impacts in the west. If forest cover were to be sufficiently reduced, either due to direct, human-induced deforestation or the impacts of climate change (or, more likely, a combination of both), there is the potential for the regional climate to move to an alternative state in which rainforest can no longer be supported, which would prevent the future return of forest and potentially further increase the loss of forest (Hirota at al,. 2021).

Reduced forest cover in the Amazon is also observed to lead to higher temperatures, particularly daily maximum temperatures, both locally at the site of forest loss and in adjacent regions up to 60 km away, due to reduced transpiration, decreased aerodynamic roughness causing reduced dissipation and weakened horizontal transport of heat (Cohn et al., 2019). A drier, hotter climate would lead to an increase in wildfire and soil erosion, which could lead to an expansion of savanna vegetation at the expense of rainforest (Flores and Holmgren, 2021; Flores et al., 2020).

Passing a tipping point in the Amazon would therefore lead to impacts in the immediate region, and could potentially also lead to impacts elsewhere by influencing moisture transport into and/or out of the region (including via the South American monsoon, Boers et al., 2017) and by altering large-scale atmospheric circulation patterns with potential teleconnections to distant parts of the world such as to the Tibetan Plateau (Liu at al,. 2023).

In the Amazon Assessment Report 2021 (Science Panel for the Amazon, 2021), the chapter on assessing the risk of tipping points concluded: "Local-scale forest collapses could trigger cascading effects on rainfall recycling, intensifying dry seasons and wildfire occurrence, and leading to massive forest loss at continental scales, particularly in the southwest of the basin" (Hirota et al,. 2021).

RISK OF BIOME SHIFTS IN THE AMAZON

Loss of the forest would have substantial impacts on biodiversity, and the reduced evapotranspiration would lead to reduced precipitation and hence reduced water availability, with potentially large societal impacts. Loss of the forest would also lead to increased high temperature and greater risk of heat stress.

Amazon dieback would be a major threat to the biodiversity of the rainforest (Gomes et al., 2019; Esquivel-Muelbert et al., 2017). Four potential alternative states to the current closed-canopy primary rainforest have been identified as possible consequences of passing an Amazon tipping point: (i) a closed-canopy seasonally dry tropical forest state; (ii) a native savanna state; (iii) an open-canopy degraded state; and (iv) a closed-canopy secondary forest state (Hirota et al., 2021). Clearly, any of these would have major implications for species of rainforest trees and other plants.

They would also impact animal species, many of which could disappear from the system if they are not favoured by open habitats and their movement becomes restricted by loss, degradation or fragmentation of forest (Barlow et al., 2016; Laurance et al., 2004). Seed dispersal by fruit-eating species may become limited if such species avoid open disturbed habitats, thus reducing tree recruitment and forest regrowth, especially where disturbances are most severe (Turner et al., 1998). Studies in the tropical Atlantic Forest indicate that 30 per cent tree cover is a threshold in which many forest-adapted animal species are replaced by disturbance-adapted species (Banks-Leite et al., 2014).

The health and wellbeing of people in the Amazon region would also be put at increased risk by forest loss. (Wang et al., (2021) suggested that increased wildfire frequency and severity associated with Amazon die-back would put regional communities at risk and lead to increased air pollution. Moreover, heat stress is extremely dangerous to humans, increasing the risk of heat-related illnesses and death, especially for vulnerable groups such as children, the elderly and those with underlying health conditions (de Oliviera et al., 2020), and for other exposed groups such as those working in conditions of extreme heat (Spector et al., 2019). The risks of heat stress on humans and other mammals are projected to increase with global warming (Bezner-Kerr et al., 2022; Cissé et al., 2022), and since tropical forests maintain lower temperatures compared to deforested land due to higher levels of evaporation (Ruv Lemes et al., 2023), forest loss following an Amazon tipping point could increase heat stress risks further. De Oliviera et al., (2021) used the BESM-OA2.5 climate model to project the impact on human heat stress risk of a total replacement of tropical Amazon forest with savannah in two climate change scenarios. Heat stress risk was quantified using Wet Bulb Globe Temperature (WBGT) which accounts for the effects of both temperature and humidity on heat stress risk, with high humidity increasing the risk of heat stress as it reduces the body's ability to cool through sweating. In a scenario reaching approximately 2.5°C global warming by the end of the 21st century, average daily WBGT values in the hottest month were 30-31°C (high heat stress risk) across most of Amazonia with intact forest. These were elevated to 34-37°C (extreme heat stress risk) when forest was replaced by savannah (Figure 2.2.5), exposing more than 6 million people to extreme heat stress risk.

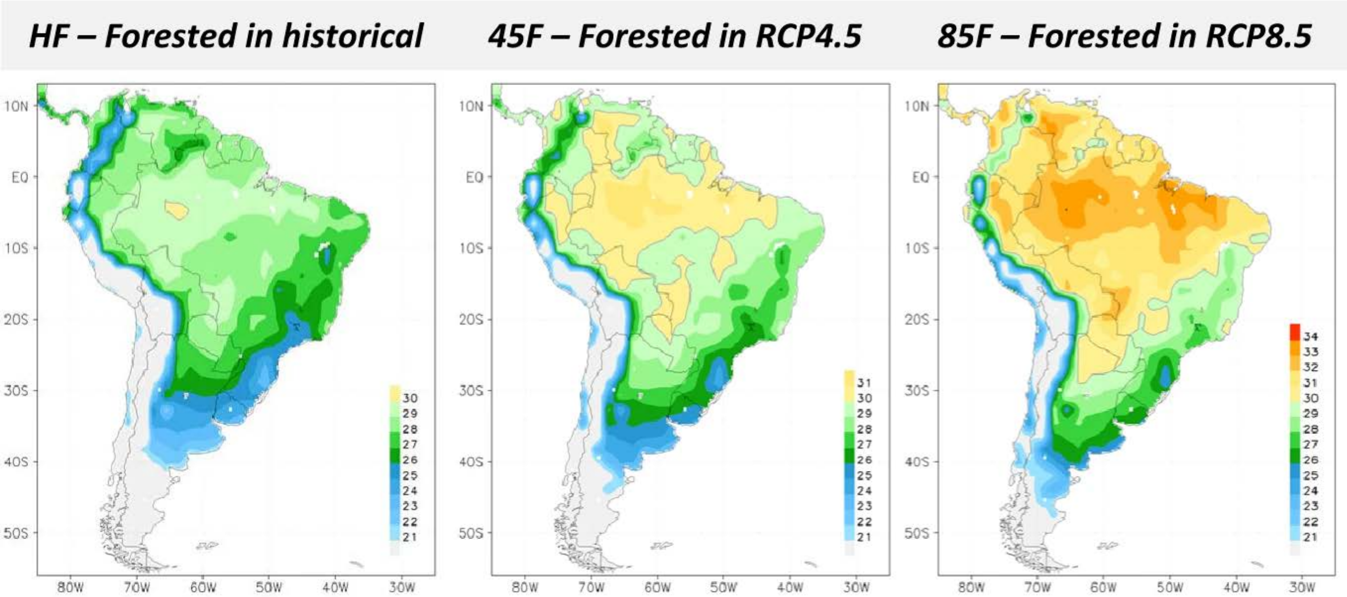

Figure 2.2.5; Projected impacts of Amazon forest loss on heat stress risk, quantified with Wet Bulb Globe Temperature (WBGT) in °C, in a climate simulation with the BESM-OA2.5 model driven by the RCP4.5 scenario. Reproduced from De Oliviera et al. (2021)

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 (Pinho et al., 2015).

Interactions between the Amazon forest and the atmosphere via the water cycle play a crucial role in the impact of forest loss on river flows, with potentially major implications for socioeconomic impacts. Importantly, although land ecosystem-hydrology models that do not account for feedbacks with the atmosphere project forest loss to increase river flows due to reduced evaporation, the opposite is projected when vegetation-atmosphere interactions are considered – reduced precipitation arising from widespread decreases in evaporation are projected to lead to reduced river flows (Stickler et al., 2013). Lapola et al., (2018) suggest that lower river water levels resulting from Amazon dieback would affect transportation, food security and health, which ultimately may influence migration from rural areas to large Amazonian cities. In a coupled climate-vegetation model and hydrology model with a potential 40 per cent decline in forest cover by 2050, river discharge in the Xingsu basin was projected to decrease by 6-36 per cent, leading to hydrological power generation to fall to approximately 25 per cent of maximum installed capacity (Stickler et al., 2013).

Lapola et al., (2018) estimate that Amazon dieback would lead to economic damages of between $US957bn and $US3,589bn (net present value as of 2018) over 30 years, mainly due to changes in the provision of ecosystem services (Figure 2.2.6). For comparison, the Gross Brazilian Amazon Product is approximately $US150bn per year.

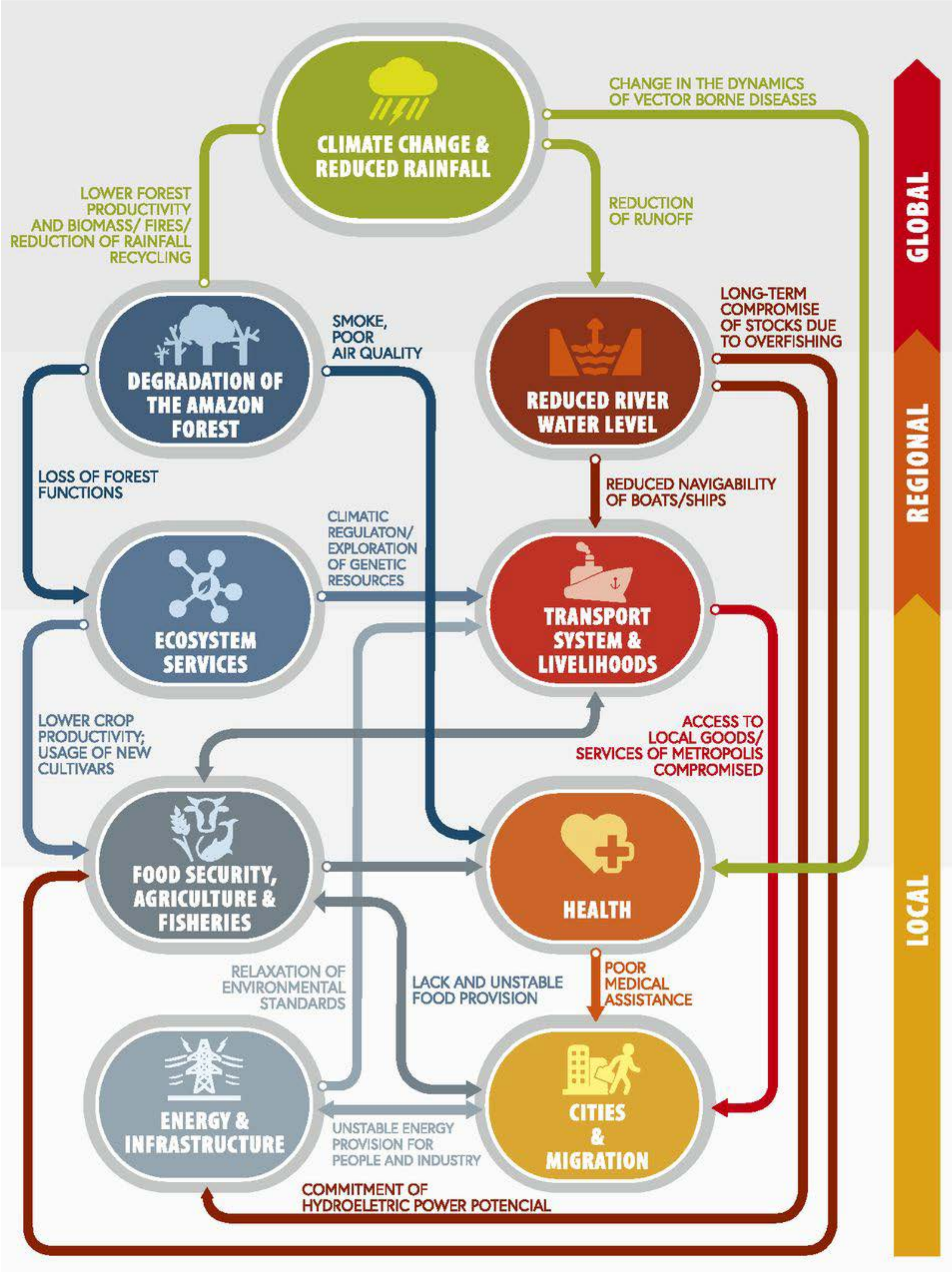

Figure 2.2.6: Socioeconomic impacts of Amazon dieback. Reproduced from Lapola et al., (2018).

Amazon dieback could magnify global warming and its associated impacts by accelerating the rise in atmospheric CO_2. The Amazon is estimated to contain between 150 and 200 GtC in biomass and soil organic matter (Wang et al., 2023), equivalent to about 15 to 20 years of current global anthropogenic CO_2 emissions. As an estimated upper bound of the contribution of the potential Amazon tipping point to the magnification of global climate change impacts, Betts et al. (2008) projected global warming by 2100 to be increased by 0.3°C in an extreme scenario of total Amazon forest die-back in which forest was almost entirely replaced by either grassland or desert.

2.2.3.2 Methane hydrate destabilisation

While there is potential for methane hydrate deposits in ocean sediments to be destabilised by warming, which could eventually have very large impacts on global temperature due to increases in atmospheric methane concentrations, current evidence and understanding suggests timescales of centuries to millennia for substantial impacts (Wang et al., 2023). Nevertheless, this process is included here for the purposes of calculating the contribution of methane hydrate destabilisation to global warming by 2100 and 2300 (2.2.5).

Methane hydrate dissociation could also potentially contribute to acidification in the deep ocean on long timescales (Garcia-Tigreros et al., 2021). Ocean acidification has potentially major implications for marine ecosystems due to impacts on calcifying organisms (Cooley et al., 2022), so these impacts could be further increased by methane hydrate dissociation in the long term.

2.2.4 Impacts of ocean-atmosphere circulation tipping points

2.2.4.1 Atlantic Meridional Overturning Circulation

The AMOC is a system of ocean currents that transports warm waters northwards in the Atlantic (Buckley and Marshall, 2016). The AMOC is considered to be a tipping element of the climate system (see Chapter 1.4). However, although it is considered very likely to weaken over the next century due to anthropogenic climate change (Fox-Kemper et al., 2021), it is considered unlikely to collapse.

If the AMOC were to collapse, it would have significant global consequences. The overall impact would depend on the level of global warming that had already occurred by the time of collapse. Large-scale temperature changes are likely to be additive (Vellinga and Wood, 2008), so the large cooling seen from an AMOC collapse over the North Atlantic ocean is likely to dominate the warming, however changes over land are more uncertain. Yet, for other impacts, an AMOC collapse may exacerbate changes caused by global warming.

Since the AMOC transports heat northwards in the Atlantic, a collapse would tend to cause a significant cooling in the North Atlantic Ocean, which would drive cooler temperatures over much of the Northern Hemisphere, especially Europe and North America, and potentially across the whole hemisphere (Bellomo et al., 2021 ; Jackson et al., 2015; Stouffer et al., 2006). This, however, would compete with the effects of global warming, with the net effect depending on the magnitude of the latter. The reduced heat transport would slightly add to warming in the Southern Hemisphere. Cooler ocean temperatures in the North Atlantic would drive reduced evaporation and hence less atmospheric water vapour for precipitation (Bellomo et al., 2021 ; Jackson et al., 2015; Stouffer et al., 2006). They would also result in an increase in Arctic sea ice.

Changes in sea surface temperature (SST) gradients also affect atmospheric circulation patterns, which have significant impacts on regional climate. One major change due to AMOC collapse would be a southwards shift in the Intertropical Convergence Zone (ITCZ), which is a region in the tropics where north and south trade winds meet and there is heavy rainfall (Bellomo et al., 2021; Jackson et al., 2015; Stouffer et al., 2006). Changes in SST patterns in the North Atlantic have also been shown to affect the North Atlantic Oscillation (NAO), which affects weather over Europe (Bellomo et al., 2022; Jackson et al., 2015; Brayshaw, 2009).

Another large-scale impact is from changes to sea level associated with the changing ocean currents. A collapse of the AMOC would cause significant increases to sea level throughout the North Atlantic, which would have impacts on the western coasts of Europe and the eastern coasts of North America (Little et al., 2019; Kienert and Rahmstorf, 2012; Lorbacher et al., 2010; Hu et al., 2009; Leverman et al., 2005)

In Europe and North America we would generally expect colder winters as a result of an AMOC collapse, with more precipitation falling as snow and more cold extremes (Wang et al., 2022; Jacob, 2005 ; Vellinga and Wood, 2002). Although there would be less precipitation in general, the shift to more positive NAO would lead to more winter storms (Jackson et al., 2015; Bellomo et al., 2022; Brayshaw, 2009) and hence windier weather with more precipitation on western coasts of northern Europe (Jackson et al., 2015; Bellomo et al., 2022). In the summer, an AMOC collapse would cause a reduction in cloud amount and an anomalous high pressure system over northern Europe, resulting in more precipitation over southern Europe and less over northern Europe (Jackson et al., 2015). In Britain, this could lead to a widespread cessation of arable farming, causing large reductions in water supply and losses of agricultural output an order of magnitude larger than those arising from climate change without AMOC collapse (Figure 2.2.7; Ritchie et al., 2020).

In the tropics, an AMOC collapse would cause a southwards shift of the ITCZ, and hence a shift of the monsoon rains in central/southern America and West Africa. There is also evidence that there would be shifts for the South Asian and Indian monsoons. Shifts in monsoons would cause significant changes in seasonal precipitation, with some regions receiving much more rain, some much less, and some with shift of rain to different seasons, potentially causing severe regional impacts (Sandeep et al., 2020; Defrance, 2017; Marzin, 2013; Parsons et al., 2013; Chang et al., 2008; Zhang and Delworth, 2005). The large shifts in monsoon rainfall over the tropics associated with AMOC collapse would be expected to have major impacts on vegetation productivity worldwide, including crop productivity, with decreases in many regions such as Western and Central Africa, Central America, Northern South America and eastern Europe, but increases in other regions such as north-east South America and southern Africa (Vellinga and Wood, 2002).

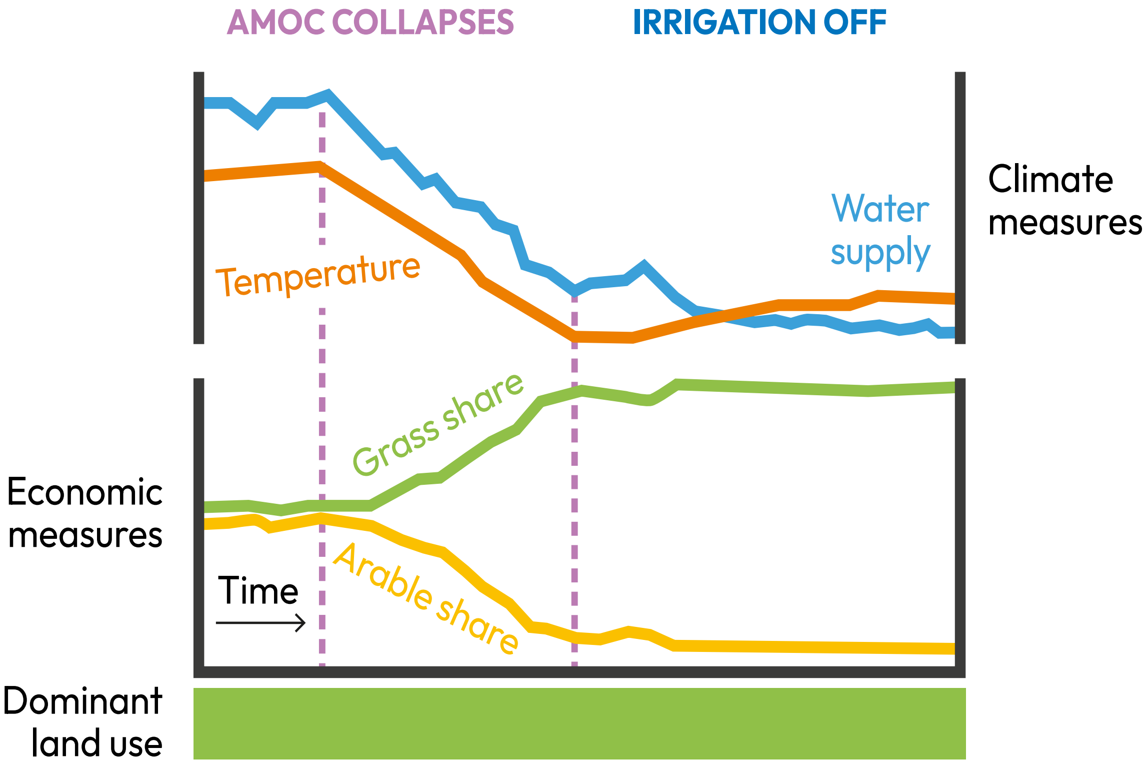

Figure 2.2.7: Impact of AMOC collapse on UK water supply and arable crops (Ritchie et al., 2020).

2.2.5 Potential for Earth system tipping points to magnify or accelerate impacts of global warming

Some tipping points might also be expected to potentially alter the rate of global warming by changing the increase in radiative forcing, either by modifying the airborne fraction of anthropogenic emissions through changes in natural sinks and sources of greenhouse gases (permafrost, Amazon rainforest, boreal forests, methane hydrates) or by changing the albedo of the planet (sea ice, ice sheets). This could change the time at which we reach specific Global Warming Levels (GWLs) such as 2°C and hence the time of reaching the associated climate hazards. This could alter the overall impact on human society because the socioeconomic conditions would be different, leading to different levels of exposure and vulnerability. If a particular level of hazard were to be reached sooner if global change were accelerated by passing one or more tipping points, this may mean that vulnerability (and potentially exposure) is higher because there has been less time to prepare/adapt. On the other hand, exposure may be smaller if (for example) the population has not grown so much when the hazard level occurs.

Wang et al., (2023) used the Finite Amplitude Impulse-Response (FAIR) simple climate model to provide a preliminary estimate of the increase in global warming that would arise from the collective effects of several Earth System tipping points for which quantitative estimates could be made with reasonable confidence. These were release of CO_2 and/or CH_4 from permafrost thaw, marine methane hydrate destabilisation, Amazon forest dieback; and increased shortwave radiative forcing from Arctic sea ice loss. With the SSP2-4.5 scenario (which could approximately represent the trajectory of global emissions under current policies), and without tipping points being passed, global warming was projected to reach approximately 3.0°C (2.8-4.2°C) in 2100 and 3.5°C (2.2-5.2°C) in 2300.

Using specific, quantitative assumptions for the contribution of each tipping point to greenhouse gas release or radiative forcing, and with several different assumptions on equilibrium climate sensitivity, it was estimated that the combined effect of passing those tipping points would be to increase global warming by 0.13°C (0.06-0.23°C) in 2100 and 0.24°C (0.11-0.49°C) in 2100. With a hypothetical very high emissions scenario SSP5-8.5, global warming of 5.0°C (3.0-7.5°C) at 2100 was increased by 0.21°C (0.10-0.36°C), and warming of 8.5°C (5.5-12.7°C) at 2300 was increased by 0.52°C (0.25-1.09°C).

Importantly, the use of the simple climate model for the above estimates did not allow for dynamical tipping behaviour or interactions between tipping points, and moreover did not include other tipping points such as rapid ice sheet loss, boreal forest loss or AMOC collapse, so should certainly not be regarded as a complete estimate of the impacts of Earth system tipping points on the projected rate of future global warming. However, the above estimates do provide a means to place the potential additional collective impacts arising from those specific, selected tipping points in context with other impacts assessments.

Table 2.2.1. Impacts of tipping points on sectors. Note that all impacts could potentially be increased by contributions of tipping points to acceleration of global warming, especially if several tipping points occur.

	Water security	Food security	Energy security	Health	Biodiversity and ecosystem services	Communities and economies
AMOC collapse	Changes in regional rainfall globally (both increases and decreases)	Large losses of crop productivity in regions affected by reduced rainfall	Increased demand for heating in Northern Hemisphere	Widespread risks to health from reduced water and food availability in regions affected by reduced precipitation, and from more severe cold weather in winter	Radical changes to North Atlantic ecosystems including fisheries	Severe challenges for North Atlantic region countries
Ice sheet collapse	Salination of groundwater in coastal regions	Impacts on coastal crop productivity through salination Disruption to Sahel agriculture inland through reduced West African monsoon rainfall	Potential for flooding of coastal energy infrastructure, e.g. power stations	Spread of diseases due to inundation of coastal areas	Loss of coastal ecosystems	Potential loss of atoll nations 480 million people vulnerable to annual coastal flood event by 2100 with 2m sea level rise
Arctic sea ice loss	Potential to affect regional climates, but uncertain. Specific impacts on water not assessed	Potential to affect regional climates, but uncertain. Specific impacts on food not assessed	Potential for increased fossil fuel extraction and export	Potential to affect regional climates, but uncertain. Specific impacts on food not assessed	Risks to Arctic biodiversity, both direct through loss of sea ice as part of a habitat, and indirect through amplified warming	New shipping routes and potential for increased mineral extraction and export
Permafrost thawing	Reduced water quality through release of contaminants	Challenges to traditional practices for provision and storage of food	Damage to energy infrastructure	Risks to health from contaminated drinking water supplies and food chains	Changes in species composition in permafrost ecosystems	70% of current infrastructure in permafrost regions is in areas with high potential for thaw by 2050
Amazon dieback	Reduced river flows	Risks to agricultural productivity through reduced availability of time for outdoor working due to heat stress risks	Hydropower productivity in Xingu basin reduced to 25% of installed capacity due to decreased river flows	Exposure of 6 million people to extreme heat stress risk Reduced air quality from wildfires	Shifts from rainforest tree species to dry forest or savanna tree and grass species, with associated loss of animal species adapted to closed-canopy conditions	Economic damages of US$957bn and US$3,589bn Transport difficulties due to reduced river flows Risks to communities from wildfires Potential migration to cities

2.2.6 Sector-based impacts assessment of climate system tipping points

2.2.6.1 Water security

Water security encompasses a wide set of issues, including water scarcity (which is affected by demand as well as supply), water quality, water hazards, access to water, and governance (Caretta et al., 2022). A key challenge for water is the difficulty in long-term planning for adaptation, due to large uncertainties in regional climate changes, particularly precipitation. The potential for tipping points may make this worse in some cases, if the existence of a potential tipping point adds an additional element of uncertainty in regional precipitation or evapotranspiration, or in the timing of global changes.

AMOC collapse is simulated to change patterns of precipitation and water availability worldwide (Jackson et al., 2015), with reduced annual mean precipitation in Europe, northern South America, central Africa and southern Asia, and increased annual mean precipitation in southern North America, north-eastern South America, southern Africa and western Australia. Decreased precipitation could reduce water security by increasing the risk of water scarcity. Simulated rainfall reductions in the growing season in the British Isles would have very large negative impacts on crop yields (Ritchie et al., 2020).

Sea level rise as accelerated by ice sheet collapse can result in groundwater salinisation, having secondary impacts upon water and food security. Mean sea level rise affects the water table height, while coastal flooding events directly salinate freshwater (Magnan, 2022). Water salinisation impacts on coastal ecosystems, drinking water supply and also water supply for agriculture (Mazhar et al., 2022). Such changes could be compounded by drying patterns also projected under climate change.

Bangladesh is one nation with extreme vulnerability to sea level rise, where salinisation is posing a risk to both water and food security (Chen and Mueller, 2018; Barbour et al., 2022). Khanom (2016) reports that the intrusion of saline water occurs 15km inland, increasing up to 160km in the dry season, although other factors such as water abstraction and rainfall also impact saline water incursion (IPCC, 2019).

It is estimated that around 200,000 people are displaced annually in Bangladesh from the effects of salinisation on reducing agricultural productivity (Hauer et al., 2020), many moving to other regions of Bangladesh (Chen and Mueller, 2018). For example, certain crops are no longer produced due to intolerance of salinated soils, including oilseed, sugarcane and jute (Khanom, 2016). The same study indicates that rice cultivation is more appropriate under increasing salinity, and others suggest a move towards aquaculture production would increase resilience and reduce threats to food security (Hauer et al., 2020). However, it is unclear how sustainable these levels of adaptation are under extreme sea level rise.

Increasing salinisation of soils, surface water and groundwater aquifers, in part due to rising sea levels, reduces availability of freshwater resources (IPCC, 2019). The salinisation of groundwater due to sea level rise may result in the uninhabitability of atoll island nations in the coming decades, before inundation would force abandonment (Bailey et al., 2016). Impacts from rising sea levels in atoll nations are compounded by reduced precipitation, also associated with climate change impacts (Bailey et al., 2016, Hauer et al., 2020). Delta regions are also susceptible to vulnerability from salinisation of groundwater resources, including in Bangladesh. In the present day, traces of salt in drinking water in coastal regions of Bangladesh raise health concerns, for example having consequences on maternal health during pregnancy (Khan et al., 2011). Adaptation approaches, such as rainwater harvesting, are currently used in Bangladesh to provide safe drinking water (Rahman et al., 2017), and limits to the approaches are not well understood. The effectiveness of adaptation approaches under more rapid and extreme sea level rise, such as those associated with ice-sheet disintegration, are not well researched, but limitations likely apply.

Water quality in Arctic rivers and lakes is reduced by thawing permafrost releasing contaminants (Schäfer et al., 2020). Permafrost thawing also leads to damage to infrastructure including pipelines (Hjort et al., 2018; Hjort et al., 2022), which can reduce access to fresh water.

Amazon dieback is projected to lead to reduced river flows (Stickler et al., 2013; Lapola et al., 2018) which could potentially increase water scarcity.

A very rough indication of potential water-related impacts of some tipping points can be obtained by considering projected rates of increase in impacts with global warming and applying these to the estimate of the increase in global warming due to the group tipping points from Wang et al., (2023), as described in section 2.2.5. These tipping points were: release of CO_2 and/or CH_4 from permafrost thaw, marine methane hydrate destabilisation, Amazon forest dieback; and increased shortwave radiative forcing from Arctic sea ice loss.

For example, Gosling and Arnell (2016) projected the global exposure to increased water scarcity to be over 1 billion people at 3°C global warming and 1,161m people at 4°C global warming, with very large uncertainties. Assuming a linear relationship between people exposed and the level of global warming, the Wang et al., (2023) estimate that 3°C global warming would be increased by 0.13°C (0.06-0.23°C) due to the above group of tipping points would imply an increase of 13.8m (6.4m to 24.4m) people exposed to increased water scarcity.

Similarly, Alfieri et al., (2016) projected the population exposed to river flooding to be 97m and 211m at 2°C and 4°C global warming respectively, again with large uncertainties. Again assuming a linear relationship with warming, this suggests an exposure of 154m people to river flooding at 3°C global warming, increasing by 7.4m (3.4-13.1m) with the Wang et al., (2023) estimate of increased warming due to the collective effect of the above tipping points.

As noted in section 2.2.5, these estimates do not account for dynamical tipping behaviour or interactions between tipping points, and do not include other tipping points such as rapid ice sheet loss, boreal forest loss or AMOC collapse, for which quantitative estimates could not be made. This is therefore not a comprehensive analysis of the effect of tipping points on water-related climate impacts. Rather, it illustrates their potential to have substantial impacts on water scarcity and flooding. Further research is required to provide a more comprehensive assessment.

2.2.6.2 Food security

Food systems are highly vulnerable to tipping point impacts as they are affected by multiple environmental dimensions, with particular sensitivity to precipitation and temperature (Figure 2.2.8). Agricultural systems are strongly sensitive to changes in the functioning of a wide range of supporting systems in soil, water, pollination and natural pest suppression. Rapid environmental changes threaten to disrupt such functions in ways that are likely to impair agricultural production (Benton et al., 2017). The global food system is also a potential amplifier of tipping point impacts as it sits within a complex set of interacting biophysical and social systems.

For example, ocean current tipping elements such as AMOC and the North Atlantic Subpolar Gyre could have immediate impacts on food production. Moreover, harvest failures occurring simultaneously in more than one major crop-producing region would pose a major threat to global food security (Kornhuber et al., 2023). Significant reductions in global production are likely to produce wide-ranging social, economic and political disturbance (Gaupp, 2020). Consequently, the activation of climate tipping elements could drive significant structural changes in agriculture, with profound consequences for global food security (Benton, 2020).

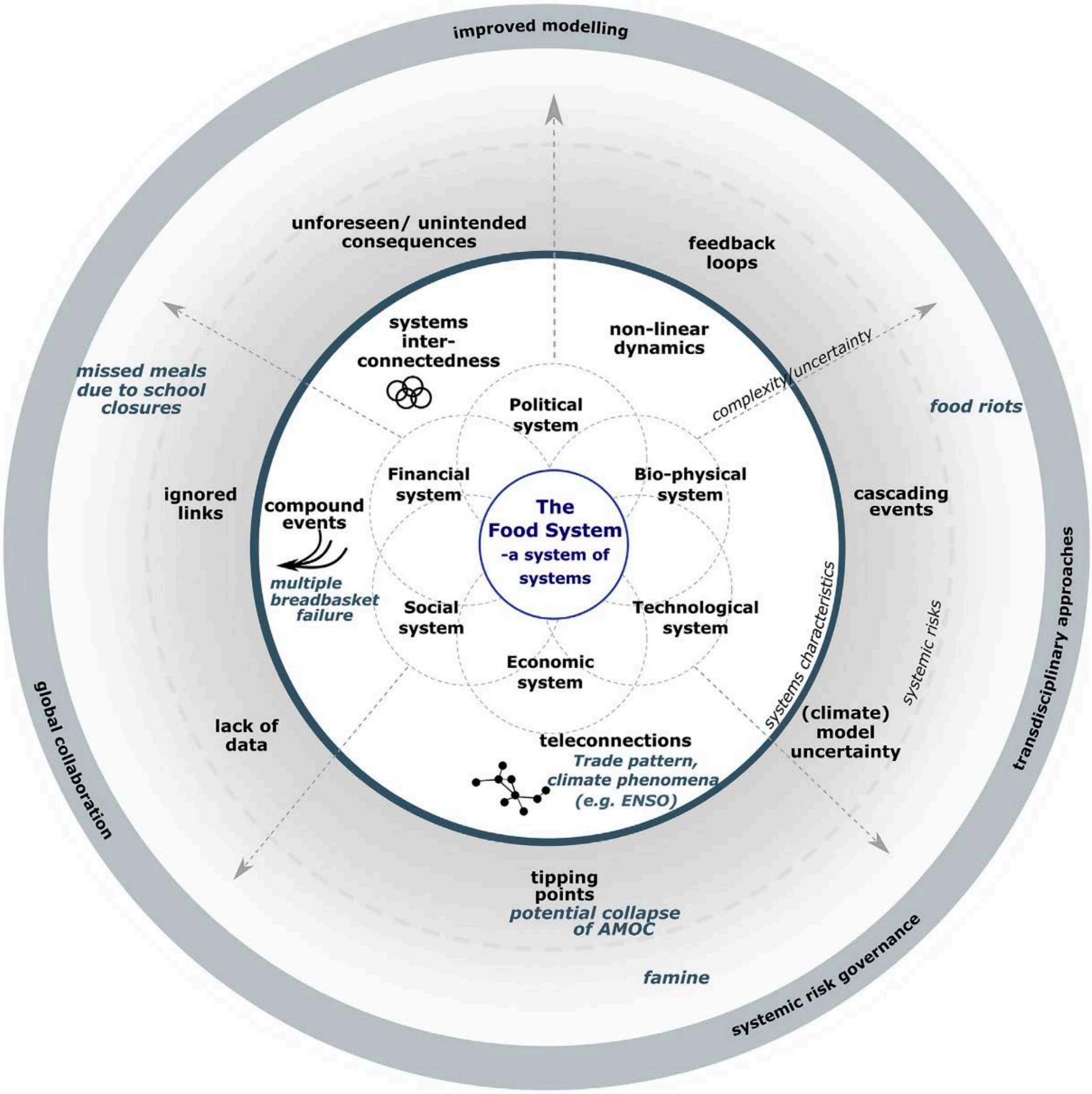

Figure 2.2.8: The complexity of the global food system and its inherent systematic characteristics. Reproduced from Gaupp (2020).

An AMOC collapse could have significant impacts on food production through various pathways. Impacts on crop productivity could be negative in many regions but positive in others, with overall global net primary productivity simulated to reduce by 5 per cent (Vellinga and Wood, 2002). Crop productivity in Europe would decrease due to colder and drier conditions (Jackson et al., 2015). Rainfall reductions in Britain due to AMOC collapse are simulated to be too large for irrigation to be economically feasible as a mitigation measure (Ritchie et al., 2020).

Tipping elements in the cryosphere have the potential to produce regional to global impacts on food systems. (Defrance et al., 2017) suggested that the loss of significant ice mass from the Greenland Ice Sheet could lead to droughts and significant disruption to agriculture in the Sahel region by reducing West African monsoon rainfall. Kwiatkowski et al. (2019) projected how Greenland Ice Sheet loss could reduce primary productivity in the North Atlantic.

An AMOC collapse could also have large impacts on the marine ecosystem and consequently marine food systems by causing a large reduction of plankton in the Atlantic (Schmittner, 2005), potentially affecting the development of fish. Economic impacts on key Barents Sea fisheries and economies are one possible outcome from a reduction in the strength of the AMOC (Link and Tol, 2009).

2.2.6.3 Energy security

A collapse of the AMOC would lead to widescale cooling of the northern hemisphere, particularly in Europe and North America (Jackson et al., 2015; Stouffer et al., 2006), which could lead to increased demand for energy for heating. One study (Jacob et al., 2005) suggested increases in heating energy consumption of 10-20 per cent in the UK and Europe. Regional changes in weather patterns might also have an impact on energy generation, for instance through changes in precipitation (Haarsma, 2015; Jackson et al., 2015) which might affect hydropower, changes in average cloud amounts (Jackson et al., 2015; Laurian, 2010) which could affect solar power, and changes in windiness (Jackson et al., 2015) which could affect wind energy. However, these potential societal impacts from regional changes in weather patterns from AMOC collapse have not yet been assessed.

Thermal power stations (including both fossil fuel and nuclear) are often sited on coasts to provide access to water for cooling, so are potentially vulnerable to sea level rise triggered by ice sheet tipping points, while Amazon dieback could affect the production of electricity from hydropower on rivers in the Amazon region. A potential 40 per cent decline in forest cover by 2050 is projected to lead to hydrological power generation in the Xingu basin to fall to approximately 25 per cent of maximum installed capacity due to reduced river discharge (Stickler et al., 2013).

2.2.6.4 Health

Crossing climate system tipping points could lead to an increase in the frequency and intensity of extreme weather events such as heatwaves, floods and droughts (Heinze et al., 2021; Schellnhuber and Martin, 2014). More frequent and intense heatwaves can lead to heat-related illnesses, such as heat exhaustion and heatstroke (Sorensen and Hess, 2022), while high temperatures can also worsen existing health conditions, such as cardiovascular and respiratory diseases (Covert et al., 2023). Severe storms and flooding, for example due to AMOC collapse (Jackson et al., 2015) could directly cause injuries and deaths as well as displacement, and damage to infrastructure (Lane et al., 2013).

As discussed in Chapter 2.2.6.1, fresh water sources and water security would be perturbed significantly by crossing tipping points such as AMOC collapse and in the cryosphere. Reduced rainfall and increased evaporation can result in water scarcity, making it challenging for communities to access safe and sufficient drinking water, especially in the Global South (Dos Santos et al., 2017). Changes in precipitation patterns and flooding events can contaminate water sources and increase the risk of waterborne diseases such as cholera and gastrointestinal infections (Nichols et al., 2018) and lack of access to clean water and proper sanitation can also contribute to the spread of disease (WHO, 2011).

Biogeophysical tipping points could potentially disrupt agricultural systems and lead to crop failures and reduced yields (Defrance et al., 2017), resulting in possible food shortages and increased food prices (d'Amour et al., 2016) and malnutrition, especially in developing nations (Pawlak et al., 2020). Inadequate nutrition can weaken immune systems, making populations more susceptible to infections and diseases (Calder, 2021).

Wildfires due to Amazon and boreal forest dieback may result in hazardous air quality, exposing populations to smoke and particulate matter (Chen et al., 2021; Cascio, 2018) , which can worsen respiratory conditions (Alahmad et al., 2023; Chen et al., 2021). Amazon forest loss is also projected to increase the risk of heat stress. In a climate model simulation reaching approximately 2.5°C by 2100, total conversion of forest to savannah would expose approximately 6 million people to extreme heat stress risks from Wet Bulb Globe Temperatures above 34°C, at present population levels (de Oliviera at al,. 2021).

Climate change and ecological disruptions can alter the distribution and behaviour of disease vectors and reservoirs, potentially facilitating the spread of infectious diseases to new areas (Nova et al., 2022). Climate change-induced shifts in temperature and precipitation patterns can influence the distribution and transmission of vector-borne diseases like malaria, dengue fever, Zika virus and Lyme disease (Beermann et al., 2023; Fox et al., 2015), and these climatic patterns can be shifted due to tipping points. Accelerated melting of the Greenland Ice Sheet could impact malaria distribution in Africa through cooling and shifts in precipitation. This could result in a moderation of the increase in malaria risk in East Africa and an increased risk in southern Africa (Chemison et al., 2021). Expanding geographic ranges of disease-carrying vectors can expose new populations to these diseases (Caminda et al., 2019). There is also concern that future warming and increased glacier melting would make disease emergence more likely in the High Arctic region due to 'viral spillovers', by creating new associations and increasing the likelihood of contact between viruses and their animal, plant or fungal hosts (Lemieux et al., 2022).

Rising sea levels may also impact upon the spread of diseases locally during inundation of low-lying areas (Dvorak et al., 2018; Ramasamy and Surendran, 2011). Examples include vector-borne infectious diseases, with the expansion of shallow low-lying brackish and saline environments providing breeding sites for mosquitos and increasing the prevalence of vector-borne diseases such as malaria (Ramasamy and Surendran, 2011). Risks from these could be realised sooner, and happen at a faster pace than adaptation can respond to, in the event of extreme sea level rise caused by ice-sheet disintegration.

Lastly, the health impact due to various sectors discussed above would have consequences on the decision making of migration/settlement abandonment due to perception of climate risks (McLeman et al., 2011), especially when amplified by the likelihood of crossing tipping points. Displacement can lead to overcrowded living conditions and increased vulnerability to certain transmissive health risks (Suhrcke et al., 2011). Increased climate-related health impacts can place additional strain on healthcare systems, especially in regions already facing resource limitations (Ebi et al., 2021 ; Salas et al., 2019).

The disruption to community (see also Sub-section 2.2.6.5) would also further exacerbate the health risks, especially related to mental health (Simpson et al., 2011). Studies have shown population displacement and loss of livelihoods can have significant psychological effects on individuals and communities, including increased stress, anxiety and trauma-related disorders (Garry and Checchi, 2020; Math et al., 2015; Siriwardhana and Stewart, 2013). In addition, there are wider climate change-related mental health concerns (Charlson et al., 2021; Palinkas and Wong, 2020) relating to acute (e.g. hurricanes, floods, wildfires) and subacute events (e.g. drought, heat stress) as well as long-term changes (e.g. a permanently altered and potentially uninhabitable environment).

2.2.6.5 Biodiversity and ecosystem services

Arctic sea ice loss has substantial implications for biodiversity in the region, both directly by profoundly changing the nature of the habitat to more open ocean, and indirectly by amplifying regional warming.

Amazon dieback would lead to major impacts on biodiversity in the region, with large-scale replacement of rainforest tree species with other trees and grasses, and impacts on animals especially those that are adapted to closed canopy conditions rather than open environments (Hirota et al., 2021). Loss of ecosystem services would have major economic impacts, of magnitudes comparable with the current Gross Brazilian Amazon Product (Lapola et al., 2018).

2.2.6.6 Communities, economies and displacement

Ice sheet tipping points pose a substantial threat to communities in coastal regions. A potential sea level rise of 2m by 2100 due to Antarctic instability would mean that 480 million people would be vulnerable to an annual coastal flood event by 2100, based on current population dynamics (Kulp and Strauss, 2019). (Defrance et al., 2017) suggested that a rapid melting of the Greenland ice sheet could have a significant impact on displacement in West Africa through its impact on agriculture via changes in monsoon rainfall.

Arctic sea ice loss has potential economic implications by opening up new routes for shipping and providing increased access for extraction and export of fossil fuels (Challinor and Benton, 2021) and minerals.

Permafrost thawing is already impacting communities through damage to buildings and infrastructure, with 70 per cent of current infrastructure in permafrost regions in areas with high potential for thaw by 2050 (Hjort et al., 2022).

Amazon dieback is projected to lead to substantial impacts on communities in the region, as well as major economic impacts (Lapola et al., 2018). Degradation of the forest would lead to a loss of ecosystem services and threaten food security through risks to agricultural productivity, and reduced river levels could impact productivity of fisheries as well as transportation (rivers provide the main means of transport in the Amazon region) and the energy sector through redacted production of hydropower. Economic damages of Amazon dieback are projected to be between US$957bn and US$3,589bn (net present value as of 2018) over 30 years, mainly due to changes in the provision of ecosystem services (Lapola et al., 2018).

An AMOC collapse would put considerable stress on communities through impacts on water and food.

Story of one collapse: AMOC

The following narrative explores one climate tipping event: the collapse of the AMOC. It is set in the not-too-distant future. Although judged unlikely, it is plausible that an AMOC collapse could occur this century (see Section 1). The narrative is based on the best available knowledge on the hazards arising if the AMOC were to collapse and uses expert judgement to explore the consequences for societies, as well as OECD 2021 and OECD 2022. The purpose is to 'bring alive' this threat, which might otherwise appear abstract when presented in more academic formats. Exploring scenarios is crucial to properly recognising, assessing and managing risks from tipping points and their effects on societies.

Social media is awash with frightening rumours. A group of scientists and government officials gather to give a press conference about an important system of ocean currents in the North Atlantic. For years, evidence from sensors has been suggesting that the Atlantic Meridional Ocean Overturning Circulation is changing. The press conference confirms that the AMOC, which transports warm waters northwards from the tropics and is crucial to the functioning of the global climate system, has started to collapse, stalling the northward movement of heat.

The collapse plays out over the following few decades. Across Europe and the wider Atlantic region, average temperatures begin to steadily drop. Initially, this is confused as a welcome reprieve from the relentless rise in temperatures caused by climate change, though seasonal and weather extremes increase. But soon rainfall levels begin to drop, exacerbating water insecurity already made extreme by climate change. Large shifts in the monsoon rains in the tropics mean that some regions experience much less rain, and some too little, deepening what is now a profound global water emergency.

This interacts with an increasingly dire outlook for farming. The number of places suitable for growing major staple crops are diminishing as a result of how the AMOC collapse has affected the climate. Ultimately, the land across the world suitable for wheat and maize – which are critical to global food supply – falls by nearly a half in each case. Europe is particularly hit, with arable farming largely lost in the British Isles. The pace and scale of these changes outstrips the ability to diversify which crops are grown and where. Shortages of food and higher prices cascade through connected food systems, driving hunger, malnutrition and social and economic instability globally.

This is a common problem: changes are happening faster and more severely than systems – whether food, financial, economic or social – are adapted to or able to keep up with. There is general anger and resentment at the failure to foresee such risks, which feeds into a wider sense of betrayal, resentment and fear, with repercussions for cooperation and political stability.

The impacts of AMOC collapse combine with the ongoing effects of climate change, biodiversity loss and other environmental problems, with catastrophic consequences. The conditions that make for good health and economic development are severely affected across large parts of the world, while the conditions for conflict are growing. Societies struggle to cope with the multitude and pace of problems impacting all facets of life. Some are simply unable to cope. The escalating instability gets in the way of decarbonisation, leading to higher temperatures, more instability and less decarbonisation and this vicious cycle further degrades the prospects for civilization.

2.3. Negative social tipping points

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Summary

This chapter describes to what extent Earth system destabilisation and tipping can trigger negative tipping in various social systems, which in turn can reinforce the destabilisation of the Earth system through reinforcing feedback effects, mainly by preventing climate action. Specifically, with the Earth system further destabilising, we are likely to see social cohesion breaking down, while mental disorders and deviant behaviours will increase, further undermining societies' ability to respond to crises. We are also likely to see greater radicalisation of various groups and polarisation, making it harder to find collective solutions.

Though not the only cause, escalating climate change will undermine human security through an array of indirect – at times non-linear – pathways, thereby increasing the risk of violent conflict, which in turn will undermine societies' ability to cooperate on climate change mitigation. Further destabilisation of the Earth system is likely to trigger large-scale displacement, but also lead to trapped populations unable to leave increasingly inhospitable places. Displacement may increase ecological pressures within host communities, potentially adversely impacting the Earth system. Financial destabilisation is also likely to increase, diminishing the means to respond effectively to Earth system destabilisation.

Key messages

- Escalating Earth system destabilisation threatens to disrupt societal cohesion, increase mental disorders and amplify radicalisation and polarisation. It has the potential to escalate violent conflicts, mass displacement and financial instability.
- Negative social tipping points would hamper collective mitigation efforts and capacities to respond effectively to Earth system destabilisation, thus impeding the realisation of positive futures.
- If societies fail to re-stabilise the Earth system, we will not stay in a business-as- usual state. Rather, through mechanisms of negative social tipping, another social system state will emerge, likely characterised by greater authoritarianism, hostility, discord and alienation.

Recommendations

- Increase efforts to close knowledge gaps on negative social tipping points. Current knowledge is very patchy and fragmented, with many estimations and models likely to be underestimating the effects of breaching Earth system tipping points. We also need a better understanding of the interplay between various ecological and social drivers for negative social tipping.
- Future loss calculations and risk assessments (including assessment of human and cultural loss) should be done in close collaboration with climate scientists and social scientists to ensure adequate representation of climate catastrophes.
- While the prospect of negative social tipping points coupled with the Earth system destabilisation is unsettling, societies can and should attempt to prevent these; related governance options and challenges are revisited in Section 3.
- Focus on enabling positive social tipping and transformation processes (see Section 4) to help prevent the onset of negative social tipping.

2.3.1 Introduction

In recent years a range of climate change and social development processes, often compounding, have been observed to interact and affect social, economic and political systems. For instance, there is a trend of weakening and retreat of democracies worldwide (Freedom House, 2022; International IDEA, 2022) and some studies (e.g. Rahman et al., 2022) suggest a link with global warming. Not every trend exhibits social tipping dynamics, yet such trends can be indicative of underlying processes that may be approaching negative social tipping points. We regard the social tipping process as negative if the phase transition or the resulting new equilibrium leads to further destabilisation of the Earth system, which has potentially catastrophic consequences for human societies and ecological systems (IPCC, 2022; Lenton et al., 2023).

Disentangling the social dynamics and identifying social tipping processes and drivers is challenging, and research on social tipping, particularly in the context of climate change, has predominantly focused on 'positive' social tipping points (see Section 4). But research into negative social tipping is urgently needed, as these may impede the realisation of positive tipping points that are crucial for larger societal transformation (Spaiser et al., 2023). Figure 2.3.1 provides an overview of the tipping elements (TE), i.e. social subsystems, where negative tipping processes (TP) can occur. The figure also indicates potential feedback relations between various negative tipping processes; this will be further explored in the subsequent Chapter 2.4.

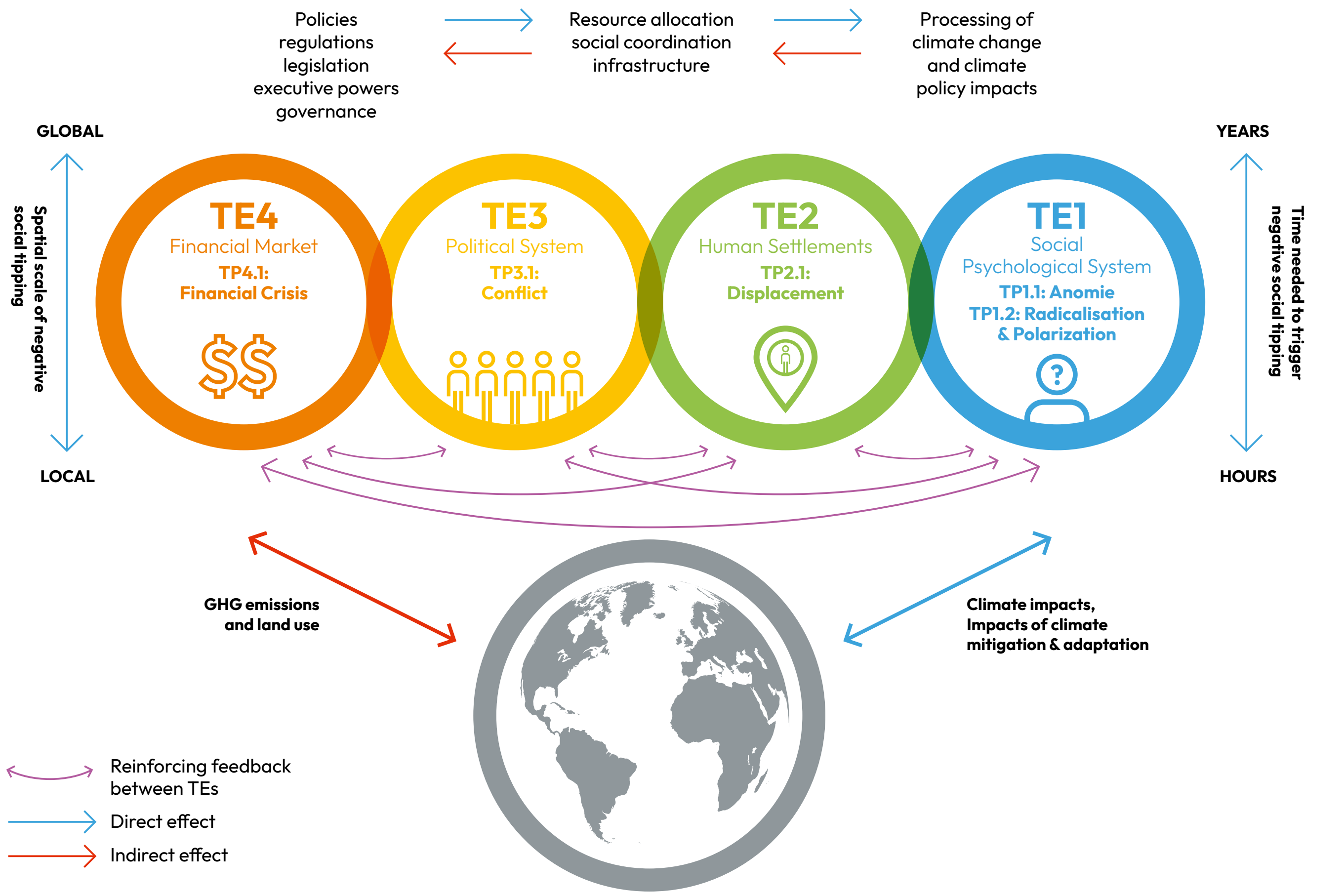

Figure 2.3.1 Tipping elements (TE) and associated negative social tipping processes (TP) with the potential to further destabilise the world–Earth system. The processes they represent unfold across levels of social structure on different time- and spatial scales. Tipping in all tipping elements can occur very rapidly (hours), triggered by a major shock event or unfold more slowly (years) over cascading pathways as the effects of Earth system tipping accumulate. Tipping in all systems can also occur only locally, affecting a specific community or spread across the globe. The identified interactions between the various negative tipping processes mean that they can potentially reinforce one another, making destabilisation more likely (see Chapter 2.4). Figure adapted from Spaiser et al., 2023.

We will focus here on five main negative social tipping processes identified in Figure 2.3.1: anomie (TP1.1), radicalisation and polarisation (TP1.2), displacement (TP2.1), conflict (TP3.1) and financial destabilisation (TP4.1). We do not claim to have captured all possible negative social tipping points; other social subsystems could experience negative tipping, e.g. breakdown of (certain) global supply chains (Marcucci et al., 2022) or of the public health system (at least in certain areas) triggered for instance, by an extreme heat event or the breakout of a disease due to climate change (Skinner et al., 2023).

We focus here on possible negative social tipping points that could have feedback effects on the Earth system. In each of the subchapters we will show how each of these phenomena can be impacted by rapid changes in the Earth system, in particular Earth system tipping points, but we will also discuss to what extent the tipping of these phenomena can then feedback on the Earth system itself, either directly or indirectly through mediating mechanisms. Therefore, the focus is on social processes that can reinforce the very ecological conditions that contributed decisively to the emergence of these social processes.

All the phenomena discussed here are extremely complex and have multiple drivers. In our discussion we will focus on Earth system destabilisation/tipping points as a driver for negative social tipping on top of other important factors and drivers, such as (rising) inequality and vulnerability, institutional failure, unequal power relations, etc, which we cannot explore here in full depth. Some of these additional social drivers will be discussed in Chapter 2.4, as they can drive breaching of various thresholds, both in the Earth system and in the social system. Future research on negative social tipping should seek to understand the interplay of these multiple drivers.

2.3.2. Anomie

2.3.2.1 Earth system destabilisation and anomie

Anomie is defined here as a state of a society or community, characterised by a breakdown of social norms, social ties and social reality, resulting in social disorder and disorganisation, disorientation and disconnection, which manifests itself on the individual level often through mental health deterioration and increased suicide rates and/or deviant behaviour (Brown, 2022; Teymoori et al., 2017). Although this is a nascent area of research, there is increasing evidence to suggest that changes in the Earth system can contribute to anomie. For instance, it has been observed in the aftermath of natural disasters, made more likely by climate change (Miller, 2016), and it has been suggested (Brown, 2022) that Earth system destabilisation may result in a new form of anomie, called environmental anomie. Environmental anomie emerges where sudden changes to the physical landscape (e.g. unprecedented wildfires) can upend the established social order, undermine people's ability to comprehend (i.e. familiar environment becomes unintelligible), relate to and function within their environment. This results in a breakdown of self-efficacy, with a sense of unreality taking hold (e.g. burning tree branches falling from the sky) and feelings of security and connection to place becoming undermined.

Environmental anomie can be further exacerbated when those affected witness that traditional authorities are overwhelmed and unable to respond to the physical chaos, which undermines confidence and leads to an individuation of suffering and feelings of social isolation (Brown, 2022).

Beyond anomie resulting from extreme weather events caused by escalating climate change, there is also evidence for a rise in anomic experiences, particularly by young people and children around the world, contributing to a mental health crisis (Hickman et al., 2021). In a first comprehensive study, surveying 10,000 children and young people (16-25 years) in 10 countries (Australia, Brazil, Finland, France, India, Nigeria, Philippines, Portugal, UK and US) researchers (Hickman et al., 2021) found that more than 45 per cent said their feelings about climate change negatively affected their daily life and functioning, 75 per cent reported they think the future is frightening, and 83 per cent said they think people (adults) have failed to take care of the planet. Climate and eco-anxiety and distress correlated with perceived inadequate government response and associated feelings of betrayal and abandonment by governments and adults, constituting a sense of 'moral injury' (the distressing psychological aftermath experienced when one perpetrates or witnesses actions that violate moral or core beliefs) among many young (Hickman et al., 2021). Longitudinal studies show a rapid increase in anxiety among the young since 2010 (Haidt and Twenge, ongoing; Parodi et al., 2021; Duffy et al., 2019), though longitudinal records for climate and eco-anxiety are not available. Respondents from the multi-national survey (Hickman et al., 2021) also reported that when they tried to talk about climate change with adults they were ignored or dismissed, contributing to feelings of social isolation. But it is not just the young experiencing the effects of climate change on mental health – it is negatively affecting the mental health and emotional wellbeing of people of all ages globally, but more profoundly of poor and vulnerable populations (Lawrence et al., 2021; Whitmore-Williams et al., 2017), as well as women and Indigenous people (IPCC AR6, 2022; Sultana, 2022).

Figure 2.3.2 Examples of the impact of extreme weather events on mental health across the world, based on Ferreira et al., (2023); Atwoli et al., (2022); Hamideh et al., (2022); Lawrence et al., (2021); Jermacane et al., (2018); Carleton, (2017).

2.3.2.2 Anomie tipping dynamics

The extent of tipping dynamics in anomie have not been studied directly yet, but studies exist that have demonstrated tipping dynamics in phenomena that can serve as proxies for the anomic state of a society or community. Specifically, social contagion processes, which can result in tipping points, i.e. thresholds when the social contagion process becomes self-perpetuating, have been observed for mental disorders and distress, including suicide (Paz, 2022; Scatà et al., 2018), for deviant behaviours (Busching and Krahe, 2018), for norm violation (Mäs & Opp, 2016) or for distrust (Ross et al., 2022). Hence one way anomie can tip within a society is through social contagion. Care is necessary in identifying these social effects, and therefore we stress the importance of improving analysis methods in this area (Cohen-Cole and Fletcher, 2008).

Another pathway for tipping can result from a single weather extreme event, for instance triggered by an Earth system tipping point having been reached (Bruun et al., 2017, Teymoori et al., 2017). Such an event acts like a powerful lever on communities that have already started slowly sliding into anomie, for instance because of growing poverty, inequality and institutional failures (Burns, 2015) or because of a slow erosion of social norms, which can also affect affluent communities (Bursztyn et al., 2020; Piff et al., 2012). Such an extreme event would catapult the community straight to the tipping point. Members of the community could become scattered in the aftermath, leaving them with depleted social and mental resources (Miller, 2016), establishing the perception that society as a whole is failing as a new mainstream conviction (Teymoori et al., 2017). While natural and human-caused disasters can bring communities together and strengthen solidarity and cooperation, research suggests that this is often only a temporary phenomenon; when the experience of cohesion and unity in the disaster aftermath starts to wane, communities start to experience disillusionment and depression, followed by social disintegration (i.e. anomie), particularly if the community is left without adequate, long-term support (Townshend et al., 2015). Breaching Earth system tipping points could thus have immediate repercussions for societies, with one possible outcome being anomie tipping, i.e. the disintegration of the social system (chaotic, random and irregular behaviour of agents in the social system) (Bruun et al., 2017). Regions and communities most vulnerable to the impacts of Earth system tipping points are more likely to experience anomie tipping.

2.2.3.3 Anomie feedback on the Earth system

Anomie can have feedback effects on the Earth system, further destabilising it, through various pathways. For instance, it is likely that if social norms disintegrate, certain pro-social behaviours and collective action that are necessary to slow down the climate crisis may diminish (Schneider and van der Linden, 2023; Lettinga et al., 2020; Constantino et al., 2002). As anomie takes hold, individuals may become disconnected and detached from the importance of environmental concerns, leading to a lack of motivation to engage in actions that mitigate climate change. This absence of collective effort and responsibility can exacerbate Earth system destabilisation, pushing the planet further towards irreversible damage. The breakdown of social cohesion hampers reciprocity and hence the possibilities of finding collaborative solutions that rely on collective efforts, shared responsibility and unified action. Without strong social norms supporting collective action and fostering trust and cooperation, it becomes increasingly challenging to implement effective measures to address accelerating Earth system destabilisation, increasing the likelihood of passing Earth system tipping points (Thøgersen, 2008; Fehr et al., 2002).

Furthermore, anomie weakens people's capacity to face the challenge as they battle mental health issues. Studies have shown that mental health problems often inhibit political participation (Burden et al., 2017; Ojeda, 2015). In climate policy terms, this means there is not enough pressure on policymakers from those most affected to implement effective climate mitigation measures, as, for instance, the young lose trust and disengage (Burns et al., 2008). Or they may feel forced to engage in violent protest behaviour such as eco-terrorism (see also the sub chapter 2.3.3 on potential radicalisation at the fringes of the climate movement). An empirical link has also been found between depression and psychological stress symptoms and susceptibility to conspiracy theories (Green et al., 2023). On intermediate levels, as anomie undermines, for instance, trust (including in science and political institutions and leaders), it disrupts collective action and decision making (Rafaty, 2018; Fairbrother, 2017). Without collective action to mitigate climate change, the Earth system is further destabilised. Anomie hence could lead to collective inertia with devastating long-term consequences (de la Sablonnière and Taylor 2020).

2.3.3. Radicalisation and polarisation

2.3.3.1 Earth system destabilisation and radicalisation and polarisation

Radicalisation of certain social groups or whole societies can be a reaction to perceived external threats, including ecological threats. Research suggests that people can respond to climate change and other ecological threats by becoming more authoritarian and derogative against outgroups (Uenal et al., 2021; Russo et al., 2020; Jackson et al., 2019; Taylor, 2019; Fritsche, 2012). This effect can be further exacerbated by the well-documented effect of heat on aggressive behaviours, including online hate speech (Stechemesser et al., 2022).

Though the evidence is not yet conclusive or available for a wide range of countries, the available results suggest that at least at this stage of climate change it is mostly individuals who already show authoritarian or social dominance predispositions that become even more reactionary in response to the threat of climate change. This tendency can produce or sharpen polarisation as conservative and liberal social groups move further apart in their attitudes and outlook (Spaiser et al., forthcoming;Uenal et al., 2021; Hetherington & Weiler 2009). Polarisation can also be driven by attempts to mitigate climate change, where climate change policies, rather than the Earth system destabilisation itself, are perceived as a threat to, for example, status or identity (Ehret et al., 2022; Dagett, 2018; Dunlap et al., 2016; Hoffarth and Hodson, 2016). Polarisation can be further exacerbated by inequality and general economic decline (Stewart et al., 2020; Winkler, 2019), particularly where perceived growing status insecurity can be exploited by polarising elites (Banda and Cluverius, 2018; Smith and Hanley, 2018).

However, as climate change progresses and becomes a more concrete existential threat throughout the world, individuals with more social liberal predispositions could develop increasingly authoritarian and reactionary views, prioritising security over liberty and human rights. This trend may be further reinforced by other social processes, which may further increase the sense of threat, such as rising inequality, political instability, etc. Research shows that exposure to existential threats (such as terrorism or natural disasters) can make even socially liberal minded people more authoritarian (Rahman et al., 2022 ; Russo et al., 2020; Hetherington and Suhay, 2011; Huddy and Feldmann, 2011; Gadarian, 2010). Such a development would decrease polarisation, but authoritarianism could become predominant in the population.

In another potential path to radicalisation, a violent flank could emerge at the margins of the climate movement. There is some evidence to suggest that, in the face of political non-response to the climate crisis and climate injustice, climate activists could become increasingly desperate and turn their peaceful campaigning into more violent and even armed means of resistance (Sovacool and Dunlap, 2022; Malm, 2021).

2.3.3.2 Radicalisation and polarisation tipping dynamics

Radicalisation can also exhibit tipping dynamics. Research has described radicalisation – for example, the spread of right-wing ideology (Youngblood, 2020) – through complex contagion processes. Similarly, the spreading of extremist content on social media has been observed to follow contagion processes (Ferrara, 2017). Moreover, processes of 'cross-pollination' of radical ideas have been documented (Kimmel, 2018; Baele et al., 2023), including for climate denial (Agius et al., 2020). Cross-pollination describes the merging of previously separate radical clusters, facilitating further contagion by expanding the number of radicalised individuals and their reach to those not yet radicalised.

Polarisation may increase quickly in response to fuelling of political partisanship and may be very difficult to reverse. Macy et al., (2021) found that polarisation is most likely when the issue that is meant to unite a society (e.g. facing the threat of climate change) is not as salient as the political partisanship. Radicalisation is also more likely in affluent societies, who are typically more sheltered from climate impacts but more likely to feel a threat to their status – and recent trends seem to confirm this (Vihma et al., 2021; Dunlap et al., 2016).

In an extreme scenario, radicalisation tipping triggered by escalating Earth system destabilisation or breached Earth system tipping points, could lead to currently fringe political ideologies taking hold. One such example is ecofascism (Taylor, 2019), which reinterprets white supremacy ideology in the context of the climate crisis with the goal to defend habitable areas for the white race. Already, some recent right-wing terrorists have subscribed to and legitimised their actions with **ecofascism,** such as Brenton Tarrant, who committed a terror attack on a mosque in Christchurch, New Zealand, in 2019, killing 51 people. Finally, if radicalisation escalates we may also enter the pathway of a violent conflict (see Chapter 2.3.5).

2.3.3.3 Radicalisation and polarisation feedback on the Earth system

Radicalisation and polarisation can have feedback effects on the Earth system, destabilising it further. Authoritarian and social dominance attitudes are negatively related to environmental attitudes and support for environmental/climate change policies (Julhä and Hellmer, 2020; Stanley and Wilson, 2019; Stanley et al., 2017). Indeed, right-wing ideology has been repeatedly correlated with climate change denial (Jylhä and Hellmer, 2020; Czarnek et al., 2020; Hornsey et.al., 2016; Hoffarth and Hodson, 2016). When climate change is denied, no attempts are made to mitigate that change – on the contrary, decisions may be taken to further prop up high-emitting industries (Darian-Smith, 2023; Ekberg et al., 2023), which would fuel climate change further, contributing to yet more change in the Earth system.

Pure climate denial (or primary climate obstruction) is, however, in retreat, and instead we see a rise in secondary and tertiary climate obstruction, which can include deliberate, often elite-driven, polarisation of societies on the issue (Cole et al., 2023; ; Ekberg et al., 2023; Flores et al., 2022; Mann 2021; Goldberg and Vandenberg, 2019; Kousser and Tranter, 2018). The effects, though, are similar, because committed minorities can be sufficient to block or water-down crucial policies to deal with the climate crisis (Ekberg et al., 2023; Abou-Chadi and Krause, 2018) and lack of mitigation results in further changes in the Earth system.

Committed minorities can also polarise, for instance, through deliberate misinformation (Galaz et al., 2023). Polarisation impedes cooperation required to implement mitigation policies by degrading trust and mutual understanding, and by making it difficult to engage in constructive debate toward consensus (Judge et al., 2023; Barfuss et al., 2020). Radicalisation and polarisation taking hold in a country can also affect climate mitigation efforts of the wider international community, particularly if the respective nation holds a key international position, as happened with the US under the presidency of Donald Trump (Bomberg, 2021).

On the other hand, the effects of a violent or armed flank at the margins of the climate movement are more difficult to predict, as research on the effectiveness of this approach is inconclusive and appears to suggest a high level of context dependency (Simpson et al., 2022; Belgioioso et al., 2021 ; Muñoz and Anduiza, 2019; Schock and Demetriou, 2018; Tompkins 2015). Two pathways are conceivable:

1. The violent flank alienates the population (Feinberg et al. 2020; Muñoz and Anduiza, 2019; Simpson et al., 2018), leading to erosion of support for the cause, greater polarisation and non-cooperation on climate policies. In this case the feedback on the Earth System could be further destabilisation due to lack of agreed mitigation policies;
2. The violent flank forces policymakers and business leaders to respond to the demands of the moderate climate movement (Simpson et al,. 2022; Belgioioso et al., 2021) and this, through a reduction in GHG emissions, could lead to some stabilisation of the Earth system. However, the violent/armed strategy may itself result in significant human suffering.

2.3.4 Displacement

2.3.4.1 Earth system destabilisation and displacement

Displacement is usually a forced or involuntary, reactive movement between places, which can be short or long-term, within or between nations. Both acute and slow-onset environmental pressures, such as extreme weather events, drought and sea level rise, are projected to increase under Earth system tipping scenarios.

Measurement challenges, definitional debates, and the complex drivers of human mobility can make it difficult to document and identify causal evidence of climate-induced migration and displacement (Boas et al., 2019; Carvajal and Pereira, 2010). Climate mobilities – including cross-border and internal movements and immobility – occur along a spectrum from voluntary to pre-emptive, to forced (Capisani, 2023). These are exacerbated by weather events and deteriorating environmental conditions, but are also a product of the global state system, and historical and current political, social and economic decisions about infrastructure, housing, public services, rights, and governance responses. Nevertheless, increasing Earth system destabilisation will impact the migration (voluntary movement), displacement (involuntary movement), and immobility (inability to leave a high-risk or impacted area) of a large proportion of the population through direct and indirect effects. These include: increased hazard exposure, flooding, coastal erosion, sea level rise, droughts and heatwaves, effects on water supplies and other vital human systems and infrastructures, and threats to livelihoods and housing security, among others (Hauer et al., 2020; Meueller et al., 2014). Indeed, there are already examples of the forced and involuntary displacement of populations due to the impacts of extreme weather events (Thalheimer and Oh, 2023; IPCC, 2022; Clement et al., 2021). And many, in particular irreversible climate change effects such as sea level rise, are projected to be extremely costly, not least because of their impact on (forced) human mobility (Hauer et al., 2020; Neumann et al., 2015). Breaching Earth system tipping points would further amplify these effects.

Acute, short-term hazards result in increased migration and forced displacement, at least temporarily, especially within communities with limited adaptive capacity or resilience (McLeman, 2018). Recent estimates show that 95 million people are involuntarily on the move across the globe, many internally displaced due to extreme weather (Lenton et al., 2023). The Groundswell global modelling efforts predict 140 million people displaced within the borders of their own countries by 2030 (Rigaud et al., 2018). Additionally, the proportion of the global population living in coastal regions likely to be affected by sea level rise is growing and likely to surpass one billion people this century. Indeed, internal displacement often leads to large-scale and rapid urbanisation (Adger et al., 2020) and many of the urban centres that attract migrants and displaced people are close to the sea. These populations are likely to experience repeated displacement, which often leads to poorer outcomes for these communities (Haque et al., 2020). Ultimately, vulnerability and risk in a shifting and shrinking human climate niche are not equally distributed, and how they are spread across the planet is likely to change with the crossing of Earth system tipping points.

2.3.4.2 Displacement tipping dynamics

Droughts, floods and cyclones can destroy crops and pose severe challenges for the livelihoods of smallholder farmers in large parts of Africa, Asia and the Americas (Krishnamurthy, 2012). As global tipping points are crossed, the increase in rapid-onset hazards and sea level rise is likely to increase pulse-like migration and displacement (McLeman, 2018).

There are likely to be tipping points, for instance, in terms of sea level rise or in the steadily deteriorating conditions beyond which human migration becomes inevitable, but they are little understood (Hauer et al., 2020). Climate, cryospheric and ecological tipping points could significantly accelerate the impacts of climate change and ecosystem change on human mobility by increasing the likelihood and/or accelerating when these tipping points are reached (see Chapter 2.2; Lenton, 2011). Specifically, the impacts from triggering an Earth system tipping point could catapult communities, which are already experiencing out-migration because of deteriorating conditions, straight to such a tipping point, forcing mass displacement. Of course, how vulnerabilities are distributed will also depend on the myriad social factors and the measures taken to increase resilience, to adapt and protect communities, and to manage the relocation of populations facing the impacts of breached tipping points.

The relationship between income levels and displacement is nonlinear, with large gaps for example in flood-induced displacement and immobility between high and low-income countries and high and low-income communities within countries (see case study below for a description of such dynamics during Hurricane Katrina in New Orleans). The systematic social, political and economic marginalisation of certain communities, uneven distribution of adaptive capacity and resilience, underinvestment in disaster preparedness, and degradation of land and infrastructure have rendered some communities and people more vulnerable to both displacement and immobility (Kakinuma et al., 2020; Johnson and Krishnamurthy, 2010; Hulme et al., 2008) (see Figure 2.3.3). Important gaps remain in our current understanding of adaptive capacity and resilience, and where the limits of adaptation and habitability lie (Hornton et al., 2021; Thomas et al,. 2021).

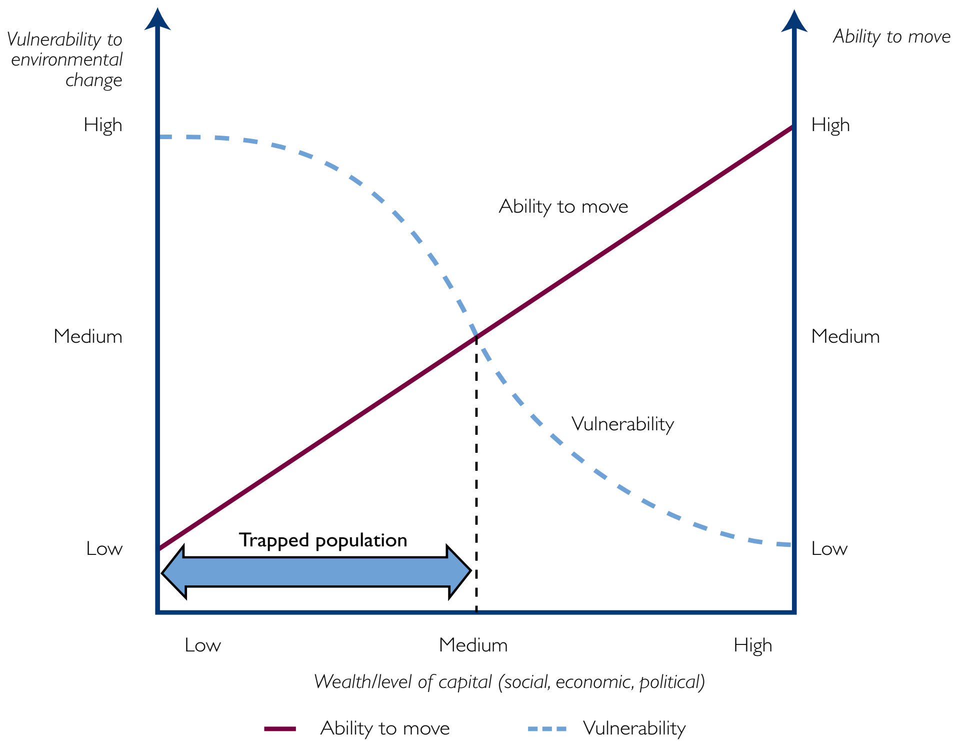

Figure 2.3.3: Mobility as a function of vulnerability and economic resources (Source: Foresight 2011).

2.3.4.3. Displacement feedback on the Earth system

In the absence of appropriate governance mechanisms and protocols for how to address the complex dynamics surrounding climate-induced human mobility – for example, how and where to relocate displaced communities, how preparedness measures and early warning signals can be used to prevent mass displacement, and when and how to consider managed retreat of populations, feedback consequences for the Earth system are possible. For example, host communities may face strains on their natural resources and/or sinks to meet the additional needs of the displaced, and conflicts may emerge between displaced and host communities without adequate measures to resolve conflicts and ensure the wellbeing of both populations (Watson et al., 2023; Tafere (2018)) identified environmental degradation resulting from the influx of displaced populations in East Africa, often in environmentally sensitive (e.g. protected forests) or already strained regions (e.g. arid or semi-arid areas). Poorly managed displacement and resettlement efforts can thus contribute to deforestation and erosion and water shortages, feeding back onto the Earth system and reinforcing vulnerabilities (Staal, 2009).

CASE STUDY:

Hurricane Katrina and displacement in New Orleans

In cases where an acute, rapid-onset disaster occurs, human mobility responses will vary at the household and individual level. For example, Hurricane Katrina destroyed around 300,000 homes, and forced the displacement of approximately 1.5 million people from across the Gulf Coast of the US. However, despite the evacuation order, an estimated 110,000 people remained in New Orleans. The majority of those remaining within the city were African American, poor, elderly, and/or living with a disability – an example of how climate disasters can compound existing social inequalities and create trapped populations (Peek and Weber, 2012). Post-disaster, many of those who remained were then forced to evacuate. They had little agency over their destinations; while the majority of the displaced population, especially those who had pre-emptively moved, remained in the region, those who were forcibly evacuated were scattered across all 50 states (Fussell, Curtis and DeWaard, 2014; Peek and Weber, 2012).

After the initial post-disaster 'pulse' of outmigration from New Orleans and the surrounding area, displaced populations had to choose whether to return or resettle elsewhere. The rate at which people returned to the city was influenced, at least in part, by racial dynamics. Even when controlling for socioeconomic status and demographic characteristics, Black residents returned to the city at a much slower rate than white residents (Fussell, Sastry and VanLandingham, 2010) due to a higher rate of housing damage sustained by Black communities, and these disparities increased with time. The least-impacted communities – often those with significant prior social advantage – were able to rebound more quickly, reducing the length and permanence of displacement.

As of 2019, New Orleans still had 100,000 fewer occupants than it had prior to Hurricane Katrina. This gap is almost the same as the number of Black residents who have not returned – a 6 per cent drop in the share of the city's population (Babb, 2021). As a result, New Orleans is now both whiter and wealthier than it was pre-disaster, with implications for social cohesion and post-event inequality retrenchment. According to Go, (2018), the stronger the civic structure, i.e. local organisational resources, the more likely spatial inequality will be deepened in the rebuilding effort. This is especially true along racial lines; white residents concentrate in geographically safer areas, while Black residents are left with lower-lying, flood-prone areas (Babb, 2021; Go, 2018).

2.3.5. Violent conflict

2.3.5.1 Earth system destabilisation and violent conflict

Although the causal link between climate extreme events and violent conflicts remains considerably debated (Selby et al., 2017 ; Buhaug et al., 2014; Solow, 2013), research nevertheless suggests that conflicts at various levels are affected by accelerating changes in the Earth System. Though not the only cause (Ge et al., 2022; Scartozzi, 2020; Mach et al., 2019; Sakaguchi et al., 2017), Earth system destabilisation undermines human livelihoods and security, because it increases population vulnerabilities (e.g. extreme events, food/water scarcity, see Chapter 2.2), grievances, and political tensions through an array of indirect – at times non-linear – pathways, thereby increasing human insecurity and the risk of violent conflict (Döring and Hall, 2023; Ide et al., 2023; von Uexkull and Buhaug, 2021; Koubi, 2019; Baalen and Mobjörk, 2017; Kelley et al., 2015; Hsiang and Meng 2014; Scheffran et al., 2012). Climate events have direct and indirect impacts on human livelihoods (e.g. life, health, income, assets) and capabilities (e.g. money, resources, vehicles, equipment, technology). These impacts will be further amplified by Earth system tipping points (see Chapter 2.2) and could trigger human responses that can stabilise or destabilise regional hot spots (Scheffran, 2020). Even short-lasting extreme weather events can cause irreversible damage to agriculture and unsettle human comfort, causing economic decline. For instance, the risk of simultaneous harvest failures across major crop-producing regions is rising with escalating climate change, exacerbated by various others factors (e.g. poor governance of water scarcity, failed subsidies etc.), threatening global food security and ultimately human security (Kornhuber et al., 2023). Over time an erosion of livelihoods could either exacerbate existing problems in fragile states, or be the beginning of a downward spiral of violence or a vicious circle of conflict escalation (Buhaug and von Uexkull, 2021). But there remain gaps in understanding the specific mechanisms, dynamics and confounding factors within and across regions and populations. Worth noting is the extreme unequal distribution of conflict risks which are increased through Earth system destabilisation (Koubi, 2019).

2.3.5.2 Violent conflict tipping dynamics

Research (Guo et al., 2018; Ge et al., 2022; Sun et al., 2022; Aquino et al., 2019; Guo et al., 2023) has demonstrated that conflicts can be described in terms of social tipping mechanisms and that the tipping can be triggered by Earth system destabilisation. Indeed, using a complex systems lens and converging the human–environmental–climate security (HECS) nexus framework (Daoudy, 2021; Daoudy et al., 2022) and the social feedback loop (SFL) framework (Kolmes, 2008) can help to understand conflict tipping mechanisms in coupled social-ecological systems. Self-reinforcing feedbacks (van Nes et al., 2016; Kolmes, 2008) emerge in social-ecological systems as a result of complex interactions among socio-economic, environmental and political events and variables, such as institutional capacity for solving social-ecological problems (Allen et al., 2012; Polk, 2011). These complex interactions result in the amplification of social-ecological shocks potentially disrupting the system in concern (Kintisch, 2016; van Nes et al., 2016; Folke et al., 2010; Homer-Dixon, 2010; Holling et al., 2002). These disruptions can result in a conflict, i.e. a phase transition takes place from cooperation to conflict, with the affected society becoming entrapped in the conflict state until sufficient incentives can move it out (Guo et al., 2023, Sun et al. 2022, Guo et al., 2018).

2.3.5.3 Violent conflict feedback on the Earth system

When conflicts escalate, exhibiting a tipping dynamic (Chadefaux, 2016), they can in turn impact the Earth system. This can happen directly as warfare itself is producing excessive GHG emissions and destroying vital ecosystems such as forests, as is for instance currently the case of Russia's war in Ukraine (de Klerk et al., 2022) or has been in the past when oil wells were burned during the Gulf War or systematic deforestation has been inflicted upon Vietnam during the Vietnam War (Stoddard et al., 2021). Even beyond involvement in war activities, everyday military operations directly generate vast emissions of GHGs (Kester and Sovacool, 2017; Crawford, 2019). Research has found that militarization amplified the effects of economic growth on carbon emissions as militaries have a significant influence on the production and consumption patterns of economies and on the ecological demands to uphold and expand military infrastructure (Jorgenson et al., 2023). The feedback impact of conflicts on the Earth system can also be indirect, through impeding humanity's ability to collaborate in order to find solutions to global challenges such as climate change. Within societies entangled in a conflict, resources are diverted to winning the conflict rather than to mitigate climate change. In Ukraine, 90 per cent of the country's wind power and 50 per cent of its solar energy capacity had to be taken off-line since the war began (Brown, 2023). Internationally conflicts moreover impede collaboration. Again, Russia's war in Ukraine is an exemplary case, as it impacted the ability of the international community to come together at COP27 and beyond. For instance The Arctic Council is currently put on hold (Harris, 2022; Brown 2023).

CASE STUDY:

LAKE CHAD

The Lake Chad region has experienced some of the most striking social and biogeophysical changes in recent times. Just 50 years ago, the lake was larger than the size of Israel (25,000km^2) and provided livelihoods to over 30 million people (Gao et al., 2011). Today, only 10 per cent of the lake waters remain due to rising temperatures (1.5 times faster than global average), longer dry season and changes in water flow from feeding rivers. These changes, combined with megadroughts, heat waves and sand/dust storms, have led to crop failures, livestock losses and depletion of fisheries, and have placed the region on the edge of systemic criticality and conflict tipping (Okpara et al., 2015).

The region has been afflicted by several political, identity/ethnic, communal and resource conflict events. Most of these events have tipped over into massive upheavals in the form of terrorism, triggering brutal violence. Conflict tipping into violence under conditions of rapid lake water oscillation and shrinkage has triggered a shift from a state of relative tension to a heightened violent situation where self-perpetuating cycles of open violence become more prevalent and harmful to the Lake Chad biogeographical/ecological landscape (Avis, 2020). Conflict tipping pathways in this setting are diverse and multifaceted. One conflict tipping pathway is the abrupt breakdown in small-scale farming, fisheries and local food systems triggered by multi-year oscillations of the Lake Chad waters (Okpara et al., 2017). This has amplified social grievances against the state. Grievances have fuelled the formation of violent solidarity networks (many with links to criminal gangs and insurgent groups) and have led to brutal regional conflicts and the death and displacement of millions of citizens. Another tipping pathway is the escalation of a conflict economy where armed groups illegally control natural resources, agricultural trade routes and food supply chains, and secretly divert arms, drugs, stolen cash and cattle into areas they control (Sampaio, 2022). Armed groups recruit and radicalise young fighters, who previously depended on the resources from the Lake. In doing so, they trigger spiralling territorial dynamics where the intensity and scope of conflict and violence rapidly increase.

At the same time, cycles of retaliation, reprisals, and counterattacks between state and non-state actors (linked to the conflict economy) have continued to create self-perpetuating chains of violence.

Conflict tipping over into violence and terrorism harm the Lake Chad biogeographical landscape in many ways. Approximately 80 per cent of the conflicts take place in nature-rich, biodiversity hotspots, and with the increasing use of the environment as a hideout, military base or camp for hostage taking, attacking the environment has become a military/warfare objective (Okpara et al., 2015). Aerial and ground bombardments by soldiers primarily target the inland hardwood forests and the mangroves covering remote insurgent groups' camps, causing direct environmental damage. And bombing by both sides produces many hundreds of thousand tons of carbon monoxide, nitrogen oxides, hydrocarbons, sulphur monoxide, and CO_2, which adversely impact humans and ecological systems in the region and beyond. Bombing also leads to contamination of water supplies in communities, undermining public health. Conflict tipping also has an indirect effect on the Earth system. Conflict tipping triggered population displacement and complex emergencies in the region, led to overcrowding in destination areas and intensified pressures on regional water, food, land, and energy systems (Vivekananda et al., 2019; Oginni et al., 2020). These outcomes in turn spurred unsustainable agricultural practices, overfishing and deforestation. Displaced people are often forced to turn to the environment to meet their basic needs (e.g. illegal logging, poaching). Finally, Lake Chad conflict tipping is characterised by a breakdown in environmental laws and governance, causing weak enforcement of nature conservation mechanisms (Magrin, 2016). For an in-depth exploration of cascading effects in this case example, please see Chapter 2.4.

2.3.6 Financial destabilisation

2.3.6.1 Earth system destabilisation and financial destabilisation

Research on the significant, non-linear effects of climate damages on the global economy is well established (Burke et al., 2015; Carleton and Hsiang, 2016; Diffenbaugh and Burke, 2019; Hsiang et al., 2017; Martinich and Crimmins, 2019), albeit likely severely underestimating climate damage (Keen 2021; Winter and Kiehl 2023). The impacts of Earth system destabilisation on the financial sector are now receiving increasing attention too, with studies suggesting that climate-related damages will impact the stability of the global Cronafinancial system significantly (Curcio et al., 2023; ECB, 2021; FSB, 2020; IMF, 2020; ESRB, 2020; Crona et al., 2021; Kemp et al., 2022). Escalating climate change, particularly where it leads to breached Earth system tipping points, would progressively, or abruptly, destroy the capital of firms, reduce their profitability, deteriorate their liquidity and reduce the productivity of their workforce, leading to a higher rate of default and harming the financial sector (Dafermos et al., 2018). Such an impact on firms' bankruptcies would cascade down to banks, accumulating a stock of bad debt and destabilising their own balance sheets, resulting in more frequent banking crises (Lamperti et al., 2019). Globally, consequences of climate change and breached Earth system tipping points are likely to trigger correlated shocks across large regions (Walker et al., 2023).

Breached tipping points are also likely to overwhelm the insurance industry. In 2015, ahead of COP 21 in Paris, the former CEO of AXA declared:

"A2°C world might be insurable, a 4°C world certainly would not be (Bacani, 2016)".

At a hearing on climate risks and its potential threat to the federal budget organised by the US Senate Budget Committee in March 2023, representatives from the insurance industry noted that, with climate change escalating, the industry is experiencing a crisis of confidence with respect to its ability to predict loss. Reinsurance companies are withdrawing increasingly from areas exposed to high climate change risks – for example, areas vulnerable to wildfires and floods (Frank, 2023). The multiplication of extreme weather events will certainly impact the value of physical assets (Caldecott et al., 2021). For instance, hurricane damage to properties could rise by as much as 275 per cent by 2050 due to their higher frequency and intensity (Schulten et al., 2019). However, the models used to estimate climate risks have been found to be often inadequate and likely to underestimate the risks (Trust et al., 2023; FSB and NGFS, 2022; Kedward et al., 2023).

Additionally, climate change mitigation, such as shifting to renewable energy production, fossil fuel divestment and/or phase-out, are likely to lead to the stranding of various types of assets, notably related to the fossil fuel industry, which may have wider implications – for example for pension funds, but also for state revenues in fossil fuel-producing nation states (Mercure et al., 2018; Semieniuk et al., 2022; Caldecott et al., 2021). The danger of destabilisation because of stranded fossil fuel assets is particularly big when force majeure (e.g. the breaching of an Earth system tipping point) would require an abrupt and badly managed transition to zero carbon.

Early and stable policy frames can facilitate smooth asset value adjustments as part of fossil-fuel phaseout, but late and abrupt policy frameworks could have adverse systemic consequences (Battiston et al., 2017).

However, by far the biggest issue with the existing empirical evidence, predictions and models that try to estimate climate damage for the financial sector is that they do not account for Earth system tipping points (Keen et al., 2022; Galaz et al., 2018).

2.3.6.2 Financial destabilisation tipping dynamic

Financial markets are increasingly conceptualised as complex network systems that can be affected by tipping points and cascades (Battiston et al., 2016). An expected function of financial markets is to aggregate individual forecasts about future profitability, and as such to manage future risk. In theory, markets can thus adjust – more or less smoothly depending on the smoothness of individual agents' perception changes – to foreseeable problems, similarly to traders, who reduce demand for equities in exposed companies. Financial crises are likely to result either from tipping points that defy predictions either in timing or magnitude, or from further cascade effects such as the collapse in mortgage insurance markets in the financial crisis of 2008. Indeed, the 2008 financial crisis is a good example for a tipping cascade: home-loan defaults caused a decrease in the value of collateralised debt obligations, leading to the insolvency of banks and insurers, resulting in a credit crunch, an economic downturn and ongoing repercussions that persist today (Sharpe, 2023).

Similar dynamics will probably unfold with escalating climate change, and particularly when tipping points are breached. If the banks' equity deteriorates due to economic imbalances reaching a certain threshold (see Chapter 2.3.6.1), secondary systemic effects would be triggered. The troubled banks would fail to meet their financial obligations to other banks and hastily sell their assets at lower prices, eroding confidence in similar banks (Kiyotaki and Moore, 2002; Roukny et al., 2013; Chinazzi and Fagiolo, 2015). Such contagion phenomena can result in a tipping point being reached, when contagion becomes self-perpetuating due to feedback loops in the system that amplify the initial shocks (Haldane and May, 2011; May et al., 2008; Gai and Kapadia, 2010). For example, a drop in asset prices can lead to margin calls, which force investors to sell more assets, which further depresses prices. This can lead to a cascade of failures across the financial system, resulting in a full-blown financial crisis, with collapsing of value of loans and of insurance companies, risking destruction of much of the value of the world's savings pools. At least a third of these savings – around $60 trillion – is held in pension funds, paying income to pensioners and storing value for future generations as they get older (OECD Global Pension Statistics, 2021).

Finally, if Earth system tipping points are triggered, destroying assets and the economic productivity of whole regions, we can expect rapid non-linear tipping point effects in the coupled global financial sector (Battiston et al., 2017; Galaz et al., 2018). The financial and economic system would eventually settle into a new stable phase, although this phase may be characterised by recession, high unemployment, austerity and other deteriorating economic conditions.

2.3.6.3 Financial destabilisation feedback on the Earth system

There are various pathways through which financial destabilisation and tipping would feed back on the Earth system. Governments will likely try to stabilise financial markets through bailing-out policy such as providing fresh capital and saving insolvent banks and it is predicted that climate change will likely increase the frequency of bailouts (Lamperti et al., 2019). Recent government bailouts in response to COVID-19 have shown a distinct lack of sustainability focus (Rockström et al., 2023). Bailouts negatively affect the public budget and lead to increasing government debts, leaving decreasing resources for addressing Earth system destabilisation, for instance through effective climate change mitigation measures. Financial destabilisation would also deplete businesses and individuals of resources to invest in post-carbon transition.

2.4. Cascades of tipping in impacts

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Summary

This chapter advances the state-of-the-art understanding of tipping cascades across scales and systems between Earth system and social tipping points. We consider a tipping cascade to occur when extremes or passing of a tipping point in one system triggers or increases the likelihood of reaching a tipping point in another. Here, this means that crossing an Earth system tipping point or experiencing an extreme volatility in the natural system can lead to cascading impacts that trigger social tipping points, and vice versa.

Our analysis of the literature shows that most is known about the tipping cascades in the large-scale Earth System, while hardly any research analyses tipping cascades within socio-economic systems. We further illustrate the complexity of identifying tipping cascades with five case studies. These examples show the challenges in establishing the state of systems involved, identifying and modelling dynamics over time and space, as well as capturing the context dependency of interactions, especially in the social system.

Further research steps include development of conceptual understanding of causal chains and feedbacks, as well as systematic accumulation of the empirical evidence base over temporal and across spatial scales. Research on governance of tipping cascades is in its infancy, with little insight into how the risks of tipping cascades can be identified and managed.

Key messages

- Although empirical evidence is currently scarce, extrapolating 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.
- Less is known about cascades from biophysical to socio-economic systems than those between biophysical systems. This is due to limited experience, and time lags between crossing Earth system tipping points and the reaction of social systems.
- Research on tipping cascades in human systems thus far has focused on accelerating mitigation action, rather than preparing for potential consequences of physical climate risks.

Recommendations

- Transdisciplinary research initiatives are required to help build understanding and consensus around tipping cascades and their role in the emergence of systemic risk.
- Focused research is needed on the mechanisms and consequences of tipping interactions, including identifying distinct feedbacks fuelled by policy, economic, financial and behavioural dynamics that can potentially lead to cascades.
- Monitoring programmes should be created to systematically gather data about potential tipping point interactions over long periods of time, founded on research into which variables to monitor.

2.4.1 Introduction

We review the role and prevalence of cascading impacts in relation to tipping points. We focus on identifying cascading impacts across biogeophysical and social systems in order to illustrate how a cascade from a tipping point in one system can lead to an increasing likelihood of breaching a tipping point in another. We do this by focusing on the interactions between natural and social systems across different temporal and spatial scales. The outcomes of these tipping cascades can be negative or positive, depending on the systems involved, actors in those systems and over different periods of time.

The literature is clear that there are interactions and feedbacks between systems that affect each other and can lead to abrupt changes (Liu et al., 2023; Wunderling et al., 2023). These are often termed as cascading impacts, which can be defined as "a sequence of events where abrupt changes in one component lead to abrupt changes in other components. These changes could also interact with each other and propagate from larger to smaller spatial scales or vice versa" (Brovkin et al., 2021).

Cascade as a term has multiple meanings, generally describing the sequential occurrence of similar events. e.g. A is followed by B, which is followed by C (Klose et al., 2021). Cascade as a term has also become commonly used in assessing climate risks (Simpson et al., 2021), implying that risks are passed on from one stage to another. Cascading risk, for example, has been defined as one event or trend triggering others and these interactions can be one-way (e.g. domino or contagion effects) but can also have feedbacks (Helbing, 2013). Klose et al., (2021) propose an ideal model of three different types of cascades: 1) two-phase cascade, 2) domino cascade, 3) joint cascade. However, it is not clear to what extent this can be extended to the study of cascades between biogeophysical and social systems.

Cascade as a term is increasingly used to characterise systemic risk (i.e. a risk that a failure of one element will lead to system-wide adverse impacts or an entire system collapse). According to Sillmann et al., (2022), systemic risk is exemplified by cascades that spread within and across systems and sectors (such as ecosystems, health, infrastructure or the food sector) via the movements of people, goods, capital and information within and across boundaries (for example, regions, countries or continents). The spread of these impacts can lead to potentially existential consequences and system collapse across a range of time horizons (Sillmann et al., 2022).

So far, there has been increasing interest in cascading impacts of tipping points (Brovkin et al., 2021) but less conceptual development or empirical work of the processes constituting such cascades. Many of the contributions highlight the nature and the importance of the problem (Franzke et al., 2022), but there is a shortage of empirical knowledge or clear conceptual understanding of the role that cascades play in facilitating or hindering tipping points between systems.

We interpret cascades here to refer to a tipping cascade, which occurs when passing one tipping point triggers at least one other tipping point. Here, this means ecological tipping points can lead to cascading impacts that trigger social tipping points, and vice versa. It is useful to point out that a cascade effect in current literature is considered a causal change where a change in one system can trigger a further change in another system. In these instances, tipping can be driven by such cascades but not necessarily.

The aim of this chapter is to advance the state-of-the-art understanding of cascades across scales and systems between Earth system and social tipping points. We argue that this understanding is constrained by lack of conceptual clarity and empirical evidence. In order to address this gap, we review the current state of literature on cascading tipping events and identify where most of the evidence base is. We also use five case examples to identify emerging research questions regarding what temporal and spatial scales, and associated dynamics and sequences, are relevant to study tipping cascades.

Box 2.4.1: Methods used

Topic modelling is a statistical technique used to discover latent topics within a collection of documents (Blei, 2012). Here, BERTopic (a state-of-the-art Python library) is used to generate topic clusters to define how the study of climate-related tipping points has evolved (Grootendorst, 2022). For data, as a starting point, a search of Scopus was conducted using the term 'climat* AND tipping point* OR cascad*'. For the purposes of this paper, a cluster is taken as a proxy for a research area of interest. After the 'parent' cluster of 'climate_change_tipping_points', there were several clusters of similar density. The fuzzy search terms 'climat*' and 'cascad*' were chosen in order to encapsulate any variation of climate-themed wording (i.e. climate, climates, climatic, etc). The volume of publications per year is displayed in Figure X. This yielded 1,434 document results covering the period 1998-2023. The title, abstract and associated metadata of these results formed the modelling dataset.

A causal loop diagram (CLD) is a qualitative and conceptual method to capture cascades in a system of interest. A CLD maps out the structure of a system and its networks and reveals causalities and feedbacks within the system (Haraldson, 2004; Sanches-Pereira and Gómez, 2015). In a CLD, system elements are connected with arrows that indicate causal links between them with "+" representing a positive link. Here, we use a CLD to identify feedback effects between biogeophysical and social-ecological systems, which may arise when elements affect each other in the system. This loop can be reinforcing (R), in the sense of a positive feedback, if events or behaviours created by the elements in the loop amplify each other, leading to unbounded growth or decline. Or the loop can be balancing (B), in the sense of a negative feedback, if some elements create a damping or counteracting of initial changes, resulting in oscillations and sometimes equilibrium.

2.4.2 Research approach

To address the research questions, we used two methods, as described in Box 2.4.1. First, we employed topic modelling to scan the literature for trends that illustrate the knowledge base quantitatively. Second, we employed expert judgement to select five cases of tipping cascades to illustrate how they take place and capture their cascading characteristics in causal loop diagrams.

2.4.3 State of literature on cascades and tipping points

We use topic modelling (see Box 2.4.1) to identify 30 unique clusters, which indicate research areas, of tipping point topics (Figure, 2.4.5) to see what areas are being researched. The results show that focus is on large-scale ecosystem phenomena, such as sea ice, coastal flooding, and coral reefs (see Figures 2.4.1-2.4.4). At the same time, human-related research tends to focus on how behaviour and policy can influence the natural world. Through this lens, humans are viewed almost exclusively as the driver of tipping cascades. Though some clusters, notably adaptation_coastal_flood_rise, do flag 'urban' as a focus, there is a notable lack of topic clusters dedicated to how humans will be impacted by climate-related tipping cascades.

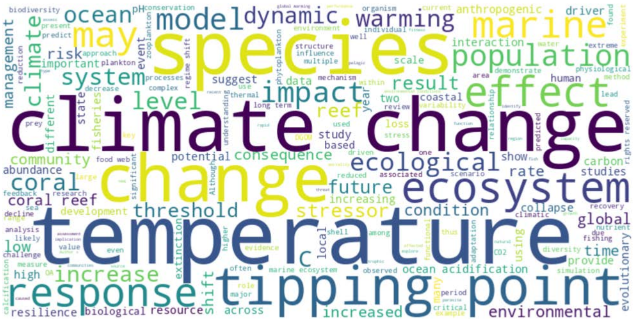

Figure 2.4.1: Climate change tipping points

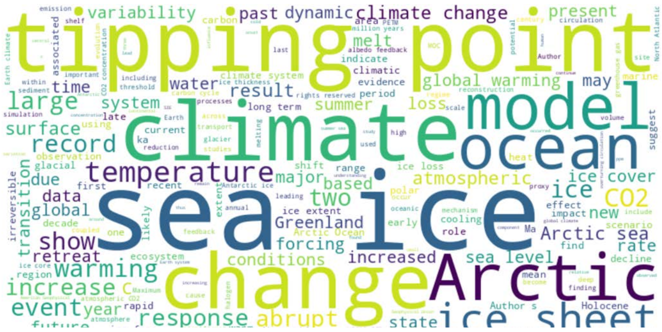

Figure 2.4.2: Ice arctic sea seaice

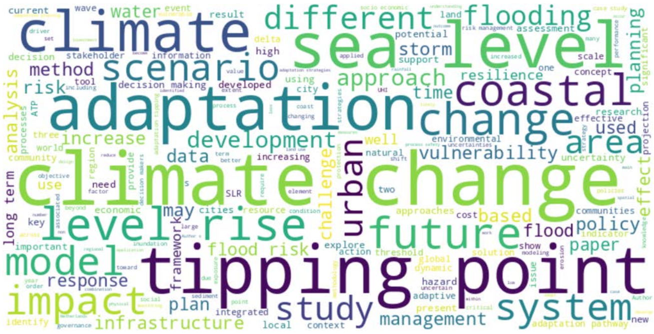

Figure 2.4.3: Adaptation coastal flood rise

Figure 2.4.4: Marine species reef coral

Growth in climate tipping point and cascade-related literature has been steadily increasing since 1998, as shown in Figure 2.4.5 but this overall trend is not reflected consistently across research fields. The majority of research areas appear to undergo a 'feast or famine' cycle, with publication spiking and dropping. Several research areas also experience publication droughts. In these, nothing relevant to the topic cluster is published, sometimes for several years. In the research areas relating to policy, there are significantly more publications pertaining to carbon regulation than there are relating to conflicts, disasters or financial issues. This could imply that, to date, more focus has been on the identifying mechanisms for carbon emissions-related tipping, rather than the preparation for potential consequences.

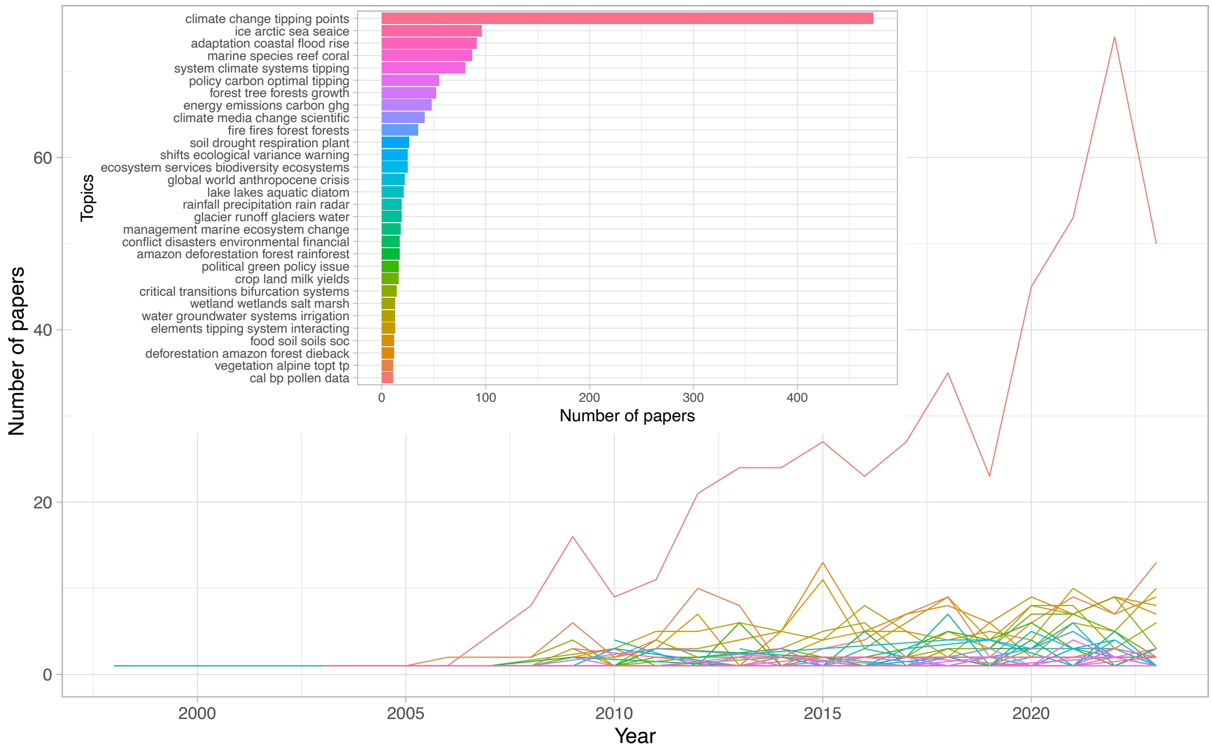

Figure 2.4.5: Unique topic clusters generated using BERTopic ranked by the associated volume of publications within each, and the temporal dynamics thereof.

2.4.4. Case phenomena exemplifying tipping cascades

In the following, we present five case studies that illustrate how tipping cascades can emerge between biogeophysical and social-ecological systems. The first two cases cover broader phenomena in large-scale ecosystems: the Amazon rainforest and coral reef degradation, where there is more evidence base of tipping cascades. The third case presents the case of forced migration, which demonstrates tipping cascades in human mobility. The two final cases present examples of past events: the Arab Spring and the shrinking Lake Chad, where tipping cascades have been identified. Both case studies include tipping elements in the socio-biogeophysical systems.

2.4.4.1 Amazon rainforest

Forests are complex social-ecological systems that provide a diverse range of ecosystem services, including carbon storage, hydrological regulation and the provision of biodiversity-related goods and services (Zemp et al., 2017). The Amazon rainforest, the world's most biodiverse terrestrial ecosystem, plays a critical role in global climate regulation (Mitchard, 2018). However, human activities and climatic extremes are increasingly threatening the forest's integrity and the services it provides, leading to tipping cascades. There are already signs of a loss of resilience in large expanses of the Amazon (Zemp et al., 2017; Rocha, 2022; Boulton et al., 2022), with trees taking longer to recover from natural and human-induced disturbances. For a summary of the underlying feedbacks and potential impacts on climate dynamics, see Chapter 1.3.2.1.

In addition to climate-related disturbances, human-induced deforestation and land-use changes driven by agricultural and socio-political development in the Amazon region have led to increased forest dieback (Aragão et al., 2018; Nepstad et al., 2008). In contrast to deforestation, forest degradation is characterised by damages to the structure, composition and function of the forest, with no change in land use (Bourgoin et al., 2021). Extraction of timber and increased use of land for agriculture are the causes that drive this (Lapola et al. 2023). In the Amazon, forest degradation exceeds deforestation and, unlike drivers of deforestation, which have been studied at length, is a complex social-ecological dynamic in which the potential for cascading impacts is less well known (Bourgoin et al., 2021).

Changes in temperature and precipitation, caused by anthropogenic climate change and large-scale climate phenomena such as El Niño–Southern Oscillation (ENSO) influence plant functioning and forest stability. ENSO-driven fluctuations have been associated with droughts affecting large Amazonian forest areas (Nobre et al., 2016). A tipping cascade can emerge if ENSO shifts to a higher-frequency occurrence, increasing the risk of severe droughts and longer dry seasons, resulting in water loss and increased forest fires. The reduced moisture recycling also leads to increased vapour pressure deficit, which further increases the frequency and intensity of forest water stress (Staal et al., 2020; Xu et al., 2022) and is a key driver in critical plant physiology thresholds (Kath et al., 2022). Forests under water stress are also more susceptible to fires, and this is especially prevalent in forest/pasture margins (Cumming et al., 2012). The recent increased severity of droughts could represent the first manifestations of this ecological tipping point (see Figure 2.4.6). These, along with the severe floods over South West Amazonia as well as the increasing dry season, suggest that the system is oscillating (Lovejoy and Nobre, 2018).

While evidence for the effects of gradual environmental change on forests exists, evidence for tipping points at which feedbacks have caused forest ecosystems to enter alternative stable states remains sparse (Reyer et al., 2015), see Figure 2.4.6. Modelling studies have identified estimates of two potential future tipping points for the Amazon's transformation: 1) a 3-4°C increase in global temperature (Lenton et al., 2008; Nobre et al., 2016; Lovejoy and Nobre, 2018; Armstrong McKay et al., 2022) or 2) deforestation levels which exceed 40 per cent (Sampaio et al., 2007; Lenton et al., 2008; Nobre et al., 2016).

While the possibility of a system-wide tipping point remains debated, local feedbacks can lead to alternative stable states (Staver et al., 2011) (see also Causal Loop Diagram (CLD), Figure. 2.4.6). Climate change may exceed the adaptation capacity of the forest and subsequently trigger these local-scale tipping elements that cascade through the Amazon rainforest system. As forest dieback occurs, the amount of drier forest edge gradually increases, as well as the risk of fire (Cumming et al., 2012; see also Chapter 1.3.2.1).

Rainforest fauna are also critical for the dispersal of seeds for many rainforest flora species, and particularly for the larger, fleshy fruits of dominant competitors. Reductions in organism connectivity can thus create a second tipping point that further reduces the capacity of forest to regenerate (CLD, Figure. 2.4.6). Through reduced ecosystem functioning, the forest degradation and dieback has fundamental impacts to regional land-atmosphere processes, which further amplify the risk of droughts, fires and biodiversity loss (Lenton et al., 2019; Aragão et al., 2018; Lenton & Ciscar, 2013), or decreasing rain and thus tipping risk in adjacent ecosystems.

The importance of Amazon moisture for forests and other land use sectors south of the Amazon is multifaceted. The most important is the contribution of dry season Amazon evapotranspiration to rainfall in south-eastern South America. Forests are able to sustain a consistent evapotranspiration rate throughout the year, whereas evapotranspiration in pastures is dramatically lower in the dry season (Lovejoy and Nobre, 2018). There is a heavy reliance on this moisture for agriculture as well as human wellbeing (Lovejoy and Nobre, 2018). Therefore, various large-scale drivers of environmental change are creating cascading impacts and strong feedback effects. These may be summarised as climate and human-induced drivers that influence forest functioning, which then affects moisture cycling, albedo and ecosystem services. In turn, these factors impact socio-economic dimensions such as agriculture as well as climate.

The governance of the Amazon rainforest represents a complex and multi-faceted challenge due to the conflicting interests and demands placed upon its ecosystem services. As a provider of global public goods, the rainforest is crucial for biodiversity conservation and carbon sequestration, playing a pivotal role in mitigating climate change (Zemp et al., 2017; Mitchard, 2018). However, the immediate benefits derived from activities like logging, mining and deforestation for commercial purposes pose a significant threat to its sustainability. Consequently, the governance of the Amazon is characterised by the intricate interplay between preserving ecosystem services and depleting activities, which are often short-term concentrated benefits (Paes, 2022). As a terrestrial ecosystem, forests fall under the jurisdiction of states, granting them ultimate authority in deciding which ecosystem services are to be realised. The Amazon rainforest, specifically, falls within the jurisdiction of eight South American states, accentuating the intersection of interests between local and global beneficiaries (Reydon et al., 2020; Paes, 2022). Furthermore, the fragmented jurisdiction intensifies the challenges faced in governance, necessitating policy coordination and joint governance among the overlapping countries to ensure the sustainable realisation of globally dispersed services.

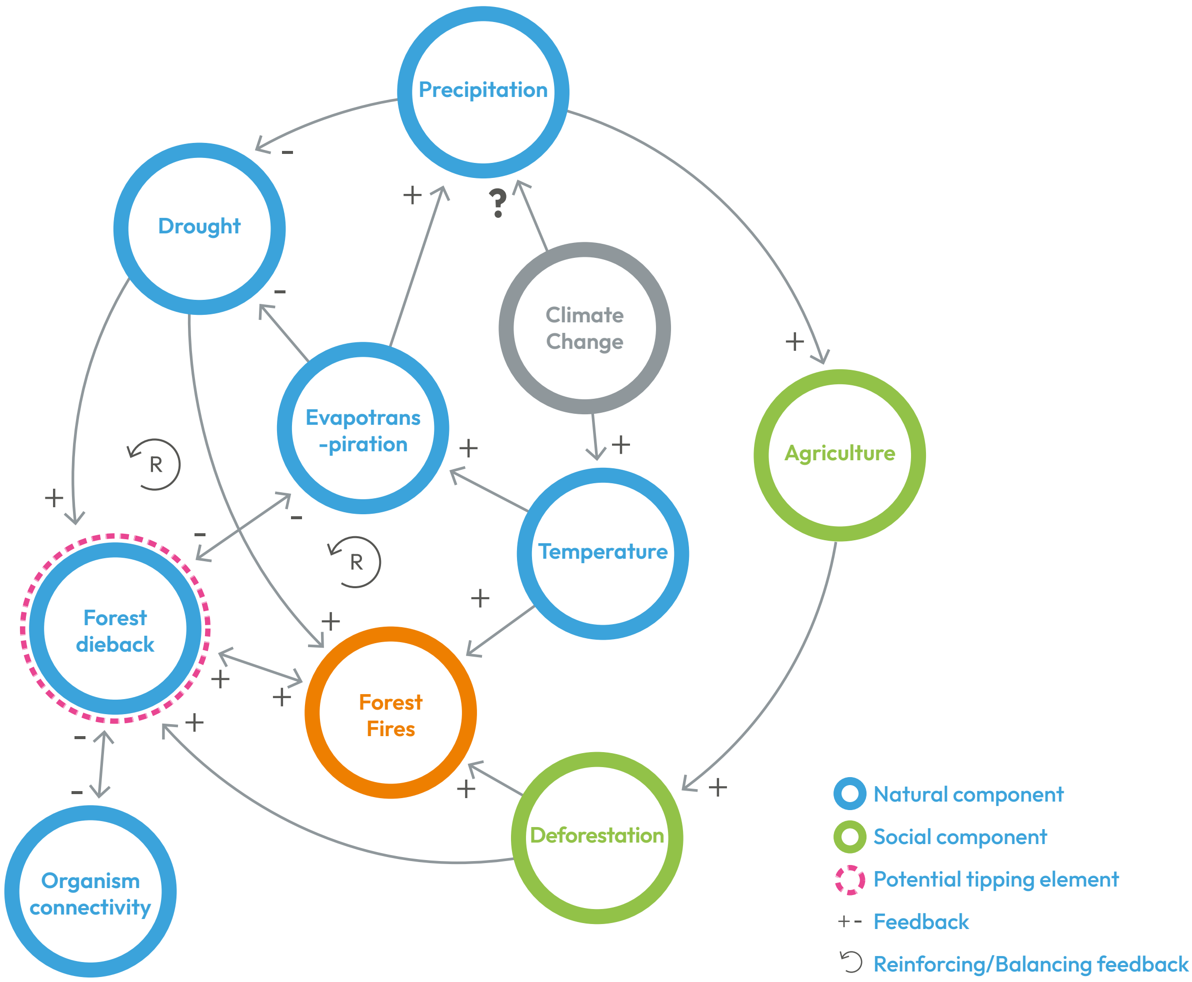

Figure 2.4.6: Tipping cascades in the Amazon rainforest.

2.4.4.2 Coral reef degradation and small-scale fisheries

Shallow-water tropical coral reefs are an example of an ecosystem that is already being heavily affected by climate change (Hughes et al., 2017; Hughes et al., 2018). Coral loss in today's oceans can tip entire reefs into less desirable states in which other kinds of benthic cover (e.g. macroalgae, rubble, algal turfs) become dominant (see CLD, Figure 2.4.7) (Tebbett et al., 2023). These long-lasting shifts can have significant consequences for people who depend on reef-based fisheries and tourism for their livelihoods.

Two elements are critical in understanding the nature of ecological tipping points on coral reefs. First, many of the more ecologically significant coral species are slow-growing, and may take years to reach their full reproductive potential; after a mortality event, recovery is initially dominated by weedy, faster-growing corals that are also more vulnerable to bleaching (Darling et al., 2013; Cannon et al., 2021). Second, corals must compete for space with other species (e.g. algae, sponges and sessile invertebrates such as giant clams) and their growth and survivorship are strongly influenced by water quality (Cooper et al., 2009). Corals typically favour clear, low-nutrient waters. Human activities in coastal environments (e.g. dredging activities in harbours, fertiliser-rich nutrient runoff from agriculture, over-fishing of keystone species such as parrotfish) can tip the balance of ecological conditions such that coral mortality is high and growth rates are slow (Cooper et al., 2009). These changes in turn often mean that either corals can no longer survive in degraded habitats, and/or other taxa are able to out-compete them.

The social and economic elements of coral reef tipping points arise through the reliance of many coastal communities on coral reefs and the resources they provide. It is estimated that a billion people live within 100km of a coral reef (~13 per cent of the global population) – a number that has significantly increased in the last 20 years (Sing Wong et al., 2022). Reef fish and invertebrates provide a year-round source of critical nutrients in locations where other sources of protein may be scarce (Mellin et al., 2022). Both artisanal fishing and gleaning are important activities in many Indigenous cultures, providing a wide range of social, economic and psychological benefits (Grantham et al., 2021). Some reef fish are harvested commercially (e.g. coral trout) and coral reefs contribute to local and regional income more generally through tourism and related industries. Some estimates state that coral reefs provide up to US$9.9trillion/year through ecosystem services and goods (Costanza et al., 2014). On the Great Barrier Reef in Australia, for example, coral reefs in 2012 were estimated to support the employment of more than 68,000 people and provide a benefit of AUS$5.7billion per year, mainly from tourism (Deloitte Access Economics, 2013). Coral reefs also support other industries, such as the provision of tropical fish and coral pieces for aquaria, and the harvesting and sale of snail shells (e.g. 'Triton's Trumpet').

The impacts of coral loss on fish communities are still poorly understood. Negative impacts have been documented for coral-dependent species such as butterfly fish and parrot fish (Thompson et al., 2019; Magel et al., 2020). Loss of these species further increases the challenge of restoring coral reefs because of the important role that herbivorous fishes play in keeping reefs clear of algae; overfishing has been blamed independently for declines in coral cover and algal overgrowth on reefs. Conversely, other research has shown limited effects of past bleaching events on fish communities (Wismer et al., 2019a). Based on these findings, some scientists have argued that the loss of corals may have little impact on net fish biomass production if habitat structure (benthic complexity) remains (Wismer et al., 2019b). The potential time lags between coral loss and impacts of coral loss on the fish community make these debates harder to resolve; and it is also possible that threshold effects exist whereby the fish community has a form of resilience and only exhibits marked changes beyond the loss of a particular proportion of coral. Most available evidence, however, points to a potentially significant impact of coral loss on fish communities. Documented impacts of coral cover declines include a loss of fish species, reductions in overall fish biomass and productivity, and potential destabilisation of the food web (Bellwood et al., 2019; Magel et al., 2020).

If reefs are forced by climate change into low-productivity states, and if these states in turn force fish communities across a tipping point into a less diverse and less productive state, many coastal human communities will be forced to modify their lifestyles in significant ways (Hoegh-Guldberg et al., 2019; Lam et al., 2020; Strona et al., 2021). These changes may in turn lead to tipping points in socioeconomic systems. In many coastal cultures, fish and corals are central to nutrition, income streams, social dynamics and established cultural practices and traditions (Eddy et al., 2021). Changes in fish species composition and abundance will also lead to shifts in the interactions of coastal communities with external actors, such as overseas markets, tourists and fisheries companies (Bartelet et al., 2023). These interactions in turn are likely to create further changes in the interactions between people and ecosystems, potentially leading coral reef social-ecological systems along new trajectories. Coral reefs may also provide coastal protection against storm surges, which may increase exposure to climate change impacts. For reef-dependent human communities in isolated locations, the options for adaptation (e.g. fishing open-water fish stocks or importing protein) may be dangerous or unviable. Available evidence suggests that tourists have flexible baselines, with degraded reefs still providing benefits (Bartelet et al., 2022); but dive tour operators, for example, may switch into other kinds of business, leading to a potential loss of expertise and local knowledge (Bartelet et al., 2023).

Reductions in coral reef fish diversity and biomass have significant implications for the nearly one billion people globally who depend on tropical seascapes, and particularly their reef-based small-scale fisheries, for nutrition and livelihoods (Cumming et al., 2023). Coral reefs provide a wide range of economically valuable ecosystem services, including provisioning services, regulating and supporting services, and cultural services (Eddy et al., 2021).

Thresholds and tipping points may occur in coral reef social-ecological systems in numerous different ways (Figure 2.4.7, adapted from Van de Leemput et al. 2016). Coral reefs may exhibit at least five different states that appear to be relatively stable: hard coral-dominated, soft coral-dominated, macroalga-dominated, rubble and algal turf (Bellwood et al., 2019). These each have different values for fisheries and tourism. Van de Leemput et al. (2016) show how even relatively weak effects acting in concert can lead to shifts between some of these states. Hard coral-dominated reefs offer the highest values for most ecosystem services, but are vulnerable to bleaching.

There are again numerous pathways by which coral reef degradation may cascade into social and economic tipping points. For example, Crona et al. (2016) show how the interactions of small-scale fisheries with the global seafood trade may shift between different economic states. Small-scale fisheries may be exporters of seafood; competitors with the global trade; or victims whose livelihoods are destroyed by commercial over-harvesting (Figure 2.4.7). Shifts between these economic arrangements will have profound consequences for local communities. Another pathway by which social-ecological tipping point cascades may occur in coral reef systems is via the effects of coral reef degradation on tourism (Figure 2.4.7) (Bartelet et al., 2022; Bartelet et al., 2023). If a region that has been known for its snorkelling and diving opportunities loses much of its coral, it may gradually lose business to other areas with more intact ecosystems. Lower income from tourism will place greater pressure on local livelihoods and drive either a shift into other activities, some of which may have consequences (e.g. harbour enlargement or dredging) that are harmful to coral remnants. In either case, investment into the conservation and management of corals and other marine ecosystems is likely to decrease and the perceived value of coral reefs to local people is likely to decline, leading to lower levels of stewardship and enforcement and potentially resulting in further knock-on effects via overfishing and pollution (CLD, Figure 2.4.7). In this way it is plausible that an entire social-ecological system shifts into a self-reinforcing state in which coral recovery becomes increasingly difficult and unlikely, even in the absence of pressure from climate change.

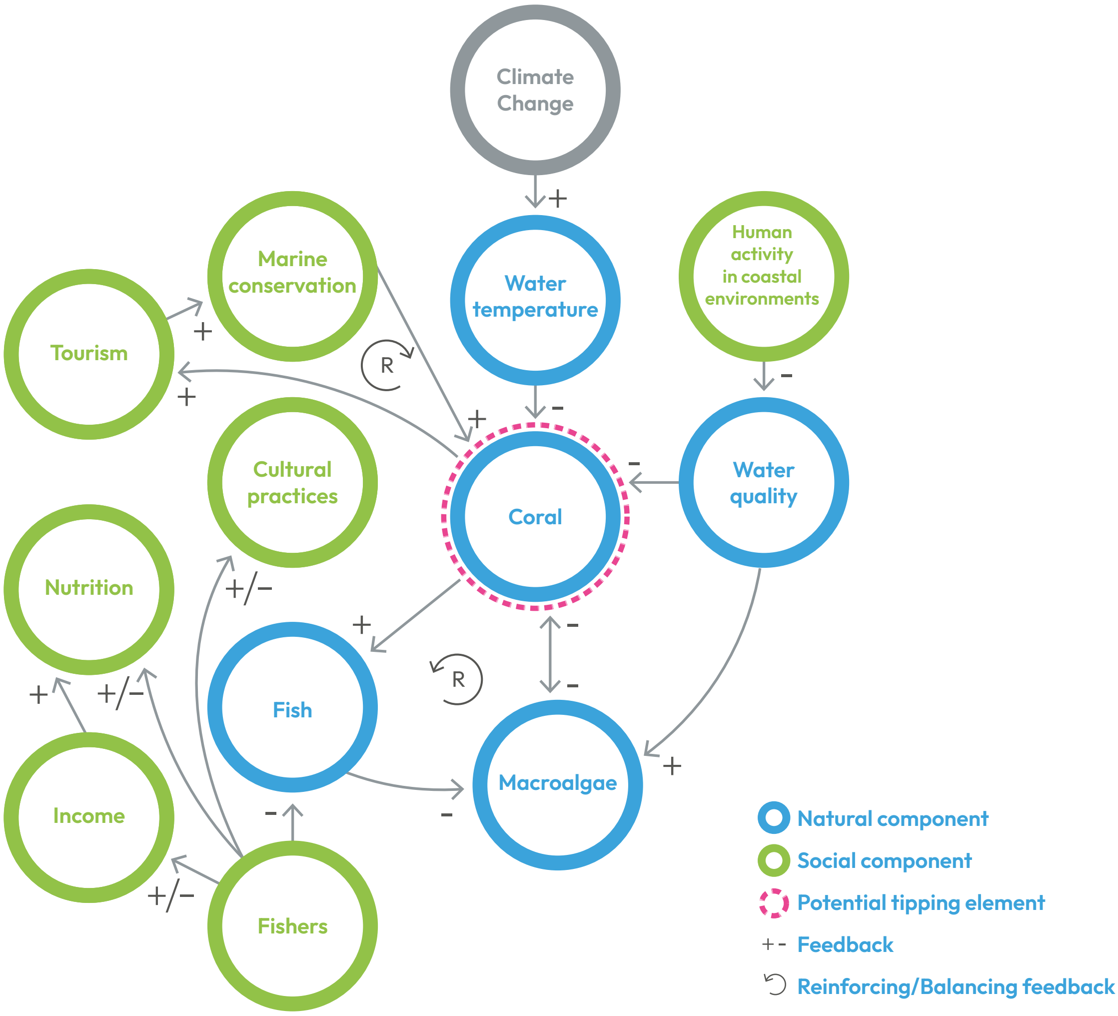

Figure 2.4.7: Tipping cascades in coral reefs and small-scale fisheries.

2.4.4.3 Forced migration

Migration, also referred to as 'mobility', is defined by the UN Migration Agency (IOM) as "the movement of persons away from their place of usual residence, either across an international border or within a state", and has been a fundamental part of human behaviour for millennia (IOM, 2023).

As the overarching concept of migration encapsulates both voluntary and involuntary movement, it is often split into subcategories to better contextualise. These are summarised in Table 2.4.1 . Here, the focus is on forms of forced migration.

Table 2.4.1 Definitions of migration

Concept	Definition
Voluntary migration	Movement resulting from an active choice. This could be in response to either acute or gradual processes, both environmental and social, or purely driven by 'pull' factors such as the opportunity to earn a better income. Depends on income levels, demographic characteristics and access to social networks, including to individuals who have already migrated (IOM, 2019).
Displacement/ forced migration	The movement of persons who have been forced or obliged to flee or to leave their homes or places of habitual residence, in particular as a result of or in order to avoid the effects of armed conflict, situations of generalised violence, violations of human rights and/or natural or human-made disasters (IOM, 2023).
Seasonal/ cyclic migration	Short-term movement of populations in order to 'make use of resources outside their immediate geographical vicinities', often repeated on a regular temporal scale (Zieba, 2017).
Refugee	Defined by international law as an individual who is fleeing persecution or conflict in their country of origin (UN, 2023).
'Trapped' Populations	While not technically migration as it does not involve movement, populations who would otherwise like to relocate but, for reasons outside their control (e.g. lack of resources) cannot, may become involuntarily immobile or 'trapped' in place. These communities are often especially vulnerable (IOM, 2023).

When faced with challenges and/or incentives (also known as push and pull factors), people and communities may desire to stay where they are or to relocate. Migration can improve people's livelihoods, but it can also pose many challenges and hardships. Climate change may impact migration flows both directly (i.e. the local environment becomes unsuitable for favourable habitation) and indirectly (i.e. by impacting relative wages through effects on farmers' crop yields). The combination of 'push' and 'pull' factors is key to understanding how the migration is best characterised.

There is a risk to human mobility and social cohesion when livelihoods are threatened. This results in increased conflict, violence and shifts in migratory patterns (Mackie, E et al., 2020). Indeed, climate change is projected to increase both internal and external migration patterns dramatically in the coming years. It is therefore of increasingly urgent importance to understand the relationship between climate change, migration and conflict, especially as the potential for tipping points in the Earth system poses additional uncertainty and risks that could alter and potentially exacerbate these dynamics.

In the context of migration, the influence and impacts of climate change are likely to be non-linear. The systems involved, therefore, will vary on a case-by-case basis. However, some consistency can be expected. In many cases, movement of people is primarily driven by socio-economic phenomena, with climate-related factors more likely to play an important multiplier role, leading to cascade events, rather than forming the single most important driver. This could initially manifest as a drought and subsequent crop failure, which, depending on the level of hunger and economic loss experienced by individuals and communities, could drive rural-to-urban migration in search of better prospects. However, it is important to note that this decision is closely linked to factors such as family structures, youth aspirations and a host of wider historical factors, alongside the impact of successive drought (Franzke et al., 2022). Depending on the scale and level of governance surrounding this movement, it is possible that tensions could arise between the new arrivals and the receiving community. In cases such as the Syrian civil war and the Chittagong Hill Tracts conflict in Bangladesh, these dynamics have been flagged as one of the potential drivers for the outbreak of violence.

Although not applied as widely as in natural systems, efforts to understand tipping points in social systems have grown in recent years (Scheffer et al,. 2009; Haldane and May, 2011; Neuman et al., 2011; Saavedra et al., 2011; Kuehn et al., 2013; Moat et al., 2013; Barrett and Dannenberg, 2014; Kallus, 2014). In the context of migration, tipping cascades can manifest as a domino effect, where an environmental or socio-political event causes displacement or voluntary migration as people search for improved living conditions and better economic opportunities. Migration and displacement are likely to create cascading risks: as populations move, perceived threat and conflict over natural and social resources in receiving communities can create new environmental and social pressures (Podesta, 2019). This is well documented in the Lake Chad Basin case, where climate change and unsustainable resource management affect the sustainability of natural resources, increasing vulnerability and leading to coping strategies such as migration (McLeman et al., 2021).

Displacement can in turn disrupt livelihoods, human security (such as food and housing, but also exposure to violence and conflict), the social fabric of communities (Stal, 2009), and can result in further disinvestment in these communities due to a decreased tax base, population density, and representation in local politics and other post-disaster efforts (see case study of Hurricane Katrina, case study in 2.3.4.3, for an example). This can render these communities less hospitable or inhospitable for displaced populations to return to, creating a cycle that reinforces, extends or renders the displacement permanent or more disruptive, and can make them more vulnerable to future displacement (see case study). In addition, restrictive migration policies can lead to a situation of forced immobility (Sydney and Desai, 2020). Displaced populations must grapple with the loss of their livelihoods, often by identifying new temporary sources of income that can become permanent due to the challenges of and barriers to quickly returning to origin communities. Displacement can thus fracture social cohesion, erode social capital and increase the economic precarity of already-marginalised communities. Additionally, decisions to migrate are in part determined by social networks, rendering it easier for higher-income populations to engage in adaptive migration decisions, while lower-income communities face forced or involuntary displacement and immobility (Dun and Gemenne, 2008; Dun O, 2009; Cattaneo and Peri, 2016). These compounding and reinforcing effects can exacerbate pre-existing social inequities, and shape the pattern of displacement (e.g. short or long-term/permanent, near or far) among different populations.

There is also limited knowledge about the complexity of interactions and drivers of climate-induced displacement and mobility more generally, and how multiple and systemic risks compound, propagate or cascade through coupled human-environment systems (Pescaroli, 2018; Renn, 2019; Lawrence et al., 2020; Simpson et al., 2021).

By mitigating common flash points that lead to migration-driven conflict (for example, resource scarcity, group resilience, housing stability) and proactively counteracting grievance narratives (such as state favouritism or ethnic-based identity disputes, for instance) it may be possible to reduce the post-displacement conflict risk. However, as state fragility is one of the greatest predictors of migration-related conflict, the feasibility of this in practice may be limited. In cases where displacement cannot be prevented, evidence suggests that those displaced – either by conflict or by rapid climate impacts – tend not to move long distances. In these cases, failure to provide proper and timely humanitarian relief may put pressure on local resources, creating a potential source of conflict.

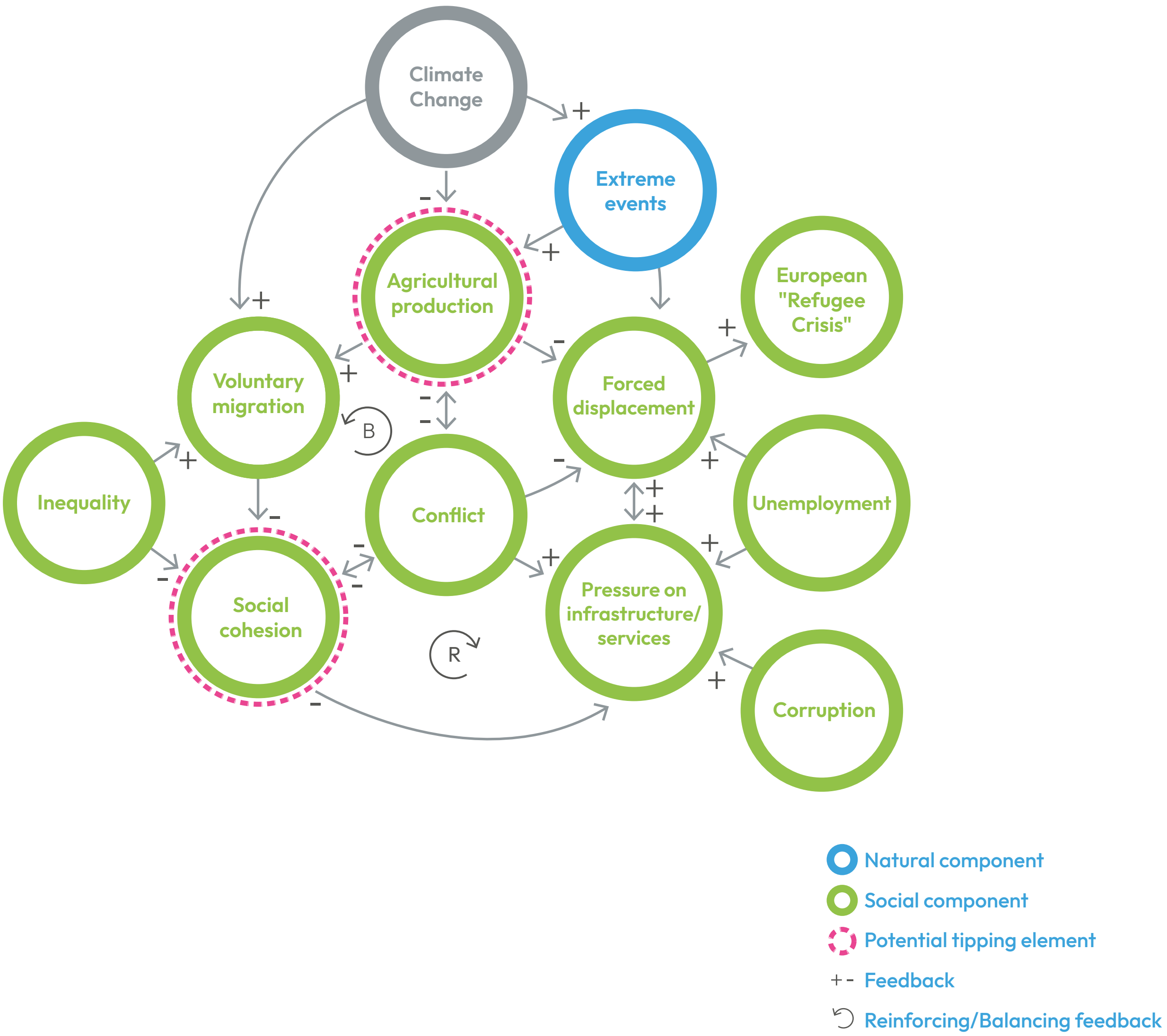

Figure 2.4.8: Tipping cascades in migration.

2.4.4.4 The Arab Spring

The connection between violence and environmental hazards has been explored in the literature, and it has been proposed that first exposure to environmental hazards may influence societies becoming more vulnerable to violence, which may in turn make them more prone to negative consequences from environmental hazards (Scheffran et al., 2014). The Mediterranean region has long been a crisis region where many natural drivers can be identified together with political, social and economic ones, leading to armed conflict. One of the most well-known examples is the Arab Spring, during which protests spread from Tunisia to elsewhere in North Africa and the Middle East (Juhola et al., 2022), see Figure 2.4.9.

In this case, the global food system was experiencing multiple supply crises, leading to a tipping cascade that began in 2008 and 2011. The reasons included high oil prices, extreme weather events that resulted in droughts and harvest losses in major wheat-producing regions including China and Eastern Europe, land investments and bioenergy demand. All these contributed to a speculation on food prices, which led to export restraints and pressure on the international market price of wheat. As a tipping cascade, these factors triggered shortages and rising international market prices of food crops (Johnstone and Mazo, 2011).

In 2010, the Russian Federation, Kazakhstan and Ukraine (all among the world's top 10 wheat exporters) were affected by severe weather anomalies, such as droughts, heatwaves, wildfires and air pollution, while the Republic of Moldova was struck by floods and hailstorms, causing significant losses of grain yield (Giulioni et al., 2019).The Middle East countries are heavily import-dependent in terms of their food, wheat in particular, and are highly vulnerable to fluctuations in the price of food in global markets (Schilling et al., 2020). Increases in food prices and low incomes created a situation where food insecurity was rapidly rising (Sternberg, 2012). The self-immolation of street vendor Mohamed Bouazizi in Tunisia in 2010 is largely seen as a trigger which provoked riots across the neighbouring countries (Kominek and Scheffran, 2011).

These events took place in the changing geopolitical landscape, which included the fall of autocratic regimes; political destabilisation and the rise of populist movements in Europe; refugees and civil wars in Libya, Syria and Yemen; terrorism; and interventions from external powers. It is important to note that no protests took place in Middle East and North Africa (MENA) countries with high per-capita incomes because of adequate levels of food security and sufficient adaptive capacities, while political and economic responses in Tunisia, Egypt and Libya led to changes in regimes (Sternberg, 2012).

Several studies analysed the role of climate change as a contributing factor to the Syrian civil war (Selby et al., 2017a; Gleick, 2017; Kelley et al., 2017; Selby et al., 2017b). In the years before the Syrian rebellion (2007 to 2009), a long drought period hit the region, which increased the vulnerability of the population, especially in rural areas (Kelley et al., 2015). Accumulating agricultural losses led to farmers leaving their land and putting pressure on governments to address the crisis, leading to overall dissatisfaction with governance in the region. Environmental factors were complemented by a complex constellation with economic, social and demographic conditions, governmental failure and dissatisfaction with existing regimes (Juhola et al., 2022).

Another tipping cascade of the Syrian civil war was the US invasion in Iraq 2003, the Arab Spring, regional power rivalries and the emergence of the 'Islamic State'. The climate role is disputed, between those who highlighted the catalytic and cascading effect of the drought on the conflict (Gleick, 2014) and those who found the failed government policy more influential compared to neighbouring countries which did not have a civil war, like Jordan (Selby et al., 2017a).

Reviewing the evidence, Ide (2018) concludes that large economic losses to the agricultural sector and the resulting rural-to-urban migration are supported but are still poorly understood and contested as reasons for conflict.

These two tipping cascades of the Arab Spring and the Syrian civil war further contributed to the refugee crisis of 2015, when hundreds of thousands of refugees entered Europe. These events demonstrate how cascading stressors can trigger multiple events that overwhelm adaptive capacities and stability of several countries (see CLD, Figure 2.4.9) (Scheffran, 2016). These events further demonstrate how in an interconnected world tipping points can escalate into a chain of cascading events, which undermine international stability. The EU was unprepared to govern the situation, media coverage reinforced threat perceptions, tensions, nationalism, populism and the securitisation of migration (see Migration sections 2.3.4 and 2.4.4.3). In order to govern these types of tipping cascades, it is suggested that continued collaboration between Europe and the Middle East is required to build long-term structures that can absorb or stop tipping cascades, or alleviate their impacts when they take place (Demirsu and Cihangir-Tetik, 2019).

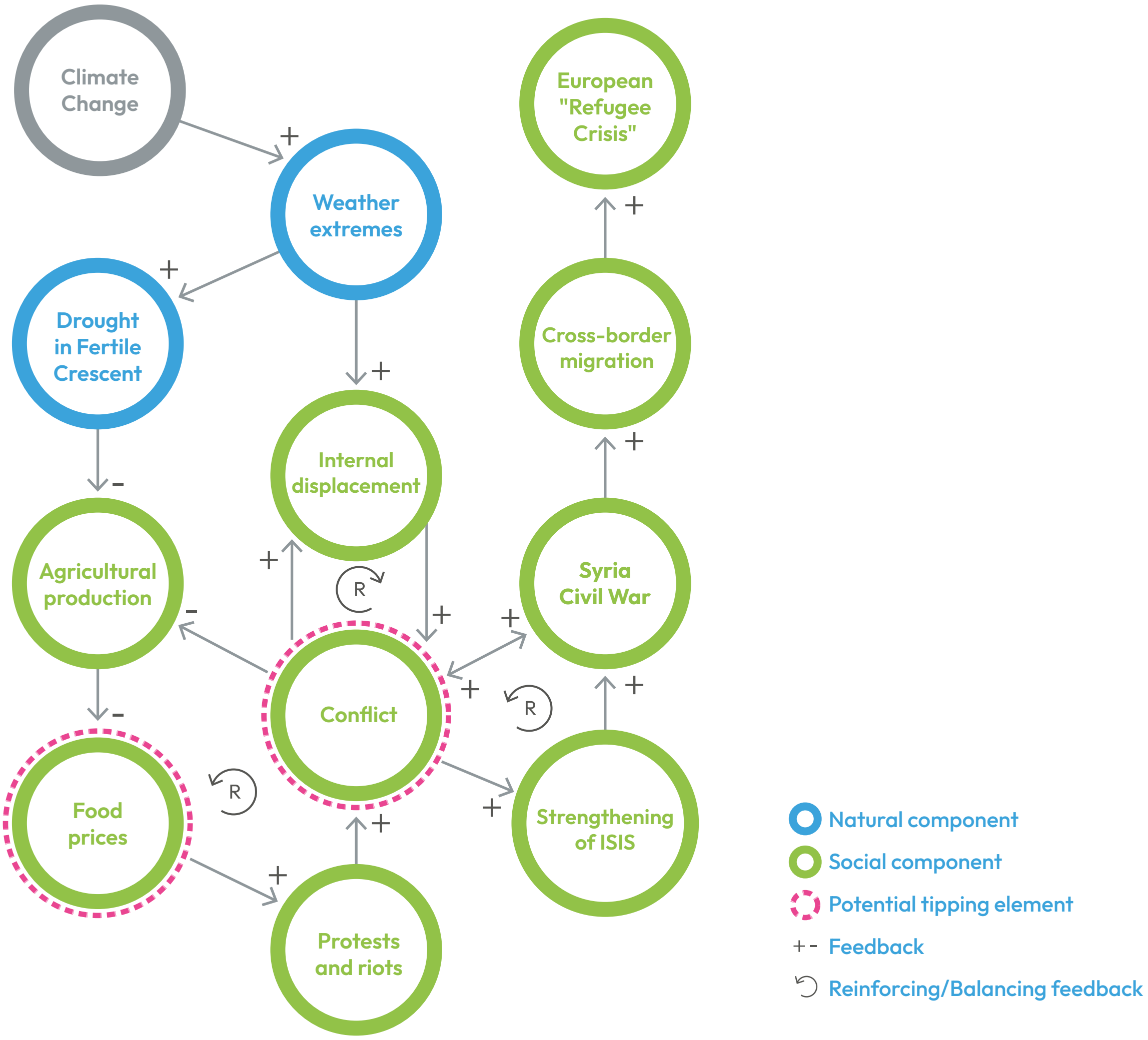

Figure 2.4.9: Tipping cascades in the Arab Spring.

2.4.4.5 Shrinkage of Lake Chad

Lake Chad is a large, shallow lake located in the Sahelian zone of west-central Africa. It is bordered by Chad, Niger, Nigeria and Cameroon. The lake is fed mainly by the Chari and Logone rivers, and its surface area varies depending on the rainfall in the region. The West African monsoon is the main driver of precipitation in the area, and current models cannot reliably predict future rainfall. It is one of the largest lakes in Africa, covering an area of approximately 1,350 sq km at its maximum during the rainy season and shrinking to as small as 10 per cent of this during the dry season. Known for its ecological diversity, the lake supports a variety of plant and animal species, including more than 300 species of bird (Magrin and De Montclos, 2018; Nagarajan et al., 2018).

Lake Chad is an important resource for the people living in the surrounding area, providing fishing as well as transportation and water for irrigation. However, in recent decades, the lake has been shrinking due to a combination of climate change, overuse of water resources and population growth in the region. This has led to environmental degradation, loss of biodiversity and displacement of people who depend on the lake for their livelihoods (Franzke et al., 2022). The reduction in water resources has also led to increased competition for resources among communities and countries sharing the lake, leading to tensions and even violent conflict. This competition can be exacerbated by ethnic and religious differences, historical grievances and political tensions (Magrin and De Montclos, 2018).

This example highlights how climate change can exacerbate existing economic, environmental, political and social pressures, creating a self-reinforcing loop between livelihood insecurity, climate change vulnerability, conflict and fragility (Franzke et al., 2022). Conflicts over natural resources may worsen due to climate change, affecting different occupational groups and reducing their opportunities to meet their livelihood needs. Climate change can change the availability and access to natural resources, creating new winners and losers. The impact of climate change on Lake Chad's water balance and precipitation is uncertain. The conflict has negatively impacted the population's ability to adapt to climate change, restricting access to natural resources, displacing people and damaging social cohesion. The self-reinforcing feedback loop between increasing livelihood insecurity, climate change vulnerability, conflict and fragility can perpetuate the current crisis and take the region further down the path of conflict and fragility, creating cascading risks that can spread to other regions (Nagarajan et al., 2018).

In the context of Lake Chad, a further tipping point could occur if the lake shrinks or rainfall variability increases to a point where it can no longer sustain ecosystem services for the surrounding communities, leading to a rapid and significant deterioration of the region's environmental, economic and social conditions (Nagarajan et al. 2018; Vivekananda et al., 2019).

Another tipping cascade is the potential collapse of the lake's fisheries, which are a vital source of food and livelihoods for the surrounding communities. If the lake continues to shrink, the fish populations may decline to a point where they can no longer sustain commercial fishing, leading to a loss of income and food security for the local population (See CLD, Figure 2.4.10).

Another possible cascade is increased desertification and land degradation as the lake shrinks, which could further exacerbate environmental degradation and contribute to the displacement of people and loss of livelihoods. The environmental degradation caused by the loss of water resources and the encroachment of the desert can also lead to further soil erosion, loss of biodiversity, and reduced carbon sequestration. These factors can contribute to climate change, exacerbating the problem of water scarcity and creating a vicious cycle of environmental degradation (see CLD, Figure 2.4.10) (Franzke et al., 2022.

Potential tipping points in the social-ecological context can also occur due to increased conflict over resources as water becomes scarcer (Figure 2.4.9). If tensions between different communities and states in the region escalate to the point of violence, it could lead to further displacement of people, increased economic hardship and a more significant loss of life and property (see also Box on Lake Chad in 2.3.5. Violent Conflict).

Related to this, a tipping cascade can emerge as a result of loss of trust in the ability of state and local governments to provide security and basic services for their citizens. If the violence and conflict in the region continue to escalate, it could lead to a breakdown of the social contract between the state and its citizens, further fuelling tensions and distrust. This can be exacerbated further by the spread of extremist ideologies and the entrenchment of Boko Haram and other extremist groups in the region. If these groups continue to gain support and expand their control over the region, it could lead to a significant deterioration of the security situation, making it even more challenging to address the underlying drivers of conflict (Magrin and De Montclos, 2018).

Addressing the complex challenges facing the Lake Chad region will require a comprehensive and coordinated approach that takes into account the systemic nature of the issues (Sillmann et al., 2022). Efforts are being made to address the problem of the shrinking lake, including the development of irrigation schemes, the promotion of sustainable agricultural practices and the conservation of wetlands and other important ecosystems. International organisations such as the Lake Chad Basin Commission and the United Nations are also involved in efforts to address the environmental and humanitarian challenges facing the region (Nagarajan et al., 2018). Some potential solutions include sustainable water management, environmental conservation, conflict prevention and resolution, economic development and regional cooperation (Sayan et al., 2020). In cases such as this, there is a continued need to build consensus around the reasons for the emerging conflict, and support long-term policies with regional water governance plans (Nagabhatla et al., 2021).

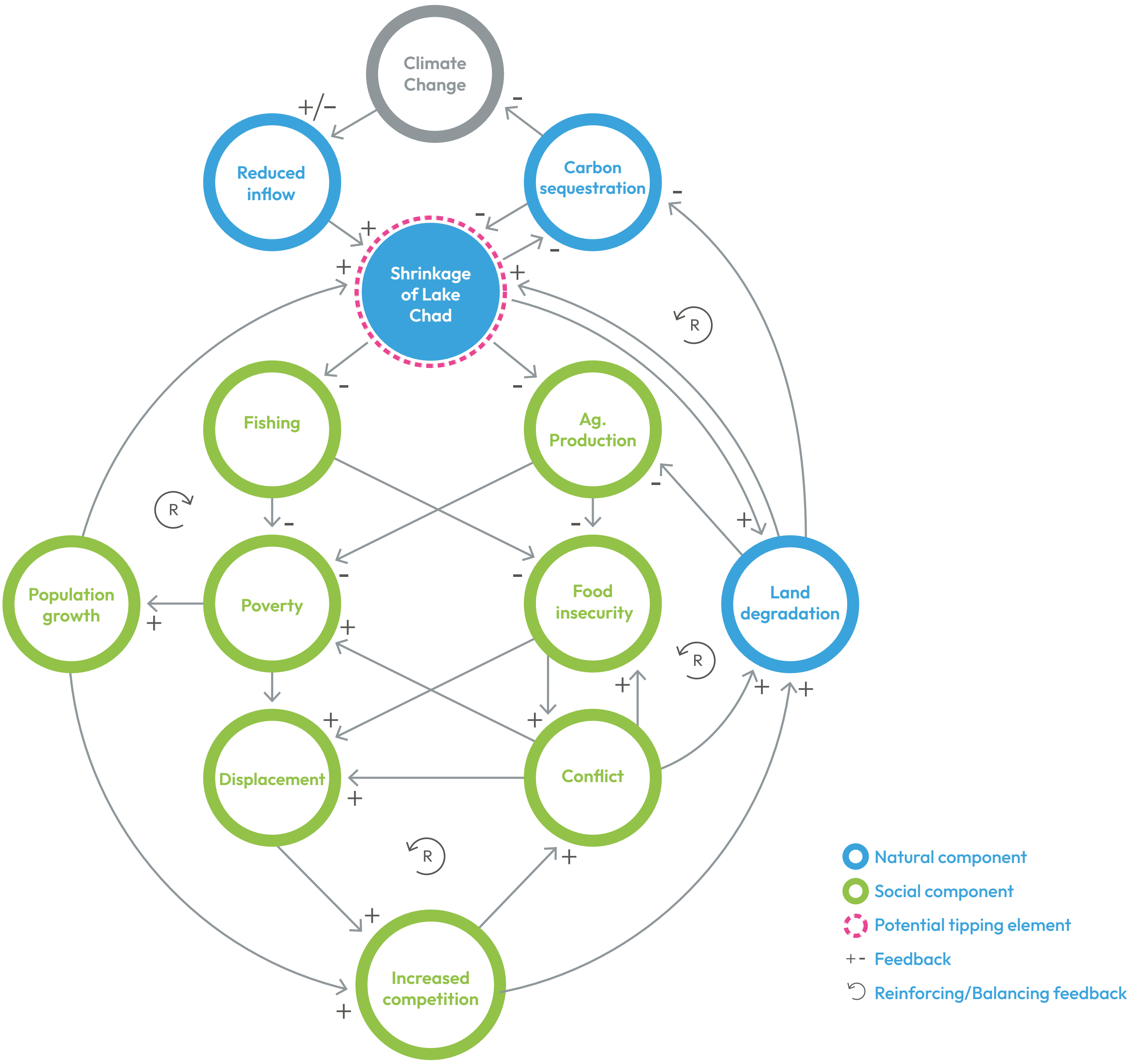

Figure 2.4.10: Tipping cascades in Lake Chad.

2.4.5. Future research needs

Our case examples illustrate the complexity and context dependence associated with identifying tipping cascades, the need for further studies to map the empirical evidence base, and the challenge to generalise across cases. In the following, we outline emerging questions for future research.

2.4.5.1 Clarification of concepts

Most of the current research has focused on understanding the tipping processes in different natural systems. Recent research on cascades has illustrated the role that they have in the emergence of different types of risks (Simpson et al., 2021; Sillmann et al., 2022). However, the role that cascades can play in tipping is less well understood, especially when they involve a combination of social and Earth system tipping points.. This section of the report identifies the following concerns that ought to be addressed in future research.

When identifying tipping cascades, it is necessary to identify clear boundaries of which systems are involved. This also involves establishing what are the system states and dynamics in order to identify how the tipping cascades alters them (i.e. a change in the reference condition of the system). For example, identifying differences between system states can be unclear, such as 'fragmented' vs 'non-fragmented' landscapes, or 'forested' vs 'deforested', which are continuums with easily recognisable end points but a hazy centre. This is particularly challenging in a social system, where identification of system state, dynamics and drivers of change is nascent and where observations over time are scarce.

It is also necessary to clarify whether cascades are identified within or across system boundaries. Furthermore, there are ambiguities regarding whether there is a threshold when a cascade emerges or stops and whether these can be identified.

It is also necessary to clarify the type of relationships between tipping cascades that relate to causality. For example, does the occurrence of a tipping point in a system (A) increase the likelihood of another system (B) tipping? Systems A and B may be far away in space and have different temporal scales. For example, non-linear relationships between phosphorus levels in shallow lakes and the growth rates of phytoplankton mean that, under certain conditions, small additions of phosphorus can lead to algal blooms and a rapid, hard-to-reverse deterioration in water quality (Carpenter et al., 1999; Scheffer et al., 1993; Scheffer, 2020). Declining water quality can cause a similarly non-linear or disproportionate response in the social and economic components of the freshwater social-ecological systems, for example through a rapid reduction in tourism revenue or property prices around a lake. Since management responses to removing phosphorus from the system, for example by limiting runoff from dairy farms upstream, are often slow to become effective, the initial ecological tipping point can trigger cascading effects through the broader social-ecological system (Schindler et al., 2016).

2.4.5.2 Key systems for research

In this chapter, we have focused on cases in which there is emerging evidence of tipping cascades. In particular, case studies on Lake Chad and the Arab Spring offer focused evidence of how tipping cascades affect the systems in question. The broader examples of the Amazon rainforest illustrate the necessity to focus key systems in key regions due to their global significance. In particular, one region not covered here is the Arctic, where tipping points have global implications.

Our topic modelling points towards most research being conducted in relation to the climate system, with focus on Arctic sea ice loss and coastal flooding, as well as energy transitions. There is also considerable focus on coral reefs, forests, the Amazon and organic carbon and soils, indicating that the knowledge base is more established with shared concepts.

There are three things to note in terms of tipping cascades in social systems. First, among the 30 clusters that the topic modelling based on the currently published literature identifies, there are no clusters related to social tipping specifically, only to ecological or climate tipping. While there is a growing concern that a socio-economic system could also exhibit tipping behaviour cascading from the unprecedented stresses in natural systems, there appears to be a significant research gap on systematically documenting these tipping processes. This calls for an accumulation of empirical evidence, particularly in terms of identifying long-time series data and suitable variables to detect these trends.

Second, it is also of note that, within the literature pulled back with the specified search terms, the majority of human-related terms seemed to relate to drivers rather than outcomes or processes in social systems. Correspondingly, social tipping processes started to be systematically conceptualised in the domain of climate change mitigation (Otto et al., 2020), understanding of the tipping dynamics of socio-economic systems hit by accelerating adverse impacts of climate change is in its infancy. This is despite the rising awareness of the possible collapse of livelihoods, forced migration or trapping, and key assets being stranded causing cascading damages to the financial and economic systems (i.e. a tipping process labelled as 'Climate Minsky Moment'). Although it is accurate to label human activity as a major driver of climate-related tipping cascades, humans will also experience the consequences. A research gap in this area was, therefore, unexpected.

Third, in terms of systems where there is less literature, it is worth pointing out that our search yielded few human-related clusters and none relating explicitly to tipping cascades within social systems. For example, topics such as tipping cascades in urban systems is not yet an established research topic, or at least was not visible in our data set. This is interesting, given that over half of the world's population resides in urban settings. There are two potential explanations for this lack of focus. First, this type of research does not yet exist or is not yet systematically documented.

Or second, different types of terminology and conceptual frameworks are used to describe the same or similar phenomena. For example, concepts such as urban land teleconnections (Seto et al., 2012), telecoupling (Kaspar et al., 2019) and cross-border impacts (Groundstroem and Juhola, 2019; Carter et al., 2021) have all been used to describe the interlinkages between biogeophysical and social systems.

2.4.5.3 Key methodological advances

Thus far, methodologies for identifying cascades have focused on conceptual mapping (Klose et al., 2021) or different modelling approaches, which have their shortcomings (Juhola et al., 2022). The soft modelling CLD approach that we used here has allowed us to identify causal pathways for tipping cascades from the Earth system to social systems and show how tipping cascades can be identified in complex systems. There are also examples of further developing CLD modelling towards the inclusion of stakeholders (Inam et al., 2015; Sohns et al., 2021). Inclusion of stakeholder knowledge may yield insights on what the potential thresholds are for tipping cascades. Further method questions include what are the key feedback loops and nonlinear dynamics that can lead to cascades across scales in different systems and how can these dynamics be quantified and integrated into models and assessments. Here, complex systems approaches grounded in network science, agent-based modelling and evolutionary approaches could be especially useful, as they directly capture feedbacks and restructuring of a system based on its changing elements, and could explicitly treat the emergence of different tipping dynamics (Filatova et al., 2016).

In addition to advancing modelling, there is a need to connect the models to empirical evidence, despite there being reservations in terms of how well they could be suited for early warning (see Chapter 2.5) or other governance purposes. For this, monitoring programmes are needed to gather data over time, keeping in mind that it is not always clear which variables are meaningful. When gathering empirical data on cascades, it is important to note that quantifying cascading impacts is challenging due to measurement and monitoring. For example, dependencies on infrastructure systems can be far away from the affected area. As such, cascading impacts would not be apparent using traditional risk assessments (Lawrence et al., 2020). Furthermore, the extent to which this information could be gathered in real time and acted upon presents another set of challenges.

2.4.5.4 Key governance implications

There is very little research on how to govern tipping cascades and how a lack of appropriate governance also feeds into the system, or even cascades that are not related to tipping points in particular. A key question is whether it is possible to identify the conditions for tipping cascades and to avoid them with governance mechanisms, and this requires more evidence and more detailed documentation of the success of adaptation (Owen, 2020). This of course raises notions of early warning systems and ensuring that there are legitimate and just governance mechanisms in place to address this. Literature on governing systemic risk (Schweizer and Renn, 2019) may offer some advice here. The governance of systemic risk includes dealing with risks which are characterised by complexity, transboundary cascading effects, non-linear stochastic developments, tipping points, and lag in perception and regulation (Schweizer and Renn, 2019). It is also important to note that there may be diverging consequences for actors within systems when governing them. Therefore, one needs to consider what are the trade-offs and synergies between efforts to address individual tipping points versus addressing the interactions and cascades between them.

2.5. Early warning of tipping points in impacts

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Summary

Tipping point research has traditionally focused on environmental systems, but there is increased interest in understanding whether the social and coupled social-environmental systems that are impacted by Earth system tipping points themselves exhibit characteristics of tipping points and whether they can be anticipated using early warning signals. While this question is highly relevant in a context of a changing climate, there are two major challenges in developing early warning systems for tipping points in social-environmental contexts: first, social systems may respond unpredictably to changes in environmental conditions as they adapt to change; and second, datasets for social systems may not always be available for detection of tipping points.

Evidence is emerging to demonstrate that social-environmental systems exhibit signals of tipping points through autocorrelation, skewness, variance and threshold exceedance. In food security early warning, lag-1 autocorrelation of soil moisture has demonstrated great utility in predicting transitions into and out of food crises up to six months ahead of a transition – with potentially transformative opportunities for humanitarian interventions. In grazing systems, higher variance of vegetation indices have been associated with changes in environmental conditions that lead to more degraded environments. Research has also demonstrated the exciting opportunities to leverage deep learning to detect tipping points in vaccine opinion using social data. Increasing availability of data from Earth observation, machine learning and social networks open up an unprecedented opportunity to improve early warning of tipping points in social-environmental systems.

Key messages

- Methods used to detect tipping points and loss of resilience in biophysical systems such as the Amazon rainforest can be applied to anticipate tipping points in socio-economic impacts.
- Recent applications of these methods have shown valuable additional early warning information of changes in food insecurity, and in predicting land degradation in managed vegetation systems.
- New technologies like deep learning, and new information like social media data, have the potential to enhance the ability to anticipate tipping points in socio-economic impacts.

Recommendations

- Existing knowledge of undesired tipping points (summarised in this report) should serve as sufficient 'early warning' to motivate urgent action, but could be augmented by more formal early warning of specific Earth system tipping points.
- While there is considerable room for further development, it is timely for interdisciplinary research to consider how, where and when early warning systems for Earth system tipping points should be developed.
- Further research is needed into early warning of negative tipping points in socio-economic systems, particularly to determine appropriate data sources, their relevant characteristics and the types of statistics that can provide robust early warning information.

2.5.1. Early warning signals in social-ecological systems: The challenge

Substantial research has demonstrated the potential for early detection and anticipation of tipping points in ecological systems and Earth system processes (see Chapter 1.6). The basic principle is that additional stress can transition an environmental system from one 'potential well', such as a tropical forest, to another – for example, a dry savannah. The social-ecological systems impacted by Earth system tipping points can themselves behave in a similar manner, whereby continued environmental stress can lead to (practically) irreversible changes in socioeconomic conditions (see also Chapter 1.6 for an overview of early warning signals for Earth system tipping points). Pastoralist systems serve as an illustration of how such transitions can occur: the addition of livestock in a grazing land might degrade pasture and cause accelerated soil erosion, permanently transforming the landscape from a fertile pasture to a semi-arid shrubland or even a desert, and rendering traditional pastoral livelihoods unfeasible (Ibáñez et al., 2007; Feng et al., 2021). Chapter 1.6 presents analogous examples in environmental systems.

However, social-ecological systems are highly complex and do not always exhibit traditional bifurcation and early warning signals, which may provide misleading results. As such, before designing early warning systems it is important to understand the nature of the hazard, the vulnerabilities being driven from both social and biophysical drivers, exposure to risks, and whether the system can exhibit signs of bifurcation. For instance, in the case of social media, high autocorrelation of tweets might be interpreted as an early warning signal of a tipping point, when in reality the autocorrelation trend can be explained by knowledge that a specific event or holiday is approaching (Bentley et al., 2014; Kuehn et al., 2014).

While there is potential to borrow and adapt elements from traditional tipping point theory (which focuses on ecological applications), there are a number of considerations in social systems. First, social systems have features that cannot be compared to those of environmental systems, limiting their predictability (Milkoreit et al., 2018). For instance, even when comparing two communities in the same country there will be differences in power structures, access to information, economic equality, engagement in decision-making processes, knowledge, and capacity to adapt to changes, all of which can affect the manifestation of a tipping point in a social context. Second, continuous data in social systems are not always available. Often social elements are rather abstract – even if an adequate indicator or proxy is identified, it may not be feasible to collect data over time to enable detection of tipping points. Moreover, social science methods such as ethnographies, interviews, surveys, and focus group discussions are expensive and time-consuming; as such, they tend to be *ad hoc* and of insufficient temporal resolution to identify critical transitions (cf. Shipman, 2014).

Milkoreit and colleagues (2018) illustrate the complexity associated with detection of tipping points in social-ecological systems using resource extraction as an illustration. In a fishing context, an 'ecological' regime shift might be the collapse of fisheries as measured by fish stock, the health of the local coral reefs, or even water quality. A social tipping point might be a collective decision to engage in alternative livelihoods and reduce (or altogether cease) fishing. In turn, the local identity as a fishing community might change to an entirely different social state. The first tipping point (the decision to engage in non-fishing activities) could be measured through various surveys and livelihood assessments, while the second, more abstract indicator (community self-identification) would require qualitative methods. In both cases, it is unlikely that regular data would exist to determine when exactly the transition has occurred. Research has shown the potential to quantify tipping points in emotional states through temporal autocorrelation, variance and correlation of self-recorded emotions (van Leemput et al., 2014). So, elements of tipping point theory may be applied to more abstract concepts that are pertinent for social science application, depending on data availability. For example, Koschate-Reis et al., (2019) have shown that tipping point theory can be applied to automatically detect feminist/parent identities from textual data.

The data challenge is significant – however, recent research has shown the potential to use polling data (Winkelmann et al., 2022), online surveys (Ehret et al., 2022) and Earth observation (Swingedouw et al., 2020; Krishnamurthy et al., 2022) to provide early warning signals of tipping in coupled social-environmental systems. For data to be maximally useful, they need to be available at an appropriate frequency to enable analysis of system dynamics. For example, in a food security application of tipping point theory, (Krishnamurthy et al., 2022) determined that data from the Soil Moisture Active Passive (SMAP) Earth satellite mission – which are available every 3.5 days – were the most appropriate for detecting an impending food crisis. Datasets available at coarser temporal resolutions (including other soil moisture products and vegetation health indices) were less accurate for early warning signals, though future observations at higher spatiotemporal resolutions and accuracies may improve results even further.

Another significant challenge is interpretation of false positives. Predictions of catastrophic change – such as Elrich's (1968) predictions of famine due to excess population, or peak oil in the 1990s and 2000s (Bardi, 2019) – have failed to materialise, creating a public sense of mistrust.

While early warning systems are extremely useful to anticipate (and avert) the worst effects of climate change, the history of high-profile false positives has created an easy target for critics seeking to belittle social risks associated with climate change (and other environmental crises).

2.5.2. Early warning signals: What can we learn from social-ecological models?

Social-ecological models often consist of existing classical ecological models coupled to a human system where the population size, the behaviour of individuals in the population or both are represented as state variables (Figure 2.5.1). In most cases, the rate of harvesting or pollution is a function of the state of the human system and the evolution of this state is determined by a number of feedbacks, some of which are described below. Social norms work to either reinforce dominant behaviours or encourage sustainable behaviour through incentives or sanctions imposed on defectors. Rarity-based conservation occurs when public support for conservation increases as the natural system approaches collapse. Conservation cost represents the effort, financial or otherwise, required to interact with the ecological system in a sustainable manner.

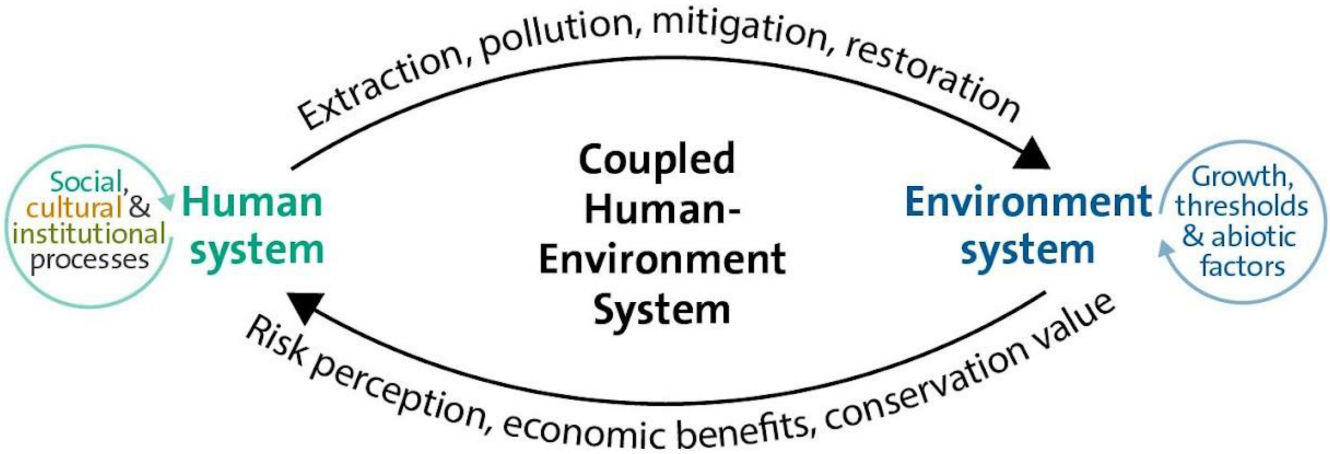

Figure 2.5.1: An illustration of key feedbacks in coupled social-ecological systems. Identifying tipping points in social-ecological systems is a difficult task because of the complex feedback loops and response of social systems. However, recent examples in the literature have shown how social-ecological systems can exhibit tipping in conservation, greenhouse gas mitigation, and species populations. [Source: Farahbakhsh et al., 2022].

Many models in the literature, including generalised resource models (Lade et al., 2013; Bieg et al., 2017; Sigdel et al., 2019), forest-cover models (Bauch et al., 2016; Innes et al., 2013), a grassland model (Thampi et al., 2019) and a fishery model (Horan et al., 2011) have directly compared traditional ecological models to their coupled social-ecological counterparts. In all cases, the addition of a coupled social system leads to more alternative stable states, and in turn a greater number of tipping points, which are not present in the uncoupled model.

The increased propensity for these coupled systems to abruptly transition motivates the necessity of tools that can give sufficient warning to these tipping events so that actions can be taken to mitigate potential catastrophes. These tools, known as early warning signals, typically look at statistical signatures in time series data which exhibit significant trends as a tipping point is approached (Dakos et al., 2012). The ambiguity in the transitions that early warning signals herald, paired with a muting of the strength of these signals, provide a unique challenge in the prediction of tipping points that may occur in social-ecological systems. However, there has been some work done in the modelling literature comparing the strength of early warning signals between the time series of state or auxiliary variables in social-ecological models. These studies have found early warning signals in the social time series data to be the only reliable indicators of the system approaching a tipping point (Lade et al., 2013; Bauch et al., 2016; Richter & Dakos, 2015).

These data range from fraction of conservationists to average profits by resource harvesters and catch per unit effort. This suggests great potential for the monitoring of ecological resilience through analysing socio-economic data, which fortunately is much easier to gather and is already more frequently generated than ecological data (Hicks et al., 2016).

Economic time series allow for straightforward monitoring of profits tied to resource extraction and the use of early warning signals on previous financial tipping points (Figure 2.5.2) shows promise for use of this data social-ecological systems. This is especially pertinent as financial tipping points will be exacerbated in the future both by climate change risks and mitigation (see Chapter 2.3.6 on financial tipping points). A caveat is warranted, though. Financial systems do not act like other social systems as the constituent actors in the system are themselves trying to predict its future, and act based on those predictions, potentially affecting predictability.

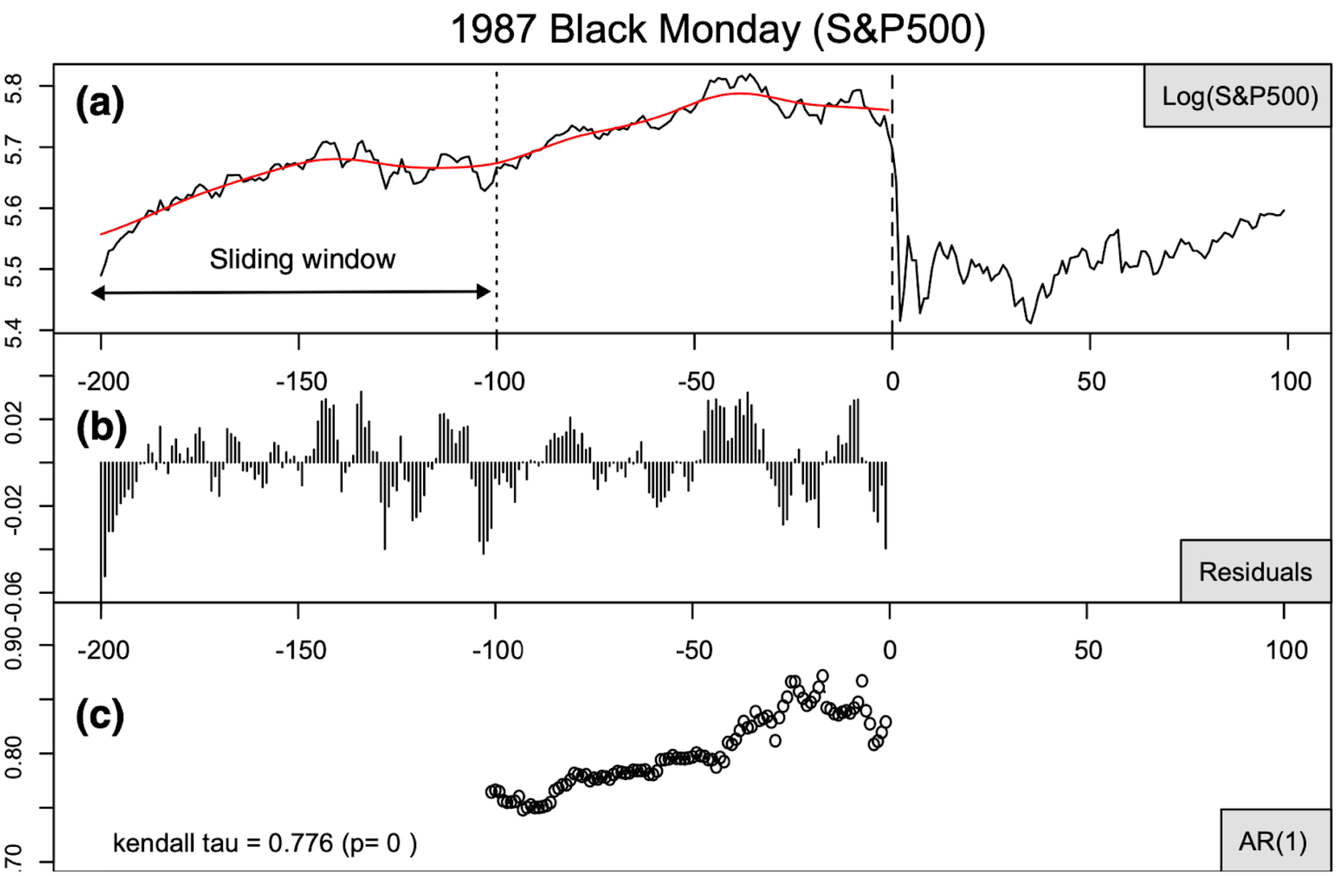

Figure 2.5.2: Early warning signals for financial time series data leading up to the 1987 Black Monday financial crisis. This analysis could also be performed on financial data directly related to resource extraction. [Source Diks et al., 2019].

Sentiment analysis of social media data – for example the number of tweets in a given area raising concern over an exploited resource – can give estimates of the fraction of conservationists that have stakes in the social-ecological system. Additionally, citizen science generates not only ecological data, but social metadata through the number of engaged users monitoring specific areas. Using existing infrastructure such as CitSci.org, we have the ability to use this data as a proxy for trends in conservationists (Wang et al., 2015). This approach allows for the deployment of generic real-time monitoring of ecological systems with existing data without requiring extensive knowledge or models of the system. Social data over longer timescales may also provide valuable resilience indicators, as seen in archeological data using variance in settlement size as a reliable indicator for societal collapse under environmental forcing (Spielmann et al., 2016).

2.5.3. State of Affairs: Application of early warning signals in social-ecological systems

With increasing amounts of socio-economic data being generated on a daily basis, there are tremendous opportunities to use cutting-edge and established techniques in early warning signals as ways to monitor resilience and respond promptly to critical transitions that will increase in probability as our social and ecological systems become further intertwined. This will require deliberate coordination with scientists, policymakers and institutions that collect social data in order to monitor these systems and respond to the threat of catastrophic tipping points before it is too late. Below, we illustrate some examples of applications of early warning signals for tipping in social-ecological systems.

2.5.3.1. Food security

Systematic early warning for food security applications has been in existence since at least the 1980s (Funk et al., 2019). These systems have helped avert catastrophic food crises, such as during the 2017 drought in Kenya. In this particular case, the drought was analogous to the crisis of 2011, but sufficient early warning and early action reduced humanitarian needs for 500,000 people – demonstrating the potential of early warning systems to trigger response (Funk et al., 2018). The most simple systems focused on translating climate parameters such as rainfall anomalies into predictions of crop production (and, indirectly, impacts on food security). Food security early warning systems have developed to include other considerations in forecasting food insecurity, such as political instability, fluctuations in food prices, labour availability and violent conflict. As technologies and methods to predict different triggers of food insecurity become increasingly available, predictions of food crises and famine will also improve.

Food security can change seasonally. As such, it does not exhibit traditional bifurcation in the sense of irreversibility. A permanent change towards a state of food insecurity would be catastrophic, representing a permanent food crisis. Krishnamurthy et al., (2021) offer a framework to identify “transitions” as prolonged periods of food insecurity using the Integrated Food Security Phase Classification (IPC), the leading global metric for standardised food security assessment which combines data on agricultural production, food prices, nutrition rates, weather patterns and other variables to determine the general food security situation in a given location based on five classes (1: minimal food insecurity, 2: stress, 3: crisis, 4: emergency, 5: famine) (Figure 2.5.3). With these metrics, a tipping point in a food system can be thought of as a shift between periods with low food insecurity (IPC 1 or 2) to periods of sustained food crisis (IPC 3 or higher) (see Figure 2.5.3 for an illustration of this concept).

An example of a potential tipping point using the IPC categories is found in East Africa after the 2015/2016 El Niño episode. Usually El Niño events yield extended autumn rains in East Africa, which is beneficial for livestock grazing (Korecha and Barnston, 2007). This was not the case for the 2015/2016 event, which saw anomalously low rainfall in both the summer and autumn. This trend, combined with insufficient drought preparedness, resulted in crop failures and livestock mortality – and consequently a depletion of livelihood assets, food stocks and overall food security in northern and eastern regions of Ethiopia (Figure 2.5.3).

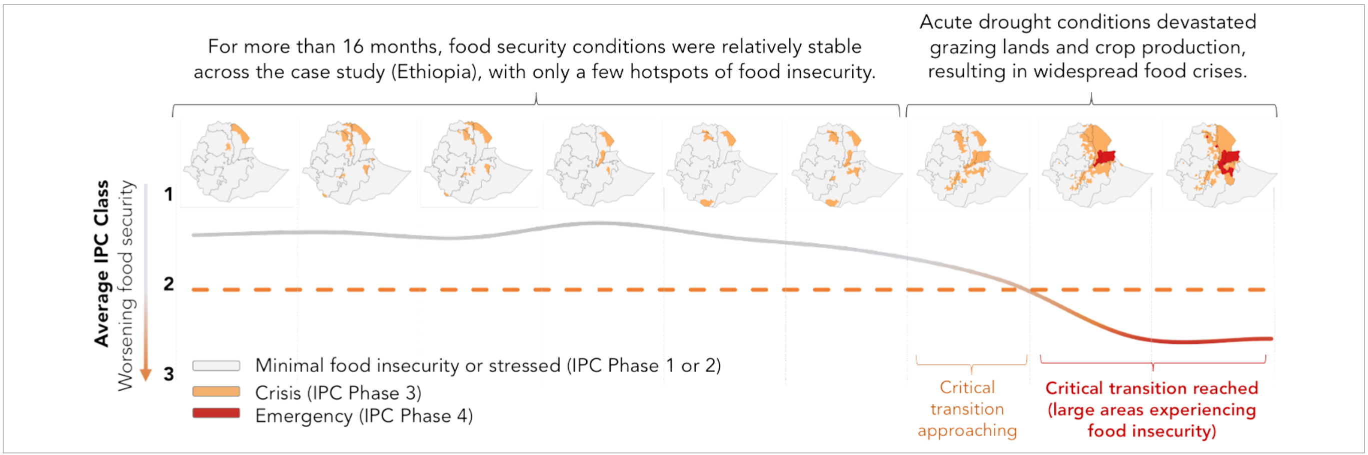

Figure 2.5.3: Example of a tipping point in the context of food security, showing the transition from stable food security conditions to a food crisis resulting from drought in Ethiopia. [Source: Krishnamurthy et al., 2020].

Building on this approach, Krishnamurthy et al., (2022) were able to detect transitions in food security states by integrating lag-1 autocorrelation statistics into remotely sensed observations from the SMAP mission with food prices. The research reported dramatic improvements in anticipating the timing and intensity of food crises across arid, semi-arid and tropical regions, suggesting universality in the approach.

The analysis highlights the potential to use elements of tipping point theory in social systems. In this particular context, the approach showed improvements in predictions of impending food crises, with a lead time of up to three to six months – a sufficient period to mount a humanitarian operation. The trigger based on lag-1 autocorrelation of soil moisture anticipates the timing of the transition and the magnitude of the food security change among small to large transitions, both into and out of crises (Figure 2.5.4).

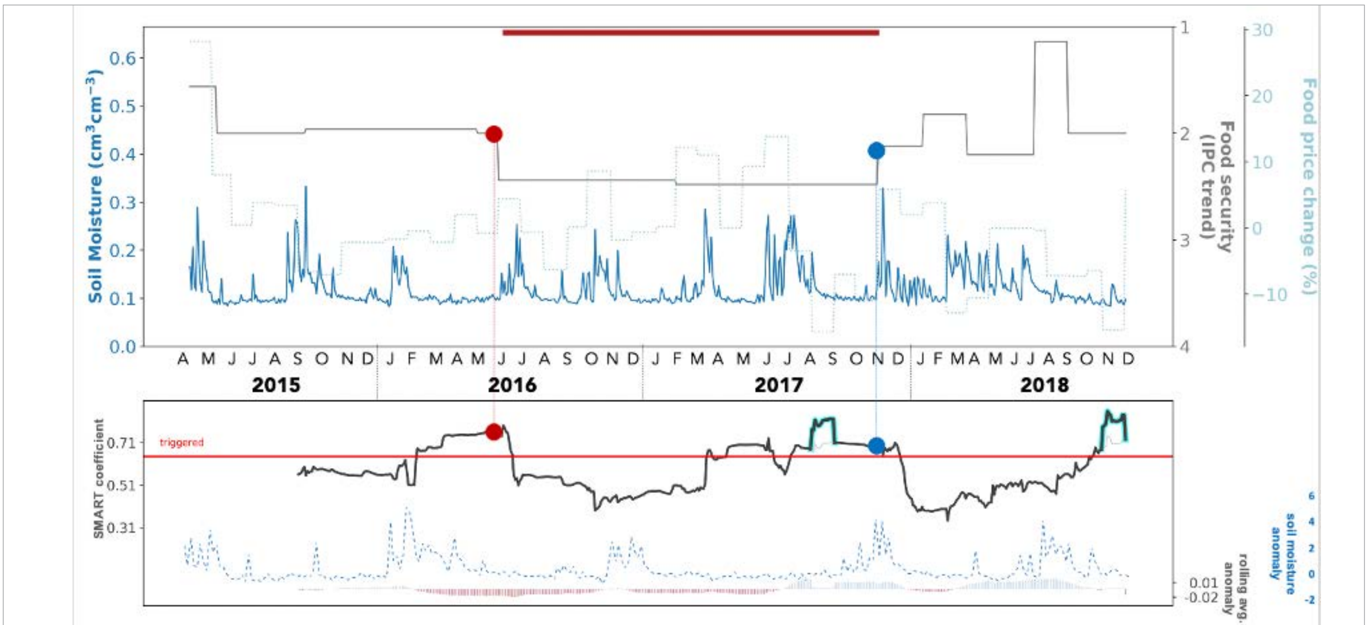

Figure 2.5.4: Data visualisation dashboard showing how food security transitions are detected with remotely sensed soil moisture data and food price data. Top panel: Integrated Food Security Phase Classification (IPC) (grey line), remotely sensed soil moisture from SMAP (solid blue line) and food price anomalies (dashed blue line). Bottom panel: soil moisture autocorrelation (black line, with blue highlight when price-influenced), trigger threshold (red line) and soil moisture rolling average (light red/blue bars). When soil moisture autocorrelation exceeds the triggered threshold by at least 60 days, a food security transition forecast is signalled; the indicator is skilful up to three to six months ahead of a transition. The period of state change is indicated by the maroon bar in the top panel. The red dot denotes the exact point when the threshold has been exceeded, suggesting a deterioration of food security conditions, and the blue dot highlights the point in time at which the threshold for an improvement in food security conditions was met. The example shown above is for the north-eastern region of Kenya. [Source: Krishnamurthy et al., 2022].

2.5.3.2.Tipping points in managed vegetation systems

Remote sensing datasets also have potential applications in the detection of tipping points in managed vegetation systems like pastoral systems (Swingedouw et al., 2020). For instance, Fernandez-Gimenez et al., (2017) have used Earth observation data to monitor the impact of increased livestock pressure on grazing lands as well as potential shifts in crop density and vegetation types (Figure 2.5.5).

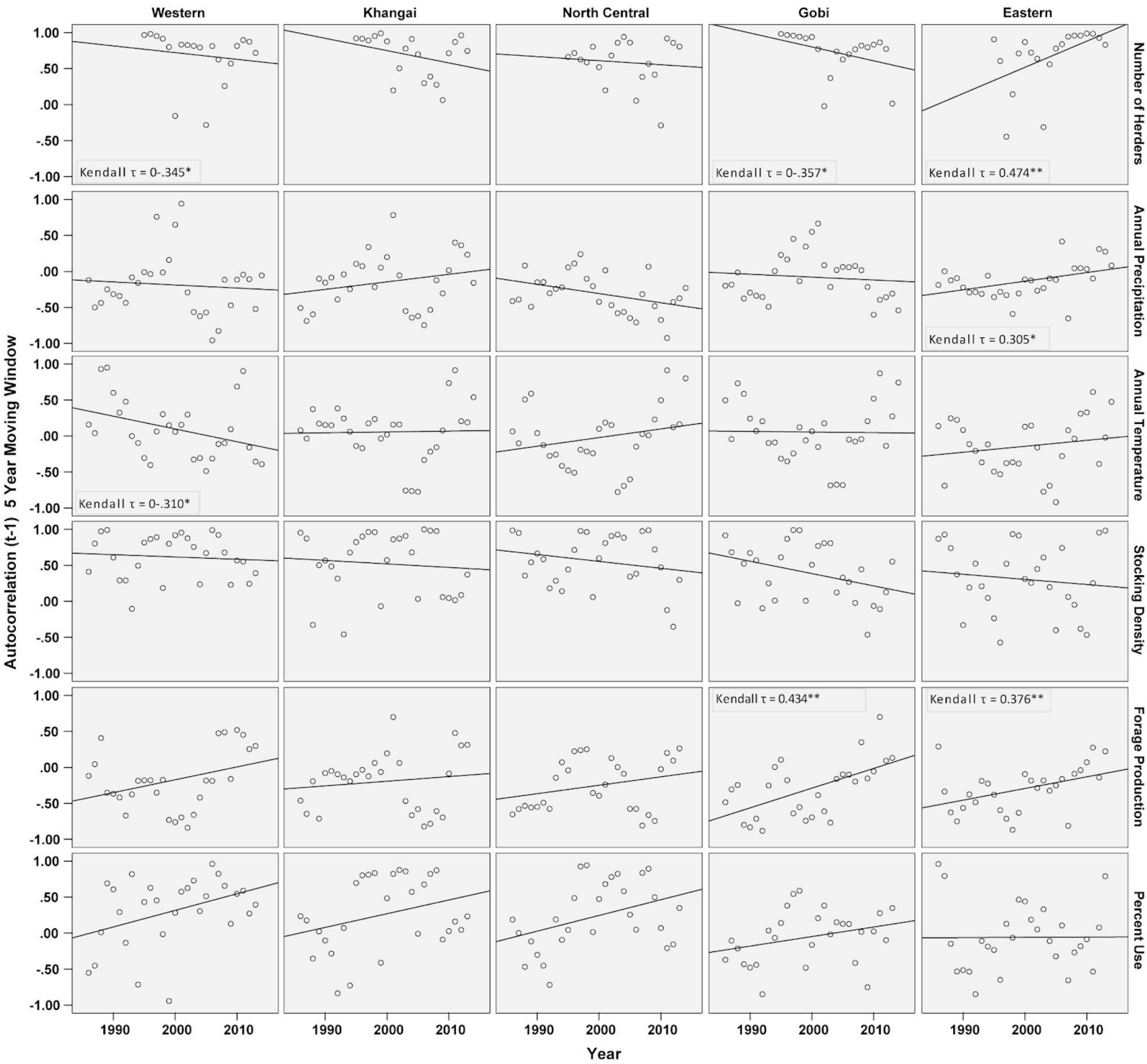

Figure 2.5.5: Trends in five-year moving window autocorrelation. Where original values indicated a significant trend, data were detrended before analysis. Strength of correlations is indicated by Kendall's Tau where significant. * indicates p < 0.05, ** indicates p < 0.001. Reproduced from (Fernandez-Gimenez et al., 2017).

With normalised difference vegetation index (NDVI) data derived from the Advanced Very-High-Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS) missions, the authors detected higher autocorrelation and variance in variability of forage production, which could be interpreted as a potential tipping point in rangeland conditions. Implications for pastoral communities can be significant as grazing lands transition to a more degraded ecosystem that cannot sustain their livelihood.

In tropical forest settings, too, remote sensing products have been used to identify potential critical transitions. (Verbesselt et al. 2016) used MODIS NDVI and RADAR Vegetation Optical Depth (VOD) monthly data time series of evergreen tropical forests across Africa, South East Asia and South America to detect declining rates of recovery through temporal autocorrelation. The results provide practical thresholds to anticipate collapse of tropical forests facing drought and high temperatures. (See also Chapter 1.6 for further analysis outlining how proximity of landscapes to human activity leads to lower resilience.)

2.5.3.3. Tipping points to detect anomie

Social tipping points resulting from Earth system destabilisation are under-researched. Consequently, no specific early warning signal tracking mechanisms have been established. But as suggested above, new datasets and methodological developments could prove to be useful for sensing the states of various social subsystems, ideally to prevent negative social tipping being triggered. For instance, early warning signals for anomie induced by Earth system destabilisation could be developed by tracking what people post and share online. Deep learning approaches have been developed to detect mental illness from user content on social media (Kim et al., 2020; Uban et al., 2021). Monitoring user content over time for signals of mental illness could allow detection of changes (e.g. acceleration, jumps) and/or monitoring the spread of content linked to mental illness across social networks for (complex) contagion processes (Wiedermann et al., 2020). This could provide information that a likely tipping point is approaching. Similar approaches could be used to detect deviant behaviours (Coletto et al., 2016). Combining these various measures and others such as distrust (Sampson et al., 2016) could produce a tool to monitor the dynamic anomie state of a society exposed to Earth system destabilisation.

2.5.3.4. Tipping points to detect social crises

Detection of acceleration in radicalisation and polarisation, which, as was established in Chapter 2.3, could be exacerbated by Earth system destabilisation, can be pursued using similar machine learning and social network analysis approaches applied to user-generated online content (Gaikwad et al., 2022). Conflict early warning systems (CEWS) are well established and researched (Rød et al., 2023). A notable example is the ACLED (Armed Conflict Location & Event Data Project) CAST platform (Conflict Alert System), which is meant to predict violent events up to six months in advance. These CEWS could be enhanced with new ML/AI-based models that can capture coupled climate-conflict-tipping processes (Guo et al., 2018; Guo et al., 2023).

Finally, ML/AI-based tools are also emerging to develop early warning systems to predict financial crises (Samitas et al., 2020), which, as was established in Chapter 2.3, could be triggered by Earth system destabilisation. Near real-time monitoring is also feasible with these types of data and methods, as demonstrated by the GDELT project, which monitors the world's broadcast, print and web news from around the world in 100 languages for significant events and trends. With respect to ethical questions around surveillance and privacy concerns, it is important to emphasise that early warning systems focus on broad patterns and do not track individuals, so personally identifiable information is not included in these systems.

2.5.4. Where next: Areas of future research

From a communications perspective, the idea of abrupt transitions to irreversible (and undesirable) states can be an effective call for action. However, for tipping points to be operationally meaningful, it is important to prioritise detection of early warning signals, especially in social-ecological systems. Here we outline seven areas of research which require additional investment to significantly advance science. We classify these into two broader topics: data and policy questions.

2.5.4.1 Data questions

1. **What are the most relevant and appropriate datasets for early warning of social tipping points?** As outlined in this chapter, social tipping points are more complex than environmental tipping points due to the interacting relationships between climate parameters and social responses. Given this complexity, there is a need to identify relevant data sources that can be used to detect and anticipate tipping points. Moving forward, it would also be useful to explore datasets that can predict endogenous social tipping, as opposed to predictable events stemming from primarily environmental issues. Recent advances in remote sensing and Earth observation, machine learning and deep learning, and increasing social data from social networks all offer an unprecedented opportunity to understand early warning signals for social tipping points. In this chapter we outlined a handful of use cases, but additional research is needed to fully unpack the potential of these emerging datasets. Once datasets are identified, ensuring that these are accessible and usable for analysis is highly important. For instance, data from social media which could be used for detecting tipping points are often only available at a cost, rendering them inaccessible. Moving forward, it will be important to consider sharing platforms to ensure access to critically important datasets.
2. **What are the characteristics of datasets that can render them more (or less) useful for detecting social tipping points?** A key practical question for tipping point analysis is whether there are specific characteristics that make datasets more appropriate for detection of critical transitions. Early warning of tipping points ultimately depends on reliable, high-frequency data. For example, in an analysis of data requirements for early warning of food security tipping points, (Krishnamurthy et al., (2020) highlighted the importance of temporal resolution over spatial resolution in order to detect autocorrelation or flickering in coupled climate-food systems. A long historical database (with at least 30 years of data) is also preferred as it can help determine climatology and anomalies that could lead to tipping. However, research has shown that even limited datasets such as SMAP soil moisture (available since 2015) can provide transformative opportunities for detecting food security transitions (Krishnamurthy et al., 2022).
3. **Which early warning signals (autocorrelation, variance, skewness, threshold exceedance) are more meaningful for different applications?** Identifying the most useful metrics and statistics for early warning of tipping points translates to actionable information. For instance, recent work has shown that increased autocorrelation and variance can detect transitions in managed vegetation systems (Fernandez-Gimenez et al., 2017). In food security applications, too, autocorrelation is the key metric used to detect a transition in food security states, with the rolling average statistic indicating the direction of the transition (Krishnamurthy et al., 2022). Such insights can help leverage resources in a timely fashion to avert negative effects associated with social systems that exhibit tipping points.

2.5.4.2 Policy questions

4. **Do climate tipping points exacerbate poverty traps and other negative development trends?** One of the most severe social impacts of climate change is the potential for reversing the hard-won development gains achieved in the last two decades. It is entirely plausible that transitions in rainfall distributions or ecosystem changes driven by climate change could push people into poverty. Indeed, the World Bank estimates that climate change will push up to 130 million into poverty as a result of damage to infrastructure, changes in rainfall seasonality which will render rain-fed agriculture less predictable, and overall deterioration of environmental systems. Additional research is needed to understand which climate tipping points are likely to intersect with poverty traps to create high-risk transitions.

5. **How do multiple climate extremes and other shocks and stressors combine, especially as slow-onset climate change processes occur to drive systemic changes and tipping points?** The challenges of cascading risks and tipping points are discussed in Chapter 2.4. Evidence suggests that severe climate events, such as droughts and hurricanes, can result in highly complex social change, including deterioration of livelihoods, migration and conflict (Burrows and Kinney, 2016). Additional research is required to understand if and how climate and social tipping points interact, and whether one tipping point can result in a plethora of other transitions.

6. **As critical transitions unfold, how does the risk landscape shift in response?** Societies respond to environmental stress and resource scarcities. However, these responses may lead to new risks. For example, as pastures become less viable (due to overgrazing), new risks are created as pastoralists shift grazing patterns to marginal agricultural areas or shift migration routes and deplete resources in other areas (both of which can increase land degradation and desertification rates). Understanding how critical transitions affect the current (and future) risk landscape can provide essential information for decision makers to prioritise investments in adaptation and mitigation.

7. **What are the processes required to integrate research into policymaking?** There is growing research on early warning signals for tipping points. However, once suitable datasets and early warning diagnostics are identified, what are the enabling processes and steps required to integrate actionable early warning systems into decision making? To illustrate, while research has shown the potential to use remotely sensed soil moisture for food security early warning, precipitation and vegetation indices are still the go-to metrics – largely because of familiarity with these products. New data analytics, dashboards and communications material may go a long way towards facilitating the transition to early warning systems of tipping points that can translate into action.

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Section 3

Governance of Earth system tipping points

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Section summary

Governance efforts to address the specific and severe threats of Earth system tipping points (ESTPs) are currently lacking and urgently needed. A future governance framework for ESTPs should prioritise efforts to prevent tipping events, while also minimising impact-related harms, fostering adaptation and resilience, and facilitating knowledge co-production. Failure to prevent tipping would likely impede the achievement of the Sustainable Development Goals (SDGs). These objectives can only be reached together, through systemic changes that address the root causes of Earth system change with transformations to sustainable and just societies.

In all domains of governance (prevention, impact governance, knowledge production), the diversity of tipping processes (their timing, drivers and impacts) need to be carefully considered and used to inform approaches tailored to distinct ESTPs.

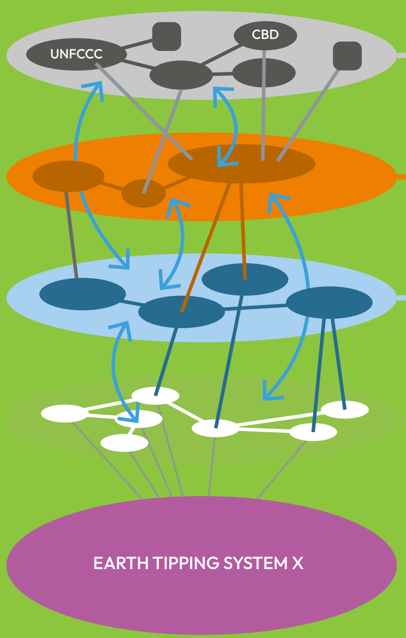
Governance of Earth system tipping points should be based on existing principles of global governance and international law, such as precaution, equity and justice, as well as care for future generations. The nature of threats presented by tipping dynamics in the Earth system challenges the common reactive and linear logics of decision making in global governance. Short-term decisions can have severe, even catastrophic, consequences over extremely long time horizons, potentially affecting life on Earth for several millennia, and future generations' chances for survival and wellbeing. These extremely high stakes place a major burden of responsibility on the present generations and – unlike other global challenges – dramatically elevate the logic of precaution. Scientific uncertainty (for example, about how close we might be to a tipping point) should be reason for action, not delay, with anticipatory approaches and systemic risk governance of particular importance in guiding decision making.

Section summary (continued)

Effective prevention strategies need to address the multiple, interacting drivers of ESTPs, which often operate at different scales. We distinguish primary (often global-scale) and secondary (often regional-scale) drivers to aid decision makers in devising multi-scale approaches and selecting appropriate governance venues. The primary driver in many cases is global temperature change, which makes accelerated mitigation of greenhouse gases the most important and effective prevention strategy. Rapid, near-term mitigation efforts should be combined with enhanced management of short-lived climate pollutants (SLCPs) and scaling efforts for sustainable carbon dioxide removal (CDR) to minimise the rapidly increasing risk of transgressing ESTPs. Solar geo-engineering approaches remain speculative and subject to concerns over side-effects and governance. For the time being, they are not available to support prevention efforts, although additional research is merited. Overall, effective prevention strategies need to address all drivers of diverse tipping processes with coordinated cross-scale approaches.

Global institutions across multiple domains, including climate change, development and international migration, need to consider the implications of tipping processes for their effective operation, adjusting existing frameworks, approaches and practices for governing the impacts of global environmental change.

A 'polycentric' architecture that would distribute responsibilities for prevention and impact governance across multiple sites and scales of action, and attend to linkages, coordination and effective information flows between different actors and institutions, is the appropriate model for governance. Important decisions concern the differentiation between global-scale tasks, especially mitigation of GHG to limit global temperature increase, and those at regional and national scales, such as addressing secondary drivers of specific tipping systems (for example, deforestation for Amazon dieback). Regional and national institutions with a direct geographic relationship to a tipping system could also have responsibility for impact management, such as resilience building, adaptation or managed retrea



SCALE	SCALE-SPECIFIC ESTP GOVERNANCE TASKS	ACTOR EXAMPLES
GLOBAL	-Frameworks and principles -Prevention 1 (GHG mitigation) -Funding and capacity building for adaptation. Loss and Damage -Knowledge co-production, systemic risk assessment	-UNFCCC -CBD -UNEP -IMO -Transnational civil society organizations
REGIONAL (CORRESPONDING TO ESTP SCALE)	-Prevention 2 (regional drivers) -Coordination of adaptation planning and measures -Monitoring and early warning systems -Tipping-system specific learning and experience sharing	-Arctic Council -ACTO -OECD -International NGOs -Missing for many ESTPs
NATIONAL	-Prevention 3 (national drivers) -Planning and preparedness for impacts (adaptation, disasters, loss and damage, migration,-) -Monitoring and early warning systems -Science funding, knowledge co-production	-National governments -Indigenous peoples governing bodies -National Industry associations -NGOS
LOCAL	-Implementation of prevention measures (national and regional drivers) -Adaptation planning and action -Knowledge co-production	-City and municipal governments -Community organisations -NGOs

Figure 3.0.1: Polycentric Governance of an Earth system tipping point

Stylised depiction of polycentric governance for a tipping system, i.e., distributing and sharing responsibility for various tasks across multiple scales and institutions with multiple, networked actors at each scale and linkages (e.g., membership, information flows, coordination) across scales. The table summarises how key governance tasks could be distributed across scales for a specific ESTP. Not all relevant scales of governance are included; e.g., bi- and multilateral levels are missing.

There are well-developed global and national sustainability governance institutions that can and should adopt responsibilities for the governance of ESTPs. At the global scale, this includes the UN Framework Convention on Climate Change (UNFCCC) and Convention on Biological Diversity (CBD). Existing governance expertise across scales is strongest regarding mitigation, and weaker regarding impact management.

Existing institutions and measures need significant adjustments and strengthening in light of ESTPs, and we illustrate this need for reform specifically for the Paris Agreement (e.g. NDCs and the Global Stocktake, loss and damage). But many other institutions will need to reassess their efforts with regard to the risks of ESTPs. Governance capacity at the scale of specific tipping systems is currently limited (as in the Arctic and Amazon) or lacking (as in the tropical coral reefs, major ocean currents and monsoons). This is where most innovation and work is needed, including the consideration of new institutions or initiatives.

Key messages

- Governance of Earth system tipping points is lacking and existing global governance institutions do not address the specific risks they pose.
- Preventing the transgression of Earth system tipping points should become the core goal and logic of an urgently needed global governance framework. Such efforts need to pursue multiple objectives simultaneously, including risk minimisation, impact governance, justice and equity.
- Current climate mitigation efforts, including governance of short-lived climate pollutants and carbon dioxide removal need to be strengthened rapidly, and address non-climate drivers at regional and national scales.
- Governance of Earth system tipping points should be based on existing principles of global governance and international law, such as precaution, equity and justice, including care for future generations and deep cooperation, with decision making guided by anticipatory approaches and systemic risk governance.
- Governance of Earth system tipping points should be polycentric, distributing responsibility, authority and accountability across multiple scales and institutions, including at the regional scale of the tipping element.
- Earth system tipping processes challenge existing governance structures, e.g., for climate change impacts, because of the expanded scope of change, the increasing speed of change, the potential for regional trend reversals, and the novel distribution of vulnerability.
- Existing institutions for impact governance need to be adjusted to match the temporal patterns and spatial scales of different tipping systems to adequately anticipate, respond to, and mitigate their risks and impacts. In some cases, this might require new institutions or mechanisms.
- The transgression of Earth system tipping points would significantly increase the need to address irreversible losses. Loss and damage mechanisms within and beyond the UNFCCC would have to be expanded.
- Knowledge institutions need to be reformed to better support effective governance through solutions-oriented, context-specific, actor-relevant and anticipatory knowledge, while learning challenges must also be addressed.

Recommendations

- Now is the time for governance actors, including UN bodies, international organisations, national governments and non-state actors, to engage in the process of learning, interest formation/positioning, coalition building, and agenda setting for the governance of Earth system tipping points.
- Given that Earth system tipping points risks are already moderate at current levels of warming, and increase substantially above 1.5°C above pre-industrial levels, countries need to reduce GHG emissions rapidly and dramatically in the near term and reach zero by mid-century to minimise the risk of transgressing tipping points.
- Parties to the Paris Agreement should include Earth system tipping points in future Global Stocktake processes, assessing collective progress towards their prevention and impact governance.
- Parties to the Paris Agreement should include a discussion of Earth system tipping points in future revisions of their NDCs and mid-century decarbonisation strategies, including an assessment of how the country contributes to tipping-points risks, how it will be affected by their impacts, and national measures and plans to prevent their transgression and to prepare for their impacts.
- Parties to the Paris Agreement should initiate an evaluation of the adequacy of current mechanisms for addressing climate change impacts (e.g. adaptation, loss and damage, finance) in light of the specific risks posed by Earth system tipping points.
- Countries within the geographic scope of a specific Earth system tipping element should consider the need for new initiatives for collective impact governance.
- International organisations, national governments and science funders should foster urgent international research collaboration, especially in the social sciences and humanities, by promoting open, trans and interdisciplinary, solutions-oriented, networked knowledge systems focusing on Earth system tipping points.
- Regional and national science and knowledge institutions and boundary organisations should foster anticipatory capacity building with participatory co-production processes involving policymakers, scientists, other knowledge holders, artists, and designers.

3.1 Governing Earth system tipping points
Introduction

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Summary

Existing institutions of global sustainability governance do not address the specific risks and challenges posed by Earth system tipping points (ESTPs). State and non-state actors need to engage in agenda-setting for the development of a governance framework that can close this gap. This chapter seeks to inform emerging discussions, decisions and actions as tipping points move onto global and national policy agendas.

This chapter explores possible goals for the governance of ESTPs and relevant governance principles, actors and institutions, sites, and scales. Future governance efforts will have to simultaneously pursue and balance multiple objectives, prioritising the prevention of ESTPs. Several principles of international law and global environmental governance apply to this domain, including justice, precaution and adaptability. Focusing on the time-specific features of tipping processes and their implications for governance, we heavily emphasise the need for anticipatory governance with multiple time horizons, including some that exceed the scope and capacities of current global governance approaches.

A 'polycentric' governance approach is best suited for Earth system tipping processes, which play out at multiple scales. Principles for sharing responsibility, devising efficient information flows and learning at and across scales will be vitally important tasks for effective governance. Many existing institutions can adopt responsibilities related to tipping-point governance. At the global scale, the UNFCCC is key among these. A number of features of the Paris Agreement would need to be adjusted and revised to account for the specific challenges presented by ESTPs. Strong institutions at the regional (multilateral) scale of Earth system tipping elements are often missing, inviting consideration as to whether new initiatives are needed, for example, with a specific governance mandate for the tropical coral reefs or Atlantic Meridional Overturning Circulation (AMOC).

Key messages

- Governance of ESTPs is lacking. Existing governance institutions, e.g. for climate change, do not address the specific risks posed by ESTPs.
- Unavoidable tensions between the governance needs for ESTPs and other objectives – especially social and economic development and justice – need careful consideration. However, failing to prevent ESTPs would undermine and likely impede the achievement of the SDGs.
- Governance of ESTPs should be polycentric, distributing responsibility and authority across multiple scales and institutions. This includes the regional scale of specific tipping systems, where existing institutions are weakest or lacking.
- The diversity of Earth system tipping processes, e.g. in terms of their geography, timing and impacts, demands governance approaches that are to some extent tailored to a specific tipping point or class of tipping points.
- Tipping dynamics imply that short-term decisions (years) have consequences on short and very long time horizons (years to millennia). Once tipping points are transgressed, the unfolding of change processes can become unstoppable. These connections between the short and long-term dramatically elevate the imperative of near-term preventive action, requiring anticipatory governance and new risk-governance approaches.
- Public understanding of tipping processes is likely limited and hard to change with common forms of science communication. Public risk perceptions are unlikely to generate public pressure for climate action in the short term.

Recommendations

- Now is the time for governance actors, including UN bodies, international organisations, national governments and non-state actors, to engage in the process of learning, interest formation/positioning, coalition building and agenda setting for the governance of ESTPs.
- Existing sustainability governance institutions across multiple scales, especially those related to the international climate change regime complex, should consider including ESTPs in their mandates and action agendas. At the same time, coordination, transparency, and network development efforts between various governance sites need to ensure an effective division of labour, alignment and synergies between initiatives.
- Parties to the Paris Agreement should include a discussion of climate tipping points in future Global Stocktake processes, assessing collective progress towards their prevention and impact governance.
- Countries within the geographic scope of a specific tipping system (e.g. all countries with tropical coral reefs) should consider the need for launching new initiatives with the specific mandate to address this tipping process (prevention, impact governance, knowledge development).
- Governance actors and institutions in the public, private and civil society domains should strengthen their capacities for anticipatory governance and systemic risk governance, expanding and adjusting existing approaches to decision making with novel methods.

3.1.1 A new governance agenda for Earth system tipping points

While attention to the threats posed by ESTPs is growing, explicit governance efforts to address them do not yet exist. Governance refers to rules, regulations, norms and institutions that structure and guide collective behaviour and actions. This includes the processes that create governance, which often involve politics, policymaking and mechanisms for holding actors accountable for their actions and inactions. We consider not only governments and their intergovernmental initiatives as key actors, but also corporate and industry bodies, civil society organisations, cities and municipalities, as well as transnational networks.

The current landscape of global and regional (multilateral and non-state) environmental and sustainability governance efforts does not yet consider the specific challenges presented by ESTPs. For example, the constantly evolving regime complex for climate change centred on the UNFCCC is relevant and directly shapes tipping-point risks, especially through mitigation policies. But, even though tipping points have been given increasing attention in IPCC assessment reports (see Chapter 3.4), so far, the international climate change regime does not explicitly consider their risks in its goals and mechanisms. Similarly, the long-standing governance efforts for biodiversity, oceans, forests, the Arctic and Antarctic do not yet address ESTPs.

Given this status quo, the key task for the global community is the establishment of a governance agenda for ESTPs. To the extent possible, this requires adjusting existing institutions to account for ESTPs. But there might also be circumstances where such adjustments will not suffice, and novel frameworks, actors or institutions will be needed to anticipate, prevent the transgression of, and handle the adverse impacts of tipping processes. In some cases, such as climate change, the existing governance regimes are already complex, politically contested and cumbersome. Integrating a new set of challenges into their already-crowded agendas requires political attention, a set of committed actors, and (human, institutional and financial) resources, all of which are limited. Yet, this work is necessary and urgent and would re-frame and re-orient some of the existing governance efforts. Grounded in scientific knowledge, discussions about governing tipping points need to provide a clear and convincing logic for action. Strategic efforts are needed to build this agenda, helping various stakeholders develop an understanding of ESTPs and the risks they present, and fostering alliances of actors with shared perspectives.

Agenda-setting efforts need to consider several fundamental questions in this early stage of ESTP governance. These include:

Goals. What could and should be done about tipping points? What are the most important governance goals?

Actors. Who should be involved in tipping point governance? Who has responsibility, who is affected, who has relevant skills and capacities to address tipping points? How to ensure a voice for the most vulnerable or marginalised actors?

Scales. At what scales should tipping point governance take place? How can multi-actor and cross-scale interactions be coordinated?

Sites. What are suitable governance institutions to address ESTPs, and to what extent are new institutions needed?

Principles. What should be the governance logics and principles guiding the development of norms, processes and mechanisms?

Resources. Who finances governance efforts related to ESTPs?

Knowledge. What is the role of science, knowledge and predictive capacity in tipping point governance, and how should effective science-policy engagement be designed?

Below, we begin to address some of these questions with a specific focus on the specific tipping points identified in this report, including the questions related to governance goals and principles (3.1.2), actors, sites and scales (3.1.3). The chapter concludes with a brief discussion of some of the likely political challenges of ESTP governance (3.1.4). The following chapters address some of these topics in more depth. Chapter 3.2 explores prevention of ESTPs as a central governance objective. Chapter 3.3 is concerned with the governance of tipping-point impacts, including adaptation, loss and damage, and migration. Chapter 3.4 addresses questions of knowledge production and science-policy interactions related to ESTPs.

3.1.2 Governance goals and principles

Given this status quo of lacking specific governance responses to ESTPs (pre-governance), fundamental questions include what actors collectively want to achieve, and which principles should guide their collective decisions and actions. A central challenge in developing governance for tipping points is the scarcity of obvious procedural analogues or instructive case studies. However, governing ESTPs is still a question of governing political, economic and social systems where there are familiar repertoires involving goal setting, institutional design, regulation, financial incentives and behaviour change across multiple scales and sectors and communities.

3.1.2.1 Governance goals

Based on the significant risks posed by Earth system tipping processes – major self-sustaining reorganisations of natural systems with potentially significant, negative consequences for human wellbeing – there is a strong argument for prevention as the primary objective of governance in this domain. Climate tipping points present a variety of risks, but for many people, communities, ecosystems and even entire countries, they present an existential threat. Importantly, due to their specific causal dynamics (self-amplifying feedback mechanisms), the vast majority of tipping processes cannot be halted once they have started; after passing a critical threshold, systemic reorganisation is inevitable and often irreversible on human timescales.

That means that short-term decisions, actions and inaction (i.e., over the next 5-20 years) can have extremely long-term consequences and ripple effects over millennia. The here and now is causally connected to the deep future. Policymakers have to consider their responsibility for future impacts that only they are able to prevent.

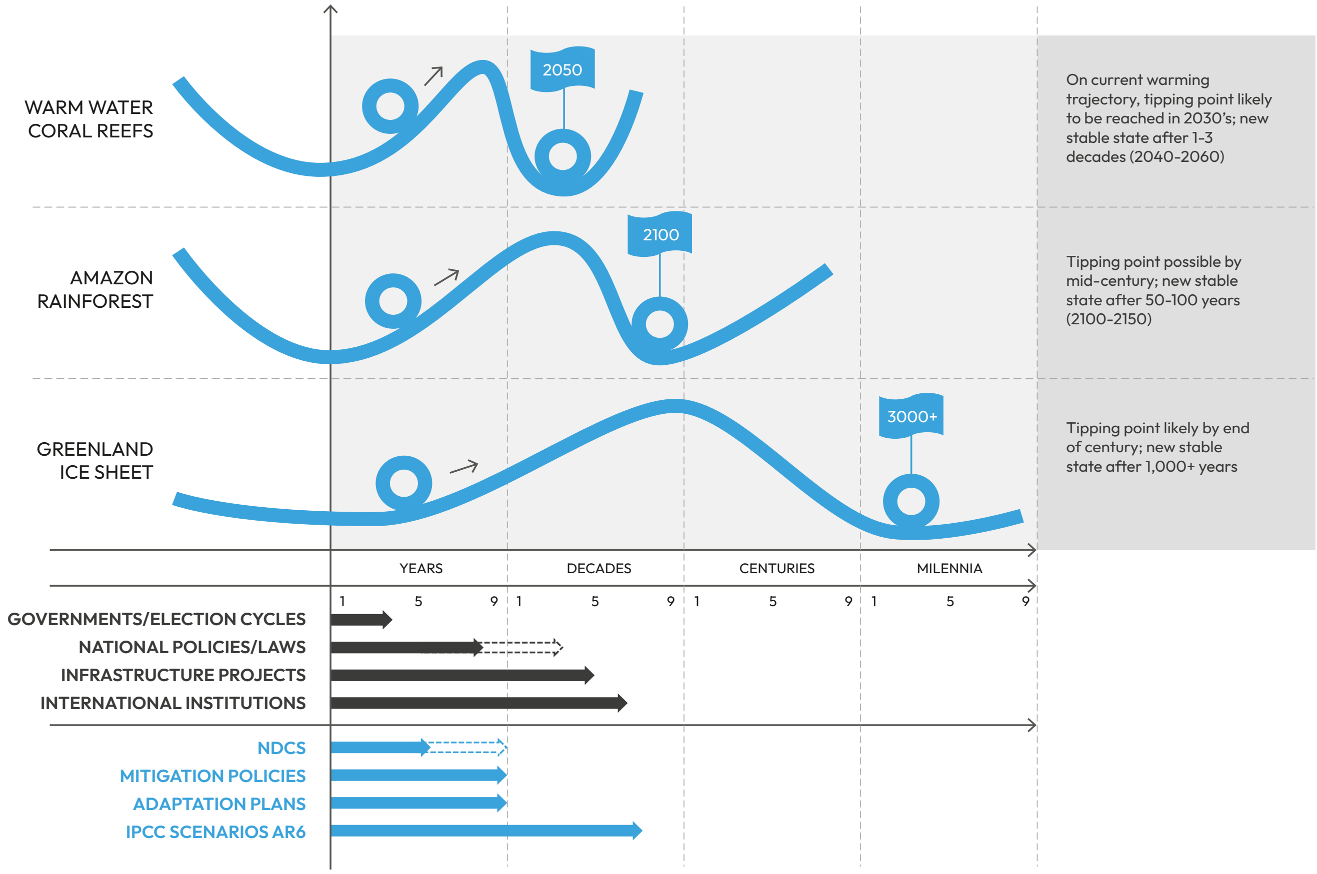

Figure 3.1.1: Temporal diversity of Earth system tipping processes

Stylized representation of the time-related characteristics of some tipping systems, especially differences in 'time until tipping' and differences in the length of the reorganisation process, and the comparative time horizons of political institutions and decision making. The figure does not represent system dynamics. There are significant uncertainties regarding these temporal characteristics. Assumptions about global temperature changes in the course of the century are based on Climate Action Tracker 2023, i.e., 1.5°C in the 2030s, 2.7°C by 2100.

While a focus on prevention is essential while it is still possible, governance actors have to consider additional objectives, especially the anticipation of adverse impacts of tipping processes. Some Earth system tipping processes, including the disintegration of the West Antarctic and Greenland ice sheets (see Chapter 1.2.2), might no longer be preventable, and some tipping points might be passed despite collective prevention efforts, making early impact governance imperative. Actors will need to balance their efforts between these multiple governance domains and objectives, and they will have to adjust their priorities to changes in the state of tipping processes over time – e.g. prioritising impact governance once scientific evidence for the transgression has become sufficient.

Figure 3.1.2 depicts how different governance objectives and corresponding activities would be distributed across the timespan of a tipping process. For this purpose, we outline three phases of a tipping process: pre-tipping, reorganisation after the transgression of the tipping point and stabilisation in the new system state. Based on current evidence and understanding, all ESTPs are in the pre-tipping phase. Given the existence of multiple potential ESTPs, future tipping-point governance would likely be in different phases regarding different tipping systems at any point in time. For example, there might be ongoing prevention efforts regarding the Amazon rainforest dieback (pre-tipping) while efforts regarding warm-water coral reefs might be focusing on impact governance (reorganisation).

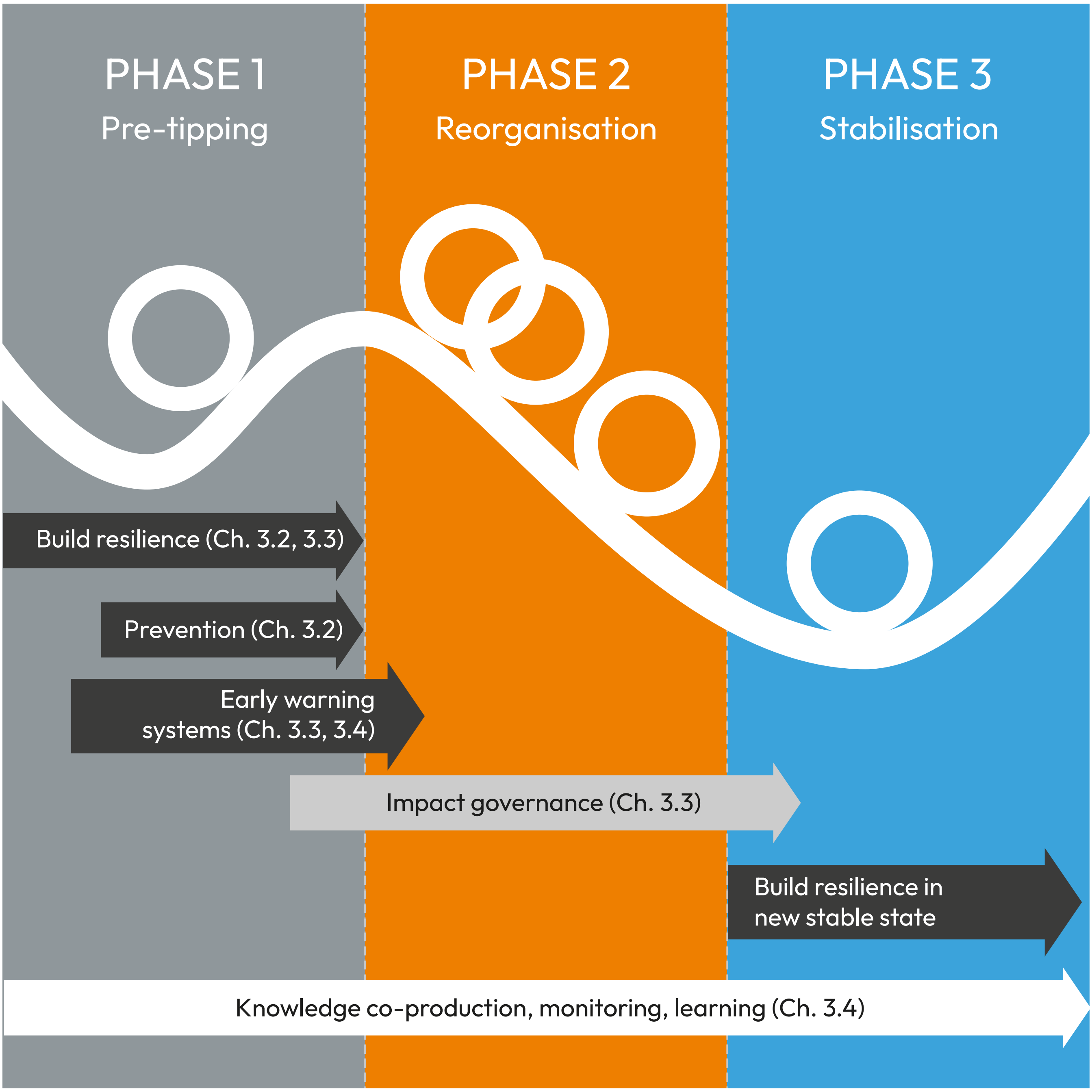

Figure 3.1.2: Governance tasks across different phases of tipping processes. The temporal distribution of governance objectives and activities across the timespan of a tipping process. Three phases can be distinguished: (1) pre-tipping, (2) reorganisation after a tipping point has been passed, and (3) stabilisation of the new system state. Each phase is associated with distinct objectives and corresponding governance activities. In Phase 1, the focus of governance should be on preventing the transgression of the tipping point and fostering resilience of the tipping system in question as well as potentially affected communities. Impact governance has to start in this phase (anticipation, preparation, planning), and becomes the single focus of governance efforts in phase 2. Once the tipping process (system reorganisation) has started, prevention efforts are no longer effective with regard to this tipping system, but continue to be needed for other ESTPs. In phase 3, governance needs to focus on stabilising new conditions and rebuilding resilience. Knowledge production and learning are necessary across all phases.

Addressing the expected impacts of ESTPs is strongly linked to the existing governance frameworks for climate change adaptation, vulnerability, resilience-building, and loss and damage. In light of tipping points, the goals, approaches and institutional frameworks in this domain will require adjustments and rethinking. Some tipping processes can unfold over decades, centuries and millennia, presenting decision makers and affected communities with the prospect of continuous change over long time periods until the tipping system in question reaches a new stable state (i.e., the loss of stable climatic conditions for decades/foreseeable future). The type and scale of their impacts will change over the entire period of the state shift. What's more, tipping processes display changing time-related characteristics while they unfold (e.g. increasing rates of change in certain time periods). Impact governance, especially adaptation planning, needs to take these characteristics into account.

Further, tipping processes in major Earth systems imply that the current, familiar state of these systems will be irrecoverably lost (e.g. coral reef state vs. algae-dominated state), and not merely temporarily altered with the option to re-establish current conditions. Affected communities will experience this disappearance of current Earth system characteristics as losses – the removal of the climatic foundations of current social structures. These losses of current economic, social and cultural conditions can occur on relatively short time horizons after the transgression of tipping points. Therefore, loss and damage institutions will have increased importance in the governance of ESTPs. At the same time, tipping point impacts could undermine institutional governance capacities, either directly or via political disruption or conflict (Howard and Livermore, 2019; Laybourn, Evans, and Dyke, 2023).

In some cases, tipping processes could challenge or render meaningless current governance logics and approaches due to their unexpected impacts. For example, the potential slowing or shutting down of convection in the North Atlantic Subpolar Gyre (see Chapter 1.4.2.1) could lead to regional cooling in Northern Europe and along the North American East coast, as opposed to currently expected warming trends in these regions. Existing adaptation plans will have to take these insights into account and be prepared for the fundamental changes in logics and approaches that might be needed.

Importantly, the set of ESTPs that have been identified to date are highly diverse in terms of the affected systems, the timing and length of the tipping process, and the kinds of interacting impacts they will have on societies and ecosystems. The design of risk assessments, prevention approaches, adaptation strategies, and loss and damage institutions will have to be specific for and targeted to each affected region and climate tipping point. At the same time, impact governance needs to consider potential interactions between multiple tipping dynamics (see Chapter 1.5) and their impacts (double or multiple exposure).

Prevention efforts serve as important 'brakes' on the drivers of climate change and tipping points; impact management is necessary to the extent prevention might be ineffective or fail. A more holistic – and systemic – approach to the governance of ESTPs would seek levers that could simultaneously reduce pressures on tipping systems and contribute to resilience to impacts. Scholarship on transformation and climate justice points out that ingrained societal, economic and geo-political structures drive resource extractivism as well as inequality and vulnerability (Gupta et al., 2023; Whyte, 2020; Ghosh, 2021). Transformations towards sustainable and just societies (Patterson et al., 2017; O'Brien, 2018; Bennett et al., 2019; Scoones et al., 2020) would simultaneously reduce emissions, foster social-ecological resilience, increase justice and equality, and create the conditions of trust (between individuals, communities, countries and generations) that are needed for the effective, cooperative governance of ESTPs (see also Section 4). For example, increasing access to renewable energy in communities without electricity could increase adaptive capacity, reduce vulnerability and contribute to mitigation at the same time. Depending on the way new energy infrastructure is developed and ownership rights are designed, these changes could also increase justice and social cohesion.

3.1.2.2 Governance principles

Many existing principles of international law and global environmental governance – shared beliefs of a fundamental nature that guide collective decision making and behaviour – are relevant for the governance of ESTPs. Below, we briefly discuss some of the principles we consider most important in the specific context of rapid state shifts in large Earth system components, recognising that others also matter. For instance, accountability and transparency are general governance principles we do not discuss here, as is the no-harm principle. Further, recent debates in international environmental law address the human right to a clean, healthy and sustainable environment and the legal rights of nature, which we only mention in passing. We also observe an emerging debate about shifts from international law and governance to Earth system law and governance (Patterson et al., 2018; Kotzé and Kim, 2019; Kotze et al., 2022).

More generally, the governance of complex and complex-adaptive systems like the climate, which are characterised by non-linear dynamics, threshold effects, cascades and limited predictability, demands an approach that is distinct from presently dominant patterns of governing that usually assume linearity and simple causality (Duit and Galaz, 2008). Core principles of complex systems governance include multi-scale and multi-network approaches attending to cross-scale interactions (Galaz et al., 2016), anticipatory governance addressing unusual temporalities (Muidermann et al., 2020; Boyd et al., 2015), diversity in response capacity (Galaz et al., 2016), and adaptive governance, i.e., the ability to adjust to the changing conditions of the system that is being governed (Duit and Galaz, 2008). The latter requires managing tensions between "the dual needs of institutional stability and change" (Duit and Galaz, 2008, p. 320) – i.e., the ability to work in stable patterns of cooperative rules and processes and the need to search for, explore, and experiment with novel patterns.

Across all principles, here we emphasise the need for a significantly strengthened **anticipatory approach** in the context of Earth system tipping. The potential for irreversible yet delayed harms calls for foresight and anticipatory actions despite incomplete knowledge. Delayed action can make managing tipping points in the future much more costly or even impossible due to their self-perpetuating and irreversible nature. At the same time, uncertainties, delayed impacts, distant planning horizons, and the more immediate demands of present challenges, undermine the motivation or perceived need to act now.

Anticipatory governance is a "flexible decision framework that uses a wide range of possible futures to prepare for change and to guide current decisions to ensure a range of future alternatives and to minimise future risks" (Quay, 2010). It differs from conventional policymaking and planning, which tends to rely on expert-driven forecasting and quantitative modelling. Anticipation often involves collaborative and participatory processes; systems for experimenting, exploring, or envisioning future scenarios qualitatively and identifying pathways of change; strategic investments that increase the resilience or robustness of a system; and the capacity to adapt quickly to changing and dynamic conditions. The incorporation of Earth systems tipping dynamics in simulations, scenario development and public communications may help make the impacts of these processes more tangible, and thus easier to respond to. It is important to note that anticipatory processes can open up but also close down possibilities for action, depending on their design (e.g. who participates). Avoiding the mere reproduction and reinforcement of existing and dominant paradigms requires designing processes that can expand possibility thinking (Muiderman et al., 2023) by carefully managing the role of power in anticipatory processes.

Governance actors, including international institutions, can increasingly rely on anticipatory processes and tools to develop shared understandings of possible futures and pathways towards them, including participatory scenario development and serious gaming (Flood et al., 2018; van Beek et al., 2022; Vervoort et al., 2022). Strengthening long-term governance capacities and deliberate approaches to dealing with uncertainty is time consuming, more resource intensive than conventional science-policy interactions, and requires openness to non-conventional ways of collective learning.

Uncertainty and precaution: Like many other environmental issues, the governance of ESTPs relies on evolving scientific knowledge and must grapple with a range of uncertainties related to scientific evidence at a given point in time. Key uncertainties concern which Earth system elements exhibit tipping dynamics, the specific conditions and timing of the passing of tipping points, and the types, location and timing of various impacts of tipping processes on the natural world (e.g. changes in storm and precipitation patterns) and even more so societies (see Section 2). Given these uncertainties, the precautionary principle is relevant for the governance of ESTPs. It has been defined in different ways, including in the 1992 Rio Declaration (UNCED 1992): "Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation." Yet, beyond this definition, the nature and contents of the precautionary principle has been debated (O'Riordan and Jordan, 1995; Stirling, 2007; Brunnée and Streck, 2013; Read and O'Riordan, 2017).

Developing practical approaches to implementing the precautionary principle is a key part of the tipping point governance agenda.

Justice and equity: Justice and equity must be key considerations of environmental governance. The concept of environmental justice has national roots in US politics (Bullard, 2021), requiring the fair treatment and meaningful involvement of all people, regardless of their race, gender, colour, nationality, religion or other characteristics, in the development and implementation of public laws and policies. But the fundamental principles of distributional, recognitional and procedural justice also apply between countries in the international system (Vanderheiden, 2008; Bennett et al., 2019), especially in a North-South context (Najam, 2005). Recently, scholars have attempted to integrate concepts of justice with that of Earth system boundaries (Rockström et al., 2023) to propose Earth system justice as a guiding framework for global governance (Gupta et al., 2023). This framework emphasises just ends, ensuring that we remain within planetary boundaries, and just means, which calls for an equitable distribution of resources, responsibilities and harms, both within and across generations.

A specific expression of the principle of justice in international environmental law and governance is Common-but Differentiated Responsibilities and Respective Capabilities (CBDR-RC). This principle has been fundamental to the climate change regime. In a general sense, it concerns the fair distribution of a shared responsibility to act on climate change, including emission reductions and the provision of international assistance (e.g. in terms of finance, technology, capacity building), taking into account national circumstances and historical contributions to emissions. Significant differences exist in interpretation of the principle, reflecting deep, unresolved disputes in international climate politics. Given the central role of atmospheric warming as a driver of all Earth system tipping processes, a future discussion about the shared but differentiated responsibility for Earth system tipping will likely mirror existing debates between the Global North and South, more and less-developed nations, fossil fuel producers and consumers, and more and less-vulnerable nations. This will include questions of historical responsibility and corresponding expectations for the provision of financial support for climate action (Colenbrander et al., 2022). At the same time, new questions will arise about specific tipping systems – e.g. whether and to what extent individual governments, industries, companies or other actors have responsibility for so-called 'co-drivers' of tipping, such as deforestation in the world's major forest biomes or ocean pollution near coral reefs.

Future care and intergenerational justice: While we may be nearing certain critical thresholds today and may experience the impacts of tipping points in the coming years and decades, many tipping processes and their largest impacts will unfold over hundreds and even thousands of years. This poses a long-term and intergenerational social dilemma, elevating the importance of intergenerational justice (Barry, 1997; Gardiner, 2011; Meyer, 2017) and long-term i.e., - future care. Intergenerational justice concerns the relationship between generations, more specifically the rights of future people and how they should be recognised and safeguarded in the present. A broader socio-ecological perspective of long-term care for planet Earth must also consider ethical obligations towards future non-human life, which also depends on the decisions and actions of present generations.

There are different perspectives on principles of future care, and to what extent it could and should shape decision-making processes. For example, in asserting the equal importance of inter- and intra-generational equity, the Earth system justice framework (Gupta et al., 2023) promotes equality and inclusion today to minimise harms from inherited inequality in the future. It also asserts the right of all future people to enjoy a standard of living comparable to the one of present generations and argues that current people bear responsibility for future harms and inequalities arising from our actions. This mirrors the Iroquois principle of thinking for the seventh generation, which entails both providing for the interests of descendants and making reparations for past harms inflicted by our ancestors.

Humans have the ability to plan for posterity and to take actions that will resonate hundreds of years into the future, yet this ability is not reflected in mainstream institutions, decision-making logics and governance approaches (Krznaric 2020).

Many of our existing institutions have short time horizons relative to the temporal scale of some of the Earth System tipping elements and do not value the interests of future generations (Gardiner, 2006; Krznaric, 2020).

Recent efforts to better protect the interests of future generations include fostering representation of present-day children and youth in policymaking (e.g. lowering the voting age, establishing youth and climate councils) and increasing climate litigation on the grounds of intergenerational equity. Creating dedicated institutions with the central aim to safeguard the interests of future generations may be another promising pathway to increasing intergenerational justice (Slobodian, 2019). Examples include the Welsh Well-being of Future Generations Act, which requires public bodies to consider projects' impacts on future generations and created the position of the Future Generations Commissioner. Further, some countries already recognise the rights of nature with legal – including constitutional – means. For example, Ecuador and Bolivia have adopted constitutional rights of 'Mother Earth', while other jurisdictions have recognised the legal personhood of specific ecosystems like rivers (New Zealand, India). These could offer blueprints for the protection of future non-human life.

Adaptive governance, agility and continuous learning: The Earth system consists of coupled natural and human systems and can be described as a complex-adaptive system. Tipping points are features of complex-adaptive systems. The inherent limits to control and planning in complex (as opposed to mechanistic) systems have consequences for the design of governance institutions. One of these is the need for continuous system monitoring and learning about the system's responses to decisions, policies and governance efforts. Building ongoing learning, responsiveness to observed changes, and flexibility to adjust policies into the design of institutions is called adaptive governance – actors adapt their approach in response to the feedback they receive from the system (Young, 2012; Armitage, Marschke, and Plummer, 2008; Folke et al., 2005). More broadly, recognising that knowledge about the dynamic processes of Earth and social systems is always evolving and never complete, governance has to take place in a close relationship with science and other ways of knowing, with frequent learning loops, monitoring and early warning mechanisms at the science-policy interface.

Systemic risk governance: ESTPs present significant – possibly irresolvable – challenges for conventional risk management approaches in organisational decision making due to the nonlinearity of the change process, the long time horizons, and the potential severity and irreversibility of impacts. Tensions in integrating tipping points into risk management frameworks may arise around commodification or monetisation of nature, mirroring tensions around natural capital accounting (Smessaert, Missemer, and Levrel, 2020). Tipping processes and the threats they present are better characterised as deep uncertainties, existing in a problem context where neither the probability of an event nor its impacts (i.e., harm) can be adequately expressed in terms of economic costs or other quantitative measures. Hence, the suitability of cost-benefit analysis and the standard practice of discounting - translating the financial value of future assets, resources or costs and damages into 'present value' by applying a specific rate smaller than 1 resulting in a reduction or devaluation - is severely limited in this decision context, even raising ethical concerns with regard to intra- and intergenerational justice (Weitzman, 2009; Gollier and Weitzman, 2010; Stoddard et al., 2021; Roemer, 2011).

More generally, this type of risk cannot be managed in the common sense of risk management (e.g. quantitative assessment, mitigation and hedging), but demands novel risk governance approaches (Galaz et al., 2017). Existing discussions about global systemic risk (Homer-Dixon et al., 2015; Centeno et al., 2015; Schweizer, Goble, and Renn, 2022; Juhola et al., 2022), telecoupling (Liu et al., 2015), polycrises (Homer-Dixon et al., 2021), risk-transfer analysis (Graham and Wiener, 1997), and 'integrated catastrophe assessment' (Kemp et al., 2022) offer important starting points. These approaches share a set of concerns that should form the foundation of risk assessment and decision making related to ESTPs. First, they consider a broad spectrum of risks (socio-political, material, technological, environmental) that also include risks stemming from human and governance responses to problems, such as abatement measures, maladaptation or authoritarianism. Correspondingly, they stress the need to assess risk trade-offs and balances. They also encourage risk assessment that captures a broader set of possible outcomes, especially catastrophic risks – e.g. related to high-end climate scenarios (Kemp et al., 2022). Second, systemic risk assessments take into account multiple possible interactions between determinants, drivers and types of risk, rather than assessing single risks in isolation (Simpson et al., 2021). This includes the possibility of compound risk at one scale but also scale-crossing dynamics (risk propagation) (Homer-Dixon et al., 2015; Centeno, Miguel A., Manish Nag, Thayer S. Patterson, Andrew Shaver, and A. Jason Windawi. 2015. "The Emergence of Global Systemic Risk." Annual Review of Sociology 41 (August): 65–85). Third, they consider how these interactions can create cascading dynamics across different systems (e.g. industries, countries, ecosystems), including tipping point cascades. This third dimension highlights the need to consider cascading risks in decision making and the development of governance approaches to cascade dynamics in complex systems.

Systemic risk governance should be informed by an in-depth analysis of feedback mechanisms and cascading effects between systems and subsystems, and it needs to be adaptive toward rapidly shifting societal contexts and demands. Containing systemic risks requires adaptive governance approaches at multiple institutional levels that are able to assess and respond to the underlying complex systems mechanisms. Governance needs time-sensitive monitoring of social-ecological systems and the implementation of early warning systems to manage cascading effects and tipping points.

Engaging with stakeholders, the affected public, and establishing regulatory frameworks and networks of institutions and actors is essential.
(Juhola et al., 2022).

Response diversity: Diversity in governance responses and capacities is particularly important for governing complex systems (Walker et al., 2023). "Response diversity is a system's variety of responses to disruptions of all kinds. (...). It suggests keeping options open for unexpected situations (...)", including through creation of generic capabilities that can be adjusted as new information comes in and that have ideally positive externalities and co-benefits (Frank et al., 2014). Response diversity can be realised spatially, temporally, and between actors and institutions. For example, international trade provides spatial response diversity against disruptions at national or local scale, which can be further strengthened through trading with multiple sources and using various transport routes or modes. Temporal response diversity refers to variation in resource use over time and requires storage infrastructure; examples include storage in granaries and reservoirs, or banks and insurances. It is also important to account for possible cross-scale interactions, as building response diversity at smaller scales can erode response diversity at larger scales if local initiatives copy each other. Cross-scale interactions that erode the overall resilience can also occur between social and ecological systems. This facilitates complementarity and backup responsiveness, i.e., if one response fails, a higher level one can be activated.

Diversity in response capacity comes at high costs because it requires redundancies. The design of such a governance infrastructure needs to balance response diversity and efficiency. While fostering diversity and functional redundancy runs counter to standard policy making logics that prioritise efficiency, it will be key for building impact management governance of tipping points. Response diversity can also lead to fragmentation, conflict, and overlapping mandates; hence, smart a principled coordination is needed (Galaz et al., 2016).

Deep cooperation: By their nature, ESTPs require cooperative solutions of all kinds – international, multisectoral, regional, even intergenerational – in addition to existing cooperative efforts related to climate change. But while more cooperation is needed, it will also become more challenging to develop cooperative solutions because of tipping points. They could easily trigger short-sighted responses such as resource grabbing, elevating nationalism and fronting security concerns with competitive logics that could undermine effective governance or even worsen the problem. The changes created by tipping dynamics could add their own, quickly growing, pressures on governance actors, threatening to overwhelm longer-term governance agendas with increasingly frequent crisis management and new international tensions related to migration and geopolitical changes (Howard and Livermore, 2019). The more effort needed to deal with the immediate, the less that will be available for the longer-term global governance required (Homer-Dixon et al., 2015; Laybourn, Evans, and Dyke, 2023). Despite the significant challenges of devising cooperative and effective global governance solutions, the logic of deep cooperation – across scales, borders and sectors – must supersede other more competitive, nationalistic or profit-seeking ones when dealing with Earth system tipping processes.

3.1.3 Actors, institutions, and scales of action

At this early stage of governance efforts related to ESTPs, there is not yet an established set of governance actors and institutions with explicit mandates or roles.

Given that many ESTPs are a consequence of climate change, it might seem obvious to address this set of challenges in the existing governance institutions for climate change. In line with this rationale, most of the scholarship on climate tipping points so far treats them as a single, global-scale issue that should be added to the agenda of the UNFCCC. However, a more nuanced perspective is needed that accounts for the complex existing climate change governance institutions at multiple scales, (the diversity of ESTPs with different drivers and impacts at multiple scales, and the corresponding need for a multi-scale, polycentric governance approach. The international regime for the governance of climate change is not the only one with a mandate that is relevant for ESTPs; other multilateral institutions could play an important role, including the Convention on Biological Diversity (CBD), the Arctic Council, the Antarctic Treaty, the recent High Seas Treaty, and the UN Environment Programme. More generally, different kinds of multilateral and international institutions can be distinguished:

- General bodies and specialised agencies of the United Nations (UN) system (global scale).
- International organisations based on treaties like the UNFCCC or the CBD.
- Regional bodies that can be treaty-based (e.g. Amazon Cooperation Treaty Organization, ACTO) or serve the purpose of political cooperation (e.g. Arctic Council).

Each kind has different characteristics and corresponding strengths. For example, treaty-based organisations have relatively rigid mandates formulated in an international treaty, while political cooperation platforms have more flexibility in adjusting their scope and agendas.

Here, we focus on the climate change regime before briefly discussing other institutional settings where tipping points could be addressed. This discussion seeks to open a debate about the need for novel governance institutions (and actors) that operate at the scale of a specific tipping element.

3.1.3.1 The multiple scales of tipping point governance

When considering what institutions of governance would be the most appropriate to address the risks posed by ESTPs, three non-mutually exclusive logics can be employed. First, ESTPs are arguably of **global concern** that requires global-scale governance, especially with a view to the possibility of tipping point cascades. While some tipping systems have a more regional character or focal point than others, they can have global-scale – or at least globally distributed – drivers. Additionally, most tipping processes have impacts and impact chains that would reach far beyond the regional scope of the tipping element. Given that Earth system tipping processes are a result of climate change, the international climate change regime centred on the UNFCCC might be the most suitable place to address tipping points, supported by the global-scale scientific knowledge production in the IPCC. Other global institutions could include the CBD and IPBES or UNEP (particularly for biosphere tipping systems).

Second, **governance might correspond to the geographical scale of the tipping system**. All tipping systems have a large geographical extent or distribution, crossing multiple national boundaries and affecting people in specific but often disconnected and widely dispersed regions. For instance, the world's warm water coral reefs can be found in multiple countries around the Pacific, Indian and Atlantic Oceans, while the Amazon rainforest stretches across eight countries. A number of tipping systems are close to the Arctic. Given this sub-continental/regional character (a scale below the global but above the national) governance institutions that operate at the scale of the tipping element might be most suitable to address the challenges specific to each tipping process. In some cases, like the Arctic, regional bodies already exist that could consider including tipping points in their mandate (Aakre et al., 2018) and changing their current character from coordination platforms to governance institutions. For example, a recent Amazon summit has given momentum to the idea of pan-Amazon governance, e.g. to tackle deforestation, potentially via the Amazon Cooperation Treaty Organization (ACTO). In other regions, existing governance fora might be weak and not willing to expand their scope and mandate. In cases where institutions at the scale of the tipping system do not exist (e.g. coral reefs, mountain glaciers, or the AMOC), the creation of new ones with a tipping point-specific mandate could be considered to match this scale and the corresponding problem structure (Galaz et al., 2008; Lebel et al., 2013).

Box 3.1.1: Regional institutions and tipping point governance

The **Arctic Council** operates at a scale that corresponds to a number of Earth system tipping elements, including the Greenland Ice Sheet (GrIS), the Arctic winter sea ice, and permafrost thaw. Based on this geographical scope, the council could be considered as a potential site for addressing tipping systems in the Arctic region.

An intergovernmental political forum among the eight Arctic states, with the involvement of Indigenous peoples, the council's main purpose is to promote cooperation in the Arctic – a mandate that does not yet encompass governance in the sense of collective rule-making. Although it does not develop binding frameworks, it has a strong science-policy interface and scientific capacity, including the Arctic Monitoring and Assessment Program (AMAP), and, in the past, it has been effective in setting policy agenda on novel issues of environmental concern.

The Arctic Council's work is organised in working groups, task forces and projects, with multi-annual priorities set by a rotating chairship. Despite its weaknesses, the existing model of involving Indigenous peoples in the Arctic as permanent representatives is a good foundation for engaging affected communities in governance related to Arctic tipping points. The council's limited membership could benefit effective decision making, but might also create challenges when other countries desire to be involved in decisions regarding Arctic tipping points. Such a desire could arise, for example, when a country believes it will be affected by an Arctic tipping process or by a cascade of Arctic and other tipping systems. Such tensions and questions around membership and participation already arise today in the context of new mineral discoveries and extractive interests, as well as changing security profiles as ice sheets recede and geographic conditions change.

The Arctic Council also illustrates some more general challenges of intergovernmental tipping-point governance. Its current operations (as of October 2023) are suspended following the Russian invasion of Ukraine. International politics, conflicts and other developments that are not directly related to the Arctic or climate change can hobble this and other institutions at any point in time, possibly undermining the chances of effective governance. Given the need for stable and continuous cooperation and decision making over very long time horizons, coupled with the potential need to respond swiftly to new scientific information, it is unclear how effective, uninterrupted governance institutions can be designed for Earth system tipping points.

Third, **governance could follow the Earth system component** relevant for a tipping system – for instance oceans, corals, forests, etc. However, for some of these issue areas, global and regional institutions are weak (e.g. tropical forests) or non-existent (e.g. corals, permafrost). Regarding the cryosphere, existing bodies are primarily of a scientific character (e.g. the Arctic Monitoring and Assessment Programme), pointing back to a responsibility for the climate regime. Further, the impacts of Earth system tipping processes will always be felt at the local (municipal), national, and regional scales, where most adaptation and impact governance will take place.

Given the relevance of multiple scales and their interactions, a **polycentric approach** (Ostrom, 2010; Jordan et al., 2018) that purposefully crosses these and governance sites would be most suitable for addressing ESTPs. "Polycentric systems are characterised by multiple governing authorities at differing scales rather than a monocentric unit" (Ostrom, 2010, 552), with each unit having significant independence and rule-making authority. Polycentricity builds on the concept of multilevel governance, which "takes place through processes and institutions operating at, and between, varieties of geographical and organisational scales involving a range of actors with different forms of authority" (Duit and Galaz, 2008, p. 318).

A polycentric governance network for ESTPs would distribute responsibility across scales, where some issues are addressed with global frameworks (e.g. emission reductions, financial mechanisms, international migration), while others are tackled at the regional scale (e.g. addressing secondary drivers of tipping processes), and some centre on local communities (e.g. adaptation). Regional actors might play important roles for framing, norm setting, mobilising action and building adaptive capacity related to a specific tipping element. They are often best positioned to support knowledge production regarding the tipping system in question, including the detection of early warning signals, by drawing on local and Indigenous knowledge. For example, in 2023, the Inter-American Network of Academies of Sciences launched a new initiative on the Amazon region that could provide the knowledge base for governance efforts at the scale of the Amazon rainforest (e.g. in regional bodies like ACTO or the Organization of Amazon States), and in 2022 Indigenous organisations under COICA from across Amazonian countries collaborated with scientists on a report highlighting that localised dieback is already occurring in some areas (Quintanilla et al., 2022).

Regional governance bodies also provide strong platforms for mutual learning and sharing governance experiences, amplifying the effects of successful interventions. Importantly, they could be responsible for addressing regional drivers of tipping processes – e.g. deforestation in the case of forest biomes. (For a more detailed discussion of multi-scale prevention approaches, see Chapter 3.2.) Bodies at this scale tend to face challenges in attracting signatories, establishing binding agreements, and enforcing and monitoring agreements. At the same time, the interests of the participating countries are more likely to be aligned, the scope for cooperation is smaller and the need for action is likely to be more immediate and salient. National and local actors also have the authority and expertise to deal with the impacts of a tipping process.

Importantly, "global networks need to build a capacity to coordinate actors at multiple levels and from different networks as they attempt to respond to potential 'tipping points' of concern" (Galaz et al., 2016, p. 198). A polycentric approach would require strategic efforts to align and coordinate across the network of governance institutions, managing institutional interplay (Elsässer et al., 2022), and maximising synergistic effects. At the same time, these linkages need to avoid rigidity and introducing their own vulnerabilities to cascading failure. Mutual learning and sharing of experiences among actors at a specific scale and across scales is an important component of effective polycentric governance.

3.1.3.2 The international climate change regime

While this report covers ESTPs beyond the climate system, climate-related tipping points present the majority of the tipping systems addressed. This raises important questions regarding the relevance and ability of the international climate change regime to govern climate tipping points.

The global climate governance landscape is polycentric, with a wide variety of actors from international regimes, transnational institutions, city and municipality-based initiatives, with a major role for national governments, but also non-governmental organisations and (transnational) civil society, the private sector and Indigenous peoples (Jordan et al., 2018). Yet, this landscape lacks institutions to specifically address tipping points. The international climate change regime orchestrates activities in this landscape (Hale and Roger, 2014) – for example, the UNFCCC and its treaties, especially the Paris Agreement, adopted in 2015.

The climate change regime is the most relevant global-scale option for the governance of ESTPs. Addressing such tipping points falls directly within the scope of the UN Convention (Art. 2 "to achieve, […,] stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system") and its related treaties. Climate tipping points present dangers in the sense of the convention that need to be prevented (Lenton, 2011). The relevant objective of the Paris Agreement is to "strengthen the global response to the risks of climate change" (Article 2), including limiting global temperature increase, strengthening adaptation abilities and changing international financial flows to support mitigation and adaptation efforts.

Tipping points have found their way into the climate negotiations only recently with a speech by UN Secretary General Guterres at COP26 in 2021 and a first mention of tipping points in the cover decision of COP27 (UNFCCC, 2022). However, they are not yet a part of the negotiation agenda. The climate regime's rules and processes, especially regarding mitigation and adaptation, would need to be reviewed and adjusted to account for tipping points. Responsible bodies and decision-making procedures exist and could add climate tipping points to their agendas.

Even though climate tipping points squarely fall into the scope of the existing climate change treaties, relevant processes for addressing tipping point risks within the regime remain underdeveloped. The following components of the **Paris Agreement** are particularly relevant for the governance of climate tipping points and offer the potential for reinterpretation or adjustment: the global goals, especially the temperature goal, the timing of emissions peaking (i.e., reconsidering acceptable mitigation pathways), the content of Nationally Determined Contributions, and review and transparency mechanisms, especially the Global Stocktake, are relevant for efforts to prevent tipping points (see Chapter 3.2). The Paris Agreement's stipulations on adaptation, and the still-skeletal loss and damage mechanism are relevant for governing the impacts of tipping processes (see Chapter 3.3). Tipping points present a strong logic for the expansion of international loss and damage provisions, possibly adding more tensions to this ongoing, contentious debate between countries.

The important role of sub-national and non-state actors ('non-party stakeholders') for global climate governance has been formally recognised by the UNFCCC (Hale, 2016), and is the foundation for an increasing number of initiatives that bridge the intergovernmental and non-governmental spheres, e.g. the Global Climate Action Portal and the High-level Champions. These existing initiatives could be important for making and implementing decisions related to climate tipping points. For example, the High-level Champions are supporting the Breakthrough Agenda efforts to accelerate decarbonisation.

Table 3.1.1: Features of the Paris Agreement that need adjustment to account for climate tipping points.

Topic	Paris Agreement stipulations	Adjustments required
Global goals	Art. 2 (1)	Reinterpretation of the global temperature goal to minimise the risk of transgressing a tipping point; strengthening rationale for 1.5°C and recognising that an even lower long-term global temperature goal would be safer.
Emissions peaking	Art. 4 (1)	Establish an ad-hoc working group on acceptable mitigation pathways that takes tipping point risks into account, especially the need to minimise peak temperature and temperature overshoot period.
NDCs	Art. 4 (2) - (19)	Include climate tipping point risks in NDCs; Parties should map and describe their exposure and contribution to tipping point risks (which tipping points, what kinds of contributions and impacts), and how their plans and actions address these risks (e.g. mitigation ambition, measures to address secondary drivers of tipping processes, adaptation measures, support for knowledge development).
Adaptation	Art. 7	Account for tipping points in adaptation frameworks, especially the possibility of trend reversals, non-linear changes and new vulnerabilities to tipping points.
Loss and damage	Art. 8	Interpreting Art. 8 (4) items c and d to include climate tipping points. Anticipatory expansion and funding of the loss and damage framework, taking the risk of climate tipping points into account.
Public engagement	Art. 12	Experiment with and foster novel forms of public engagement and anticipatory learning, including participatory, active, immersive, multi-sensory learning – e.g. using serious games, storytelling and visioning.
Transparency framework	Art. 13	Within their obligations under the Transparency Framework, especially (7) item b, Parties should include information regarding their achievement of goals related to climate tipping points, differentiating prevention and impact governance.
Global Stocktake	Art. 14	Include climate tipping points as a distinct item in the agenda of future GST processes, including material collection and assessment of collective progress towards prevention and impact governance in the technical phase and deliberation in the political phase.

The international climate regime appears to be the most relevant global avenue for addressing tipping points for now, but the effectiveness of such an approach is not clear. Discussions under UNFCCC are heavily politicised, making progress hard to achieve, while the number of agenda items is becoming unmanageable. In this context, introducing a new set of challenges that has implications for many existing governance processes and negotiation topics will doubtless be challenging despite its significance and far-reaching implications.

3.1.3.3 Other existing institutions and actors

Beyond the UNFCCC and IPCC (see Chapter 3.4), a number of other international and transnational fora may be relevant to consider for the governance of ESTPs. The UN Secretary General could establish a governance forum to make recommendations to be taken up by the UN General Assembly. The UN Environment Programme (UNEP) is an issue-specific UN agency and general authority regarding global environmental governance which could serve as a facilitator, agenda-setter and authoritative source of information on tipping points. The World Meteorological Organization (WMO), also a specialised UN agency, could continue to provide scientific assessments and advice regarding ESTPs, building on its most recent effort to coordinate multiple international science bodies for an up-to-date assessment of climate change science (World Meteorological Organization (WMO) et al., 2022). And while not part of the UN system, the International Energy Agency (IEA) could lend its modelling and assessment capacity related to the world's energy system. (Issues of data ownership and access, model selection and transparency will have to be addressed.)

The Convention on Biological Diversity (CBD) should consider the potential for tipping points in various biological and ecological systems, including tropical coral reefs, forest biomes, savannas and drylands, and marine systems. The recent UN High Seas Treaty might address tipping points in marine ecosystems and its relationship to tipping points in ocean circulation patterns.

A set of global and regional institutions that address global forest governance can consider forest-related tipping elements, including ACTO, the UN Forum on Forests, the International Tropical Timber Organization, the Food and Agriculture Organization and the Forest Stewardship Council (a mixed membership organisation). Given the highly fragmented landscape for forest governance, it might be challenging to create a focal point and momentum for addressing tipping points. At the same time, this setting provides opportunities for polycentric, multi-scale governance.

A range of existing international actor coalitions and initiatives might engage with tipping points, including the High Ambition Coalition, the Climate Overshoot Commission, or the Climate Vulnerable Forum. All national governments are policymakers with relevant authority regarding Earth system tipping processes – e.g. fostering energy transitions, managing deforestation, regulating pollution or conducting climate adaptation planning. For example, the UK government's net zero target and associated revision of the national Climate Change Act explicitly reference tipping point risks as part of the regulatory rationale. Other legislatures might also have to take tipping points into account when developing future regulations and policies. Several industries, corporate actors and private-sector alliances, such as the Global Commons Alliance, might also have relevant interests and authority as, for example, research on the financial industry has pointed out (Galaz et al., 2018; Folke et al., 2019). And of course, a diverse set of civil society actors and NGOs will be engaged in the governance of ESTPs.

3.1.4 The politics of tipping-point governance

Several political dynamics will accompany the development of governance institutions related to climate tipping points. While many of these are unpredictable, the following are likely to emerge, especially in the early phase of agenda setting and governance venue identification.

Governance of ESTPs is currently in the agenda-setting phase, where the provision of knowledge needs to be accelerated and diversified, attention needs to be created and existing institutions need to be engaged in conversations about governance venues and priority topics. Science-policy interactions, policy and institutional entrepreneurs, and certain international organisations like UNEP, the WMO and the IEA can play a critical role in this phase, constructing shared knowledge and concern, and building momentum towards discussions and meetings.

Another key actor with the power to galvanise action on new topics through speeches and convening power is the UN Secretary General (Johnstone, 2003). For example, the UNSG could establish a high-level forum, science advisory panel, or similar initiative to foster immediate engagement with ESTPs across the UN system.

Importantly, in this phase different meanings of the concept of ESTPs are created through the interactions between scientific and political actors. Different interpretations and understandings of the problem will lead to different proposals for its solution and corresponding priorities for governance, dividing some actors and aligning others. As with the climate agenda generally, we should expect deliberate resistance and disinformation as well as genuine diversity on interpretations of tipping points rooted in cultural and epistemic differences. Governance mechanisms should seek to anticipate this and enable inclusion of diversity while resisting bad-faith interventions.

To the extent that a deeper understanding of ESTPs unite and mobilise new groups of actors, for example those with a shared regional interest in preventing certain tipping elements (e.g. the Arctic, or actors with livelihoods that depend on a thriving rainforest), **new political coalitions** may emerge that could differ from the well-established groups and their relationships in the regime complex for climate change. In some instances, existing actors might be reinforced in their shared positions, such as the Alliance of Small Island States (AOSIS). When AOSIS was formed more than 30 years ago, the concept of climate tipping points did not exist. Today, especially tipping points that can affect the speed and degree of sea level rise (e.g. the Greenland and West Antarctic ice sheets) have major implications for small islands' climate vulnerability and are likely to strengthen the group's identity and interests. In other cases, tipping points might lead to alliances between state and non-state actors.

The possibility of new actors emerging or existing actors adopting tipping-related positions also applies in various national and regional (e.g. European) contexts of climate policymaking. New alliances may try to shape domestic, regional and international policy to mitigate the impacts of tipping, in particular if they represent the interests of constituencies who will be negatively impacted by certain tipping points or by the immediate impacts of efforts to prevent tipping (Aklin and Mildenberger, 2020). Earth System tipping thus opens the possibility for new interest groups and actor coalitions to form, which could set in motion new political dynamics domestically and internationally.

In this context, the key task for the multitude of potential governance actors for ESTPs, including national and sub-national governments, international organisations, non-state actors, business actors, etc, consists of developing a sufficiently detailed understanding of ESTPs that allows them to assess the risks they present to the communities they represent. This understanding forms the foundation of each actor's political interests, goals and strategies for engaging in governance processes. It is also a pre-condition for identifying partners with shared interests and forming coalitions. Raising interest in and creating political momentum for addressing specific tipping points – or the phenomenon of tipping points in general – will depend on the affected countries' status in the negotiations, and their ability to influence other parties and negotiation groups.

Different countries and political actors will care more about certain tipping points than others depending on the extent to which they expect to be impacted. Countries that expect to experience impacts of ESTPs in the near future (e.g. countries with tropical coral reefs or hosting a part of the Amazon rainforest) will likely be more interested in developing prevention measures, especially by increasing mitigation ambition globally, than countries without obvious or direct expected impacts. National-scale factors, such as changes in political leadership, will play a big role in shaping a country's interests in tipping points, as the cases of Australia (Great Barrier Reef) and Brazil (Amazon rainforest) demonstrate. Mirroring existing patterns of climate politics, major emitters or beneficiaries of greenhouse gases are more likely to resist efforts to increase the speed and scale of mitigation.

While the urgency of ensuring that we do not cross critical thresholds strengthens the case for rapid transformations to just and sustainable futures, actors with a vested interest in the status quo might – and already do – predictably engage with the topic of tipping points using an increasingly well-understood repertoire of delay and obstruction tactics (Lamb et al., 2020) to obscure or avoid engaging with needed structural changes, social challenges and environmental justice.

This includes the strategic creation and distribution of mis- and disinformation, sowing doubts regarding the science of ESTPs and shaping public opinion to prevent the passing of policy response measures. The long time horizons and non-linearity of many tipping elements invite arguments that these are not the most pressing issues of the day, that anticipated impacts are exaggerated, while scientific uncertainties can be exploited to advocate for more knowledge rather than action. At the same time, actors can use climate tipping points to spread fatalistic ideas that also inhibit effective responses. Fatalists would (and already do) argue that preventive action regarding tipping processes is pointless because massive impacts are already inevitable. Since these tactics of delay and disempowerment can be anticipated, it is possible to attempt 'public inoculation' and 'prebunking' against misinformation (Lewandowsky and van der Linden, 2021).

3.1.5 Public communication and risk perceptions

Public risk perceptions shape the politics of climate change (Sjöberg, 2001) and will be important for the policy trajectory of ESTPs. Public risk perceptions can both enable and constrain public policymaking and are a good indicator (Sjöberg, 2001) for the public's willingness to engage in behaviour change. In recent years, international polls have found growing concern about climate change and strong global support for urgent and decisive action (UNDP, 2021, Ipsos-MORI, 2023). A recent Ipsos MORI survey conducted for the Global Commons Alliance finds that three quarters of people in G20 nations believe that human activity has pushed the Earth close to tipping points (Gaffney and Tcholak-Antitch, 2021). At the same time, significant misperceptions and public knowledge gaps remain (Galaz et al., 2023). However, very limited research has been conducted on public understanding and risk perceptions specifically related to climate (or Earth system) tipping points.

Contrary to researchers' expectations, work so far suggests that the concept of climate tipping points, especially the feature of non-linear change, does not generate increased concern when compared to climate change more generally (Formanski et al., 2022). Higher risk perceptions in response to information about tipping points tends to be limited to specific cultural groups with egalitarian values (Bellamy, 2023) and to people who are highly engaged in climate change policymaking (Van Beek et al., 2022). However, these preliminary findings might be based on a broad lack of understanding of the issue and its implications rather than public indifference (Nadeau et al., ESD preprint). Given the learning challenges related to tipping points, non-linear change, and complex systems dynamics more generally, media coverage and public communication related to tipping points might face serious challenges.

While risk perceptions can drive action on tipping points, overwhelming fear of them may have the opposite effect and paralyse action (O'Neill and Nicholson-Cole, 2009). When communicating about tipping points, a careful balance needs to be struck between accurately characterising the risks and potential impacts, but also conveying potential solutions and agency. Further, the same message will be received very differently by different audiences, depending on, for example, their age, profession and ideology. Overwhelm and/or avoidance may lead to inaction or, even worse, to polarisation and the exacerbation of social and political divisions, which could hinder any progress in tackling those risks. In addition, an overemphasis on the potential impacts and the wrongful idea that 'it's too late' may warrant the consideration of deployment of dangerous unproven solutions, which could have harmful and unforeseen consequences in the Earth system. Addressing these fears and overcoming their potential paralysing effects requires effective communication, education and engagement strategies.

Emphasising the wide-ranging and tangible co-benefits of action to avoid tipping points, providing tangible solutions, and building a sense of empowerment, and shared responsibility can help alleviate fear and inspire meaningful action.

3.1.6 Final remarks

ESTPs present a distinct set of challenges that should be addressed with policy and governance measures. The time is now for state and non-state governance actors across multiple scales to engage with this topic and elevate it on the international political agenda. Actors need to understand how tipping points affect their interests to develop agency, form coalitions, and actively engage in the agenda-setting process. A range of existing principles of global governance and international law should shape discussions and decisions, including the need for anticipatory approaches, precaution in the face of uncertainty, and the need for intergenerational, intra-generational and international justice.

Given the nature and scope of ESTPs, governance efforts must be coordinated across multiple spatial and temporal scales, managing cross-scale dynamics and potential tipping cascades in coupled human-Earth systems. It is useful to distinguish three phases of tipping processes (pre-tipping, re-organisation and stabilisation), and to shift the focus of governance efforts corresponding to these phases. There is significant scope for incorporating governance of ESTPs into existing institutions, especially the UNFCCC, but novel actors, approaches and institutions will likely be needed to cover the full range of emerging challenges, especially at the scale of tipping systems.

3.2 Prevention of Earth system tipping processes

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Summary

Preventing the transgression of Earth system tipping points (ESTPs) (hereafter 'prevention of tipping points') should become the central objective of this domain of global governance. This chapter addresses the question of how governance actors, especially governments, could achieve this objective.

ESTPs have multiple interacting drivers that operate at different scales. Effective prevention strategies need to address all drivers with coordinated cross-scale approaches (polycentric prevention). Many institutions, from the Convention on Biological Diversity (CBD) to the Arctic Council, can assume prevention responsibilities and will need to be involved in governance. Global temperature increase is the most common driver of tipping processes, making climate mitigation the most effective prevention strategy across the diverse set of ESTPs identified to date. Hence, we see important opportunities for UNFCCC to provide a context for preventive governance measures. Beyond strengthening mitigation efforts for long-lived GHG, we discuss the need to manage short-lived climate pollutants (SLCPs), and advance carbon dioxide removal (CDR). We also assess the potential contribution of novel kinds of climate intervention (geo-engineering), concluding that, for the time being, these are not available options to support prevention.

Non-climate drivers are diverse and specific to each (type of) tipping element – for example, deforestation as a driver of forest dieback, or pollution contributing to coral reef die-off. Given this diversity, each tipping system requires a tailored prevention approach, likely involving different constellations of regional and national actors and institutions, cooperating and coordinating their efforts across scales.

Many governments and other actors have not yet sufficiently engaged with the challenges presented by tipping points and still need to define national and organisational interests in this domain. Prevention efforts related to ESTPs are likely to be subject to political dynamics and contestations that mirror current global climate change politics, especially diverging interests regarding the speed, scale and responsibilities for GHG emission reductions.

Key messages

- Prevention of Earth system tipping processes should become the core goal and logic of the future ESTP governance framework. A short window for preventive action is open now and will close at different points in time for each Earth system tipping element – for some, as early as the 2030s**.**
- Preventing the transgression of ESTPs requires:
  - rapidly strengthening current mitigation efforts to minimise temperature overshoot beyond the global goals and the length of overshoot periods, by tackling both CO_2 emissions and emissions of SLCPs;
  - increasing sustainable capacities for CO_2 removal as an addition to mitigation efforts, while seeking to minimise potential side-effects on other drivers of tipping processes;
  - addressing non-climate drivers at regional and national scales, such as deforestation.
- Speculative solar geoengineering approaches to prevention face deep ethical, technical and political uncertainties, and should not be considered technically available to use safely and swiftly within the coming decades. Such approaches could at most supplement, not replace, mitigation efforts.

Recommendations

- UNFCCC member states should engage in the next Periodic Review process to assess whether the current long-term global temperature goal is adequate in light of current evidence of climate tipping points.
- Parties to the Paris Agreement should include an assessment of collective progress towards preventing climate tipping points in future Global Stocktake processes.
- Governments should immediately increase and accelerate near- and medium-term climate mitigation efforts, for example by pursuing a rapid phase-out of all fossil fuels globally, bringing forward their target year for reaching net-zero, increasing their mitigation ambition in NDC revisions, supporting the development of just and sustainable forms and levels of carbon removal, accelerating corresponding national policy measures, and through democratically validated efforts at social transformation.
- Governments should ban commercial deployment of solar geoengineering, declare a moratorium on any other deployment, and develop a multilateral regime to regulate research and experimentation.

3.2.1 Prevention as a governance goal

Given the significant risks posed by ESTPs (severe, even catastrophic, consequences for human wellbeing and ecological stability) the irreversibility of these impacts, their cascading potential, and with a view to precaution, **prevention** of all tipping processes should become the **primary objective of governance in this domain**. Given the severe threats that crossing ESTPs pose to the achievement of the SDGs (see Section 2), effective prevention is essential to support the delivery of the SDGs at a global level.

For all ESTPs, a short window for preventive action is open now and will close at different points in time for each element. For some ESTPs that are assessed to become likely beyond 1.5°C this could be as early as the 2030s, or possibly even this decade (IPCC 2018, 2021; Armstrong-McKay et al., 2022; Ditlevsen and Ditlevsen, 2023).

BOX 3.2.1: The rationale for prevention

We ground the proposal to make prevention the central objective of tipping point governance in (1) the nature of tipping point impacts (severity and permanence), (2) their cascading potential, (3) the precautionary principle, and (4) the specific intertemporal nature of decision making.

1. **Impacts:** ESTPs present a variety of severe risks. They imply that the current climatic or biospheric conditions in large parts of the world will effectively be permanently lost, threatening the lives of people, the survival of species and ecosystems, the livelihoods and cultural identities of communities, the stability of local and national economies, and even the existence and sovereignty of some states (see Section 2).
2. **Cascades:** Many ESTPs have some potential to contribute to tipping-point cascades, i.e., they increase the likelihood of additional tipping processes being triggered (see Chapter 1.5). That implies the potential to create additional, more distributed harms beyond the scale of the tipping system and wider Earth system destabilisation (see Chapter 2.4).
3. **Precaution:** Some of the harmful impacts of crossing ESTPs can be predicted with confidence (such as sea level rise from ice-sheet disintegration), but many others (such as the impacts of ocean convection collapse) warrant further research. Estimates of the probabilities of triggering tipping points on any given timescale are uncertain and include an element of irreducible uncertainty. Conventional methods of policymaking and risk management that rely on quantified estimates of impacts and probabilities are therefore inappropriate (Stirling, 2007) in the context of ESTPs. Rather, we require tools for responding in the face of deep uncertainty. These include the widely adopted precautionary principle (Jordan and O'Riordan, 1999), systemic risk governance, and anticipatory governance (Guston, 2013).
4. **Intertemporality and committed change:** Importantly, due to their specific causal dynamics (internal self-amplifying feedback mechanisms), for most tipping systems, the change process becomes effectively unstoppable once a tipping point has been reached – i.e. a causal process set in motion in the coming years and decades, such as ice-sheet melting, would continue to unfold over decades, centuries, or millennia even if global temperatures are successfully reduced back to current levels, or if other causal drivers are returned to pre-tipping conditions (see Chapter 1.2 for delayed activation). It is useful to distinguish realised and committed change related to a tipping point at any particular moment in time. At the time the tipping point is crossed and amplifying feedback loops are set in motion, the system will inevitably move to a new state – it is committed to change, although none of those impending changes might be observable yet. The actual change might take a long time – decades, centuries, or even millennia –to become noticeable and disruptive. For example, it is possible that the Greenland tipping point will be crossed later this century, committing the entire ice sheet to disintegration. The melting process, however, could take several thousand years and most impacts would occur beyond the year 2100 (though would still amplify sea level rise to some extent before this). Policymakers have to consider their responsibility for future impacts that only they are able to prevent. Such long-term and intertemporal decision making faces significant practical challenges given dominant decision-making logics and policy practices, such as cost-benefit-analysis, cost-efficiency maximisation, and discounting (leading to the 'tragedy of the time horizon') (Morgan, 2021; Granoff, 2023).

Given that most ESTPs share global warming as a key driver, prevention measures that limit global temperature increase always reduce the likelihood of future tipping point transgressions and remain needed and effective even if one or several tipping points have been passed. Emission reductions will always be the primary tool for reducing the risk of passing (further) tipping points.

Prevention as a central goal does not imply that other objectives, especially fostering resilience in Earth system tipping elements and human societies, and impact governance (see Chapter 3.3) should be deprioritised. No matter how quickly we progress with mitigation, a significant risk of tipping already exists and will increase substantially within the Paris Agreement's temperature range. If prevention efforts are insufficient, impacts may accumulate too rapidly for adaptation and resilience building to cope (see Chapter 3.3). Governance actors will have to consider how to best balance their attention and efforts across these different action domains, but should seek synergies between actions that build social resilience and accelerate mitigation through sustainability transformations.

Prevention efforts can have a variety of outcomes in addition to success (permanent aversion) and failure (tipping dynamics unfold). Prevention can delay the timing of a tipping process – i.e. moving the time when the critical threshold is reached further into the future. This could be beneficial, for example for anticipatory adaptation planning, ensuring that societies are better prepared for the expected impacts of the tipping process (see Chapter 3.3). It can also slow the rate at which the impacts of crossing a tipping point unfold (for example, the rate of ice-sheet melt), somewhat easing the corresponding adaptation challenges. Another form of partial success concerns tipping systems with more than two stable states, and corresponding multiple tipping points. The GrIS might be an example for a multi-stable tipping element (Höning et al., 2023), although disagreements remain about this. 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 the case of an ice sheet, prevention efforts could maintain the ice sheet in the partially melted state, avoiding full disintegration.

3.2.2 Multiple drivers of tipping processes

Most Earth system tipping processes have multiple drivers. Prevention of ESTPs requires tackling all of them. Given this multi-causality, the term prevention is related to, but not synonymous with, mitigation. The familiar concept of climate mitigation in the narrow sense of reducing GHG emissions can be applied to ESTPs; emission reductions serve to limit atmospheric GHG concentrations and correspondingly limit future increases in global average temperature, which is key for reducing the general risks of climate change. Since global temperature increase is a causal variable for most Earth system tipping processes of interest here, **mitigation in the sense of reducing emissions of GHG will be the most important approach to preventing the crossing of ESTPs**. This includes the management of SLCPs.

Most ESTPs have multiple interacting causes (see Table 3.2.1), and effective prevention strategies will also have to attend to causes other than warming. It is important to distinguish between a primary cause, which in many cases is GHG-induced climate change (through atmospheric or ocean warming pathways and precipitation changes, which we categorise as 'direct climate' drivers), and secondary causes. Some secondary causes, such as ice sheet meltwater effects on ocean currents, land 'greening' due to warming and CO_2 fertilisation, or ocean acidification, are second-order effects of climate change or other effects of GHG emissions (i.e. 'Climate-Associated' drivers). Others are independent of climate change – e.g. pollution affecting coral reefs or deforestation of the Amazon rainforest (i.e. 'non-climate' drivers). These secondary causal drivers can bring forward a system's tipping point, hence tackling them can help prevent tipping. The importance and number of additional causes differs across tipping elements.

Table 3.2.1: Multiple drivers of ESTPs

Primary and secondary drivers of the ESTPs identified in this report. DC: Direct climate driver (direct impact of emissions on meteorological variables via radiative forcing); CA: Climate-associated driver (including second-order and associated effects of climate change); NC: Non-climate driver. Drivers can enhance (↗) or counter (↘) tipping.

Tipping point	Primary drivers	Secondary drivers
Cryosphere		
Ice sheet collapse (Greenland, West/East Antarctica)	DC: atmospheric warming (↗) DC: ocean warming and circulation changes (↗ GrIS, WAIS, EA marine / ↘ GrIS)	DC: precipitation increase (↘) DC: black carbon deposition (↗) CA: sea ice decline (↗) CA: atmospheric circulation (?)
Sea ice loss (N.B. tipping unlikely in this report, but affects other key ESTPs)	DC: atmospheric warming (↗)	DC: atmospheric circulation shifts (↗/↘) DC: ocean warming (↗) DC: ocean circulation shifts (↗/↘) DC: black carbon deposition (↗) DC: storminess increase (↗) CA: ocean stratification increase (↘)
Glacier retreat (regional)	DC: atmospheric warming (↗)	DC: deposition of dust, black carbon etc. (albedo) (↗) DC: reduced snow (input & albedo) (↗) DC: local thermokarst (↗)
Permafrost thaw (regional; and subsea)	DC: atmospheric warming (↗) DC: ocean warming (subsea, ↗)	CA: vegetation change (↗/↘) CA: wildfire intensity increase (↗) CA: precipitation change (rain extremes, snow cover albedo (↗) CA: sea ice loss (subsea, ↗) CA: water pressure reduction (subsea, ↗)
Biosphere		
Tropical forest dieback (regional: Amazon, maybe Congo)	DC: atmospheric warming (↗) NC: deforestation/degradation (↗) DC: drying (↗) CA: increasing fire frequency/intensity (↗)	DC: heatwaves (↗) CA: ENSO intensification (e.g. Amazon, SE Asia (↗) CA: AMOC/SPG weakening/collapse (e.g. Amazon, (↗) CA: terrestrial greening (↘ declining)
Boreal forest southern dieback/ northern expansion	DC: drying (↗) CA: fire frequency/intensity increase (↗) DC: atmospheric warming (↗) CA: permafrost thaw (↗) CA: insect outbreaks (↗)	NC: deforestation & degradation (↗) DC: heatwaves (↗) CA: terrestrial greening (↘) CA: vegetation albedo (↗) CA: sea ice albedo decline (↗) DC: precipitation changes (?)
Temperate forest dieback N.B. (uncertain in this report)	DC: atmospheric warming (↗) DC: droughts (↗) DC: heatwaves (↗)	CA: insect outbreaks (↗) CA: windthrow (↗) NC: deforestation & degradation (↗) CA: fire frequency increase (↗) NC: fragmentation (↗)

Tipping point	Primary drivers	Secondary drivers
Savanna degradation	NC: fire suppression (↗) NC: overgrazing (↗)	DC: increased precipitation intensity (↗) CA: terrestrial greening (↗) NC: afforestation (↗) CA: regional circulation changes (e.g. Sahel) (↗)
Dryland degradation	DC: drying (↗) DC: atmospheric warming (↗) NC: land use intensification (↗)	DC: extreme events (heatwaves, floods) (↗) DC: increased rainfall variability (↗) CA: terrestrial greening (↘) CA: insect outbreaks (↗) CA: invasive species (↗)
Lake eutrophication/browning	NC: nutrient pollution (↗) CA: terrestrial greening (↗) NC: afforestation (↗)	DC: atmospheric warming (↗) DC: precipitation changes (↗)
Coral reef die-off	DC: ocean warming (↗) DC: marine heatwaves (↗) CA: disease spread (↗)	CA: ocean acidification (↗) NC: water pollution (nutrient / sediment) (↗) NC: disruption (ships, over-harvesting) (↗) CA: disease spread (↗) CA: invasive species (↗) DC: storm intensity (↗) CA: sea level rise (↗)
Mangrove and seagrass meadow die-off	DC: climate extremes increase (↗) NC: habitat loss/degradation (↗) CA: sea level rise (esp. mangroves (↗) NC: nutrient pollution (↗) NC: shoreline change (↗)	DC: ocean warming (seagrass, ↗) CA: disease spread (seagrass, ↗) NC: invasive species (seagrass, ↗)
Marine regime shifts (some fisheries, kelp, lipid pump, hypoxia)	NC: over-exploitation (↗) DC: ocean warming (↗) NC: water pollution (nutrients / sediment) (↗)	NC: habitat loss (↗) DC: marine heatwaves (↗)
Ocean/atmosphere circulation		
Ocean overturning collapse (AMOC, SPG, Southern Ocean)	DC: ocean warming (↗) DC: precipitation increase (↗) CA: ice sheet meltwater increase (SMOC ↗, in future for AMOC/SPG ↗) CA: river discharge increase (AMOC/SPG ↗)	CA: sea ice extent & thickness decrease (↗) DC: regional aerosol forcing increase (↘) CA: regional ocean circulation changes (?) CA: wind trends (SO, ?) CA: sea ice formation (SO, ?)
Monsoon collapse / strengthening (West African, maybe Indian summer and South American)	DC: increased water vapour in atmosphere (ISM ↘, WAM/SAM ↗) NC: increased summer insolation (↘) DC/NC: increased aerosols, dust (↗, ?)	NC: land-cover change, e.g. deforestation (↗) CA: desertification (↗) CA: regional SST variations (?) CA/NC: regional soil moisture/veg variation(?) CA: ENSO / Indian Ocean Dipole change (?) CA: AMOC slowdown (SAM, WAM ↗) CA: low cloud reduction (ISM ↘) CA: ocean warming (ISM ↗)

Given this multi-causality of ESTPs, prevention requires tackling all of the drivers. The familiar concept of climate **mitigation** in the sense of reducing GHG emissions applies to ESTPs. Emission reductions serve to limit atmospheric GHG concentrations and correspondingly limit future increases in global average temperature, which is key for reducing the general risks of climate change. Since global temperature increase is a causal variable for most Earth system tipping processes of interest here, **mitigation in the sense of reducing emissions of GHG will be the most important approach to preventing the crossing of ESTPs**. This includes the management of SLCPs.

At the same time, conceiving of prevention only in terms of climate mitigation is too narrow. Prevention of most tipping points will involve a combination of mitigation and measures to address other drivers. Different tipping processes have distinct causal profiles requiring a tailored approach to prevention. Some tipping processes share characteristics that might allow developing prevention strategies for groups of tipping points (e.g. for major ice sheets or forest biomes).

However, even within a cluster of similar tipping systems, significant differences might exist that affect the design of effective prevention approaches (e.g. different threshold temperatures for different ice sheets or different secondary drivers for forest dieback).

Prevention strategies that consider multiple causes might be more challenging because different causal variables can operate at different scales, both spatially and temporally. Correspondingly, effective governance approaches will have to be multi-scale and capable of taking cross-scale dynamics into account (see Chapter 3.1). For example, preventing Amazon dieback requires not only limiting temperature and precipitation changes, but also regional and national land management and other policies. Such a multi-causal approach to prevention could be advanced within the current framework of global sustainability governance with adjustments of existing institutions and strategic efforts to link and coordinate efforts across different scales.

BOX 3.2.2: Multiple drivers of Amazon rainforest dieback

The Amazon rainforest plays an important role as a climate regulator and biodiversity hotspot, but is at risk of dieback. If tipped, large parts of the Amazon could change relatively quickly (over multiple decades) into either a degraded forest or dry savannah-like state, leading to impacts that would be catastrophic for natural and human systems. These impacts include increases in regional and global temperature, decrease in precipitation across the Amazon and southern South America, droughts, fires and biodiversity loss, to name a few (see Chapter 1.3 & 2.2.3.1). Recent scientific evidence based on remotely sensed vegetation data suggests that more than three-quarters of the Amazon rainforest has been losing resilience since the early 2000s, which is consistent with parts of the forest nearing a tipping point (Boulton, Lenton, and Boers, 2022). Resilience is being lost faster in regions with less rainfall (which are more at risk of dieback) and in parts of the rainforest that are closer to human activity.

Global atmospheric temperature increase leading to drying is a key driver of potential tipping in the Amazon (see Chapter 1.3.2.1). Deforestation and forest fragmentation are also important drivers that contribute to and accelerate the shift from rainforest to degraded forest or savanna, raising the probability of crossing a tipping point during the 21st Century. Given these multiple drivers operating at global (temperature increase), regional (forest fragmentation), national and even lower (deforestation) scales, the Amazon tipping system is amenable to prevention efforts at multiple scales. Global mitigation efforts to limit atmospheric GHG concentrations present one approach, but other governance efforts need to address regional-scale drivers beyond the climate sphere. Slowing deforestation and forest fragmentation requires strong governance efforts outside the international climate change regime – e.g. collaboration among, and national policies in, Amazon states, changes in global investor behaviour and shifts in global consumption patterns. Strategic prevention efforts need to consider, and ideally coordinate, dynamics across these multiple scales.

Deforestation is an insightful example. Trends in the Amazon over the last decade have been a major concern. The annually deforested area increased by about 75 per cent between 2016 and 2022, but decreased during the first seven months of 2023 by more than 40 per cent compared to the same period in the previous year (Reuters, 2023). Deforestation in the Amazon has many interacting drivers linked to the global economy, but it is influenced primarily by national-scale policies, especially in Brazil. Between 2005 and 2016, Brazil experienced a notable reduction in deforestation rates (approximately 70 per cent (PRODES), demonstrating the effectiveness of the government's efforts to combat it during that period. A combination of factors contributed to this, including increased law enforcement and the implementation of sustainable land use policies and programmes in the Amazon region.

In particular, Brazil's Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm) played a crucial role in driving down deforestation rates and promoting sustainable practices. Its application was effectively suspended in recent years, leading to an increase in deforestation, but reinstated in 2023 by the incoming Brazilian presidency. In addition, the Amazon Fund, established in 2008, is a financial mechanism to support local communities, NGOs and governmental initiatives in their efforts to reduce deforestation, increase recognition of land rights for Indigenous peoples, and promote sustainable development in the Amazon region. Actions taken during the previous Brazilian government resulted in significant changes to the Amazon Fund, leading to its temporary suspension, which may have contributed to the increase in deforestation. New pledges have been made in 2023 with the incoming presidency of Brazil.

The successful deforestation programmes in Brazil, as well as the dramatic impacts accompanying their suppression over recent years, demonstrate the importance of national-level politics for tipping point prevention in addition to, and largely independent of, global-scale climate governance institutions. Effective approaches to prevent a tipping point of the Amazon rainforest have to address deforestation locally and nationally in the Amazon states, but also global temperature change in the UNFCCC to protect and maintain this critical biome.

For some, especially biosphere-related, tipping points, one could conceive of tipping point prevention more broadly as efforts to build social-ecological resilience of a tipping system in its current stable state. Beyond countering the destabilisation of tipping systems by reducing tipping drivers, resilience-building measures can increase the capacity of the system to withstand disturbances. Fostering resilience can be achieved with a variety of strategies, including restoring diversity and redundancy in a system (e.g. species diversity in forests), reducing stressors and fostering sustainable land use. Efforts to protect and at least partly restore biosphere tipping systems such as the Amazon rainforest or coral reefs can both reduce pressures on them and increase their resilience to tipping event drivers like climate change. For example, restoring degraded or lost rainforest and protecting remaining rainforest (through, for example, improved land rights for Indigenous peoples, promoting agroforestry, and improved governance) can reduce deforestation and lead to substantial recovery of a degraded forest within a couple of decades (Poorter et al., 2021; (Science panel for the Amazon, 2021). This can maintain moisture-recycling feedbacks (see 1.3.2.1), thereby helping to maintain rainfall in at-risk forests downwind, as well as improving local resilience to climate change-induced droughts.

3.2.3 Prevention approaches and institutional options

The recognition of multiple drivers of tipping processes is important for thinking about prevention approaches. But given the important (direct or indirect) role of increasing atmospheric temperatures for almost all Earth system tipping processes, the central focus of tipping point prevention efforts has to be mitigation – the reduction of both long-lived and short-lived GHG emissions to the atmosphere. These need to be coordinated with parallel efforts to address various other drivers.

Deep and early emission reductions based on principles of international law (Rajamani et al., 2021) are a core part of any effective prevention strategy for almost all tipping points (see Section 4 for approaches to accelerating decarbonisation). It is the only reliable way to limit global temperature increase, which can prevent the crossing of most tipping points altogether. Existing global governance efforts supporting mitigation should be strengthened immediately and maximised in the future (see Chapter 3.1). Urgent efforts to support social transformations, reducing emissions more deeply and rapidly than can be achieved through conventional policies, market mechanisms and technological substitution, are justified by the substantial co-benefits for health, livelihoods and equity that such transformations offer (see also Section 4 on positive social tipping points). To best support tipping point prevention, mitigation efforts should focus on long-lived GHG emission-reduction efforts, supported by measures to cut SLCPs and to develop and scale up GHG removal as a supplement to emissions reduction.

Other drivers of Earth system tipping processes (see Table 3.2.1) are tipping point specific and may work at different spatial and temporal scales to global temperature change. These other causes are frequently more localised (e.g. the role of deforestation in accelerating the tipping of the Amazon, or water pollution in influencing the die-off of coral reefs), and can be associated with a specific set of stakeholders. Therefore, more national, regional or local prevention strategies that can take the specific characteristics of the tipping system into account will be needed. Many governance actors, especially local jurisdictions, will need guidance and support to identify and effectively prioritise prevention measures.

The following sections explore existing governance mechanisms for the mitigation of long-lived GHGs (3.2.3.1) and SLCPs (3.2.3.2), the emerging conversation regarding carbon removal (3.2.3.3) and solar geoengineering (3.2.3.4), as well as existing institutions that can address non-climate causes of specific tipping elements (3.2.3.5). We discuss how existing governance efforts could be strengthened or complemented with new approaches to consider the risk of crossing climate tipping points.

3.2.3.1 Mitigation

The Paris Agreement adopted in 2015 provides the foundation for current global climate mitigation efforts. Three components of the agreement are central for mitigation efforts and should be re-evaluated in light of the growing knowledge of tipping points: global goals related to global temperature and corresponding discussions about suitable mitigation pathways, Nationally Determined Commitments (NDCs), and the system of transparency and review mechanisms that are supposed to ensure accountability and drive ambition (see 3.1.3.2 for more detail).

The Paris Agreement established a two-pronged global long-term temperature goal – limiting warming to well below 2°C, and aiming for 1.5°C, above pre-industrial levels (Art. 2 (1) PA), combined with an objective of global peaking of GHG emissions (as soon as possible), and balancing emissions and removals of GHG (in the second half of this century) (Art. 4 (1) PA). These objectives need to be read in the context of the overarching aim of the Agreement to "significantly reduce the risks and impacts of climate change" (Art. 2), which requires the consideration of the most recent climate science. The newest scientific evidence regarding ESTPs creates an imperative to revisit the meaning of the global long-term temperature goal, its adequacy and its implications for the types of emission pathways that can achieve it (Pouille et al., 2023).

Adopting the prevention of climate tipping processes as an explicit objective of global climate governance has important **implications for the selection of global and national emission pathways** towards the temperature goals established in the Paris Agreement. Only a subset of the emission scenarios included in IPCC AR6 are suitable if decision makers take into account the need to prevent the passing of tipping points.

A recent OECD working paper (Pouille et al., 2023) identified a set of criteria for the selection of emission pathways that are consistent with the temperature and mitigation objectives of the Paris Agreement (see above), and specifically considering the risk of crossing ESTPs. These criteria include, among others, the likelihood of keeping global warming below 1.5°C by 2100, avoiding or limiting temperature overshoot to 1.6°C, and early peaking of global emissions (2025/2030). Applying these criteria at two levels of stringency to the emission scenario database for IPCC AR6, the analysis demonstrated that only a subset of all 'likely below 2°C' emissions scenarios used by the IPCC can be considered in line with the long-term goals of the Paris Agreement, especially when also considering the objective of minimising tipping risks.

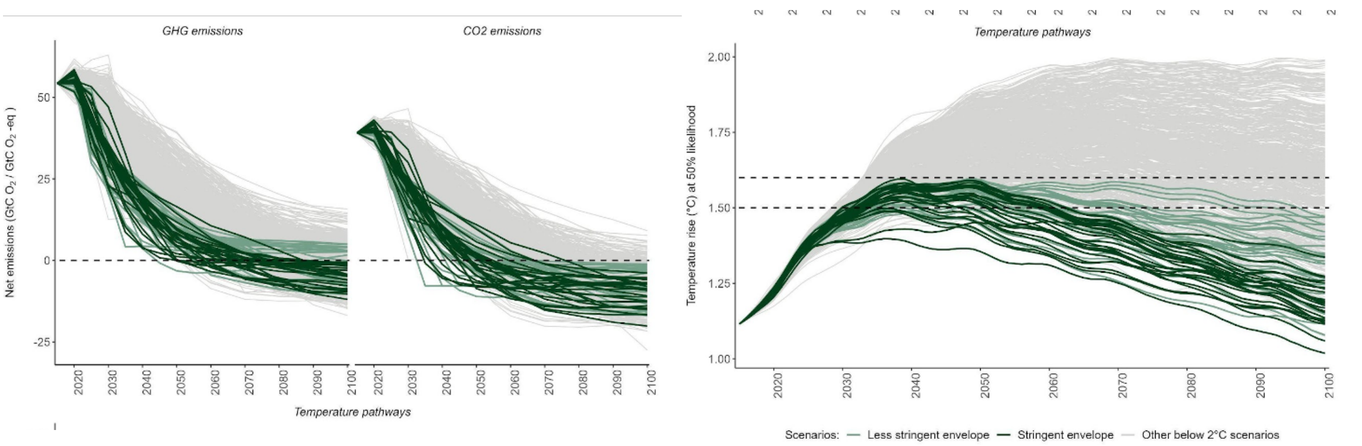

Fig. 3.2.1: Mitigation pathways minimising the risk of transgressing ESTPs. Modelled mitigation pathways to 2100 compatible with achieving the temperature goal of the Paris Agreement are depicted in green. Pathways in dark green satisfy the more stringent interpretation of the language in the Paris Agreement ([1] 50% chance of holding warming below 1.5°C by 2100, [2] 50% chance of keeping global warming below 1.6°C throughout the century, [3] 90% chance to keep warming below 2C throughout the century, [4] global GHG emissions peak at or before 2025, [5] global net-zero GHG emissions before 2100), while pathways in light green satisfy a less-stringent interpretation of the Agreement (detailed in Pouille et al., 2023). The pathways in grey correspond to all other scenarios that remain below 2°C with a likely (66%) chance or more throughout the century. Graph from Pouille et al., 2023, using data from the IPCC AR6 scenarios database (Byers et al., 2022).

More specifically, emission pathways that are consistent with the objective to prevent climate tipping points have three important common features. First, they minimise 'temperature overshoot'. While accepting that warming of more than 1.5°C warming above pre-industrial levels can likely no longer be avoided, emission pathways that **minimise temperature overshoot** beyond this level have a higher chance of avoiding the crossing of tipping points (Palter et al., 2018; Drouet et al., 2021; Wunderling et al., 2022). In other words, considering only long-term (end of century in most analyses) temperatures is not sufficient; global peak temperature is an equally important measure for achieving global objectives, Second, emission pathways that are more likely to avoid tipping points **keep the duration of the overshoot period as short as possible** (Wunderling et al., 2023). These two features lead to a third characteristic of emission pathways that effectively prevent tipping points: **rapid, early emission reductions (this decade)** coupled with rapid scaling of carbon removal capacities.

The UNFCCC Periodic Review and the Global Stocktake provide opportunities to discuss and adjust the shared understanding of the long-term global temperature goal within the current institutional framework of the Paris Agreement. These processes should be used to consider the risk of ESTPs and the need to prevent their transgression. Further, in 2021, the UNFCCC established a Mitigation Work Programme with the objective to scale up mitigation ambition and implementation. This negotiation stream offers opportunities to discuss the question of 'tipping safe' emission and mitigation pathways, for example as a topic of a future global dialogue. Specific criteria for acceptable emission pathways that comply with the temperature and mitigation objectives of the Paris Agreement should also inform short- and medium-term national policymaking – e.g. mitigation strategies to achieve net-zero goals.

The Paris Agreement's pledge and review system requires all participating countries to iteratively submit **Nationally Determined Contributions** (NDCs), which include national pledges of future emissions reductions, sink management measures, and the development of carbon-removal capacity. Future NDC revisions should include specific considerations of ESTPs, and to what extent national mitigation plans, policies and decarbonisation strategies contribute to their prevention. This should include an effort to identify the country's historic and current contributions to creating tipping point risks. In addition to affecting most ESTPs with domestic GHG emissions, multiple national processes can contribute to secondary drivers of tipping processes – e.g. deforestation, pollution or other extractive activities, and globally sourced consumption via international trade. Based on an understanding of its responsibility and capacity to engage in tipping point prevention, countries could describe how national measures and cooperative initiatives with other countries and non-state actors contribute to the prevention of specific tipping points. For example, Norway, Canada, the US and Russia could detail efforts to reduce pressures on boreal forests to prevent dieback at their Southern boundary, including logging policies and other extractive activities, fire and pest management (see 3.2.2).

Countries are also required to develop longer-term (**mid-century**) **strategies** for national decarbonisation. Many countries have adopted 'net-zero' commitments when developing their mid-century strategies, setting specific dates for reaching the point where remaining emissions are balanced by removal. These mid-century strategies have important implications for mitigation pathways and the governance of tipping point risks. Future revisions of these strategies should include an analysis of ESTPs, and to what extent long-term national decarbonisation strategies contribute to their prevention. For example, many net-zero strategies today imply high reliance on carbon-removal methods, which are needed but could impose additional pressure on other drivers of Earth system tipping (e.g. from afforestation in unsuitable locations that add pressure to biosphere tipping systems like grasslands or lakes). Further, countries should consider shortening net-zero timelines to accelerate decarbonisation and reduce tipping point risks.

The architecture of the Paris Agreement encourages increasingly ambitious NDCs and national action over time through transparency and review mechanisms like the **Global Stocktake**. The reporting requirements of the transparency mechanism provides another opportunity for countries to describe national mitigation measures and their impacts, not just with a view to the global temperature goals, but to the prevention of tipping points. The Global Stocktake serves to review collective progress towards the goals of the Paris Agreement – i.e. illuminating whether the international community is on track towards achieving the temperature goals, allowing countries to adjust their levels of ambition if needed. **Starting in 2028, the Global Stocktake could explicitly address to what extent national and collective prevention efforts have limited the risk of passing ESTPs.** This would require collecting tipping point-specific materials (e.g. this report, a potential IPCC special report on tipping points, a report by IANAS on the state of the Amazon rainforest, reports by AMAP on the state of Arctic tipping points) in the technical phase and providing a technical assessment of collective progress on reducing tipping risks. Building on our discussion of criteria for acceptable mitigation pathways above, this assessment would consider whether actual mitigation pathways fall within the envelope of modelled pathways that limit tipping risks. The political component of the GST could include deliberations on tipping point prevention and to what extent tipping point risks warrant increased global mitigation ambition. Including tipping points in the GST could stimulate the formation of multi- and minilateral initiatives for tipping point governance.

While the Paris Agreement provides an international framework for climate mitigation efforts, the actual work of reducing emissions takes place at the **national scale**. Countries pursue the aim of decarbonising economies and societies using a vast range of national policies, especially in the domains of energy production (transitions towards renewable energy sources) and use (energy efficiency), mobility (e.g. electrification of road transport), housing and agriculture. There are vast differences among the approaches and successes of different countries so far. While decarbonisation measures often create resistance and face political challenges (Egli, Schmid, and Schmidt, 2022; Martin and Islar, 2021), they need to accelerate and expand in scope to address the growing risk of transgressing tipping points. This includes the removal of fossil fuel subsidies (Skovgaard and van Asselt, 2019; Coady et al., 2019) and other forms of government support for the fossil fuel industry, cancellation of government licences for new extraction projects, and ultimately publicly guided deliberate phase-out strategies for fossil fuel industries that proactively and carefully consider justice implications (Pellegrini et al., 2021; Whitfield et al., 2021; Heffron, 2021; Newell and Mulvaney, 2013). Civil society actors also play a crucial role in advancing mitigation and societal decarbonisation efforts, including by pressuring national governments to acknowledge that effective climate change mitigation requires phasing out all fossil fuels.

3.2.3.2 Short-lived climate pollutants

Outside of the UNFCCC, intergovernmental efforts to manage SLCPs are an important dimension of global climate mitigation efforts, especially because they can have short-term benefits. SLCPs, including methane, tropospheric ozone and black carbon, can have disproportionate regional impacts on particular tipping systems. For example, black carbon deposition is particularly effective at melting snow and ice. Hence the mitigation of specific SLCPs can have a disproportionate benefit in preventing specific ESTPs. Mitigating SLCPs can also contribute to limiting global warming pressure on most ESTPs. According to IPCC AR6 WG1, across the Shared Socioeconomic Pathway climate scenarios, "the collective reduction of methane, ozone precursors, and hydrofluorocarbons (HFCs) can make a difference of 0.2°C with a *very likely* range of [0.1 to 0.4]°C in 2040 and 0.8°C with a *very likely* range of [0.5 to 1.3]°C at the end of the 21st Century".

On global and regional levels, several institutions address SLCPs. A focal arena is the Climate and Clean Air Coalition (CCAC), a state-led transnational partnership established under UNEP in 2011, which has become a key actor in global policy advocacy and knowledge exchange on SLCPs. In addition, other international fora have made concrete steps to mitigate specific SLCPs. For instance, in the Northern hemisphere, black carbon emissions are integrated into the targets to reduce particulate matter pollution under the Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone. In 2015, the Arctic Council agreed on the Framework for Action on Enhanced Black Carbon and Methane Emission Reductions. In 2016, the Montreal Protocol on Substances that Deplete the Ozone Layer was complemented with the Kigali Amendment on the phase-out of HFCs. Further, under the Paris Agreement, some countries have included SLCP mitigation targets or policies in their NDCs, and various global cooperation efforts, including the Global Methane Pledge (Sun et al., 2021), have been launched to address methane emissions. Elevated action on SLCPs is essential because the effects are felt more rapidly than those of CO_2 abatement.

Other short-lived pollutants, such as sulphates and particulates, can have cooling effects, and their elimination would increase warming (also on short time scales) (IPCC SR1.5 2018). For example, reducing sulphate emissions from shipping for health reasons has a climate trade-off (Sofiev et al., 2018). While this creates challenges for policy design, it cannot justify the intentional release of sulphates or other particulates (even sea salt) in efforts to compensate for warming effects through deliberate geoengineering. In addition to the ethical differences between deliberate interventions and unexpected side effects (Morrow, 2014), we discuss the practical and political uncertainties of geoengineering below.

3.2.3.3 Carbon dioxide removal

With some exceptions (Riahi et al., 2021), the bulk of emissions pathways for reaching ambitious temperature goals still *exceed* the near-term carbon budget, lead to temperature overshoot, and are brought down in the latter half of the century by a speculative scale of novel carbon sinks (IPCC AR5, 2014; IPCC, 2018; IPCC AR6, 2022). Carbon removal is emerging as a key pillar of climate assessments and policy. IPCC AR6 argued across all three working groups that carbon removal will play an essential role in strategies that limit warming to no more than 1.5°C and is an important feature of "well below 2°C" scenarios. Correspondingly, countries increasingly integrate carbon sinks into their net-zero goals, NDCs (Hale et al., 2022) and mid-century strategies (H. B. Smith, Vaughan, and Forster, 2022). For now, they predominantly repurpose land use and ecosystem management practices as carbon removal. Engineered carbon removal prototypes and practices are piloted at small scales, but these remain immature or speculative as socio-technical systems (Sovacool, Baum, and Low, 2023). The prospects for scaling to the multi-gigaton levels foreseen in integrated assessment modelling are doubtful, with only limited attention so far to the demand side and policy beyond research and development (Nemet et al., 2018). It is uncertain if these can reach the scale envisioned in pathways in line with well below 2°C or 1.5°C. Hence some filtering of plausible emissions pathways to not rely on excessive carbon removal is necessary.

It is important to recognise that carbon removal is understood as playing two roles. First, it can balance residual, recalcitrant emissions in a net-zero state. The currently projected scale of such residuals and removals is substantial at close to 20 percent of current emissions (Buck et al., 2023). The second role is to reverse overshoot of carbon budgets (reducing ultimate outcome temperatures). The more removal capacity required for the first task, the greater the challenge of providing sufficient, rapid, sustainable capacity for the second.

The development of removal approaches also requires careful governance to avoid their use as a substitute for achievable mitigation, rather than a supplement. One analysis of the risk of mitigation deterrence through carbon removal estimates as much as 1.4°C additional warming (over the 1.5°C goal) could result (McLaren, 2020).

Assessment of the relationship between carbon removal and tipping points is nascent. While **large-scale CDR efforts might have desirable effects on global temperatures**, it faces significant scaling challenges and would likely operate more slowly than many other mitigation approaches. These challenges likely limit its potential as a prevention tool in comparison to GHG emission reduction.

Carbon removal techniques could also have other positive and negative effects on ecosystems and hence tipping point risks. For example, some carbon-removal approaches, such as forest conservation and afforestation, could increase forest resilience and counteract tipping dynamics. But opposite effects are also possible. At scale, most carbon-removal techniques compete for land and/or low-carbon energy supplies, with negative effects on both sustainability and justice (Smith et al., 2015; McLaren, 2012). Moreover, large-scale conversion of natural forests for the purpose of Bioenergy with Carbon Capture and Storage (BECCS) might increase ecosystem vulnerability and the possibility of forest loss, and afforestation in drylands and grassland ecosystems could make tipping more likely in those ecosystems (see Chapters 1.3.2.4 and 1.3.2.5). Proposals for large-scale oceanic carbon removal through alkalinisation or fertilisation also raise questions about their interactions with tipping point drivers, effectiveness and ecosystem disruption (Fakhraee et al., 2023; Tagliabue et al., 2023). Overall, there is so far limited research on the nature and net balance of such effects.

3.2.3.4 Solar geoengineering

Solar geoengineering or solar radiation modification (SRM) is a group of hypothetical and controversial methods that might help decrease global temperature by directly altering the Earth's energy balance, typically by reflecting a small fraction (around 1 per cent) of the incoming sunlight (NASEM, 2021). The best-known suggestions are Stratospheric Aerosol Injection (SAI), which would involve creating a thin reflective cloud layer of reflective aerosol in the higher atmosphere, and Marine Cloud Brightening (MCB), which would involve making oceanic stratocumulus clouds more reflective by providing sea salt dust particles to increase the number of cloud droplets.

It has been suggested that solar geoengineering techniques might reduce the likelihood of crossing temperature-related tipping points, postpone their arrival, or, more speculatively, even reverse ongoing tipping processes (Heutel, Moreno-Cruz, and Shayegh, 2016; Felgenhauer et al., 2022). The latter possibility is ruled out by Lenton (2018). The linkages between different kinds of solar geoengineering and the drivers of tipping points are understudied and uncertain. Moreover, proposed techniques are currently hypothetical, and not practically available as options to contribute reliably to the prevention of ESTPs. There is already early consensus that geoengineering techniques would not offer an emergency response to anticipated tipping events (Horton, 2015; Lenton, 2018). However, assessment over whether they might provide pre-emptive measures to support prevention is ongoing, and heavily contested (Gupta et al., 2020).

Modelling studies on stratospheric aerosol injection suggest beneficial effects on particular tipping systems (e.g. delay), such as AMOC decline (Xie et al., 2022), Greenland ice loss (Moore et al., 2019), West Antarctic ice loss (Sutter et al., 2023) or permafrost thaw (Chen et al., 2023). However, in these studies **geoengineering interventions typically appear less efficacious than GHG mitigation.** This underscores that they could at most complement, but not replace, mitigation. Nevertheless, these studies come from modelling simplified or idealised deployment scenarios at the global scale, which suffer from model uncertainties and bracket out technical, social, ethical, political and economic considerations which would be crucial for the conditions of deployment (Corry, 2017; McLaren, 2018). For other, more regional or localised techniques – including marine cloud brightening and ice albedo modification (see Box 3.2.3) – even the direct effects remain uncertain (Diamond et al., 2022; Johnson et al., 2022; Webster and Warren, 2022).

All approaches are poorly researched with respect to outdoor experimentation, technology development, side-effects, justice and ethics, public acceptability, and governance frameworks. Furthermore, deployment would be accompanied by the risk of termination shock (Parker and Irvine, 2018) – a risk of rapid warming if deployment were to be abruptly halted – along with other challenges and uncertainties regarding effectiveness and the regional-to-global distribution of their effects on various environmental and social systems such as weather, agriculture, health and biodiversity.

The prospect of collaborative, effective and democratic international governance – particularly of the global SAI approach – faces many practical and political challenges (Szerszynski et al., 2013; Horton et al., 2018; Flegal et al., 2019; Gardiner and McKinnon, 2020). Expectations that solar geoengineering might be deployed to avoid tipping points would carry a risk of deterring or slowing mitigation efforts (Corner and Pidgeon, 2014; McLaren, 2016; Merk, Pönitzsch, and Rehdanz, 2016). Idealised deployment that would mirror idealised modelling studies is unlikely: actual deployment would be beset by significant ethical and distributional challenges (McLaren, 2018) and would need to be sustained for decades or centuries (Baur et al., 2023). Developing required long-term, stable governance institutions (Parker and Irvine, 2018) would be difficult and slow, reflecting challenges in global climate governance on historic and future responsibilities, unequal capacities, and loss and damage (Biermann et al., 2022). In their absence, unilateral, club-based, or even corporate efforts to deploy geoengineering would present challenges regarding accountability and liability.

The prospective value of solar geoengineering approaches is greatly disputed among scientists, with networks emerging around an international non-use agreement (Biermann et al., 2022) and calls for further research and funding (Doherty et al., 2023; Wieners et al., 2023). Recently, the Overshoot Commission called for a moratorium on SRM deployment and large-scale experiments combined with 'exploration' by appropriately governed research and governance dialogue. Without commenting on these strands of activity,

We strongly caution against reliance on solar geoengineering as a major tool for preventing tipping points, or the expectation that this kind of approach will be available and politically acceptable in the future to contribute to prevention efforts. Nor should SRM ever be considered a possible replacement for mitigation.

Governments should therefore take measures on both international and national scales to prevent premature, uncoordinated, or self-interested actions on SRM, by means of an (at least temporary) international moratorium on SRM deployment and large-scale experiments, as well as a ban on commercial activities even at a small scale. Multilateral efforts should also be undertaken to govern research and enable timely public debate on SRM's potential, limitations and risks, including its potential to reduce or possibly exacerbate ESTP risks and to interact with social tipping points. The provisions of the London Protocol, prohibiting ocean iron fertilisation, with exemptions for legitimate scientific research, may provide a starting point for drafting regulations to ensure that any exploration of SRM is conducted in a responsible, safe and inclusive manner.

BOX 3.2.3: Engineering approaches at the scale of Earth system tipping elements

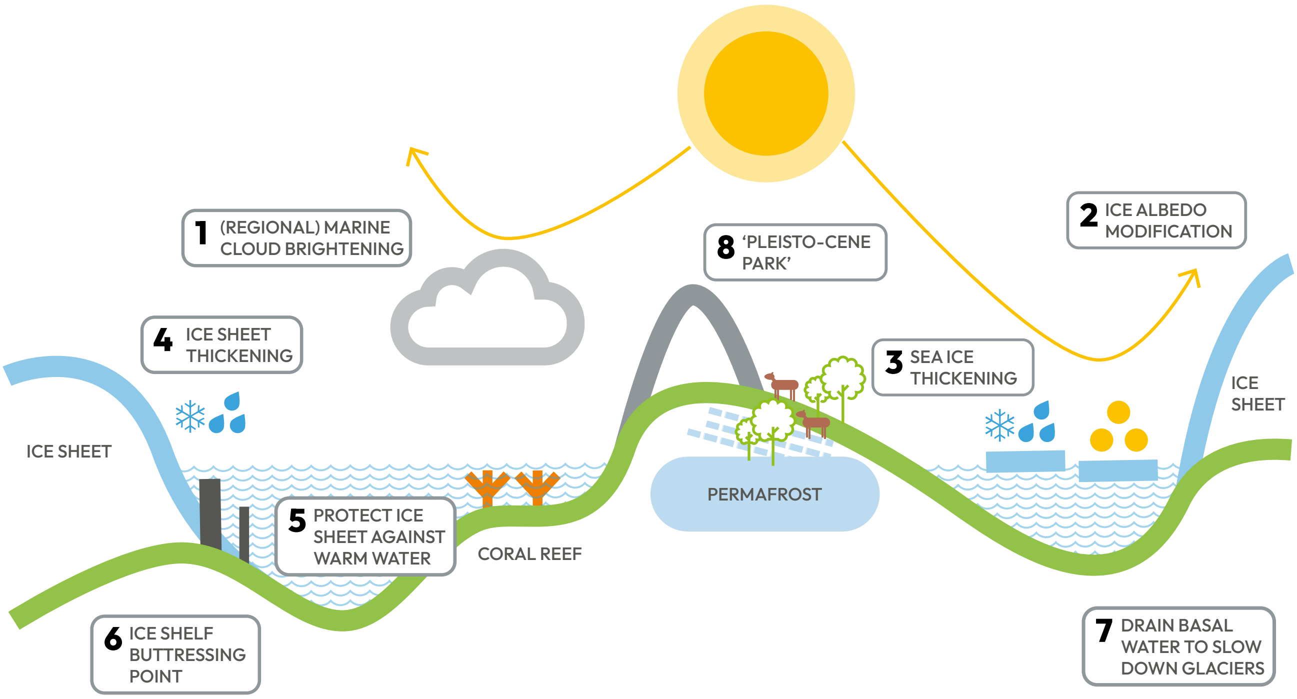

Fig. 3.2.2: Proposed engineering techniques at tipping-point scale. All of these techniques are controversial and speculative, with varying degrees of uncertainty regarding their technical feasibility, efficacy, side-effects and governance challenges, including mitigation deterrence.

1. Solar geoengineering techniques aiming to make marine stratocumulus clouds more reflective by injecting sea salt dust, either regionally, e.g. coral reef protection, or intending global cooling; technical means non-existent currently but potentially feasible and inexpensive; direct environmental issues likely limited, effectiveness uncertain (National Academy of Sciences, 2021).
2. Brightening sea ice by covering it with small reflective glass spheres. Some outdoor experimentation. Conflicting results from modelling, and concerns about side-effects and effectiveness (Field et al., 2018) vs. (Webster and Warren, 2022).
3. Thickening sea ice by spraying with water in the freezing season or applying snow cannons. Speculative ideas suggested, some modelling. Pumped seawater would release CO_2, limiting overall efficacy. Energy costs likely prohibitive. Sea ice preservation may have local benefits but the approach would have limited or even negative effects at global scale. (Zampieri and Goessling, 2019).
4. Thickening ice sheets at areas with low flow velocities to directly remove water from the sea. Technical feasibility speculative, low leverage (Moore et al., 2020).
5. Protecting ice shelves and calving glaciers in Greenland or West Antarctica from warm sea water by means of dams or membranes. Technical feasibility uncertain (Wolovick and Moore, 2018).
6. Providing additional buttressing points to ice shelves to slow down their movement and hence the flow of the glaciers behind them. Technical feasibility uncertain (Wolovick and Moore, 2018).
7. Draining meltwater at the base of glaciers in Greenland or West Antarctica to reduce lubrication and slow down their flow. Technical feasibility uncertain (Moore et al., 2020).
8. Rewilding permafrost areas with grazing animals to reduce shrub and compact snow layer and eventually conserve permafrost carbon. Speculative concept, supported by one modelling experiment (Beer et al., 2020) with some non-scientific experimentation in Russia (Moore et al., 2020).

3.2.3.5 Addressing other causes of tipping

While GHG emissions are the primary drivers of Earth system tipping processes, additional drivers need to be managed to avert the crossing of tipping points. For example, deforestation and land use intensification could trigger the tipping of the Amazon rainforest, while nutrient pollution and over-exploitation could lead to the rapid collapse of marine fisheries and habitats. While some of these drivers are tied to global activities (e.g. large-scale commercial fishing or deforestation in the Amazon, due in part to demand for food products in China, Europe and the US), the primary or most immediate locus of governance of some of these non-climatic drivers may be regional or national, closer to the immediate scale of the tipping system, rather than in international organisations. For example, despite global drivers of deforestation in the Amazon, the rate of deforestation depends critically on the actions of Brazil's federal government (see Box 3.2.2), with relatively low deforestation during President Lula's term replaced by increased deforestation during Bolsonaro's presidency (Peres et al., 2023).

The prevention of ESTPs may thus call for national efforts and new regional entities to facilitate cooperation across relevant states and sub-national jurisdictions regarding the governance of specific secondary drivers of tipping processes. Such regional initiatives could coordinate and align prevention measures with cross-border effects, pool resources, share knowledge and technologies, and engage in mutual learning about the effectiveness of prevention measures. More generally, such a regional approach would foster preventive capacities at the scale of the tipping system (see Chapter 3.1 on regional governance).

Additionally, regional entities may be able to reduce the likelihood of unintended consequences — for example, the displacement of deforestation from one region in Brazil to another or from Brazil to another Amazonian country — by facilitating coordination and consultation. Further, to the extent that global action is needed to mitigate secondary drivers or to allocate resources to support regional prevention efforts, regional entities will need to be meaningfully embedded within broader governance arrangements (see Chapter 3.1 on polycentric governance).

In addition to public entities, including intergovernmental fora and councils, there are several non-governmental organisations and private-sector coalitions focused on specific sectors or resources – such as the Marine Stewardship Council, the Forest Stewardship Council, or the Roundtable on Sustainable Palm Oil – that could play an important role in mitigating non-climate drivers of ESTPs. The consolidation of control over certain industries by a handful of companies means that the decisions of certain corporate actors play a large role in their respective sectors, and in shaping environmental conditions. Due to this influence, they have been called 'keystone actors' drawing on the term 'keystone species' in ecology (Österblom et al., 2015). Recent efforts to quantify and draw attention to the impacts of the financial sector on deforestation of the Amazon (and other forests) through NGOs such as Forests & Finance Coalition could serve a similar role for the Amazon by redirecting financial flows away from destructive activities and towards regenerative ones.

3.2.4 The politics of prevention

Given the close relationship between the prevention of ESTPs and climate change mitigation, prevention politics are likely to mirror the politics of mitigation to a large extent. At the same time, the multi-scale nature, diverse drivers (including non-climate drivers) and distinct geographic distribution of tipping-related risks can generate a set of novel political dynamics, especially at non-global scales.

Key factors that shape the politics of mitigation are countries' national interests (often defined in terms of economic growth), power distribution between high-emitting and other countries, vested economic interests, especially those of the fossil-fuel industry, and the strength of civil society forces creating pressure and public demand for action (Stoddard et al., 2021). Here, we only focus briefly on the likely role of national interests in future political dynamics related to the governance of ESTPs. Other factors deserve equal attention. All of these issues are currently under-researched.

Each government will have to assess the relevance of ESTPs for the national interest, especially through the lens of risk: the more a government expects their country be negatively affected by tipping points (or to gain from co-benefits arising from preventive action), the more it will likely favour preventive action to protect its people (including future generations), infrastructure, the position and security of borders, social stability and economic functioning, including trade flows and supply chains, from these impacts. Countries will need to consider how many and what kind of tipping systems will affect them (multi-exposure), and the possibility of complex interactions. For example, low-lying island states will likely face disproportionate tipping risks from ice sheet disintegration, while countries around the North Atlantic (Western Europe, US, Canada) would share concerns related to the North Atlantic Subpolar Gyre. Some countries might be indifferent to the topic, assuming that they will not be affected, at least in the foreseeable future. Others might expect significant challenges related to tipping points, yet oppose mitigation or other prevention efforts because of the expected costs of these measures, or even because they anticipate relative geopolitical advantage as a result of tipping points.

An additional factor that might affect the determination of national interests is the **cascading potential** of ESTPs. For example, a landlocked European country might not be directly affected by GrIS melt, and therefore not be motivated to engage in prevention when considering the GrIS. However, since the melting of the GrIS contributes to the slowing of the AMOC (cascading effect), and a collapse of the AMOC would have significant impacts on landlocked countries in Europe (e.g. changes in temperature, precipitation and storm patterns), decision makers in the country in question would have a well-founded interest in preventing the crossing of the ice sheet's tipping point. Such cascade considerations might be very different for each country.

To a large extent, such national interest determinations with respect to ESTPs have yet to be made. If such risk assessments were undertaken, they might be expected to lead to the formation of political alliances among countries with shared interests (e.g. rapid prevention, opposition to action) and disagreements among groups with opposing interests. National interests and the political alliances they give rise to are dynamic. They will change over time in response to several factors, including increasing scientific understanding of tipping points and what will be perceived as signals or impacts of ESTPs.

The choice of **prevention approaches** will be subject to political debate based on actors' diverging preferences and expectations of implications regarding the mix of emission reductions, carbon removal, and other technological solutions, including solar geoengineering. This will also be relevant at national, regional and local levels and when dealing with non-climate drivers.

An important factor to trigger action on tipping points is how national governments and publics evaluate the risk of ESTPs and risks related to potential preventive measures. The way individuals, communities and policymakers perceive the risks associated with crossing tipping points can be expected to influence their willingness to demand and/or take action and implement measures to prevent tipping points (see 3.1.5). However, based on the experience of the last three decades, even intensifying impacts of climate change do not necessarily drive accelerated mitigation motivation and action. A number of dynamics at the national scale, including strategic obstruction efforts by vested fossil-fuel and ideological interests, limit the climate response of various political systems around the world (Stoddard et al., 2021; Ekberg et al., 2022; Jacques, Dunlap, and Freeman, 2008). The prospects of future acceleration and intensification of impacts is therefore unlikely to change the slow and contentious politics of climate mitigation.

All of these dynamics are likely to unfold over the coming decade as knowledge of ESTPs expands in the international community. At the moment, the politics of governing ESTPs takes place primarily in the domain of science-policy interactions, where actors tie different techniques of knowledge production to specific future visions that create a rationale for the pursuit of specific prevention approaches and related governance proposals (Gupta et al., 2020). This form of anticipatory governance can shape the direction of future decision making related to ESTPs in ways that depend on the actors involved and their interests, the design of the knowledge production and visioning process, and other factors (Moore and Milkoreit, 2020).

3.2.5 Final remarks

Prevention has to become the central objective of Earth system tipping point governance, as a means to defend and promote achievement of other societal objectives like the SDGs. Prevention efforts need to distinguish between multiple drivers of tipping processes at different scales, including non-climate drivers. Governance needs to address all types of drivers, operate on multiple scales of the international system, and consider cross-scale dynamics and challenges in a polycentric fashion. Each tipping system and each driver of tipping requires a distinct approach, likely involving different institutions, actors and solutions. However, equitable mitigation is an indispensable and overarching tool that is vital to reduce risks in nearly all tipping elements.

Given the important role of global temperature increase as a key driver for many Earth system tipping processes, rapidly strengthening current global climate change mitigation efforts will be essential for successful prevention efforts, including boosting efforts to reduce SLCPs. Their aim should be to minimise the magnitude and length of global temperature overshoot periods beyond the global temperature goals, which requires careful reconsideration of mitigation pathways. Carbon dioxide removal could also help reduce the primary drivers of climate tipping, but is slow and difficult to scale, risks deterring or slowing other mitigation, and some methods could add to other drivers of Earth system tipping. Policy should seek to increase sustainable capacities for carbon dioxide removal as an addition to mitigation efforts, while minimising deterrence effects and potential side-effects on other tipping drivers.

Several existing institutional arrangements for climate mitigation provide opportunities for prevention efforts regarding tipping points. These include the Paris Agreement (especially NDCs, the GST and periodic review of the long-term goal) and related national decarbonisation efforts, but also other international or transnational institutions.

While there are some limited indications that solar geoengineering might have beneficial impacts on the drivers of some tipping points, they remain speculative with profound technical and political gaps in understanding, and based on limited, largely technocratic analysis. Currently, solar geoengineering is not technologically available to implement safely with a short ramp-up time. Political uncertainties cannot be eliminated through further research, assessment or monitoring. Expectations that solar geoengineering might be deployed to avoid tipping points would carry a risk of deterring or slowing mitigation. For the time being, they are not available to support prevention efforts. In any case, such approaches could at most complement, but not replace, mitigation.

3.3 Tipping point impact governance

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Summary

Given the now substantial risk of passing several Earth system tipping points (ESTPs) in the foreseeable future, it is imperative that governance actors begin to anticipate and prepare for their impacts. ESTPs present threats that are distinct from climate change as it is currently understood in important ways. We identify five such differences and discuss how these challenge current frameworks, plans, practices and resource allocation for impact governance. Multiple policy domains, including adaptation, loss and damage, international development, disaster preparedness and migration, should account for ESTPs to ensure effective decision making in pursuit of peace and prosperity for people and the planet, now and into the future.

While the literature on ESTP impact governance is nascent, we identify important considerations. The objective of impact governance is the prevention and minimisation of harm caused by ESTPs in the context of just and sustainable development. Efforts should be distributed across multiple scales and differentiate between governance tasks before and after a tipping point is crossed (i.e. match strategies to different phases of tipping processes). Early warning systems that can support timely responses to changes in Earth and social systems would be desirable, but there are significant concerns about the availability of reliable early warning signals. Attending to equity and justice requires that impact governance for ESTPs takes into account the needs and perspectives of the most vulnerable and marginalised communities.

A broad set of governance actors and institutions involved in addressing the impacts of global environmental change today will play a role in this domain. This includes global-scale and international institutions, national governments and local communities, but also the private sector and civic actors. We briefly illustrate the potential and need for changes to current governance structures in two domains. One is the UNFCCC, a treaty-based international institution with global scope. Here we focus on adaptation and loss and damage. The second is the less-formalised institutional context for governing migration, where we consider local, national and international processes of planned relocation.

Key messages

- The impacts of Earth system tipping processes differ from climate change impacts in ways that matter for impact governance. Key differences include greater magnitude and acceleration of change, novel types of impacts and distributions of vulnerability, and irreversibility of change.
- Existing governance frameworks and institutions (for climate change adaptation, migration and sustainable development, for example) do not account for the specific threats of ESTPs.
- Given the nature of Earth system tipping processes, provisions for addressing Loss and Damage would play a much bigger role than today if ESTPs were transgressed.
- The objectives of ESTP impact governance, especially minimising harm, reducing vulnerability, building resilience and preventing impact cascades, are best achieved with just transformations towards sustainability.

Recommendations

- 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.
- Adaptation governance needs to significantly strengthen anticipatory work and adopt a multitemporal perspective tied to the scale and dynamics of specific tipping systems.
- Governments should advance the institutionalisation of global migration governance, building on the Global Compact for Safe, Orderly and Regular Migration.
- 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.
- Governments should increase the use of participatory approaches to impact governance, involving local/Indigenous communities and knowledge.

3.3.1 Rethinking impact governance for global environmental change

Based on current scientific assessments, including in this report (see Section 1), the likelihood of transgressing one or several ESTPs has been increasing and will likely grow substantially beyond 1.5°C warming, but no tipping process has been set in motion yet. Given that several tipping systems have been destabilised, and could be transgressed in the near term, it is imperative that decision makers start to develop appropriate governance frameworks to address the potential future impacts of ESTPs. If transgressed, ESTPs would severely undermine the pursuit of the SDGs, and reverse recent development progress around the world. The possibly short remaining window of time before the impacts of a tipping process could be felt should be used to increase preparedness, foster community resilience and invest in resources, processes and institutional capacity that would be needed to effectively respond to tipping-point impacts.

Section 2 of this report has assessed the highly diverse expected impacts of ESTPs which are summarised in Table 3.3.1. The assessment shows that ESTPs are very diverse, each with a distinct set of **impact types** and impact distribution over time and space. Given this diversity, different tipping points (or groups of tipping points) might require distinct kinds of policy responses and impact governance strategies, involving different sets of actors.

Earth system tipping point	**Sea level rise/coastal erosion**	**Extreme weather events**	**Feedback on global warming**	**Water shortages**	**Changes in precipitation**	**Regional temperature change**	**Ecosystem change**	**Release of pollutants**	**Infrastructure damage**	**Food security**	**Triggering other ESTPs**	**Secondary societal impacts**	**Thresholds, timescales & spatiale extent**
Cryosphere													
Greenland Ice Sheet collapse	Up to 7m sea level rise overall over 1000s years, together with WAIS potentially up to c. 2m by 2100 [IPCC AR6 WG1 Ch9], affecting 480 million people	Minor impact (local circulation changes)	Minor impact (~0.1°C over 1000s y.)	Water shortages due to coastal salinisation	Local impact possible effect on tropical monsoons via AMOC disruption [Defrance et al., 2017])	Regional amplification of warming	Coastal areas, new exposed land in Greenland	Minor (some pollutants trapped in ice)	Threat to coastal power plants, Destruction of coastal built environment	Salinisation impacting agriculture & food security	Impact on AMOC/SPG as tipping may be reached sooner (but timescales unclear)	Displacement of coastal area popula- tions, conflicts over water etc, financial crises (stranded assets)	0.8-3°C GW, long period (1000s y.), global impacts
Arctic Sea Ice loss (not considered a tipping system in this report)	Increased coastal inundation and erosion from larger waves with more open ocean	Uncertain; possible contribution to increase in extreme weather events (e.g. Extreme European snowfall)	Uncertain, possibly ~+0.25°C for summer sea ice loss & ~+0.6 °C for winter sea ice loss, included in model projections	No impact	Local impact with more open water causing increased evaporation and increased precipitation, shift from snowfall to rainfall	Regional amplification of warming (particularly Arctic and Northern Hemisphere)	Details uncertain, but loss of sea ice is expected to substantially affect the marine Arctic ecosystems; impact on land ecosystems unclear	Changes in pollutant & microplastic transport in the ice-free Arctic; increased contaminant input from the Arctic coastal erosion	Possible damage through extreme weather events and through increased coastal erosion	Extreme weather events could destroy harvests, disruption of traditional Indigenous food systems	Amplifies regional warming over Greenland, AMOC/SPG, boreal forests & permafrost; coastal permafrost loss accelerated	Coastal erosion, loss of Indigenous ways of life, & possible extreme weather events contributing to conflicts, (temporary) displacement, anomie etc	NA for tipping; 4.5-8.7°C GW for gradual winter sea ice loss in models [McKay et al., 2022], fast (20 y.), global impacts
Barents Sea Ice loss (not a tipping system, low confidence)	No impact	Unclear; potential contribution to increase in extreme weather events (Europe)	Negligible impact	No impact	Possible regional impacts in Europe	Local warming	Local ecosystems (marine & bordering land)	Unclear, but changes in circulation can affect pollution redistribution (e.g. of mercury)	Possible damage through extreme weather events	Possible extreme weather events could destroy harvests	Small impact on AMOC & regional boreal forests	Possible extreme weather events contributing to conflicts, (temporary) displacement, anomie etc	NA for tipping, (but 1.5-1.7°C GW in some models) [McKay et al., 2022], fast (25 y.), regional & global impacts
Permafrost thaw	Abrupt thaw can amplify coastal erosion	Minor impact (can lead to increased lightning strikes and wildfire ignition)	Release of greenhouse gases, driving further global warming	Complex changes to the local water table via abrupt drainage, thermokarst lake formation	Minor impact	No impact	Boreal/tundra ecosystems	Release of contaminants such as mercury into the environment	Disrupts travel in Arctic and isolates settlements Built infrastructure damage and destruction	Impact on permafrost-agroecosystems and community-level food storage in frozen underground cellars	Important but uncertain impact on Boreal forest dieback/ expansion tipping points	Anomie among regional population inhabiting the areas, due to livelihood and cultural loss	NA for tipping, abrupt thaw more common from 1.5°C GW [McKay et al., 2022], medium-term (~200 y.) regional & global impacts

Earth system tipping point	Sea level rise/coastal erosion	Extreme weather events	Feedback on global warming	Water shortages	Changes in precipitation	Regional temperature change	Ecosystem change	Release of pollutants	Infrastructure damage	Food security	Triggering other ESTPs	Secondary societal impacts	Thresholds, timescales & spatiale extent
West Antarctic Ice Sheet collapse	3-5m sea level rise overall over 100s-1000s y, together with GrIS potentially up to c. 2m by 2100 [IPCC AR6 WG1 Ch9], affecting 480 million people	Minor impact; possible massive iceberg release events in Southern Ocean	Minor impact (potentially ~0.05°C over 100s-1000s y.)	Water shortages due to sea level-induced coastal salinisation	Local impact	Regional warming amplification	Coastal area, new exposed islands and seas in West Antarctica	No impact	Threat to coastal power plants, Destruction of coastal built environment	Salinisation impacting agriculture & food security	May affect East Antarctic ice sheets & possibly Southern Ocean overturning circulation	Displacement of coastal area popula- tions, conflicts over water etc., financial crises (stranded assets)	1-3°C GW, long period (2000 y.), global impacts
East Antarctic Ice Sheet (marine & non-marine) collapse	Up to 53m total sea level rise potential; sea level rise of several metres possible over 100s-1000s of years	Minor impact; possible massive iceberg release events in Southern Ocean	Additional warming of potentially ~0.6°C over 10,000s y.	Water shortages due to coastal salinisation	Local impact	Regional warming amplification	Coastal areas, new exposed land and seas in East Antarctica	No impact	Threat to coastal power plants, Destruction of coastal built environment	Salinisation impacting agriculture & food security	Collapse of ice sheet in marine basins could accelerate land-based ice sheet tipping & Southern Ocean overturning circulation	Displacement of coastal area populations, conflicts over water etc, financial crises (stranded assets)	2-6°C GW marine & 6-10°C GW non-marine, very long period (10,000 y.), global impacts
Extrapolar glacier retreat	Up to 0.2m sea level rise	No impact	Minor impact (potentially ~0.08°C)	Impact of freshwater supply from meltwater in many regions of the world (e.g. Central Asia, Europe) leading to water shortages	No impact	Localised warming amplification	Changes in surrounding montane & downstream ecosystem, new land exposed	Minor (some pollutants trapped in ice)	Destabilisa- tion of valley sides could lead to landslides, glacier collapse events can cause floods/ mud- slides	Water shortages impacting agriculture & food security	No impact	Conflicts over water etc, anomie due to livelihood and cultural loss	Regionally variable but potentially widespread from -2°C GW, e.g. in Europe (McKay et al., 2022], medium-term (200 y.), regional impacts
Ocean/Atmosphere Circulation													
Atlantic overturning AMOC collapse	Regional sea level changes (fall in convection region & North European Shelf seas, rise further south)	Shift in jet stream and storm tracks affecting weather patterns in Europe, potential increase in extreme weather events, e.g. cold winters in Europe, south-ward hurricanes shift	Partial & temporary counteraction of global warming	Southward shift in ITCZ leading to drying in the Sahel and Southern Asia; Some models project drying in parts of the Amazon	Summer monsoon weakening and shifts in Africa and Asia	Up to 10°C cooling in North Atlantic and 3°C cooling in Northern Europe / Eastern Canada, warming amplification in Southern Hemisphere	Drastic shifts in many ecosystems on land and in the sea around the world, e.g. Amazon drying	Affects dust aerosols via monsoon disruption in those regions; ocean circulation changes can affect pollutant pathways	Shifted temperatures/ precipitation & weather patterns/ extremes no longer matching infrastructure tolerance ranges	Threat to food security because of impacts on marine life (reduction of plankton), changes in precipitation severely impacting agriculture (particularly wheat and maize) & food security (particularly in Europe)	Warming amplification in Southern Hemisphere accelerating Antarctic Ice Sheet melt and coral bleaching, Amazon drying; monsoon (African and Asian) shifts accelerated	Conflicts over food and water, displacement from uninhabitable areas, anomie, financial crises, etc	NA in this report, 1.4-8°C GW elsewhere (but low confidence) [McKay et al., 2022], Possibly relatively fast (~50 y. To centuries) Complex global impacts with strong regional differences

Earth system tipping point	Sea level rise/coastal erosion	Extreme weather events	Feedback on global warming	Water shortages	Changes in precipitation	Regional temperature change	Ecosystem change	Release of pollutants	Infrastructure damage	Food security	Triggering other ESTPs	Secondary societal impacts	Thresholds, timescales & spatiale extent
Labrador- Irminger Seas Convection (Subpolar Gyre) collapse	20-30cm sea level rise along North-East seaboard of North America	Similar to AMOC but possibly smaller impact, e.g. amplified cold winter blocking events in Europe & increase in summer heat wave frequency	Similar to AMOC but magnitude of impact is unclear	Similar to AMOC but possibly smaller impact	Similar to AMOC but impact is not completely clear	Up to 2-3°C cooling in North Atlantic, global warming counteracted in Northern Europe / Eastern Canada	Large changes in ecosystems in affected regions (e.g. reduced North Atlantic productivity, regional ocean acidification, deoxygenation)	Impact unclear, but could be similar to AMOC	Similar to AMOC but smaller impact	Major disruptions of agriculture in Northern Europe and Sahel, impacting food security	Similar to AMOC but impact is not completely clear, potentially a large change in N. Atlantic ecosystems	Conflicts over food and water, displacement from uninhabitable areas, anomie, financial crises, etc	1.1-3.8°C GW, very fast (10 years), regional impacts
Monsoon shifts (intensification or collapse, e.g. South Asian, West African, South American)	No impact	Monsoon intensity & extremes projected to increase with warming, or strong drop due to aerosol-induced collapse	No Impact	Shifted precipitation may lead to water shortages	Drastic precipitation changes	Change in tropical and subtropical climates	Change in vegetation and ecosystems in general relying on the monsoon	Changes to where monsoons redistribute air pollution	More intense monsoons overwhelming current infrastructure; monsoon collapse leaving infrastructure mal-adapted	Changed vegetation, agriculture dependent on monsoon rainfall will impact livelihoods and food security	WAM could drive Sahel greening, SAM could affect Amazon	Conflicts over food and water, displacement from uninhabitable areas, anomie, etc	Interhemispheric AOD asymmetry >0.15, AMOC collapse, Amazon dieback; (McKay et al., 2022), relatively fast (50 y.), regional impacts
Biosphere													
Amazon rainforest dieback	No impact	Increasing extreme weather events (e.g. wet bulb spikes, wildfires) in region	Additional global warming (0.1-0.2°C, depending on extent)	Decreased precipitation may lead to water shortages	Declining regional precipitation in Amazon and Southern Cone region	Over 1°C extra regional warming	Parts of rainforest (particularly in South & East) shift to degraded forest or savannah	Smoke from increased wildfires	Minor impact	Decreased precipitation would impact agricultural belt of Brazil and into Southern Cone	Amplified global warming, bringing other warming thresholds closer	Conflicts over food and water, displacement from uninhabitable areas, anomie,	2-6°C GW (without deforestation) ~20-40% deforestation, relatively fast (100 y.), regional and global impacts
Boreal Forest Southern dieback / Northern expansion	No impact	Increasing extreme weather events (e.g. wildfires)	Complex effects – dieback releases carbon but reduces albedo, expansion vice versa	May change with evapotranspiration-induced weather pattern shifts	Changes to evapotranspiration likely to shift regional weather patterns	Regional changes due to changes in land albedo	Shift to open, steppe/prairie-like ecosystems in south, tundra afforestation in north	Smoke from wildfires	Minor impact	Disruption of traditional Indigenous food systems	Complex interplay with permafrost thaw, northern expansion adds to Arctic warming; drives lake browning	Anomie among regional population inhabiting the areas, due to livelihood and cultural loss	1.4-5°C GW southern dieback, 1.5-7.2°C GW northern expansion, relatively fast (100 y.), regional impacts
Warm-water coral reef die-off	Decreased coastal protection (coastal erosion)	Increased vulnerability to extreme weather events	Limited impact on GW until very long term	No impact	Minor impacts	Minor impact	Tropical and subtropical coral reefs mostly die-off, resulting in great biodiversity loss	No impact	Loss of coastal protection services may require engineered replacements	Impact on marine food web, Impact on 500 million livelihoods and food security	Possible interaction with nearby mangroves and seagrass die-off and marine regime shifts	Conflicts over decreasing fish stock, anomie because of livelihood and culture loss, etc.	1-1.5°C GW, plus non-climate thresholds, very fast (10 years), regional and global impacts
Coastal ecosystem regime shifts (mangroves/ seagrass)	Decreased coastal protection (coastal erosion)	Increased vulnerability to extreme weather events	Loss of C sink and release of GHGs, but small impact at global scale	Reduced coastal protection can allow greater seawater ingress, with storms and, aquifer salinisation	Minor impact	No impact	Many mangroves & seagrass ecosystems die-off, resulting in great biodiversity & ecosystem services loss	No impact	Loss of coastal protection services may require engineered replacements	Impact on marine food web, fishery and food security	Possible interaction with nearby coral reef die-off and marine regime shifts	Conflicts over decreasing fish stock, anomie because of livelihood and culture loss, etc	~1.5°C GW, but highly uncertain and spatially variable; Regional impacts

Earth system tipping point	Sea level rise/coastal erosion	Extreme weather events	Feedback on global warming	Water shortages	Changes in precipitation	Regional temperature change	Ecosystem change	Release of pollutants	Infrastructure damage	Food security	Triggering other ESTPs	Secondary societal impacts	Thresholds, timescales & spatiale extent
Savannahs & grasslands (ecosystem regime shift)	No impact	Greater vulnerability to drought or extremely high rainfall	Shifts in carbon storage – some GHG release possible (but globally small)	Greater groundwater depletion (with shrub encroach- ment)	Regional precipitation changes	Complex regional temperature change from changes to albedo and eco- hydrology	Change in vegetation, leading to biodiversity loss, reduced fires with shrub encroachment	No impact	Minor impact	Loss of grazing lands will impact livelihoods and food security	Possible interaction with nearby dryland and tropical forest tipping points	Conflicts over food and water, displacement from uninhabitable areas, anomie, etc	Regionally variable rainfall & fire thresholds, regional impacts
Temperate forests dieback	No impact	Increased wildfires	Carbon emissions (amplifying global warming)	Less atmospheric water supply and groundwater recharge	Changes to evapotranspiration likely to shift regional weather patterns	Regional warming in summer due to less evaporative cooling and cloud cover	Change in forest ecosystems leading to biodiversity loss	Smoke from wildfires	Minor impact	Loss of indirect ecosystem services (e.g. pollinators, groundwater recharge)	Possible impacts on nearby boreal forest	Anomie because of loss of livelihoods and cultural loss	Thresholds unknown regional impacts
Drylands (ecosystem regime shift)	No impact	Greater vulnerability to drought or extremely high rainfall	Shifts in carbon storage – some GHG release possible (but globally small)	Aridification may lead to water shortage, groundwater depletion with shrub encroach- ment	Regional precipitation changes, leading to aridification in some areas	Complex regional temperature change from changes to albedo and eco- hydrology	Aridification/ desertification or shrub encroachment, leading to biodiversity loss	No impact	Minor impact	Aridification/ desertification or shrub encroachment will impact agriculture and food security	Possible interaction with nearby savannah and tropical forest tipping points	Conflict over water and land, displacement from uninhabitable areas, anomie, etc	Aridity indices (0.2, 0.3, 0.45) for aridification, regional impacts
Freshwater lakes (eutrophication-driven anoxia)	No impact	No impact	Increased GHG emissions (reduced for salinisation) could impact GW	Water quality decline could lead to water shortages	Minor impact	Minor impact	Lake ecosystem regime shift, biodiversity loss	Some algae blooms are toxic	Minor impacts	Freshwater fish stock decline could impact food security; water shortages could impact agriculture and food security	No impact	Conflict over water, anomie due to livelihood and cultural loss, etc	Variable for each lake, but higher risk beyond 50-100 mgP/m^3 and 2.5 (1–4) mg N/l Impacts in lake regions, with great regional differences in impact severity
Marine environment regime shift	Minor impact (loss of kelp forests could reduce coastal protection in some places)	No impact	Major changes in ocean productivity, carbon sinks & ocean biogeochemistry could have moderate impact on GW	No impact	Minor impact	Minor impact	Biodiversity loss from trophic cascades and regime shifts	Coastal eutrophication can lead to e.g. toxic 'red tides'	Minor impact	Fish stock collapse could impact food security	Minor impact via reduced carbon sink amplifying GW	Conflicts over decreasing fish stock, anomie because of livelihood and culture loss, etc	Multiple drivers with highly localised thresholds; global and regional impacts; multi-decadal to centennial timescales

Table 3.3.1: Impacts of ESTPs

Overview of impacts and challenges of the various Earth system tipping elements. Please note the anticipated timescales of tipping points unfolding until new equilibrium is reached are best average estimates. GW = global warming; red highlights are temperature thresholds that we are currently approaching, the colouring of the ESTP column signifies the expected severity of the impacts, with darker red shades demonstrating greater severity. We also note the high uncertainty around secondary impacts (see Chapter 2.3 and 2.4)

3.3.1.1 The rationale for ESTP impact governance

In many ways, ESTPs would exacerbate well-established climate change impacts, such as increasing global temperatures, changing precipitation patterns, creating sea level rise, and more frequent and intense extreme weather events. They would worsen the disruption already experienced by ecosystems and societies in all regions of the world today (IPCC AR6 WGII). However, the threats related to ESTPs are in important ways distinct from climate change impacts as we have come to understand them or alter these expected changes in surprising ways. These differences matter for how we think about dealing with impacts. In other words, the current logics, frameworks, plans, practices and resource allocation to policy domains like adaptation, international migration, disaster risk reduction, and loss and damage will have to change to account for ESTPs.

More specifically, important differences between general climate change impacts and the impacts of Earth system tipping processes concern (1) the magnitude (extent) of change, (2) the speed of change due to nonlinearity, (3) the permanence (irreversibility) of change, (4) novel types of impacts (e.g. loss of ecosystems), and (5) the global distribution of impacts, creating new vulnerabilities. There is also uncertainty about the timing of ESTPs and substantial variation in the temporal and spatial scales on which impacts are likely to unfold, ranging from 10 to 10,000 years and from local to global; see Table 3.3.1). These features stand in stark contrast with the short-term nature of political cycles and decision making, and the lack of political will and public support for precautionary action in contexts with substantial uncertainty and deferred impacts (see Chapter 3.1). The following section (3.3.2) explores these tipping point-specific issues in more detail, outlining how they challenge current approaches and institutions for governing the impacts of climate change and global environmental change more broadly.

3.3.1.2 Matching problem scales and institutions

The geographic scope of current impact governance institutions do not always match the geographic scale of the tipping elements. Earth system tipping processes take place at large (regional or continental) scales, typically affecting multiple countries (e.g. all countries with tropical coral reefs, all countries affected by the West African monsoon), but sometimes in different ways across regions (e.g. AMOC collapse would have different effects in the Northern and Southern hemispheres). This spatial scale of the tipping system has to be added to existing frameworks of multi-level impact governance (see Chapter 3.1), because dynamics at this scale will determine the spatial distribution of future impacts and the distribution of these impacts over time. Without adding this scale as a specific lens for anticipating, planning for, and responding to impacts, governance efforts will be less effective, especially at avoiding and minimising harm, and forced to react to, rather than anticipate, change.

In addition to spatial scale, the temporal characteristics of tipping processes are key for successful impact governance. Three phases of a tipping process can be distinguished: (1) pre-tipping (anticipation), (2) system reorganisation after the tipping point has been transgressed (responding to impacts), and (3) stabilisation of a new system (see Figure 3.3.1). While the prevention of tipping points (see Chapter 3.2) focuses only on the first phase, impact governance has to work across all three. Each phase presents different challenges and tasks for impact governance, requiring a distinct approach and the involvement of different actors, institutions and resources over time.

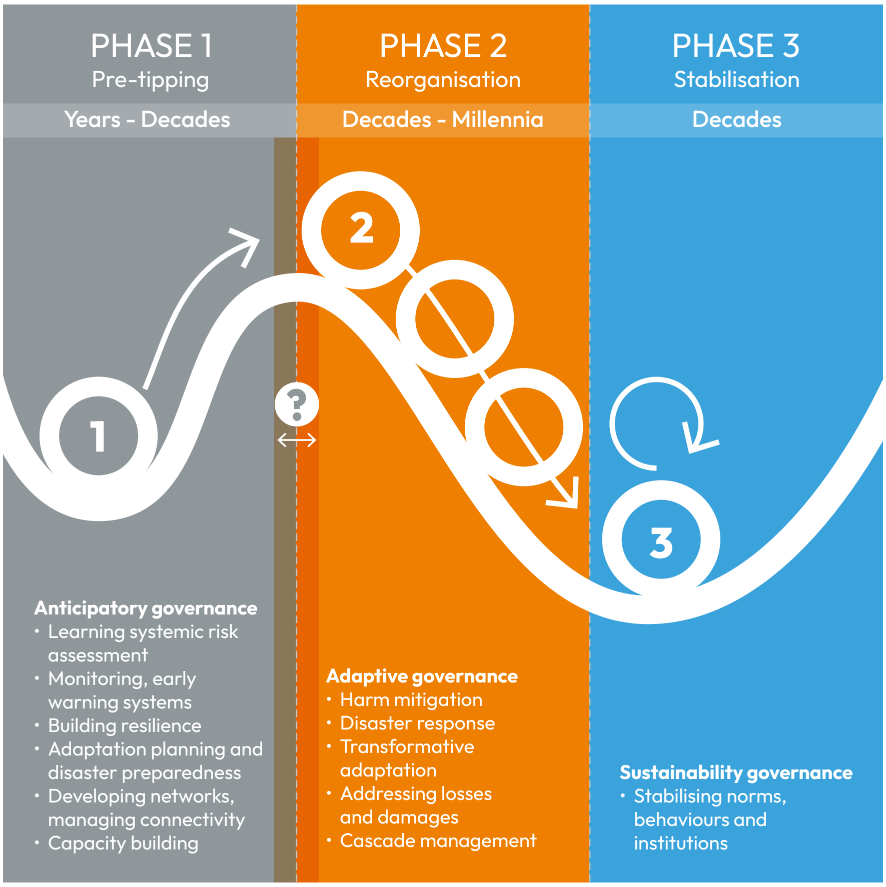

Figure 3.3.1: 3 Phases of ESTP impact governance.

Different governance approaches and tasks corresponding to three distinct phases of Earth system tipping processes: anticipatory governance in the pre-tipping phase, adaptive governance after the tipping point has been passed and sustainability governance when a new stable state has been reached.

In the pre-tipping phase (1), when a tipping system is destabilised and a tipping point might be approaching, key governance tasks include learning and knowledge-capacity building, developing early warning systems and related science-policy interaction protocols, planning and preparation for specific expected impacts, resilience building, and exploring global governance approaches for well-understood climate impacts that could be exacerbated or accelerated by tipping processes (e.g. international migration and resettlement). Network connections can be developed, including links across different governance scales to ensure well-functioning relationships in case impact governance becomes necessary in the system reorganisation phase (2). Once a tipping point has been transgressed, a period of fundamental nonlinear change – systemic restructuring – sets in, driven and accelerated by self-amplifying feedback mechanisms. In this phase, direct impacts need to be addressed, e.g. with adaptation, disaster response, or loss and damage provisions. This is a turbulent period that can extend over multiple decades or even centuries. Impact governance in this phase can be extremely challenging because of the long time period of reorganisation (e.g. multiple decades). Constantly changing system conditions would present an unreliable and unpredictable environment for decision making, disabling established modes of (adaptation) planning. This period of greater volatility would require more flexible and continuous responses by governance actors and the ability to address cascading or compounding disasters. Adaptive governance approaches with frequent learning loops, adjustments of goals and policies would be most suitable in this phase. A key aim during phase 2 is the prevention of impact cascades through multiple social systems, including negative social tipping processes (see Chapter 2.3). When the process of reorganisation comes to an end, the Earth system will settle into a new stable state, which provides an alternative environment for communities and societies. In this stabilisation phase (3), governance will be focused on stabilising human-environment relationships with new patterns of behaviours, resource extraction and corresponding institutions and decision making.

For each tipping point, each of these phases can have varying lengths. For example, the tipping point for the tropical coral reefs could be transgressed in the 2030s, limiting the remaining pre-tipping phase to about a decade. The process of repeated mass bleaching events and coral reef dieback could extend over 3-5 decades (~2035-2075). During this time, various impacts would occur in different regions and countries at different points in time. For example, reef death in a region would be followed by declining fish stocks with consequences for livelihoods, food availability and cultural identities in affected fishing communities. This could lead to changes in economic activities (e.g. transition to agriculture or migration) and social organisation (e.g. shrinking of communities, changes in family authority structures). In some locations, there would be negative effects on tourism, associated economic activities and state (tax) income. Another tipping system, such as the GrIS, would have a very different temporal distribution of the three phases. It could also reach a tipping point in the 2030s, but the second phase of reorganisation – ice melt – could last several thousand years, not settling in its new stable state on a time horizon that is meaningful for today's decision makers.

3.3.1.3 Relevant actors and policy domains

A broad set of global governance institutions is involved in addressing the impacts of global environmental change, such as climate change. Many of these will need to consider adopting responsibilities related to ESTP impacts in their mandates. This includes, for example, the UNFCCC (adaptation, loss and damage, finance, climate resilience), the CBD, the international development community, especially the UN Development Programme, and international development banks, the OECD and international financial institutions (World Bank, International Monetary Fund). Others will likely also be affected, e.g. the World Trade Organization or institutions governing international security. Impact governance is a multi-scale issue (see Chapter 3.1), with countless important actors at regional, national, and local scales (Petzold et al., 2023). Correspondingly, non-governmental and civil society organisations, transnational networks, and private-sector initiatives working in these domains will also need to consider engagement with ESTPs and their expected impacts. Below, we discuss approaches to ESTP impact governance with a specific focus on the UNFCCC and its multi-scale linkages for the governance of adaptation, loss and damage and corresponding capacity building and finance (3.3.3).

In the current pre-tipping phase of impact governance, the following questions can motivate governance actors:

- How could the international community best monitor and continuously learn about the changing risk of approaching and passing tipping points?
- What impact would the transgression of various ESTPs have on a country, community and potential migratory movements, e.g. the effects of WAIS disintegration on coastlines, coastal cities and infrastructure, expected extreme weather damage, and forced migration?
- How should the international community and individual countries prepare for and manage the passing of tipping points and their diverse consequences?
- What criteria can guide the prioritisation of measures? For example, number of affected people, critical infrastructure at risk, economic value of threatened buildings or activities.

3.3.2. Challenges of tipping point impact governance

A number of characteristics of ESTPs, especially the nonlinearity of the change process and the irreversibility of those changes, present significant challenges to current conceptions of global environmental change and the corresponding patterns and institutions to address impacts. Here, we discuss some of these characteristics in more detail. ESTPs make a major difference regarding both the magnitude of change compared to a state without tipping processes (3.3.2.1) and the speed of change expected (Lenton, 2011) (3.3.2.2). Third, the global distribution of tipping point impacts could create new vulnerabilities (3.3.2.3). Further, we discuss the potential for novel types of impact (3.3.2.4) and the permanence of change due to the reorganisation of the Earth system (3.3.2.5). Finally, section 3.3.2.6 adds important concerns about cascading effects.

3.3.2.1 Magnitude of change

Passing ESTPs can increase the magnitude of global, regional, and local changes. At the global scale, the magnitude of (eventual) sea level rise will be much increased by passing ESTPs for Greenland and Antarctic ice sheets, and the distribution of sea level height will adjust – increasing furthest away from the ice sheet that is lost (as the Earth's gravity field adjusts). AMOC collapse would cause sea level rises of up to a metre in the North Atlantic region, while SPG shift would raise them by up to 30 centimetres along the northeast seaboard of North America. Passing ESTPs can also add significantly to global warming by releasing carbon – for example, from abrupt permafrost thaw or Amazon rainforest dieback – or lowering planetary albedo – from lost cloud cover associated with the Amazon forest, or lost snow/ice cover.

At the regional scale, passing ESTPs can increase the magnitude of climate changes. For example, Amazon dieback would amplify warming and drying in the region and the neighbouring agricultural region. At the local scale, passing ESTPs can increase the frequency and magnitude of extreme events. For example, boreal forest dieback can greatly increase the severity of wildfires. These also have regional impacts on air quality.

3.3.2.2 Speed of change

Two time-related characteristics of tipping points create distinct challenges for impact governance. One is the acceleration of change during a tipping process (non-linearity). The other concerns the duration of the tipping process, which varies widely between different tipping systems (see Figure 3.1.1 and Table 3.3.1), from years (e.g. SPG) to decades (e.g. Amazon rainforest) and even millennia (e.g. ice sheets).

A tipping process involves abrupt – surprisingly fast – changes relative to the system's general patterns of development over time. Abruptness is created by self-amplifying feedback processes, which set in after the tipping point has been passed. These feedback processes increase the rate of change in the tipping system, i.e., they speed up the change process. This acceleration can have effects like higher annual rates of sea level rise and has important implications for the ability of affected communities and societies to cope with and adapt to changes (e.g. adjusting agricultural practices), and the capacity of institutions to prevent and mitigate harm (e.g. creating infrastructure resilient to quickly intensifying rain and storm patterns).

There are risks that the rate of change overwhelms existing adaptive capacities, i.e., pushes communities towards adaptation limits, or that policy measures come too late or are maladaptive (Kwadijk et al., 2010; Bentley et al., 2014; Mechler et al., 2020; van Ginkel et al., 2020; Mechler and Deubelli, 2021; Juhola et al., 2022; Schlumberger et al., 2022). For example, beyond a certain amount of sea level rise linked to ice-sheet melt, raising sea walls as a defence becomes an ineffective/unviable strategy and planned relocation must be considered (Kovalevsky et al., 2021; Sengupta et al., 2023). It is possible that social adaptation limits will be reached before biophysical ones, meaning an affected ecosystem might be capable of dealing with impacts of the tipping process, but the affected community would not (Ahmed et al., 2018).

Speed of change could also be understood in terms of the length of the change process. The amount of time it takes for a tipping system to transition to its new stable state is important for the ability of policymakers and communities to respond and adapt to the unavoidable changes. The timescale at which ESTPs can unfold is estimated to vary vastly across different tipping elements, ranging from 10 to 10,000 years. This poses immense challenges for political decision making and governance. If the tipping process occurs over a number of years or decades, the corresponding disruption of social, political and economic systems around the world could be tremendously costly and challenging to manage. This timescale could be too short for any meaningful adaptation efforts. If the changes occur over longer time periods (e.g. a century or more), adaptation processes have more time, but would struggle with identifying appropriate adaptation goals and measures because the system's new stable state would remain unknown for a long time, raising the question of what to adapt *to*. This time horizon would be too long for a consistent adaptation pathway. However, even where the timescale is very long, some effects could be felt rather soon and there would be different types of impact over time. Further, tipping processes that are perceived as slow would likely suffer from the same decision-making challenges as climate change in general: lacking a sense of urgency or motivation to act in the short term.

Combined, increases in the scope and speed of change present formidable challenges for impact governance, threatening to overwhelm adaptive and response capacities. The social-ecological impacts across various geographical and timescales might lead to 'institutional mismatches', resulting in policy measures that are poorly timed or the wrong organisational level (Walker et al., 2009).

3.3.2.3 Impact distribution and new vulnerabilities

Crossing ESTPs is likely to exacerbate existing vulnerabilities to climate change, many of which are the result of historical and current inequities. It would potentially also reveal new vulnerabilities, shifting the distributional impacts of climate change and other environmental harms. Despite a growing understanding of tipping points, there remain substantial uncertainties regarding their temporal evolution and spatial extent, which poses a challenge for efforts to mitigate their impacts (Galaz et al., 2011; Barrett and Dannenberg, 2012). Common vulnerability indices used to identify the states and communities most vulnerable to climate change, and hence most in need for adaptation (Feldmeyer et al., 2021), do not currently take into account how risks and vulnerabilities may be reinforced or redistributed or by the crossing of different ESTPs (OECD, 2021).

While we might expect that the communities identified as most vulnerable to climate change impacts are also likely to be vulnerable to some of the ESTP impacts, others will fundamentally change expected climate patterns (notably AMOC collapse) and which populations are exposed or vulnerable. Indeed, while the Global North is often depicted as less climate-vulnerable than the Global South, crossing certain tipping points would have devastating impacts on both affluent and less-affluent communities. For example, crossing the extrapolar glaciers' tipping points would heavily affect the European Alpine region, causing mega rockfalls, glacial lake outburst floods, and water shortages (see Table 3.3.1). Should the AMOC collapse, Europe would be one of the regions severely impacted, along with West Africa, India and the Amazon region (see Figure 3.3.2). The impacts of an AMOC collapse are relatively well understood, particularly in comparison to other ESTPs, as the Earth has experienced phases in its past when the AMOC was switched off. However, the projection in Figure 3.3.2 may change if several ESTPs are breached, creating compounding impacts.

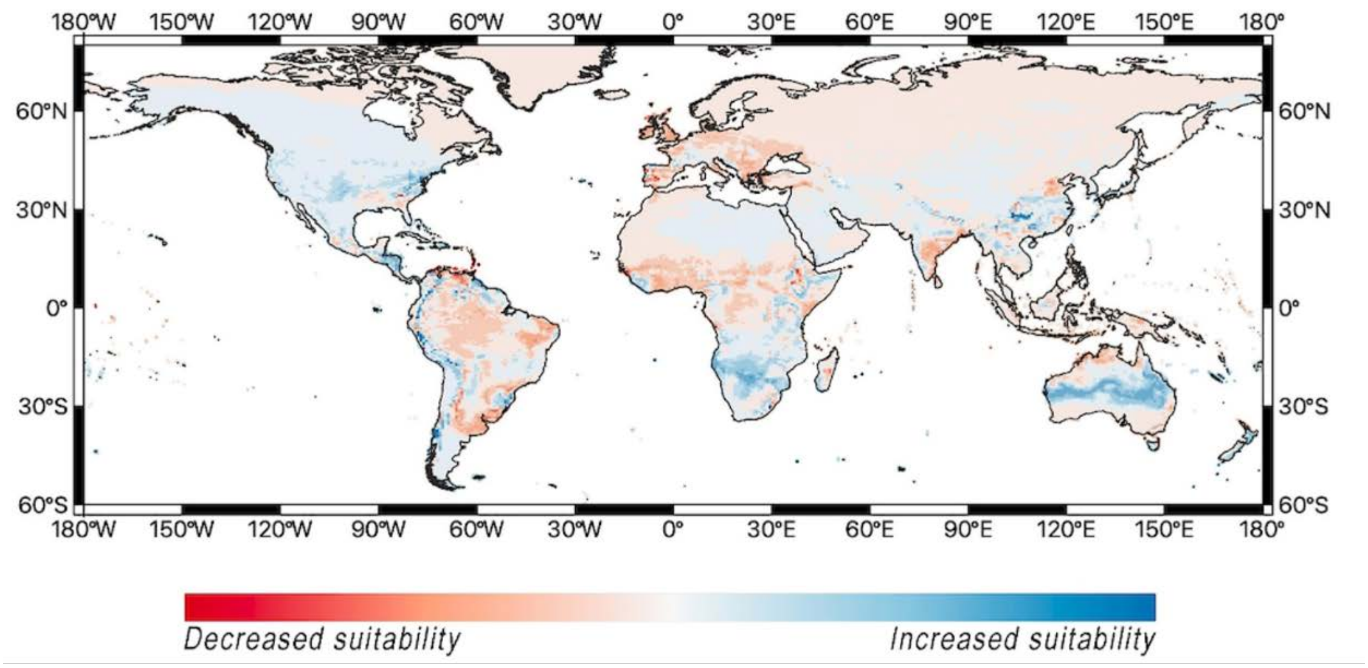

Figure 3.3.2: World map of human habitation suitability under AMOC and 2.5°C global warming.

The modelled change in the human climate niche following the simulated collapse of the AMOC after 2.5°C warming above pre-industrial temperatures according to SSP1-2.6 (Source: OECD 2021).

3.3.2.4 Novel impact types

Passing ESTPs can reverse current regional trends in climate, upsetting existing expectations, adaptation frameworks and plans. Current adaptation plans and measures may be inappropriate in the face of such trend reversals, and investments in climate-resilient infrastructure might become useless. For example, in case of a collapse of the AMOC, places like Northern Europe, that are currently adapting to marked warming and wetting, would have to adapt to radical cooling and drying instead (see Table 3.3.1 and Figure 3.3.2). Trend reversals would represent significant challenges for public communication of climate change and the justification of policy measures.

Further, the transgression of ESTPs can fundamentally alter the ecological basis of regions and livelihoods and can expose affected people and locations to novel threats. For example, the tipping of the Amazon rainforest into a savannah-like state would imply the permanent loss of the region's current ecosystems and associated loss of biodiversity, permanent changes to the region's hydrology and corresponding water availability, agriculture and power generation, and the removal of a major carbon sink. This would create tremendous cultural, economic and political disruption for all affected communities and countries, removing the foundations for much of the current organisation of social, cultural and economic life in the region (e.g. the potential for agriculture and cattle ranching). This would have radical implications for people's livelihoods, food and water security, the trajectory of industries and economic sectors, the generation of taxes, international trade and tourism, and national, regional and individual identities.

Another example is the loss of tropical coral reefs, which would impact the livelihoods of half a billion people. Loss of the fisheries they support would take away a major source of livelihood, while loss of the protection they provide to coastlines would leave them exposed to storm surges and erosion.

3.3.2.5 Irreversibility and permanence of change

A tipping point involves a shift between two alternative stable states of a system, which implies not only a fundamental (identity) change of the system in question (phase 2), but often also the stability – permanence – of the altered conditions (phase 3). For many tipping points, there would be no way back to the initial (current) conditions, at least on timescales that are relevant for decision makers today. For example, if the Amazon rainforest shifts to a savannah-like state, there would be no viable return path to a rainforest state over multiple centuries, even if temperatures were reduced back to current levels. Tipping elements such as ice sheets and related sea level rise are technically reversible, but the deposition of new glacial mass operates through a very different mechanism than those that produce ice melting. Re-establishing lost glacial mass in Greenland, for example, would thus take place on much longer timescales than the time over which current losses are occurring, and would require a decrease of the global temperature to below pre-industrial levels. The IPCC's 6th assessment report recognises the risk of irreversible climate impacts in case of temperature overshoot (IPCC AR6, WGII, SPM, 2022a), but not in a more systematic way linked to Earth system tipping processes.

The irreversibility of tipping processes is the characteristic that creates most concern among decision makers (Milkoreit, 2019), likely because it has important implications for impact governance.

First, the irreversible, structural changes associated with the crossing of ESTPs imply that **loss and damage provisions will play a much greater role** than currently recognised. Environmental conditions for human existence will be permanently altered at large scales, and current conditions – ecosystems, landscapes, natural resources, and the associated human uses and experiences of nature – will be lost. In extreme cases, these losses will be observable, like species extinctions, or the loss of a glacier or river. In other cases, the reorganisation will be more creeping, such as loss of habitable coastline, the changes to a landscape or disappearance of industries that are not sustainable in the post-tipping state. There will be a greater need for loss and damage institutions, including financing, which is already sorely lacking, to compensate for impacts that cannot be avoided by mitigation and adaptation efforts. Furthermore, as more wealthy countries grow increasingly aware of the impacts they face from the crossing of ESTPs, they may also grow wary of contributing to loss and damage funds aimed at compensating communities and countries with lower adaptive capacity.

Second, current climate change adaptation approaches might not be adequate to deal with the effects of ESTPs. Current climate adaptation frameworks focus on "reducing climate risks and vulnerability mostly via adjustment of existing systems" (IPCC AR6, WGII, SPM, 2022b). The IPCC also noted that, while there has been progress in adaptation efforts around the world, "Many initiatives prioritise immediate and near-term climate risk reduction, which reduces the opportunity for transformational adaptation." Adjustments of the current system and short-term risk-reduction measures would likely be insufficient in communities affected by profound and lasting disruptions associated with ESTPs.

The existence of ESTPs also creates risks for maladaptation, which refers to adaptation measures with adverse outcomes that reinforce, redistribute or create new sources of vulnerability now or in the future (Juhola et al., 2016; Schipper, 2020; Eriksen et al., 2021). Maladaptation can range from simply inefficient measures to those with wide-reaching negative externalities (Brink et al., 2023), including increased GHG emissions from air-conditioning in response to increasing heat, more inequitable welfare distribution or increasing social conflict (Nadiruzzaman et al., 2022).

3.3.2.6 Secondary or cascading impacts

An additional challenge is that transgressing certain ESTPs or multiple interacting tipping points may trigger not only direct impacts, but also secondary impacts or impact cascades. This can include negative social tipping points (see Chapter 2.3 and 2.4). For instance, as a result of AMOC collapse, equatorial zones could experience 'unliveable' heat, failing agriculture and water shortages, which could trigger mass displacement, poverty traps and/or political instability. Regional impacts could be further aggravated by a collapse of the West African monsoon, which could displace many people and disrupt agriculture in highly populous areas like Nigeria (see Table 3.3.1, see also Chapter 2.2). Governance should aim to avoid impact cascades and negative social tipping dynamics.

3.3.3 Governance of ESTP impacts

Guided by these challenges and the principles introduced in Chapter 3.1, especially anticipation, polycentricity/multi-scale governance, systemic risk governance, and equity and justice, here we explore where and how impact governance related to ESTPs could take place. We begin with a discussion of multiple objectives of impact governance and how to prioritise these (3.3.3.1). Sub-section 3.3.3.2 applies the concept of polycentricity to ESTP impact governance, including the need for diversity, redundancy and flexibility in response capacity. We use examples from the UNFCCC (adaptation, loss and damage) and international migration, to illustrate opportunities and challenges in the existing landscape of governance institutions, especially at the global scale. We consider cascade prevention from a systemic risk governance perspective in 3.3.3.3 and the need to generate reliable early warning signals and systems in 3.3.3.4. Finally, we discuss equity and justice implications for future impact governance efforts (3.3.3.5). This is a domain where the social science knowledge and evidence base is particularly thin, and our discussion is to a large extent speculative.

3.3.3.1 Objectives of ESTP impact governance

The core objective of impact governance for ESTPs is to prevent or minimise harm from potential tipping processes, with a special focus on preventing impact cascades. Mirroring existing objectives of adaptation and disaster preparedness, governance in this domain should aim to reduce risk and vulnerability, strengthen resilience, increase preparedness and adaptive capacity, and foster anticipatory and response capacities in relevant institutions.

It is crucial to enhance adaptive capacity and resilience in potentially affected communities and institutions to manage the significant risks associated with crossing tipping points. Given the challenges outlined above, Adaptation governance in this domain should prioritise **transformative adaptation**, which changes the fundamental attributes of a social-ecological system in anticipation of climate change (here tipping points) and its impacts (IPCC-AR6-WG2, 2022a) rather than making incremental adjustments to the existing system in response to observed changes. Transformative adaptive measures can mitigate immediate disruptions to economic and social activities, and also help prevent mid-term losses, promoting long-term human wellbeing and planetary health (OECD, 2023). More generally, transformative responses are desirable because they can simultaneously address the key drivers of tipping points, reduce vulnerability and minimise the connectivity that facilitates cascades. In turn such responses imply rapid social and cultural change (positive social tipping points, see Section 4).

One key goal of ESTP impact governance is the **prevention of impact cascades**, including negative social tipping dynamics. This is a challenging task with limited experience and expertise in existing governance institutions. Given the currently limited understanding of successful strategies for cascade management, especially the design of interventions to halt a cascade that is in progress, we suggest focusing on strengthening the resilience of societies and building adaptive as well as transformative capacity.

3.3.3.2 Multi-level, multi-phase, and multi-network governance

Responding effectively to ESTPs requires drawing on the competences and resources of actors at multiple levels, usually embedded in different organisational networks. It is important that these linkages between actors at various levels and organisations are established and functioning before a response is required (i.e. in the pre-tipping phase 1 of a tipping process, see Figure 3.3.1). It is these 'connective capacities' that allow actors to coordinate across scales, domains and sectors in response to a tipping event (Folke et al., 2005; Edelenbos et al., 2013; Galaz et al., 2016). At the same time, strongly connected, interdependent systems can be a source of instability. Care is required when building connective capacities to avoid introducing new sources of instability, abstaining, for instance, from tight coupling and instead prioritising decentralised coordination (Perrow, 1999; Scheffran, 2008; Helbing, 2013; Leonard, 2021).

Figure 3.3.3 presents a multi-level, multi-phase, multi-network governance response scheme, highlighting the importance of actors and institutions across all levels to be involved in tipping points impact governance. The multiple scales include local, regional, national and global governance institutions. The multiple phases expand on Figure 3.3.1, differentiating between anticipation, detection and four different time horizons of impact response after the transgression of a tipping point, from immediate to 1,000+ years.

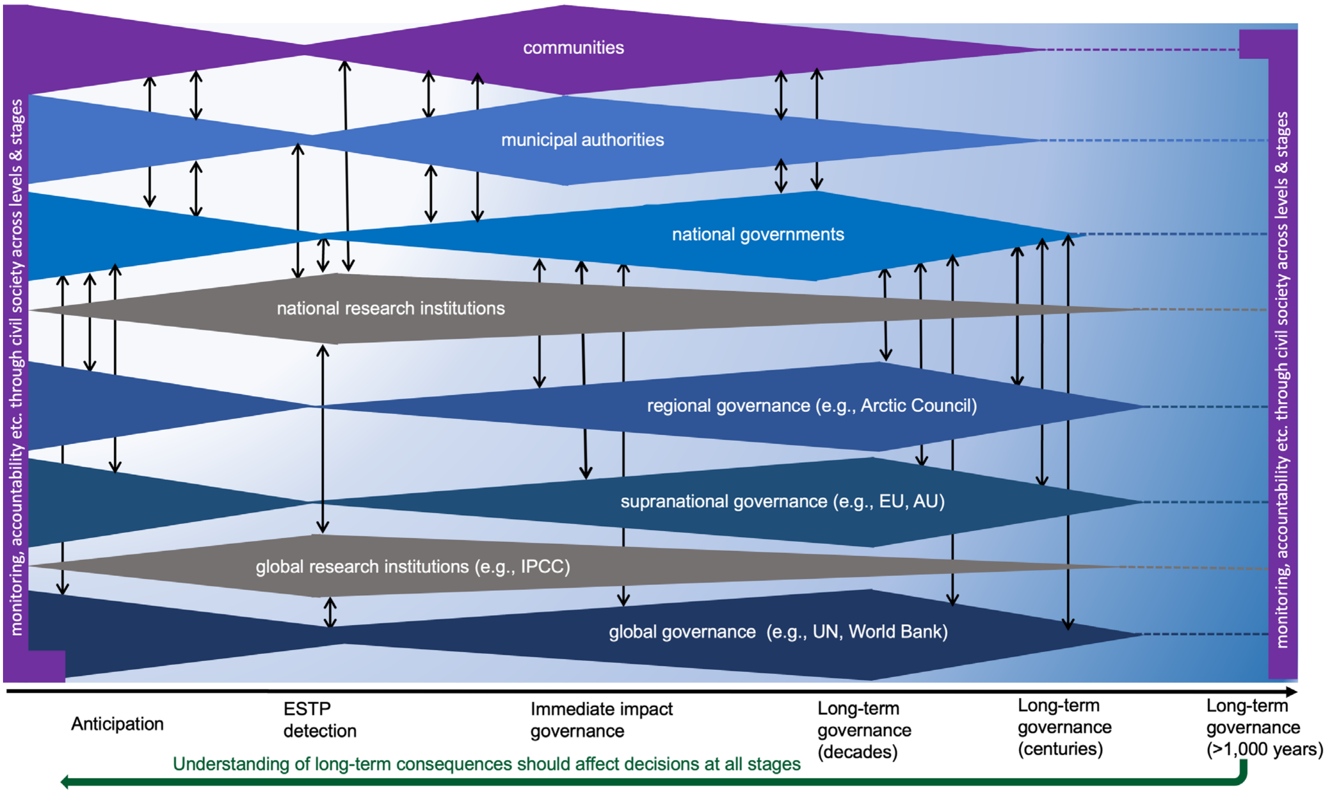

Figure 3.3.3: Multi-level, multi-phase ESTPI impact governance.

Governance institutions at local, national, regional and global level and their involvement in ESTP governance at different phases of ESTPs and their impacts. The thickness represents the importance of the respective governance institutions in a given phase. The arrows represent interactions. All interactions are two-ways with the main purpose being coordination, resource distribution, knowledge exchange and backup planning. Interactions at the regional level can include sectoral planning and cross-border initiatives. Civil society is tasked with monitoring and ensuring accountability at each governance level.

It is difficult to accurately predict the timing, scope and location of a tipping event and its various impacts. Therefore, developing and maintaining a diversity and redundancy of resources (human and economic), institutions (non-governmental to international organisations) and knowledge (scientific to local) is important to prepare for the unexpected (see 3.1.2.2). While these institutions together comprise enormous resources for problem-solving, a key challenge is to coordinate them to adequately respond to the impacts of tipping points to enable their rapid mobilisation when needed. A networked, decentralised, polycentric impact governance approach would facilitate access to these diverse resources and empower agency by balancing self-organisation and coordination (Folke et al., 2005; Bodin and Crona, 2009; Helbing et al., 2015; Galaz et al., 2016). In some instances, governance capacities and resources might be weak or lacking at particular scales or sites, or responsibilities might not be matched with required resources. Identifying and filling such gaps with a view to ESTPs will be an important component of pre-tipping governance. For example, current adaptation approaches often defer adaptation planning to the level of local governance, which has been criticised as inadequate (Nyberg et al., 2022)). This might be even more the case for ESTP impact governance. While local government and community groups are key actors in the multi-level governance set-up, they alone will not have the capacity to respond to the effects of tipping points. National governments will play a crucial role to facilitate local response in collaboration with local actors and non-governmental actors (Nyberg et al., 2022).

Multiple spatial scales: Given the diversity of tipping-point impacts and their geographic distribution, even among tipping points of the same kind (e.g. the disintegration of different ice sheets), governance efforts should carefully consider the need for tipping point-specific approaches. Further, tipping processes demand a distribution of multi-dimensional governance responsibilities in a polycentric system of actors. For some aspects of impact governance, global coordination or even rulemaking might be needed, while planning and implementation takes place primarily at other scales (OECD 2021). The case of climate change adaptation is insightful here: a global adaptation goal, information-sharing in the UNFCCC (e.g. with NDCs and reporting requirements) guide global adaptation efforts, while adaptation planning requires national and local action, and implementation is almost always a local (e.g. city-level) task. The question of resources and finance has important global dimensions (the provision of climate finance by high-income countries) and can involve international financial institutions. There are also cross-scale issues within countries, e.g. to what extent do national governments provide support and funding for local adaptation planning and measures.

In the context of ESTPs, regional governance bodies such as the European Union or African Union, but also non-government bodies such as the OECD, might play an important role in developing regional responses and cross-border initiatives. While it is not yet clear to what extent governance arrangements at the scale of specific tipping systems (e.g. West African monsoon or tropical coral reefs) is needed to support impact governance, we suggest that there would be significant benefits in coordinating activities at this scale and in learning from each other's experience of different adaptation approaches.

National governments will play an important role in identifying which tipping point risks they are exposed to and how to prepare for potential impacts. A range of existing national policy measures and activities, related to, for example, climate change adaptation, disaster preparation or immigration, will need to be updated and likely adjusted to account for ESTP risks. Further, social cohesion is regarded as a foundation for societal resilience and transformative adaptation, and should be fostered (Grimalda & Tänzler, 2018; Orazani et al., 2023). Institutional capacity building to equip local authorities and communities to respond in just ways to Earth system destabilisation is another important task for national governments.

Multiple temporal scales: Various institutions will also play different roles regarding the different phases and temporal scales of ESTP impact governance. Time-specific governance efforts range from anticipation in the pre-tipping phase (see Figure 3.3.1) to long-term governance for impacts over several hundred years in the reorganisation phase. Institutions ranging from the local to global level should be involved in pre-tipping learning, planning and capacity building. Long-term governance with time horizons beyond this century is not yet part of the toolbox of global governance in the 21st Century, and capacity building and innovation is needed in this regard. Actors like national governments and international organisations might in many cases be more suitable to this task than actors in industry or civil society due to their higher potential for continuity (see Figure 3.3.3).

Legitimacy and trust: Successful polycentric governance of tipping point impacts requires legitimacy – i.e. the shared understanding that the actions taken are fair and appropriate. Legitimacy facilitates trust, which is crucial for coordinating a networked response (Moynihan, 2008; Young, 2011; Galaz et al., 2016). One way to increase this is through public engagement in impact governance, which gives citizens agency, empowering them to develop transformative adaptation strategies and competencies to protect themselves and their communities (Oliver et al., 2023). For instance, ESTP impact governance may involve abandoning certain economic or agricultural activities in areas with ecological regime shifts (e.g. coral reef die-off or extrapolar glacier retreat) and establishing new ones. Involving local communities in decision making and transformative pathways implementation will be crucial for legitimacy and buy-in. The format and mechanisms of public engagement (e.g. online climate assembly platforms) are crucial to achieve these positive effects and avoid inequality of participation (Nisbett et al., 2022). We suggest a potential framework for community involvement based on Oliver et al., (2023) and OECD (2021) in Figure 3.3.4.

Figure 3.3.4: Community involvement in ESTP governance. The suggested scheme for community involvement in ESTP governance builds on Oliver et al. (2023) and OECD (2021) and envisions three phases: participatory systems mapping, Intervention mapping and interventions implementation & assessment. In each phase the involved actors are communities, authorities and experts.

Citizen-led adaptation approaches need to be integrated with other efforts by local and national governments within a multi-level framework. Adapting these approaches for tipping point governance likely requires the involvement of scientific experts and the acknowledgment that adaptation may not be an option in response to certain impacts (i.e. directly addressing the possibility of adaptation limits).

Box 3.3.2: Institutions for multi-level, multi-phase, and multi-network ESTP impact governance in the Amazon

Governance of the Amazon rainforest represents a complex and multi-faceted challenge due to the conflicting interests and demands placed upon its ecosystem services. Spanning the territories of nine nations, the Amazon houses various Indigenous groups, resource users and extractive industries. This multifaceted landscape has driven efforts to harmonise often-competing priorities between exogenous and endogenous forces through the institutionalisation of polycentric climate governance (PCG) approaches (Ostrom et al., 2010; Abdala, 2015). Effective governance becomes pivotal, especially when considering potential tipping points arising from the interplay of climate change, deforestation, degradation and fire (D'Almeida et al., 2007; Wright et al., 2017; Butt et al., 2020; Leite-Filho et al., 2020). The projected impacts of Amazon dieback, which could be triggered at between 2°C and 6°C global warming, are summarised in Table 3.3.1.

The triggering of the Amazon dieback tipping point would have region-wide and even global impacts. At the regional level, the main cooperation instrument deployed to promote regional coordination is the Amazon Cooperation Treaty (ACT) and its supporting forum, the Amazon Cooperation Treaty Organisation (ACTO). While ACTO has contributed to the reduction of regional discrepancies and fostered regional cooperation, its broader effectiveness as part of a polycentric governance framework remains debated. One limitation is that its membership is confined to nation states, causing some misalignment between ACTO's initiatives and the sub-national decisions of its members. This restriction also hinders the development of potential cross-boundary initiatives that could help address tipping-point drivers.

Stakeholders have responded to this absence of effective integration between regional and sub-national scales of governance through increasing participation in jurisdictional-scale intergovernmental forums, such as the Governors' Climate and Forests Task Force (GCF). The GCF currently enhances coordinated efforts against deforestation and encourages sustainable development pathways at the sub-national level (Burkhart et al., 2017). Its mandate could be extended to integrate tipping-point governance, such as water scarcity management and transformative adaptation to an ecological regime shift.

Participation of, and engagement with, local knowledge and perspectives is both a key dimension of climate justice and associated with improved governance and adaptation outcomes (Marshall, 2009; Schroeder, 2010). However, in the case of cross-scale Amazonian governance, Indigenous communities are underrepresented in decision-making protocols, particularly at the national and regional levels. The right to participate in regular ACTO meetings as observers is not explicitly afforded to Indigenous communities, nor are the latter effectively consulted in the design of policy, programmatic activities, or budget allocation (Garcia, 2011). This has decreased the legitimacy of governing authorities (Burkart et al., 2017) and undermined the effectiveness of governance efforts.

However, there are examples of effective approaches to polycentric governance in specific local contexts, where the involvement of local cooperative initiatives fosters legitimacy and social capital between stakeholders. The Brazilian state of Acre is considered as having developed one of the world's most advanced state-wide programmes for low-emission rural development, including adaptation. The state's experimentation with forest-based development and forest citizenship to address the complex challenges of sustainable forest-based development have given rise to a comprehensive approach that links policies across sectors, involves civil society, and builds institutional capacity (Schmink et al., 2014). This approach includes community and state forest management, expansion of forest-product value chains, forestry education, and technical assistance for different resource user groups (Schmink et al., 2014). Notable is the structural inclusion of the Indigenous Working Group (IWG), representing Acre's 15 ethnic groups (de Wit, 2019) in its Commission for Validation and Accompaniment (CEVA). CEVA monitors Acre's State System of Incentives for Environmental Services (SISA), which is primarily tasked with reducing emissions from deforestation and forest degradation (REDD), but which could be expanded to ESTP impact governance. The integration of the IWG in CEVA was found to have had a positive impact on Indigenous communities' internal social cohesion alongside increased trust between communities and the state.

On the other end of local-global spectrum, the question arises as to what role global institutions such as the UNFCCC could play in an Amazon dieback tipping point scenario. This would likely increase adaptation needs in the region and result in loss and damage (including loss of cultural practices, etc), suffered particularly by Indigenous communities.

(a) Impact governance in the UNFCCC

Similar to our discussion of prevention efforts (see 3.2.3), several features of climate change governance under the UNFCCC, in particular the Paris Agreement (PA), are relevant for impact governance related to ESTPs. These could be adjusted to take into account the risks of large-scale, nonlinear change processes in the Earth system. Relevant stipulations include those related to adaptation (global goal in Art. 2 (1b) and Art. 7 PA), loss and damage (Art 8 PA), finance, technology and capacity-building support (Articles 9, 10, 11), the Global Stocktake (Article 14 PA) and the obligation to regularly submit NDCs (Article 4 (2) PA).

The characteristics of tipping points and their impacts present formidable challenges for the existing global framework on adaptation. The global goal on adaptation (Art. 2 (1b) and Art. 7 (1)) sets out to enhance adaptive capacity, strengthen resilience and reduce vulnerability to climate change by supporting national-scale action. The interpretation of this goal should consider the latest scientific evidence regarding ESTPs, and the specific challenges they present (see 3.3.2). This implies, for instance, including tipping points in impact risk and adaptation needs assessments across scales and sectors, addressing ESTPs in adaptation plans and reports, and emphasising transformative adaptation. The Paris Agreement recognises the multi-scale nature of adaptation governance (Art. 7 (2) PA), and the imperative of adaptation being country-driven, taking into account major differences between affected communities around the world.

This applies in the context of ESTPs: countries need to assess their exposure to potential tipping-point impacts and determine – in a process that involves national and sub-national actors – how to prepare for and adapt to the expected changes. However, given the important scale of the tipping system, we recommend that adaptation governance increasingly considers regional coordination and cooperation regarding adaptation among all countries affected by a specific tipping process.

While the IPCC reports that progress has been made on adaptation around the world (IPCC AR6 WGII SMP 2022b), there is still a long way to go, and tipping risks have not yet been factored in adaptation strategies. There are significant risks of insufficient or maladaptive approaches, and the possibility that tipping processes push communities towards and across adaptation limits.

Based on our arguments related to Earth system reorganisations and irreversibility, loss and damage (L&D) provisions will play an ever-growing role in this domain of governance. Loss and damage is increasingly recognised as the 'third pillar' of climate change governance in addition to adaptation and mitigation (Broberg, 2021). L&D is subject of Article 8 PA, recognising "the importance of averting, minimising and addressing loss and damage associated with the adverse effects of climate change". These impacts are often described as "beyond what can be adapted to" (Huq et al., 2013; UNFCCC, 2018). As outlined above, transgressing ESTPs will make the occurrence of impacts beyond the feasibility range of adaptation much more likely.

While there is yet no official definition for L&D, a range of phenomena fall into this category, including impacts of extreme weather events, migration and displacement, and slow-onset events (e.g. sea level rise, glacial retreat, salinisation), which can cause economic and non-economic losses (NEL). The former refers to loss of income, business operations and infrastructure, while the latter concerns losses that are intangible and cannot be expressed in monetary terms. NELs are related to culture, Indigenous knowledge, sovereignty, health, or loss of territory. NELs are challenging to address or even identify, making the development of governance mechanisms difficult and slow. Given that ESTPs can result in the loss of whole territories or ecosystems, with implications for the cultural practices that were embedded in these territories and ecosystems, it is likely that breaching ESTPs would result in higher non-economic L&Ds.

Following COP27 agreements in 2022, a new L&D fund for vulnerable countries is currently being designed. ESTPs and their potential impacts should be taken into account in this process. The fund is expected to rely heavily on attribution science for any L&D claims made. If ESTPs are transgressed, the future attribution models used should include ESTPs to allow communities to make L&D claims on the basis of tipping-point impacts. Given that vulnerabilities to ESTPs are not the same as overall climate change vulnerabilities, the question arises whether (currently) affluent countries affected by ESTPs (e.g. Europe under an AMOC collapse scenario) would be eligible to access L&D funds, given they will also be expected to contribute as one of main (historic) emitters. Furthermore, the current proposals for an L&D fund tie it closely to current global finance institutions and mechanisms. Since the crossing of tipping points could destabilise the financial system (see 2.3.6), it is important to ask how the L&D fund can itself be made resilient against this ESTP impact. Finally, for L&D to effectively support communities that will be most affected by ESTPs, which often suffer from intersecting disadvantages and marginalisation, processes and actors need to be in place that can provide knowledge on L&D mechanisms and ESTPs at the local level. Empowering communities to demand compensation or other forms of support will be key for the availability of resources for re-building and transformation.

(b) Climate-related mobility

ESTP impacts are expected to increase the movement of people within and across countries. As tipping processes unfold: accelerating sea level rise, more frequent and severe extreme weather events, and the collapse of certain ecosystems and water sources are likely to increase climate-related mobility in many regions of the world. This can take different forms, including migration, displacement, planned retreat, and immobility. Voluntary migration may be an alternative to in situ adaptation, while other forms of movement, for example., forced or involuntary migration, may instead be a failure to adapt, perhaps due to insufficient public investment in adaptation measures, and a lack of anticipatory planning, leading to Loss and Damage (Pill, 2020). At the same time, ESTP impacts can increase the number of trapped or immobile populations (see chapter 2.3 and 2.4). Distinguishing among three dimensions of climate-induced human mobility-migration, displacement, and immobility-is important as each responds to different and multiple drivers, affects distinct populations, has distinct impacts, and requires different management strategies. Both those who move and those who do not move may face increased vulnerability (Black et al., 2013). Managing, anticipating, and planning for increases in temporary and permanent, voluntary and involuntary, and international and internal climate-induced population movement poses increasingly urgent governance challenges.

The ability of countries to adapt to rising sea levels varies significantly, and many coastal areas are projected to reach their adaptation limits this century, even without taking into account the transgression of tipping points. Over the past decade, weather-related events have already displaced twice as many people annually as conflict and violence, and this number is likely to grow. The United Nations International Organization for Migration (IOM) forecasts up to one billion environmental migrants by the year 2050 without taking into account the additional mobility pressures created by ESTPs. Furthermore, some nations, such as low-lying islands, are becoming increasingly uninhabitable, requiring, in extreme cases, the movement of entire populations to receiving countries. This raises new international legal questions related to self-determination and the 'right to relocation', statelessness and how to create continued political statehood after the submersion of a state's territory, and how to define exclusive economic zones or sovereign waters (Risse, 2009).

While displacement today is mostly temporary, as tipping points unfold and permanently change parts of the world (e.g., turning the Amazon rainforest into a savanna), displacement may become increasingly permanent. There is a need to anticipate these movements and understand where they are unavoidable and where they might reflect under-investment in communities. Governance reform is needed to strengthen the rights of people and obligations of governments in countries of origin, transit and destination (Kraemer, 2017). Existing reform proposals include the introduction and recognition of "climate passports'' that follow the historical model of the "Nansen Passport"— internationally recognized refugee travel documents first issued by the League of Nations' Office of the High Commissioner for Refugees to stateless refugees following WWI (BMZ, 2021).

Climate-induced mobility is a complex, dynamic, and multi-dimensional issue domain. The movement of people will happen both within and across countries, necessitating robust domestic and global governance. There is currently no firmly institutionalised global governance framework for cross-border migration. Recent progress towards such a framework includes the Global Compact for Safe, Orderly and Regular Migration (GCM) adopted by most UN member states in 2018. The GCM is a non-binding cooperation framework and provides a foundation for strengthening legal and institutional conditions for cross-border migration in the future. The IPCC has pointed to expansion of opportunities for human mobility as one measure to reduce vulnerability to climatic changes. In this context, the IPCC has highlighted that expanding opportunities for human mobility can reduce vulnerability to changes in the climate and enhance human security, particularly for exposed populations that lack resources for planned migration (Adger et al., 2014).

Planned relocation is one approach to expanding opportunities for human mobility. The planned or managed movement of communities or people away from high or at-risk areas to new locations is a specific climate mobility governance challenge with international, national, and sub-national dimensions. While one aim of impact governance is to minimise displacement through local resilience building and adaptation measures, planned relocation is likely to become increasingly necessary due to environmental changes that cannot be adapted to and due to persistent under-investment in adaptation measures (Stal, 2011; Ferris, 2012; Martin et al., 2014; Ahmed and McEvoy, 2014). As a result, planned relocation as a policy response to environmental changes has gained recent attention (Koslov, 2016; Hino et al., 2017).

Planned relocation, also referred to as managed retreat or resettlement, covers a range of cases, including the relocation of communities within a country or region (e.g., moving coastal communities to locations further inland) and across borders (e.g., relocating small-island populations to another country). This process can be driven by the community itself or happen with government support and guidance. As such, the process and associated challenges vary substantially across cases. The term is not defined under international law, and views on its key elements, including resource allocation and distribution, engagement in decision-making process, and recognition, differ among various entities including governments and legal experts. Furthermore, it challenges widely held values around freedom of movement, psychological attachments to place, and the community social fabric, and has historically been associated with racist policies and inadequate community consultation, inadequate complaint mechanisms, and limited post-relocation support (Schade, 2013; Arnall, 2019). While planned relocation has had a poor record in terms of socioeconomic impacts, it also has the potential to save lives and reduce risks (Ferris and Weerasingh, 2020). However, currently the absence of national and local frameworks, meaningful community-consultation, and sufficient anticipatory plans pose challenges for successful planned relocation efforts. Case studies suggest that planned relocation processes initiated and driven by affected communities have better outcomes than government-driven processes (Bower et al., 2023). Careful and advanced planning, legal and institutional frameworks, and adequate financial resources are also important (Ferris and Weerasingh, 2020).

In recent years, there have been a growing number of examples of sizable, planned relocation efforts that help illustrate the broad range of governance challenges associated with this approach. The government-managed relocation of indigenous tribes living on Isle de Jean Charles, Louisiana set the precedent for climate-induced planned relocation in the United States (Davenport & Campbell, 2016). The small island community lost 98 percent of its territory due to subsidence, erosion, and the construction of Mississippi River levees (Ferris & Weerasinghe, 2020), and by 2017, a large part of the population had left the island due to repeated flooding. The remaining residents, mostly members of small indigenous groups, struggled to obtain financial support for relocation due to lack of federal recognition of the tribes until receiving a grant from the US government in 2016. The Jean Charles Choctaw tribe has since released a statement (2022) that the state's handling of the relocation was conducted "without meaningful consultation with, or the explicit consent from, our Tribal leadership". Principles of consultation, consent, and support are included in the United Nations' Declaration on the Rights of Indigenous Peoples (UNDRIP), which was adopted in 2009 by all 182 states of the UN, including the U.S. The Isle de Jean Charles case illustrates the need for an organised effort by a designated (federal) agency focused on community resettlements, with greater advanced planning, more money, fewer bureaucratic hurdles, and increased sensitivity to community needs.

In 2022, the Biden Administration set a new precedent for government support for planned relocation due to climate change by allocating $75 million to relocate three Native tribes from their current tribal lands (two in Alaska and one in Washington state) (Newburger, 2022). However, the funding is insufficient to rebuild homes, schools, and other community necessities. There is still no designated federal agency to manage these resettlements, nor clear national and local frameworks to ensure that the relocation benefits communities and involves meaningful community consultation.

Other countries with sizeable areas at risk from sea level rise and extreme weather have made similar efforts, including Vietnam, the Philippines (following the devastation caused by Typhoon Haiyan), and Fiji. Some Small Island Developing States (SIDS) face existential threats from sea level rise, which will be exacerbated by the crossing of ESTPs. In 2017, Fiji had already relocated three communities to higher ground and has plans to move another 43 villages. To facilitate this process, they developed guidelines for planned relocation (Fiji and GIZ, 2018). However, it is anticipated that several SIDS may need to move their populations to other countries in the future (Vaha, 2018). In 2014, Kiribati purchased land from Fiji, becoming the first nation to purchase land in another country specifically for relocation of its people due to climate change.

As the urgency and scale of planning for the relocation of entire communities and even nations grow, a coordinated, local, national, and international governance of climate risk and adaptation will need to incorporate planned relocation among its portfolio of impact governance responses. This will require multi-level coordination both within and across countries, and the development of novel governance and legal frameworks. These frameworks might build on existing rules and provisions for the resettlement of refugees, and they might fall under the L&D mechanism of the UNFCCC. But these governance instruments will need to be adjusted to consider the relocation of entire populations, challenges related to sovereignty and self-determination, and responsibility for unprecedented losses and the substantial material, social and psychological costs associated with moving entire communities and populations.

3.3.3.3 Early warning systems

Monitoring and early warning systems (EWS) aim to indicate and signal when tipping points are being approached. Anticipatory ESTP impact governance in the current pre-tipping phase (see Figure 3.3.1) should include the development of EWS that can provide timely information about changes in Earth systems that can guide decision making. Current evidence regarding the proximity of some ESTPs justifies a range of immediate actions, including the adjustment of adaptation frameworks and plans, and the development of response capacity and network connections.

In this phase, adaptive approaches are useful to deal with the possibility of rapidly changing conditions (Franzke et al., 2022). For example, Dynamic Adaptation Policy Pathways (DAPP) (Haasnoot et al., 2013; Schlumberger et al., 2022) support adaptive actions before crossing a tipping point. EWS can support such adaptive governance with timely information about the status of the tipping system as it moves towards the tipping point. At the same time, EWS regarding the proximity of a tipping point would help actors make a timely transition in impact governance strategies to the second phase of the tipping process (reorganisation, see Figure 3.3.1). In that sense, early warning systems can support adaptive governance with rapid information flows and frequent learning loops between science and policy making (Galaz et al., 2016).

EWS can be identified not only for impending state shifts in Earth or ecological systems, but also in social systems. This type of information can be important for assessing the likelihood of ESTP impacts triggering negative social tipping dynamics.

Systematic collection of event data, expert assessments, and analyses with advanced social science techniques are important steps towards implementing EWS of negative social tipping. (Grimm and Schneider, 2011).

One area where EWS is well developed is conflict prevention. Governments can use risk and prediction models to predict violent conflicts, manage risk and consider future capabilities and responses (Muggah and Whitlock, 2022). Also advanced are early warning systems for food insecurity and famines, such as the Famine Early Warning Systems Network (FEWS NET).

There are, however, important limitations in our ability to build reliable early warning systems. Tipping points are extremely difficult to predict (see Chapter 1.6 and 2.5). While signals for moving closer to a tipping point can be detected, they do not indicate when (under what conditions) the tipping point will be reached. In many cases, scientists might only be able to observe and confirm the transgression of a tipping point years or decades after the fact. Therefore, early warning systems face major obstacles to become effective decision-support tools. There are also issues around data inequality when it comes to social tipping.

Data from low-income countries is often missing, incomplete or of poor quality. This enormously disadvantages these countries in systemic risk assessment. To address data inequality, it is important to support low-income countries in building capacities for data collection and analysis.

3.3.3.4 Cascade governance

As outlined in Chapter 1.5, the linkages between different ESTPs create the potential for cascading dynamics, where one tipping process triggers one or more others. The same cascading potential exists in highly connected human systems – i.e. complex networks of economic, technological and social interactions that span across borders and sectors, underpin the functioning of our globalised world (Helbing, 2013 ; Centeno et al., 2015, Homer-Dixon et al., 2015). The 2008 financial crisis demonstrated the systemic risks posed by highly interconnected global financial markets. Interlinked financial institutions and complex derivatives markets meant that the failure of a few single entities could trigger a cascade of failures, leading to a global economic downturn (Ruhl et al., 2020). The cascading dynamics in Earth and human systems can interact, so the passing of an ESTP can trigger cascading failures in social and economic systems (see Chapter 2.4), drawing attention to the couplings between them. For instance, persistent extreme weather events and increasing sea level rise from the crossing of an ESTP can result in mutually reinforcing crises within the agriculture, infrastructure and financial sectors. Recently, the term polycrisis has been used to describe such conditions where multiple crises occur across interconnected global systems (Homer-Dixon et al., 2021).

Cascade governance is a form of systemic risk governance (Schweizer and Renn, 2019), which recognises that systemic connections can act as transmitters and pathways of risk, making highly connected systems vulnerable to chain reactions that are hard to predict (Juhola et al., 2022). The central objective of cascade governance is to minimise the risk of cascading dynamics by managing systemic linkages, including by deliberately decoupling subsystems, slowing down flows (of materials or information, for example) and ensuring transparency and traceability of chain processes in a participatory and polycentric manner (Galaz et al., 2017; Nyström et al., 2019). Depending on the system in question, this might demand a set of regulatory measures. For instance, to manage the danger of systemic risk within the banking sector, where the collapse of an individual bank can have contagion effects, macroprudential regulations have been suggested (Renn et al., 2019; Lamperti et al., 2019).

Other measures include strengthening the absorptive capacity of each of the nodes in the financial network in response to external shocks by requiring higher capital and liquidity ratios, and encouraging modularity and diversity in the sector (Haldane & May, 2010).

Cascade governance is challenging and not yet a capacity or toolset widely available to policymakers around the world. Both predictive abilities regarding complex system behaviour and an understanding of the effectiveness of possible interventions (such as weakening or breaking key links between systems to stop a cascade in progress) are limited at this point. Further, there are psychological tendencies to underestimate and neglect systemic risks (Schweizer et al., 2022). Given these limitations, the primary goal of cascade governance regarding ESTP impacts should be prevention. This can have two dimensions: preventing the transgression of ESTPs as triggers of social-ecological cascades (see Chapter 3.2) and preventing cascading dynamics in social systems by building resilience to environmental pressure due to ESTPs.

Since prevention cannot always be guaranteed, cascade governance requires the development of comprehensive crisis preparedness plans that account for the potential ripple effects of systemic risks. Regular systemic risk assessments are needed to identify potential vulnerabilities and interdependencies within critical systems. Monitoring and early warning systems are valuable in this context (see 3.3.3.3), and should be combined with other tools, such as dynamic network mapping and iterative learning dialogues (Keys et al., 2019). Further, to address the deep uncertainties regarding tipping points and cascading risks, flexible governance approaches perform best where resources can be mobilised rapidly, aims and activities can be adjusted within networks of actors, and communication flows effectively – e.g. between private-sector organisations and government agencies. This should also include the development of redundancy and back-up systems within critical infrastructure and supply chains to ensure that essential functions can continue in the face of severe disruptions.

Cascade governance should therefore be seen as part of transformative responses which simultaneously deconstruct vulnerability, reduce the connectivity through which cascades can be transmitted, and reduce the key drivers of ESTP events (notably GHG emissions). Such responses imply rapid social and cultural changes (see positive social tipping points – Section 4).

3.3.3.5 Justice, equity and distribution of vulnerability

Climate change adaptation and mitigation measures have led to resistance from local social groups in the past, as they are often implemented top-down even where participatory language is used, entailing relocation, privatisation of resources, threats to traditional identities and norms, subordination and norm compliance, further weakening the agency of already-vulnerable groups (Woroniecki et al., 2019; Brink et al., 2023; Rudge, 2023). Any impact governance needs, therefore, to respond to concerns around equity and justice (Rudge, 2023). As Stoddard et al., (2021) write, that "powerful and affluent groups may opt for personal protections, rather than joint responses that secure communal benefit, has already been seen in concerns about exclusive adaptation that protect the privileged at the cost of those who are most vulnerable. The capacity for inequality to concentrate life-threatening harm in marginalised communities appears to have played a central role in social upheaval, including the 2008 financial crisis, as well as in societal collapses".

As we have noted, the distribution of vulnerability to impacts from ESTPs does not necessarily follow the same distribution pattern of vulnerability to climate change, but the capacity to adapt, whether to climate change in general or to ESTPs, is extremely skewed towards rich countries and affluent population groups, which makes impact management an issue of justice and international and national politics.

Moreover, human actions can produce or reinforce vulnerability or exposure, for instance when early warnings fail to reach affected populations or when marginalised groups are denied access to evacuation shelters (Otto & Raju, 2023). Recent trends in privatisation of adaptation, however, seem to only worsen the inequality with respect to adaptation (Nyberg et al., 2022). Many countries in the Global South are currently locked in inadequate adaptation due to constraints under the current international financial mechanisms (see Figure 3.3.5).

To avoid adaptation becoming a mechanism for protecting privileges, strengthened political commitment to transformative, just adaptation is needed. Social movements can play an important role in this context.

They can create pressure on governments through direct action, raise public awareness, and facilitate the monitoring and evaluation of adaptation progress (IPCC AR6 WGII 2022a). Furthermore, looking at potential synergies between mitigation and adaptation efforts that focus on social justice is important in order to not perpetuate inequities and past injustices (Ripple et al., 2019).

Figure 3.3.5: Financial barriers to ESTP preparedness in the Global South. This diagram of financial barriers for building ESTPs response capacity faced by the Global South is an adaptation of a diagram of financial barriers for mitigation and adaptation faced by the Global South, created by Goswami & Rao 2023. It captures various vulnerabilities and inequities linked to financial mechanisms that disadvantage Global South countries in their ability to prepare for ESTPs.

3.3.6 Final remarks

ESTP impact governance is currently underdeveloped, both in research and practice. Research and knowledge co-production on this topic are urgently needed as well as corresponding capacity-building among relevant stakeholders across scales – for example, global, regional and national governance institutions for climate change adaptation. Several distinct characteristics of ESTPs pose formidable challenges for impact governance, including the speed and time horizons of tipping processes, the emergence of new vulnerabilities, and the irreversibility of many impacts. Combined, these characteristics imply that ESTPs could quickly exceed adaptation limits, capacities for dealing with different kinds of migration, and current disaster risk management capabilities.

This chapter begins to develop a framework for multi-scale, multi-phase impact governance that takes these characteristics into account. ESTP impact governance should seek to minimise harms related to tipping processes, including by preventing cascading dynamics in coupled Earth and human systems. Impact governance for ESTPs is relevant across a broad set of issue domains and the corresponding institutions and actor communities, including climate change adaptation, international development, migration, human rights and disaster risk preparedness. Effective governance will require aligning existing institutions at various levels and extending their mandate, but also creating potentially new initiatives and processes.

3.4 Knowledge co-production and science-policy engagement

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Summary

Knowledge production and learning related to ESTPs face significant challenges, with implications for effective science-policy interactions. Scientific knowledge about ESTPs is increasingly reflected in IPCC assessment reports, but governance actors are not yet using this growing knowledge base sufficiently. Lack of awareness, misconceptions and learning challenges limit the demand for, and use of, existing scientific insights. At the same time, engagement with tipping points in the social sciences and humanities is lagging.

The knowledge needed to understand, assess and support governance efforts related to ESTPs in a polycentric setting must be solutions-oriented, context-specific and actor-relevant. Anticipatory knowledge and related capacities for making sense of and acting with regard to uncertain futures (e.g. complex systems thinking) are essential tools for decision makers. Currently dominant patterns of knowledge co-production and science-policy engagement do not foster learning and anticipatory capacity-building sufficiently to generate robust and actionable knowledge for policy. To effectively support governance efforts related to ESTPs across multiple scales, knowledge production should be inter and transdisciplinary, and increasingly participatory. Developing capacities for anticipation requires expanded use of methods like participatory scenario development, roleplay simulations and storytelling, which combine quantitative and qualitative data, foster participants' ability to deal with uncertainty, and strengthen long-term agency.

Experiments with some of these approaches are currently taking place in global knowledge-generating institutions like the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). However, more profound changes to current science-policy interface institutions and processes will be needed to support effective decision making on ESTPs. The needed knowledge-production and capacity-building processes are more resource intensive and require more time (longer and more frequent engagement) than common science-policy interactions. They are also difficult to include in the scope of international institutions like the IPCC. Regional (e.g. Arctic Monitoring and Assessment Programme) and national scientific organisations (e.g. national academies of science) and policy advisory bodies might be best suited to drive innovation and progress in this domain.

Key messages

- To support effective governance of Earth system tipping processes, solutions-oriented, context-specific, actor-relevant and anticipatory knowledge is needed. Existing international knowledge institutions (e.g. the IPCC) need to be reformed to better support this kind of knowledge production.
- Currently, knowledge gaps are biggest in the social sciences and humanities.
- Learning challenges specific to tipping points are significant and could slow down or impede effective governance and public engagement.
- Anticipatory knowledge and related capacities are weak and require time and resource-intensive knowledge co-production processes.

Recommendations

- International organisations, national governments and science funders should foster urgent international research collaboration, especially in the social sciences and humanities, by promoting open, interdisciplinary, solutions-oriented, networked knowledge co-production systems focusing on ESTPs.
- Regional and national science and knowledge institutions (e.g. national academies of science, EU foresight initiatives) should foster anticipatory capacity building with participatory co-production processes involving policymakers, scientists, other knowledge holders, artists and designers.
- Governments should provide funding to support knowledge co-production and anticipatory capacity building. Individual decision makers and governance institutions should dedicate more time and resources to these processes.
- A core goal of knowledge co-production should be the translation of scientific knowledge regarding the temporal and spatial scales of ESTPs into actionable understanding of feasible options across scales and actor types.
- The IPCC should develop a special report covering climate tipping points and elevate discussions of tipping points in future assessment cycles, including in summaries for policymakers.

3.4.1 Knowledge needs, status quo, and learning challenges

3.4.1.1 Knowledge needs

Responding effectively to the current and future risks associated with Earth system tipping processes requires governance actors to leverage dynamic knowledge production systems for political decision making, policy and institutional design. The mobilisation of the 'best available knowledge' is recognised in the Paris Agreement (Article 7.5), encouraging interactions between different knowledge systems for enhancing climate resilience and effective adaptation.

Governance actors need to develop and frequently update a thorough and actionable understanding of Earth system tipping processes, their characteristics, differences, and likely implications for societies. Such an understanding should be based on, and evolve with, scientific information, but also other forms of knowledge, beliefs and values that contribute to meaning making. The knowledge needed to support future governance efforts should be specific for diverse actors, taking into consideration the scale and context of needed action. Hence, effective science-policy interactions at all of these scales are crucial for the adaptive, multi-scale and anticipatory governance of Earth system tipping processes.

Knowledge and continuous learning are integral to the capacities needed to anticipate and prevent harmful tipping points in the Earth system. Other capacities needed include systems thinking (conceiving of and governing the Earth as a complex interconnected system), imagination (envisioning possible futures, including pathways and solutions to address challenges related to Earth system tipping) and institutional entrepreneurship (creating initiatives within existing institutions or establishing new ones to help anticipate and prevent ESTPs). Science-policy institutions rarely focus on these capacities, and most political and knowledge institutions do not provide incentives to invest in their development.

3.4.1.2 Status quo

Scientific knowledge about ESTPs has expanded significantly over the last 20 years, with most of this research conducted within the natural sciences. This report's scope provides a broader lens than previous work, including additional Earth system tipping elements (Table 1.7.1 & Figure 1.7.1). While modelling efforts are expanding, many Earth system and climate economy models today still lack representations of tipping dynamics, especially couplings between social and biophysical processes (Franzke et al., 2022). At the same time, despite the research summarised in Section 2, there is a significant knowledge gap regarding the social and human dimensions of Earth system tipping, from expected impacts, risks and vulnerabilities to implications for decision making and governance, including framing effects, actor motivations and the role of political power.

Given that this solutions-oriented knowledge is essential to support the development of a governance and policy agenda on ESTPs, its scarcity is a reason for concern.

The IPCC has addressed climate tipping points since its third assessment report (AR) with varying terminology (see Box 3.4.1). The topic received growing attention in more recent assessment cycles, but has not yet led to active engagement among international or national policymakers, with tipping points not yet part of the UNFCCC negotiation agenda (Milkoreit, 2015; 2019).

Box 3.4.1: Tipping points and the Intergovernmental Panel on Climate Change

The IPCC first addressed climate tipping points in its 3rd Assessment Report (McCarthy et al., 2001), using the terminology of 'large-scale discontinuities' in the report of Working Group II (Impacts, Adaptation and Vulnerability). Tipping points were included in a set of 'reasons for concern', visualised in the 'burning embers' diagram that later motivated the selection of the 2°C temperature goal (Leemans and Vellinga, 2017). At this time, the IPCC concluded that tipping points would only become likely if global average temperatures exceeded 4°C.

The burning embers were not included in AR4 (2007), but scientists independently published an updated figure in 2009 (Smith et al., 2009). It returned in the AR5 WGII Summary for Policymakers (Field et al., 2014), which referred to 'large-scale singular events' as a reason for concern, or RFC. AR5 Working Group I defined tipping points as Earth system components that are 'susceptible to abrupt or irreversible change', focusing on irreversibility and the likelihood of the occurrence of tipping points in the 21st Century (Collins et al., 2013). More than a decade after AR3, the IPCC updated its risk assessment for the transgression of tipping points, stating that they "become moderate between 0-1°C additional warming *[above 1984-2005 average]*, [...]. Risks increase disproportionately as temperature increases between 1-2°C additional warming and become high above 3°C, due to the potential for a large and irreversible sea level rise from ice sheet loss" (Field et al., 2014; Assessment Box SPM.1). AR5 also contained a table listing nine Earth system components that are "susceptible to abrupt or irreversible change" (IPCC AR5 WG I, 2014 Table 12.4, p.1115). These included AMOC, ice sheets, and tropical and boreal forest dieback. Lenton et al., (2019) showed how the IPCC's risk assessment of tipping points had changed over time (Figure 3.4.1).

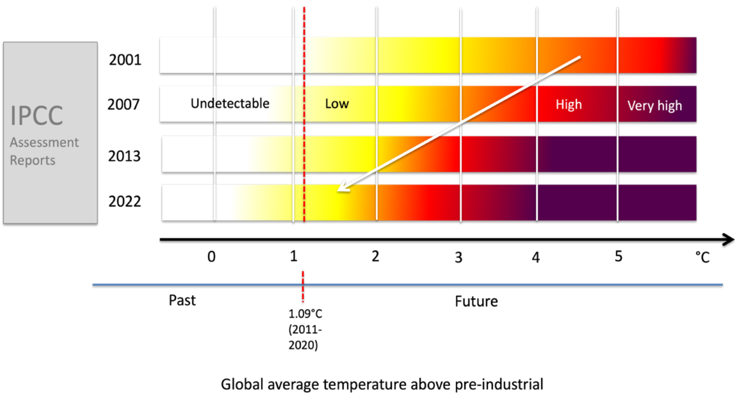

Figure 3.4.1: Changing risk assessment of tipping points in IPCC reports over time. The IPCC has assessed the risk of tipping points ('large-scale singular events') as one of five 'reasons for concern' in a bar graph ('burning embers') to motivate climate action in most of its assessment reports since 2001. Colours indicate levels of risk from white (undetectable) to yellow (low), red (high) and purple (very high). Each AR increased the level of risk expected for a specific level of warming.

AR6 (2021-2023) updated the burning embers diagram (IPCC AR6 WG2, 2023 Fig. SPM.3 a&b), maintaining the language of 'large-scale singular events' (RFC 5). The IPCC's WG I defined a tipping point as "a critical threshold beyond which a system reorganises, often abruptly and/or irreversibly". It also used the related term abrupt climate change, defined as "a large-scale abrupt change in the climate system that takes place over a few decades or less, persists (or is anticipated to persist) for at least a few decades and causes substantial impacts in human and/or natural systems". (IPCC, 2023). AR6 WGI sometimes uses 'tipping point' to refer to a class of abrupt change in which the subsequent rate of change is independent of the forcing [1.4.4.3 of (AR6 WG1 Ch1]). AR6 assessed the risk of tipping point transgression as moderate today (at more than 1°C warming above pre-industrial levels), becoming high around warming of 2°C, and very high beyond 2.5°C.

The IPCC's WG I provided an updated table (4.10) of "components in the Earth system that have been proposed as susceptible to tipping points/abrupt change, irreversibility, projected 21st Century change". This table includes 15 items, including some that do not fall under the definition of a tipping point, e.g. global sea level rise (an outcome of ice sheet melting with no clear threshold for system reorganisation in itself).

Tipping-related knowledge and expertise outside of the academy is still limited, but growing. For example, international organisations like the OECD and World Meteorological Organization (WMO) are developing expertise and programmes with a focus on climate tipping (OECD, 2022), some scientific advisory bodies are building tipping-related capacity (Science Advisory Panel to Member States at the WMO Executive Council). These growing knowledge-production efforts need to be translated into tangible decision-making support for governments and other actors.

At this point, ESTPs only play a minor role in scientific assessments, policy debates and public discourse, and stakeholders are not making good use of available scientific knowledge. Widespread lack of awareness and misconceptions around tipping points (Milkoreit, 2015; 2019) limit the perceived need and corresponding demand for knowledge about ESTPs among policymakers. In this situation, scientific knowledge production also tends to be insufficient (Weichselgartner and Kasperson, 2010).

3.4.1.3 Learning challenges

Tipping points present a set of **specific learning challenges that could undermine governance efforts**. Nonlinear state changes are a feature of many complex Earth system components (Young, 2012; 2017), which require complex systems thinking, often involving a fundamental change in decision makers' assumptions about reality and the nature of change (i.e. an ontological shift) from a mechanistic, linear and simple single-cause model to one centring emergence, nonlinearity and multi-causality. As Renn (2022) notes, tipping points are a type of systemic risk that render trial-and-error approaches to learning useless, demanding novel approaches to learning, such as immersive game-based techniques.

ESTPs occur at unusual spatial and temporal scales, for which common governance approaches are unsuitable. Tipping systems, including ocean circulation patterns or transboundary ecosystems, introduce a distinct spatial scale for governance that often cross national and even continental boundaries – for example, the Amazon basin, Atlantic Ocean or Arctic. In the absence of governance institutions or polities representing all relevant actors for this specific scale, knowledge development is challenging. For some tipping systems, such as ocean currents, scale-specific knowledge producers are scarce or disconnected from decision making. The multiple timescales of Earth system tipping, including extremely long time horizons, present profound challenges for learning, assessing and valuing potential future outcomes and for including timescale considerations in present-day decision making and governance.

The production of scientific knowledge involves dealing with uncertainties, some of which cannot be reduced through further research. This applies to ESTPs. We might detect signals that a system is approaching a tipping point, but not be able to predict when and under what specific conditions the threshold will be reached. For 'slow' tipping systems, science might not be able to state whether or not a tipping point has been crossed for decades, and given that there may be no clearly established or observable 'event' indicators at the time the threshold is crossed, tipping points may be passed with no notice. The limitations of scientific knowledge about tipping points in turn have significant implications for governance, dramatically elevating the need for precaution, an expanded toolbox for dealing with uncertainty, and processes to create anticipatory capacities such as decision makers' abilities to engage in long-term thinking. At the same time, there is evidence that this kind of uncertainty inhibits cooperation and collective action (Barrett and Dannenberg, 2012; 2014; Schill, Lindahl, and Crépin, 2015).

Some of the key questions that remain to be clarified when co-producing knowledge about tipping points include:

- How can actors identify critical information?
- What criteria should guide action priorities amidst an increasing number and severity of Earth system tipping processes?
- How can we attend to long-term processes despite short-term political pressures?

3.4.2 Needed knowledges and knowledge production

Much research on tipping points has focused on global and damaging biophysical trends, rather than on the human and social dimensions of Earth system tipping, including likely social impacts, responses, solutions and governance options. Future knowledge production should consider not only the content, but also the characteristics, of the information needed to support decision making. Below we first address key knowledge characteristics (solutions-oriented and actionable, context-specific and actor-relevant, future-oriented/anticipatory, and transformative). We then consider which knowledge-production processes and systems would be needed to support the development of this type of knowledge regarding ESTPs, including co-production and effective sharing in knowledge networks across scales, and to foster imagination and anticipation.

3.4.2.1 Knowledge characteristics

For knowledge related to Earth system tipping to be useful in governance processes, it has to be solutions-focused (O'Brien, 2013), actionable, relevant to the actor in question, and legitimate (Cash et al., 2003). While these criteria apply to knowledge production for sustainability more generally, anticipatory and transformative capacities should be added and emphasised in the context of ESTPs.

Solutions-oriented and actionable: Solutions-oriented knowledge involves a shift from investigating the nature of ESTPs (their causal dynamics and likely impacts) to actively seeking practical solutions such as prevention and adaptation strategies, with the aim to foster agency and help actors identify and evaluate action options (Tengö and Andersson, 2022; Andersson, 2022; Lang and Wiek, 2022). Actionable knowledge emphasises the application of scientific insights to develop strategies, technologies and policies that address specific challenges related to tipping points (e.g. uncertainty regarding their timing) and improves societal outcomes (Mach et al., 2020).

Context-specific and actor-relevant: This kind of knowledge is situated within particular circumstances and takes into account unique contextual factors and place-specific cultural norms. For example, in the case of ESTPs, there is an immediate need to develop information and tools that allow actors in different countries and at different scales to identify which tipping points are relevant for them, because they might be impacted by them or because of their own capacity to reduce tipping risks. By acknowledging and taking into account relevant practitioners' and researchers' diverse perspectives and linking abstract knowledge about tipping processes with case-specific insights, context-sensitive knowledge can be generated that is relevant and meaningful to the actors applying it.

Anticipatory: Future-oriented and anticipatory knowledge involves harnessing both individual and collective imagination to envision a wide range of potential scenarios and future developments. This approach goes beyond extrapolating from current circumstances and uses creative thinking to collectively anticipate diverse future possibilities (Wiek and Iwaniec, 2013; Dufva, Könnölä, and Koivisto, 2015; Iwaniec et al., 2020; Pereira et al., 2021). By combining this with existing knowledge, researchers and stakeholders can better prepare for emerging challenges and opportunities. This forward-looking perspective can enable the development of strategies and solutions that are robust, adaptable and proactive in addressing future needs and uncertainties (Pereira et al., 2021).

Transformative: Transformative knowledge is oriented to address the ultimate systemic causes of unsustainability: the social structural drivers of climate change, such as persistent inequalities in resource consumption and access, or the distribution of rights and responsibilities. This often involves developing systems thinking and questioning deep assumptions about individual or organisational practices and their social and environmental effects. Promoting second-order learning is central in transformative learning: not just doing the same faster and better, but exploring how things could be done differently under a different paradigm or worldview. Correspondingly, there is a focus on solutions in the domain of worldviews, practices and institutional structures, and on capacity building that supports transformational change across scales (Fazey et al., 2020).

Knowledge with these characteristics would empower governance actors to develop and implement scale- and context-specific governance solutions for ESTPs. Corresponding knowledge production – within and beyond science – should foster these characteristics.

3.4.2.2 Knowledge-production processes

Knowledge production to support the governance of Earth system tipping processes should be multi-, inter- and trans-disciplinary to facilitate **knowledge co-production between scientific and non-scientific actors** and provide concrete decision support tools (Thompson et al., 2017; Mach et al., 2020; Latulippe and Klenk 2020; Turnhout et al., 2020; Pohl et al., 2021). Co-production can be defined as "iterative and collaborative processes involving diverse types of expertise, knowledge and actors to produce context-specific knowledge and pathways towards a sustainable future." (Norström et al., 2020). It recognises that scientific ideas evolve together with social identities, political discourses and institutions.

Participatory approaches to knowledge production have a number of benefits regarding tipping point governance. They enable co-production by engaging participants with different expertise (scientists, policymakers and other stakeholders), promoting active learning and anticipatory capacity building (Galende-Sánchez and Sorman 2021). This approach enables relevant frame development, fosters inclusiveness and – depending on the selection and power representativeness of the participants – the use of context-specific expertise (e.g. local knowledge) with actor-relevant outcomes. Second, participatory approaches can mitigate some of the specific learning challenges related to tipping points. For example, dynamic simulation exercises provide opportunities to virtually experience the passing of tipping points, especially their time-related characteristics like nonlinearity, to identify lessons for governance and risk management today.

Building situated and context-specific knowledge for the governance of tipping points at different scales of action entails moving away from linear, flat notions and gap-filling modes of learning. Knowledge development needs to happen in a **distributed** fashion, at different scales of action and taking into account context-specific factors. Multi-scale knowledge-production systems facilitate the generation of solutions-oriented knowledge that can easily be shared in a distributed network and adjusted in different locations.

Rapid and effective knowledge sharing and information flows are essential for polycentric, networked governance approaches to ESTPs. A fundamental concern is the need for transparency and open access to scientific knowledge, especially climate models. Open models and data access allow knowledge users to better understand model results and adapt them to their own context. Open-source platforms like Wikipedia or GitHub have an important role in this context. Further, there is a need to connect and integrate different kinds of knowledge generated in distributed networks of agents who work, learn and share their experiences in managing complex systems' dynamics at different scales of action. This integration work could take the form of transformative boundary organisations (Tàbara et al., 2017), which purposefully integrate multiple sources of knowledge and focus on complex-systems thinking and learning.

There is an increased need for **processes** that can engage governance actors in future thinking and related **capacity building for anticipatory decision making** about ESTPs. This can be facilitated by bringing decision makers into structured conversations with academics as well as artists and storytellers to facilitate structured, transdisciplinary exploration of multiple possible futures (Galafassi et al., 2018; Galafassi, Tàbara, and Heras, 2018). The aims of 'futures' work include widening understanding of plausible and feasible developments based on the anticipation of interactions between a range of environmental, political, economic, technological, scientific and social factors, and challenging the assumptions embedded in conceptualising the future. Such processes help decision makers switch their mode of thinking about the future from predictive to anticipatory and facilitate a reorientation from navigating 'what will be' to thinking through alternative 'what-ifs'. They can also help participants identify policy instruments that may be robust across a range of plausible futures (Gabriel 2014; Pereira et al., 2021).

Fostering complex systems thinking has to be a key component of governance systems for Earth system tipping processes.

Complex systems thinking is fundamental for understanding and effectively addressing tipping dynamics. It provides not only analytic capacities regarding the causes and characteristics of tipping processes, but enables the systemic search for solutions.

Science-policy engagement on tipping points thus requires novel approaches that **involve unconventional mixed methods.** A combination of qualitative scenarios, expert judgements, roleplay simulations and agent-based models, and even fictional narratives and storyline development, should be used more frequently to complement the physical modelling approaches most commonly used to create knowledge about ESTPs (Gambhir et al., 2019; Elsawah et al., 2020; van Beek, Milkoreit, et al., 2022; Pereira et al., 2021; Pereira et al., 2023). This diverse range of approaches can support the search for response strategies that are robust to a broad range of possible future outcomes. Some illustrative examples of such novel methods are outlined below…

Role-playing simulations and 'serious games' can effectively support learning about complex systems, including the temporal dynamics of complex change processes like Earth system tipping dynamics over multiple decades (van Beek et al., 2022). Beyond knowledge, serious games can affect players' risk perceptions and agency, fostering anticipatory decision making. Simulations already play an important role in supporting decision making under uncertainty (Flood et al., 2018; Mangnus et al., 2019; Edwards et al., 2019; Fleming et al., 2020; Galeote et al., 2021).

Participatory, multi-scale scenario development involves creating a range of plausible future scenarios that encompass different trajectories of change. These scenarios can span different scales, and help in understanding how different drivers interact and shape potential outcomes in the short and long term, including cascading effects. This approach draws on knowledge from various disciplines and sectors (environmental science, sociology, economics, politics, and local and Indigenous communities) and integrates both quantitative and qualitative methods. The method can foster learning about the dynamics and impacts of ESTPs across different timeframes and geographical scales, illuminating, for example, how vulnerability to impacts is distributed across space and time. By considering multiple timeframes, researchers and policymakers can identify critical time-sensitive interventions and develop response strategies that will be robust across a range of potential future outcomes, thus linking knowledge development to decision making. The scenario development process should be participatory, enhancing the role of stakeholders to facilitate mutual learning and co-production of actor- and context-relevant knowledge (Biggs et al., 2007; Shaw et al., 2009; Elsawah et al., 2020; Kliskey et al., 2023; Lazurko, Schweizer, and Armitage, 2023).

Combining **multi-scale scenario development** with other forms of **qualitative engagement** can support the assessment of near- and long-term impacts, response capacities and vulnerabilities (i.e. using surveys and online democracy tools with many participants, and small focus group deliberation). This approach can capture diverse perspectives beyond academic expertise, including local or Indigenous knowledge, and contextual insights that can generate a deeper understanding of the social, cultural and ethical dimensions of governing Earth system tipping processes. Iteration is important for this approach, with scenario development and qualitative engagement informing each other (Alcamo, 2008; Trutnevyte et al., 2019; Prehofer et al., 2021; Pereira et al., 2023; Jahel et al., 2023).

3.4.3 Effective science-policy interactions for tipping point governance

Linear models of knowledge transfer from science to policy are outdated and have limited explanatory power (Beck, 2011; Beck and Oomen, 2021), but this conception continues to structure current science-policy interfaces, including the IPCC-UNFCCC relationship. Conceiving of the science-policy interface in terms of knowledge (and governance) co-production (Jasanoff, 2004; Miller, 2004; Bremer and Meisch, 2017) provides a more useful starting point in the domain of ESTPs. This implies that knowledge, understanding and meaning are the result of complex interaction processes in which scientists and policymakers mutually shape each other's perspectives.

3.4.3.1 Building on existing science-policy engagement processes

The full range of existing science-policy engagement processes across multiple scales of governance are relevant for fostering engagement and knowledge building on ESTPs. At the global scale, this places intergovernmental scientific assessment bodies like the IPCC and IPBES and their relationships to political negotiation and decision-making institutions (e.g. UNFCCC, CBD) into the spotlight. Below, we focus on these global-scale institutions, but many other formats of science-policy engagement exist, including parliamentary hearings, science advisory bodies, and expert groups at the national scale and in the European Union.

The **IPCC** is the central source of authoritative scientific knowledge for the international climate governance process. Despite multiple critiques levelled at the model in recent years (Turnhout et al., 2020; De Pryck and Hulme, 2022), it can and should play an important role in fostering knowledge related to climate (and Earth system) tipping points, elevating this topic on the negotiation agenda of the UNFCCC and possibly political systems at other scales.

However, the seven-year reporting rhythm of the IPCC is moving too slowly to reflect the rapidly evolving scientific knowledge base related to climate (and Earth system) tipping points.

More frequent, shorter learning cycles are needed to ensure the latest understanding of science is available and accessible to a wide range of actors more rapidly (De Pryck and Hulme, 2022). Contributing to this increased frequency is one of the aims of this report. Such an approach requires capacity building both on the side of knowledge provision and communication and with relation to its adoption and use. The format of IPCC special reports provides an important avenue for developing scientific and policy-relevant knowledge regarding ESTPs, but does not fully address this speed deficit. Other scientific assessment processes, including this report, can complement the work of the IPCC, but to the extent they lack the formal relationship with and mandate from a negotiation or decision-making body like the UNFCCC, they lack the authority and perceived legitimacy of the IPCC (Cash et al., 2003) and are less likely to be utilised.

Scholars increasingly recognise that anticipating multi-dimensional, multi-scale and cascading climate impacts are not well served by existing climate risk assessment processes (Simpson et al., 2021). Both Earth system models (WGI, physical science) and integrated assessment models (WGIII, global mitigation pathways) will need to integrate biophysical and social tipping points to a greater extent (McPherson et al., 2023), and connect the implications to locale- and actor-specific vulnerabilities and adaptation capacities (WGII). In this vein, climate tipping points present an opportunity for stronger collaboration across IPCC Working Groups.

Fostering more solutions-oriented knowledge elevates the importance of WGs II and III and the need to expand assessment of relevant knowledge in the social sciences and humanities. Going beyond economic perspectives and technological change, solutions work related to tipping points needs to bring in understandings of how knowledge and beliefs about the future shape future-oriented decision making and agency.

More generally, the IPCC's tendency towards conservatism (Brysse et al., 2013) is particularly problematic in the context of tipping points. This conservatism is a reflection of scientific values such as restraint, rationality, dispassion and moderation, which create a tendency towards caution and underreporting of certain scientific findings, but also results from the desire to provide information that is safe against attack or political misuse. The panel's mandate to be policy relevant but not policy prescriptive further creates a tendency towards information that supports the pursuit of existing political goals, confirming their underlying linear assumptions of change. What is needed is accelerated learning of a kind that enables a shift towards non-incremental and transformative approaches to action. Proposals for IPCC reform are emerging (Asayama et al., 2023), but they do not address the question of how anticipatory and transformative knowledge co-production could be practically enabled in the UNFCCC.

There are limits to what the IPCC can do when it comes to developing anticipatory and transformative capacities among diverse governance actors across multiple scales.

Fostering actor-relevant and context-specific knowledge demands distributed knowledge production with heavy involvement of regional (e.g. AMAP, EU), national (e.g. governmental foresight offices) and sub-national knowledge institutions.
(Hoppe, 2005; Hoppe, Wesselink, and Cairns, 2013).

Actor relevance combined with the time and resource demands of some methods for anticipatory knowledge development further minimises the potential role of the IPCC in its current form, which is already a time-consuming and unfunded commitment for most participants. Instead, it requires distributed efforts by organisations that can play a convening role for trainings and workshops, or technological resources like immersive or virtual reality environments. Major international science organisations or networks like Future Earth could adopt a role in fostering this type of learning at the interface of science and policy.

Looking beyond the IPCC, recent analyses of **global environmental assessments** consistently identify a set of challenges that need to be addressed to support global environmental decision making about the future (Norström et al., 2020; Pereira et al., 2021). These are particularly relevant for knowledge production related to ESTPs and include the need to: (1) anticipate unpredictable and diverse future conditions, (2) create knowledge that is relevant at multiple scales, and (3) include diverse actors, perspectives and contexts, and enhance the role of stakeholders including the public (Elsawah et al., 2020). Increasingly frequent iterations of learning cycles and the ability to respond rapidly to changing and new knowledge will also be needed (Norström et al., 2020). Finally, given the emphasis on distributed knowledge production in multi-scale networks, global assessment processes need to develop stronger relationships to knowledge-production processes at lower scales (e.g. national academies of science or government science advisory bodies), becoming network hubs in knowledge-production systems rather than sitting at the top of knowledge-production hierarchies.

Recently, relevant activities and venues have emerged across global environmental assessments that implement some of these recommendations, and might serve as partial templates for the mode of knowledge production that anticipating tipping points demands. The CBD's advisory body, **IPBES**, to some extent replicates the IPCC model, but with important modifications and dynamics. Through its Nature Futures Framework (Lundquist et al., 2021), the IPBES and the UN Environment Programme's Global Environmental Outlook (UNEP, 2019, chap. 23) both take note of ways to combine regional-to-global systems modelling with imagination-driven, bottom-up stakeholder engagements and perspectives. This generates both a greater range and 'thicker' detail of risks that are relevant to communities and decision makers, as well as creating buy-in around actions needed. Combining natural and social sciences with traditional ecological knowledge, Indigenous knowledge and local knowledge is facilitated by the recent establishment of the Local Communities and Indigenous Peoples Platform by the UNFCCC. The IPBES is also taking a greater interest in anticipatory and transformative knowledge and capacities with its ongoing efforts related to the Transformative Change Assessment.

The processes and impacts of ESTPs would reach across multiple global governance issues, creating often-overlooked interdependencies between them. The challenge of linkages has been increasingly recognised in climate assessment and governance, for example, regarding interactions with multiple efforts to achieve the Sustainable Development Goals (Fuso Nerini et al., 2019). Tipping point assessments and knowledge production might innovate further by building on templates like the multi-issue 'nexus' assessments of climate, biodiversity and pollution (UNEP, 2021), biodiversity, water, food and health (IPBES work programme 2019-2030), or climate change, land-use and food security (IPCC, 2019).

3.4.3.2 Using early warning signals?

Being able to provide and make use of early warning signals (EWS) of approaching ESTPs would be a strong signal for an effective science-policy interface. The main purpose of early warning systems is to alert decision makers to impending changes to enable a rapid adjustment of governance and decision making, e.g. kicking preparations for mitigation and impact adaptation into high gear with extraordinary modes of decision making, prioritisation and resource allocation. Ideally, an early warning system would relate a set of distinct signals to a set of differentiated decision-making procedures and priorities with clear and pre-determined shifts in authority and responsibility. In the case of ESTPs, EWS would indicate that prevention efforts for a specific tipping point (see Chapter 3.2) are currently insufficient and failing, and that impact management (see Chapter 3.3) needs to be ramped up within a short time window in case further mitigation is insufficient.

Successful examples for early warning systems exist in the domain of disaster preparedness (e.g. storms and floods). The International Federation of Red Cross and Red Crescent Societies (IFRC) is developing practices of early warning for climate-related extreme events. Recent assessments display an increasing orientation towards preemptive action, forestalling rather than only reacting to harms. For example, the UN Office of Disaster Risk Reduction has instituted a more prospective and holistic perspective towards disaster management, seeking to anticipate and forestall vulnerabilities through development and capacity building (UNDRR, 2022). This new emphasis supplements the more traditional mode of pinpointing hazards and managing relief and compensation processes.

Advances have been made in the domain of early warning signals for ESTPs, including different measures for identifying a system's proximity to a tipping point and proposals to apply these measures to harmful social-ecological tipping points (see Chapters 1.6 and 2.5). However, the usability of this knowledge in the domain of policy and governance remains unclear, as do processes for communicating early warnings to decision makers. Given the challenges regarding the nature of scientific knowledge about Earth system tipping processes, e.g. assessments of when a tipping point is passed potentially not being available until decades after, and early warning signals may not always be present before tipping or be clear evidence of tipping (Chapter 1.6), the benefits of early warning science for decision making might be limited for now (Galaz, 2014, chap. 4).

3.4.4 Knowledge politics

Knowledge co-production and mobilisation at the science-policy interface is never a-political, but shaped by power relations, social contexts, existing political interests, and values. Political interests often affect what kind of knowledge is produced, for example through public research funding, explicit invitations for reports (such as the IPCC's Special Report on 1.5°C) or scientific advice, as do scientists' perceptions of what is useful information to achieve political objectives – i.e. what is believed to be 'policy relevant' (van Beek et al., 2022). Other factors within the domain of science also play a role, as well as institutional co-production dynamics (e.g. the process for adopting an IPCC summary for policymakers or issuing a proposal for an IPCC special report), and knowledge mobilisation by political actors (e.g. political leaders speaking at COP sessions referring to a climate tipping process).

We can expect varying knowledge and meanings related to tipping points to emerge in different political and social contexts, and actors with competing political interests to offer competing knowledge claims (for example, using uncertainty regarding a tipping threshold value to argue for and against rapid prevention measures). Depending on their interests, and those of their constituencies, political actors are likely to develop different risk perceptions regarding ESTPs, assign varying levels of importance to them, and develop different preferences for solutions. Actors can and often do use scientific information strategically to further their pre-existing political interests and political positions (Grundmann, 2007), sometimes widening existing cleavages (Sarewitz, 2004) and reinforcing contestations. The 'same' scientific information can be used by different actors to justify very different positions (Schenuit, 2023). This can be particularly challenging for cascading shocks (Galaz et al., 2011). For example, political representatives of small island states assessing the importance of cryosphere tipping processes will likely consider the prospect of nonlinear ice sheet loss to reinforce their existing beliefs about the severe risks of sea level rise, and will use the science of tipping points to highlight island states' vulnerability and strengthen their arguments for urgent international mitigation action. At the same time, actors reluctant to engage in mitigation or curtailment of the fossil fuel industry might use tipping point science, especially related to nonlinearity and irreversibility, to build a case for their desired form of climate intervention (geoengineering), to the extent of arguing that this is the only viable option for averting catastrophe.

Scientific knowledge is only one source of **input into meaning-making processes**. One of the most important – politically relevant – aspects of meaning making at this point is the formation of national and sectoral interests related to ESTPs (see 3.1.4). Interest formation is tied to multiple factors, including the actor's identity and values (Wendt, 1992; Finnemore, 1996), institutional mandate or power positions.

Related to the strategic mobilisation of knowledge about tipping points, we must also be aware of the risk of the strategic denial of scientific knowledge. The strategic organisation of science denial involves orchestrated efforts by groups or individuals to cast doubt on established scientific consensus, often by cherry-picking data, manufacturing controversies, promoting false experts, propagating conspiracy theories, manipulating media coverage, funding questionable research, appealing to personal beliefs, attacking scientists, leveraging political influence and exploiting cognitive biases (Cook, 2020b; Dunlap and Brulle, 2020; Cook, 2020a). These tactics aim to create the appearance of uncertainty and debate around scientific issues, potentially serving the agendas or interests of those behind the denial efforts (Schmid and Betsch, 2019; Hornsey and Lewandowsky, 2022; Björnberg et al., 2017), for example fossil fuel companies, elected officials from fossil-fuel producing regions, or conservative think tanks in the US (Ekberg et al., 2022). Research indicates that engaging with rather than ignoring such dynamics is the most promising strategy for dealing with them (Cook, Lewandowsky, and Ecker, 2017; van der Linden et al., 2017; Lewandowsky and van der Linden, 2021; Compton et al., 2021).

While knowledge politics is an unavoidable component of environmental governance, it is important to make power relations explicit and transparent "to allow for pluralism, create scope to highlight differences, and enable the contestation of interests, views, and knowledge claims" (Matuk et al., 2020; Turnhout et al. 2020, 21).

3.4.5 Final remarks

This chapter has addressed knowledge production challenges related to ESTPs and their implications for effective science-policy interactions. Tipping processes are features of complex systems that present profound learning challenges that can undermine the development of actionable knowledge among decision makers and slow down urgently needed governance efforts. Attention to tipping points has grown in recent IPCC assessment reports, with the assessed risks of tipping point transgression increasing at lower levels of global warming. However, so far this has had limited effect on policy making processes. There are also significant knowledge gaps regarding ESTPs in the social sciences and humanities, which are most relevant to support governance. This context calls for concerted efforts to expand knowledge production related to ESTPs and corresponding science-policy interactions to foster learning and capacity building.

For it to be useful for governance, knowledge about tipping points needs to be solutions-oriented, actionable, context-specific and actor-relevant. Importantly, the multiple time horizons of tipping processes – from years to millennia – require anticipatory forms of knowing and meaning-making. In a polycentric governance framework, it is important to understand where, by whom, and at what scale relevant knowledge is produced, how knowledge producers and users can be connected, and how different kinds of knowledge can empower governance actors to devise, implement and upscale solutions.

Identifying significant limits to the way knowledge is currently developed at the science-policy interface, we have put forward suggestions for improving future knowledge co-production related to ESTPs with a focus on the international scale. Scientific and non-scientific actors should actively participate in knowledge co-production in distributed networks that enable effective multi-scale information sharing. Novel designs of knowledge-production approaches such as participatory scenario development and roleplay simulations are needed, as well as incentives for developing anticipatory and transformative capacities. These approaches tend to combine qualitative and quantitative information, diverse expertise, and even immersive and game-based processes that leverage art and storytelling to provide multi-modal and multi-sensorial learning.

This type of capacity building at the science-policy interface requires more time investment, openness to active learning (rather than reading or listening), and more frequent (iterative) engagement by decision makers than current approaches. Finally, we outlined the importance of grappling with political contestation around the production and mobilisation of knowledge at the science-policy interface.

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Section 4

Positive tipping points in technology, economy and society

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Section summary

'Negative' tipping points are now so close that urgent action needs to be taken to prevent them. Beneficial, 'positive' tipping points (PTPs) offer hope for accelerating responses to match this urgency. A key task will be to learn how to intervene in socio-behavioural, technological, economic and political systems in ways that enable PTPs to emerge while minimising harms and injustices. Enabling PTPs means, for example, making the desired change the most affordable, attractive, convenient, accessible or morally acceptable option. PTPs occur when the balance of system feedbacks – reinforcing/amplifying versus dampening feedbacks – shifts in favour of reinforcing ones, such as economies of scale, or social contagion. A PTP in one system can trigger one or more PTPs in other systems in a domino or cascade effect, generating widespread societal change.

PTPs are already well underway in wind and solar power generation and in leading battery electric vehicle (BEV) markets. But the supply of technological solutions on its own is unlikely to be sufficient to meet decarbonisation targets. It is also important to trigger PTPs in the demand for energy and transport services and food – for example, by making public transport the cheapest, most convenient option. Coordinated action between supply and demand amplifies the impact of each. Accelerating change in food systems also has important 'positive cascading' implications for natural ecosystems, accelerating nature recovery and restoring natural carbon sinks. Other changes – in behavioural norms, values and practices; in political institutions, policy priorities, and public pressure; in global financial systems and international funding mechanisms; and in digital and information systems – are also vitally important for delivering the necessary speed and scale of systemic change.

In certain systems we can detect the signals, or 'early opportunity indicators' (EOIs), of approaching tipping points. Further development of EOI research could help decision makers – from politicians to investors – harness the power of the PTP approach.

Key messages

- Transformative and just positive tipping points can emerge with the right enabling conditions, feedbacks and triggers.
- Climate solutions focusing on fundamental shifts in behaviours, values and institutions are as important as those that focus on technologies, materials and markets.
- An avoid-shift-improve logic which rethinks our activities – whether they can be omitted, changed or undertaken more efficiently – can be used in many sectors to design interventions to manage holistic structural change.

Recommendations

- Positive tipping point theory, methods and applications will require a comprehensive, systematic and transdisciplinary programme of research and development.
- Decision makers need a systems-thinking approach and a coordinated strategy that encompasses all economic sectors, all departments of government, civil society (including public consultation), and both supply-side and demand-side interventions.
- A systems-thinking approach understands that the most effective way to catalyse global action may be via small-group coalitions. For example, a positive tipping point in green hydrogen could be achieved if the US, EU and India implemented blending mandates for green ammonia in fertiliser manufacturing.

Section 4.1.1 Summary table

Sector-system	PTP opportunity	Emissions share	Key enabling conditions	Key reinforcing feedbacks
Energy & Power	**Shift:** Solar PV/wind + storage	26%	• Levelised cost of electricity of new solar/wind + battery storage is less than that of new coal/gas power • Sufficient transmission and distribution infrastructure	• Economies of scale • Learning effects • Social contagion for domestic installation • Technological reinforcement for domestic battery installation (with flexi-tariffs)
	Shift: Domestic heat pumps	6%	• Well insulated housing stock • Competitive on installation cost and time with gas or equivalent boiler (including subsidy) • Running costs competitive with gas	• Economies of scale • Learning effects • Social contagion for domestic installation • Technological reinforcement i.e. when integrated with home solar and battery system
	Shift: Steel production: green hydrogen DRI	7%	• Cost per ton of production lower than steel from fossil-based productionInstitutional commitment by large manufacturers • Enabling policy and market demand for low carbon steel	• Economies of scale • Learning by doing • Technological reinforcement • Path-dependency of investment decision-making
Transport & mobility	**Shift:** Battery electric vehicles	9%	• BEVs cheaper at point of purchase than ICE vehicles (including policy support) • Sufficient charging infrastructure • BEV performance seen as competitive with ICEV's by consumers • Policies that increase BEV desirability including waved parking fees, access to fast lanes, and entry to air quality zones)	• Economies of scale • Learning by doing • Social contagion and network effects
	Avoid: Enhanced active mobility	Up to 9% (or more)	• Enabling infrastructure (e.g. safe streets, compact city development, hire/rental schemes) and policy design (e.g. carbon pricing, subsidy, vehicle restriction schemes) • Norm change	• Social contagion and network effects
	Shift: Enhanced heavy capacity public transport networks	Emissions, air quality and economic (SDG) benefits (unquantified)	• Investment • Enabling policy	• Demonstration effect • Economic development feedbacks of infrastructure access
	Shift: Heavy duty freight - Battery electric trucks	3%	• Total cost of ownership lower than ICE trucks • Sufficient high-speed charging infrastructure • Performance equivalent or better than ICE trucks	• Economies of scale in battery production • Charging infrastructure network effects • Asset sharing via digital platforms to drive efficiency improvements
	Shift: Shipping: green ammonia	3%	• Green ammonia fuel cost less than fossil-based shipping fuel • Effective regulation and incentives for shipping sector	• Economies of scale • Learning by doing in green ammonia sector
	Shift: Aviation: power-to-liquid fuels	2%	• Power to liquid fuel costs less than fossil-based jet fuel for long-haul flights	• Learning by doing • Economies of scale in PtL fuel production
Food & Agriculture	**Avoid:** food loss and waste	8%	• Effective policy and regulation • Buy-in from supermarkets • Shifting norms and behaviours	• Learning by doing • Social contagion • Technological reinforcement via digital platform evolution
	Shift: more plant-based diets	Up to 12%	• Shifting norms and behaviours, e.g. via public procurement, information • Improved alternatives to animal products, which are competitive on cost with animal products	• Social contagion, demonstration effects, network effects • Economies of scale and learning by doing in production of alternatives to animal products

Section 4.1.1 Summary table

	Shift: to regenerative agriculture	Up to 4% via CDR, plus additional emission reductions and ecological benefits	• Subsidy or other incentives that support farmers to transition and diversify business models, including carbon markets • Regenerative practices have lower input costs or higher productivity than conventional • Information and education on regenerative practices is accessible	• Information cascades • Network effects • Social-ecological feedbacks
	Shift: Fertiliser	2%	• Green ammonia costs less per ton than grey ammonia for N-based fertilisers	• Economies of scale and learning by doing in electrolyser development
Social & behavioural systems	**Shift:** Anti fossil fuel norms; **Avoid:** sufficiency norms	n/a	• Free social spaces for social innovation • Supportive networks legitimising new norms • Policy intervention (e.g., remove fossil fuel subsidies) and public investment • Philanthropic funders as incubators, connectors and mobilisers of new norms	• Increasing acceptability of new social norms • Complex contagion seeded by climate activism • Facilitated routes for new information to flow • De-escalation of polarising narratives • Opportunities to experience positive exemplars
Political systems	**Avoid:** Ecocide Law	n/a	• Political coalition-building and public engagement • Policy coalition-building and international diplomacy	• Increasing awareness and support for policy • International social contagion • Ostracism of non-cooperators
	International climate clubs	n/a	• Establishment of new climate negotiation norms • New international institutionsInvolvement of business, finance and civil society	• Increasing adoption • Increasing success in catalysing global action • Coordination and network effects
Legal systems	Climate change litigation	n/a	• Public perception/acceptability • Supportive media coverage • Supportive changes in climate-relevant laws • New legal institutions., eg., commission for future generations	• Successful litigations, network effects • Increasing international standing of human rights-based grounds for legal action • International standing of adaptation- and financial compensation-based grounds for legal action
Financial systems	**Shift:** Accelerating the green transition	Potential to interact with multiple high-emitting sectors	• Expectation alignment between policy and investment communities (e.g. through public finance initiatives, policy certainty) • Low-carbon investment is seen as a strategic asset rather than a diversification asset (e.g. less risky than carbon emitting investment options) • Strategic policy intervention (e.g. signalling focus on a specific solution)	• Feedbacks between public and private finance • Network effects among financial institutions • Learning by doing (e.g. increasing experience of returns from low-carbon investment) • Investment ➔ technological development ➔ stimulating employment and technological growth
	Shift: Accelerating renewables investment in the Global South		• Investments in Global South seen as no more risky than equivalent in the Global North (e.g. via credit guarantee (schemes) • Capacity base of around 1GW wind or solar installation	• Demonstration effect ➔ countries with track record of renewable investments are more successful at attracting new investment due to investor confidence • Network effects - crowding in investment • Mobilising domestic capital initiates economic development feedbacks
	Shift: De-financing fossil fuels		• Stringent capital requirement rules • Risk of exposure to stranded assets	• Network effects • Financial feedbacks
Cascades	Multi-sector tipping points harnessing **Avoid-Shift-Improve**		• Cross-government and cross-sector coordination of climate policy • Super-leverage interventions to ensure favourable costs, accessibility, desirability and performance across target systems/sectors	• Co-evolution of coupled systems • Social contagion • Learning by doing • Economies of scale • Network effects

4.1 Positive tipping points in technology, economy and society:

Introduction

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Previous sections of this report examine 'negative' Earth system tipping points (ESTPs) (Section 1), their impacts on human society, which could also trigger 'negative' social tipping points (Section 2), and governance options for avoiding or adapting to these risks (Section 3). This section investigates the opportunities for positive social tipping points, which we shorten to positive tipping points (PTPs). A PTP can be defined as a change in a system or subsystem, which becomes self-reinforcing beyond a critical threshold, and which leads to substantial, frequently abrupt and often irreversible impacts that are predominantly beneficial (Armstrong McKay et al., 2022; Milkoreit et al., 2018). As discussed briefly in Box 4.1.1 and at greater depth in Chapter 4.6, what is considered normatively 'positive' or beneficial, and by whom, is highly debatable. In principle, tipping points may be considered positive either: a) where they reduce the drivers of 'negative' Earth system impacts such as greenhouse gas emissions or deforestation, for example in a rapid shift to renewable energy or alternative food proteins (Meldrum et al., 2023); or b) where they improve the social foundations of sustainability (Rockström et al., 2023; Gupta et al., 2023; Raworth, 2017; Tàbara, 2023).

Box 4.1.1: What do you mean, 'positive' tipping points?

It's easy to understand why climate tipping points are described as normatively 'negative' (harmful, undesirable). They risk destabilising the Earth system on which all life depends. The link between rising temperatures and negative consequences are becoming ever more apparent in the form of wildfires, flooding, storm damage, crop failure, famine, forced migration and other harms. But what about 'positive' tipping points (PTPs)? What are they, for whom are they positive, and who has the power to decide what is 'positive'?

PTPs are a relatively new approach to accelerating the transformation to a sustainable, post-carbon society. They are 'positive' because they aim to prevent the 'negative' impacts of global heating and ESTPs. But PTPs go beyond ESTPs and the prevention of harm. They also refer to those human systems that we (the international community of nations) are actively encouraging to tip, not prevent from tipping, in cases where this would (to the best of our knowledge and care) increase the likelihood of achieving the just social foundations of sustainability – the Sustainable Development Goals (SDGs). A safe Earth system and a just society are both essential for a sustainable future.

However, not all changes associated with societal transformations are universally seen as 'positive'. People working in the fossil fuel and related industries fear the loss of their livelihoods and communities. Pollution, habitat destruction and poor working conditions in the expansion of cobalt and lithium mining (battery components for the new renewable energy economy) create problems as well as opportunities for a different set of communities. Many people, even while being broadly in favour of climate action, are wary of policies that might create additional costs or restrict their freedoms. And some suspect that the new economy isn't going to look much different to the old one in terms of inequities of power, democracy and resources. Forward-thinking governments and firms are developing 'just transition' plans to try to minimise some of these fears and injustices; others maximise and exploit them in the hope of delaying climate action.

Many of us, as individuals and as representatives of organisations, sometimes face difficult decisions and trade-offs as we try to weigh harms against benefits on imaginary scales of justice. Land designated for nature restoration might otherwise be used to grow food. Finance for mitigating technologies may leave less available for adaptation, or for loss and damage. These scales are already weighted heavily on one side by the need to prevent potentially catastrophic levels of harm and injustice that would result from triggering climate tipping points. If we fail to stabilise the climate in time, the SDGs could quickly become impossible. But should ESTPs be prevented at any cost? On the other side of the scales, there may be certain moral or religious principles, minimum standards of human dignity, or duties of care, that we refuse to set aside, whatever the risks. These issues are explored further in Chapter 4.6.

'Positive' and 'negative' are clearly value judgements. However, the moral force in our use of these descriptors is based on the science of Earth system boundaries and tipping points and the ethics of social justice. Almost all people, regardless of values and other differences, believe that human flourishing is preferable to human suffering and share a common interest in securing a safe and just world.

It is easy to understand why there has been such an explosion of interest in the concept of PTPs in recent years (Tàbara et al., 2018). Faced with a polycrisis of multiple, interconnected, and potentially existential, threats, they offer hope of neutralising or mitigating these threats and of creating a safer, healthier and more sustainable world for present and future generations.

PTPs have already been crossed in sociotechnical systems in the uptake of solar and wind power, which are now doubling capacity every three and a half years (IEA et al., 2023; Nijsse et al., 2023). Sales of battery electric passenger vehicles have also crossed PTPs in leading markets such as Norway, and are fast approaching them in the rest of Europe, the US and China (Meldrum et al., 2023). Forward-thinking firms and individuals are exploiting these opportunities, often with the help of governments who alter the parameters – using incentives, direct investments, mandates, behavioural 'nudges', and so on – within which decisions are made. The evidence for PTPs in other human systems is less well established due to a lack of appropriate data, accepted definitions, assessment methods and case studies.

The increased interest has led to some overuse and misuse of the term (Milkoreit, 2023) and, inevitably, to contested definitions and meanings about what should be considered a normatively 'positive' outcome. All such claims rely on subjective judgement. There are also important ethical issues and the possibility of unintended negative consequences to be considered, as PTPs create 'losers' as well as 'winners', and costs as well as benefits (Pereira et al., 2023). These issues are explored further in Chapter 4.6

The growing risks of ESTPs and more than 30 years of inadequate climate action mean that we don't have time for a 'business as usual' mentality or for the opportunity-driven, largely unforeseen, societal transformations of the past.

(Stoddard et al., 2021; Meadowcroft, 2016; Scoones et al., 2015; Geels, 2011). **We need to move many times faster**, in the context of a "rapidly closing window of opportunity to secure a liveable and sustainable future for all" (IPCC, 2023, p. 24; Sharpe, 2023). Human civilisation will fundamentally change in the coming decades. The only question is, will that change be collectively chosen *by humanity* in ways that maximise our wellbeing? Or will it be chosen *for us,* with potentially catastrophic consequences, if we continue to ignore biophysical limits and the risks of ESTPs? It is within our collective abilities to deliver a prosperous, climate-resilient future for all. But we require different priorities and strategies to those on which we previously relied. Most importantly, we need a systems-thinking approach to rapidly accelerate towards PTPs. This means:

- Simultaneously addressing social-behavioural, technological, economic and political domains (Stadelmann-Steffen et al., 2021), and looking at **demand-side solutions** such as changing behaviours, norms, lifestyles and provisioning systems related to consumption (Creutzig et al., 2022; Akenji et al., 2021), alongside **supply-side solutions** such as achieving cost parity for renewables (Meldrum et al., 2023).
- Focusing on more fundamental interventions that connect individuals and systems together and lead to systemic change of underlying socioeconomic structures – in parallel with the easier, lower-cost, 'low-hanging fruit' (Mealy et al., 2023; Newell et al., 2021; Chan et al., 2020; Abson et al., 2017). Examples might include: a revenue-neutral carbon fee and dividend scheme (Boyce, 2019); universal basic services as part of a social guarantee or 'green jobs' guarantee (Akenji et al., 2021).
- Creating synergies between human (social) capital and natural capital (Tàbara, 2023); measuring progress both in terms of reductions in negative tipping point stressors (e.g. greenhouse gas emissions, deforestation, land/soil degradation) and in terms of increases in positive social indicators such as health, food security, education, gender and socioeconomic equality (Rammelt et al., 2023).
- Understanding that human systems are embedded within the Earth system (Figure 4.2.1). The safe operating limits of the Earth system, within which human societies have flourished for millennia, are governed by natural laws (Rockström et al., 2023; Dixson-Declève et al., 2022). Humans are immensely capable problem-solvers, but what we cannot do is adjust these laws for our political or economic convenience.

Systemic change requires us to reimagine how we eat, move, work, consume, invest, live and view the world (Tàbara and Chabay, 2013). It also requires practical changes in how we manage our lands and oceans, raise and spend public money, phase in/out affected industries and train/retrain workforces and redesign cities, energy systems and transport networks. Huge decisions need to be made about the kind of world we want to live in. They must be addressed with a clear understanding of the real risks we face, as well as the opportunities. Civil society, local communities, policymakers and businesses need to be at the heart of co-designing this better future and able to trust each other to deliver a just transition (Devine-Wright et al., 2022; Laybourn-Langton et al., 2021). Politicians need the support of a public mandate and a majority political coalition to enact policy changes (Eder et al., 2023; Willis, 2020).

PTPs therefore involve **complex interconnections and opportunities for systemic change** across multiple domains, sectors, disciplines and countries/jurisdictions. This section aims to highlight some of these interconnections and opportunities in contexts that will help decision makers navigate a responsible and evidence-based path through the complexities, using real-world examples and case studies.

Chapter 4.2 presents a conceptual framework for understanding and acting on PTP opportunities, according to the latest research. Chapter 4.3 demonstrates the usefulness of this framework by applying it to the most carbon-intensive sectors of energy (4.3.1), transport and mobility (4.3.2), and food systems (4.3.3). Previous studies have investigated the rapid innovation and diffusion of technologies in these systems (Meldrum et al., 2023). We build on this work and introduce a demand-side perspective. Chapter 4.4 identifies cross-cutting enablers of PTPs that may be applied to many kinds of human systems: socio-behavioural change (4.4.1); politics (4.4.2); finance (4.4.3), digitalisation (4.4.4) and early opportunity indicators (4.4.5). Chapter 4.5 investigates positive tipping cascades. In previous sections of the report, tipping cascades referred to processes whereby one negative tipping point triggers at least one other negative tipping point, potentially leading to a large overall deterioration across multiple systems. We adapt this concept for PTPs and, again, building on previous studies, we examine the potential for using powerful interventions at specific times and places – so-called 'super-leverage points' (Meldrum et al., 2023) – that are capable of catalysing tipping cascades across multiple systems and domains. Finally, Chapter 4.6 considers important issues of risks, equity and justice in the governance of PTPs, with particular attention paid to the potential for PTPs to create 'losers' as well as 'winners', and to bring a degree of reflexivity and inclusivity with respect to marginalised voices.

Throughout, we give diverse examples from different regions, highlighting the need for differentiated solutions in each case; these are summarised in Table 4.1.1. Some technological and behavioural solutions might be more universal than others, while organisational solutions require context-specific knowledge and tailored actions. The specific scales, levels, sectors or domains in which positive tipping occurs is also addressed. We outline where opportunities to positively intervene exist. And we assess, where possible, the impediments and uncertainties involved. Our assessments are based on empirical insights and modelling studies.

When aiming to accelerate beneficial change, the **avoid-shift-improve framework** (Creutzig et al., 2022) is helpful in prioritising action. Each of the three types of actions can reinforce the others by amplifying their effects. *Avoid* aims to eliminate harmful activities or products by reducing production/consumption or by redesigning services; *shift* means switching to cleaner or more efficient alternatives; *improve* means enhancing the performance or efficiency of the same activity or product. We use the *avoid-shift-improve* framework throughout this section to describe and prioritise PTP interventions.

4.2 Understanding and acting on positive tipping points

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Summary

The human systems and enablers of positive tipping points (PTPs) span multiple domains of technology, politics, economy and social behaviour. Many key features of Earth system tipping points (ESTPs) also apply to PTPs, including the presence of reinforcing and dampening feedbacks, nonlinear change, cascade effects, resilience, and path dependence. The primary differences with PTPs (as opposed to Earth system tipping points ESTPs) are intention, agency and desired outcomes. The intention of PTPs is to promote (not prevent, as in ESTPs) tipping and system transformation. Agency is focused on interventions that maximise the potential for tipping to occur. Desired outcomes are systems-compatible with a safe and just world. To encourage desired outcomes, agents can intervene in three ways: 1) they can create the enabling conditions for a tipping point; 2) they can enhance the reinforcing feedbacks that drive change, and/or neutralise the dampening feedbacks that resist change; and 3) they can attempt to trigger positive tipping points. PTP system dynamics typically involve three phases of enabling, accelerating and then stabilising change. Once a tipping point has been crossed, a system enters an accelerating phase of nonlinear change dominated by reinforcing feedbacks, before stabilising again in a qualitatively different state. Other, undesired outcomes are also possible, including 'shallower', less sustainable outcomes, and unintended consequences. Tipping cascades can occur across multiple sectors and domains, as one tipping point triggers another, and then another, potentially leading to widespread societal change.

Key messages

- PTPs don't just happen, they need to be actively enabled by stimulating innovation, shaping markets, regulating business and educating and mobilising the public.
- 'Positive' is a value judgement.
- Rapid decarbonisation may involve losers as well as winners.

Recommendations

- PTPs in solar and wind energy have taken several decades to emerge. Government, business and civil society all need to play a more active part in accelerating progress across all sectors and domains.
- PTP theory and methods require a comprehensive, systematic and transdisciplinary programme of research and development.
- Some PTPs, for example those in sociotechnical systems that depend on achieving price parity, are easier to define and predict than others. Decision makers need reliable information and frameworks to assess the potential for, and proximity of, PTP opportunities to beneficially transform systems.

4.2.1 Introduction

Before examining case studies and cross-cutting themes, we present a framework for helping to conceptualise the PTP approach and how to intervene in complex systems in ways that encourage tipping points to emerge.

4.2.1.1 Similarities between ESTPs and PTPs

Any sufficiently complex adaptive system, whether it is based on geophysical, ecological, or human elements, can exhibit a tipping point that leads to transformative change (Lenton et al., 2022). For this reason, many of the same terms and concepts used to study normatively 'negative' tipping points in the Earth and social system can be adapted for normatively 'positive' tipping points in human systems. The prime example is the tipping point concept itself – **a critical threshold at which an additional input into a system triggers a disproportionately large, often abrupt and irreversible change, which leads to a qualitatively different system state** (Lenton, 2008; Milkoreit, 2018). Both normatively 'negative' and 'positive' tipping point systems also have the following in common:

- Stable states that are resistant to change.
- Internal, reinforcing (positive) feedbacks that speed up change, and dampening (negative) feedbacks that slow down change (Lenton et al., 2022). These are **mathematically** positive or negative feedbacks, not to be confused with **normatively** positive or negative tipping points.
- The potential for tipping cascades, whereby the tipping of one system triggers the tipping of at least one other system, which can start a domino effect of change across multiple systems (Lenton, 2020).
- A loss of resilience or stability when approaching a tipping point. For some human (social) systems this may manifest as critical slowing down (CSD) – the time taken to recover from a shock/disturbance. CSD can be detected as early warning signals (EWS) for climate tipping points, or as **early opportunity indicators** (EOI) for PTPs.
- Path dependence, in which past states or events constrain future states or events.

4.2.1.2 Differences between ESTPs and PTPs

One obvious difference is that PTPs usually involve intentional change. The kind of beneficial change we are interested in – "collective, intentional transformation towards global sustainability" (Lenton et al., 2022, p. 2) – requires purposeful human agents, either acting alone or organised into various networks, who attempt to induce (and some who try to prevent) these tipping points (Winkelmann et al., 2022). This section therefore introduces some new terms that address the intentionality that is central to operationalising PTPs – terms such as **enabling conditions** (Lenton et al., 2022), and **strategic interventions**. As stated in 4.2.3.4, this focus on intentionality and agency does not negate the possibility of unintended PTPs or triggers.

Another difference, compared to tipping points in the Earth system, is that human systems span very different domains, which we categorise into socio-behavioural, technological, economic and political domains (Bernstein and Hoffmann, 2018) (Figure 4.2.1). The socio-behavioural domain covers changes in social norms, lifestyles, knowledge, values and cultures. The technological domain includes innovation, research and development, adaptation, coordination, and automation of technology. The economic domain includes changes in finance, markets, labour and inequality. The political domain covers changes in the law, politics, policy, institutions and governance. The domains, systems and subsystems of human societies are constantly in flux. They interact with each other and with the Earth system in highly complex ways that can be difficult to predict or steer. PTPs in human systems also manifest at different spatial and temporal scales to tipping points in the Earth system, as illustrated in Figure 4.2.1.

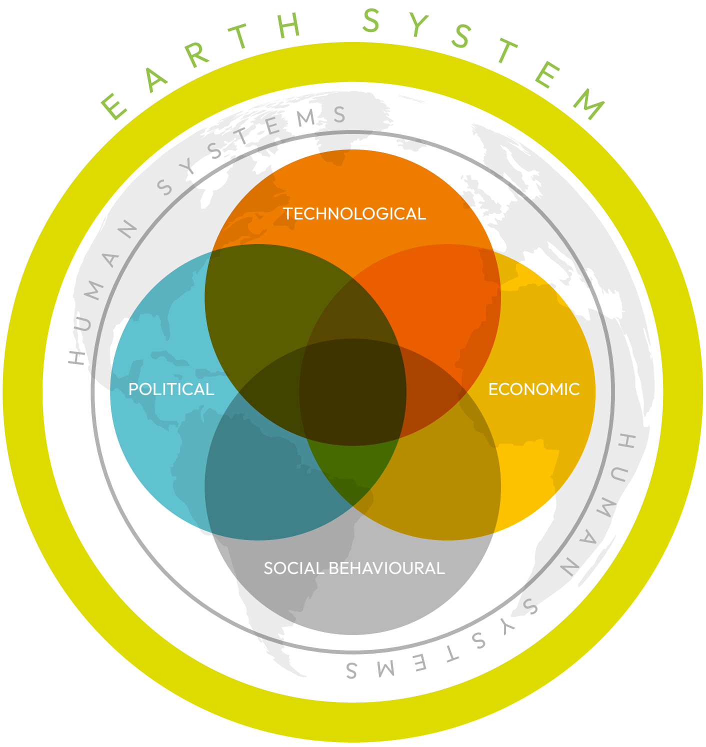

Figure 4.2.1: PTP domains. Human systems – social-behavioural, technological, economic and political – are interconnected. Human systems are also embedded within the Earth system, which means they are subject to their biophysical capacities and tipping points (Stadelmann-Steffen et al., 2021; Rockström et al., 2023).

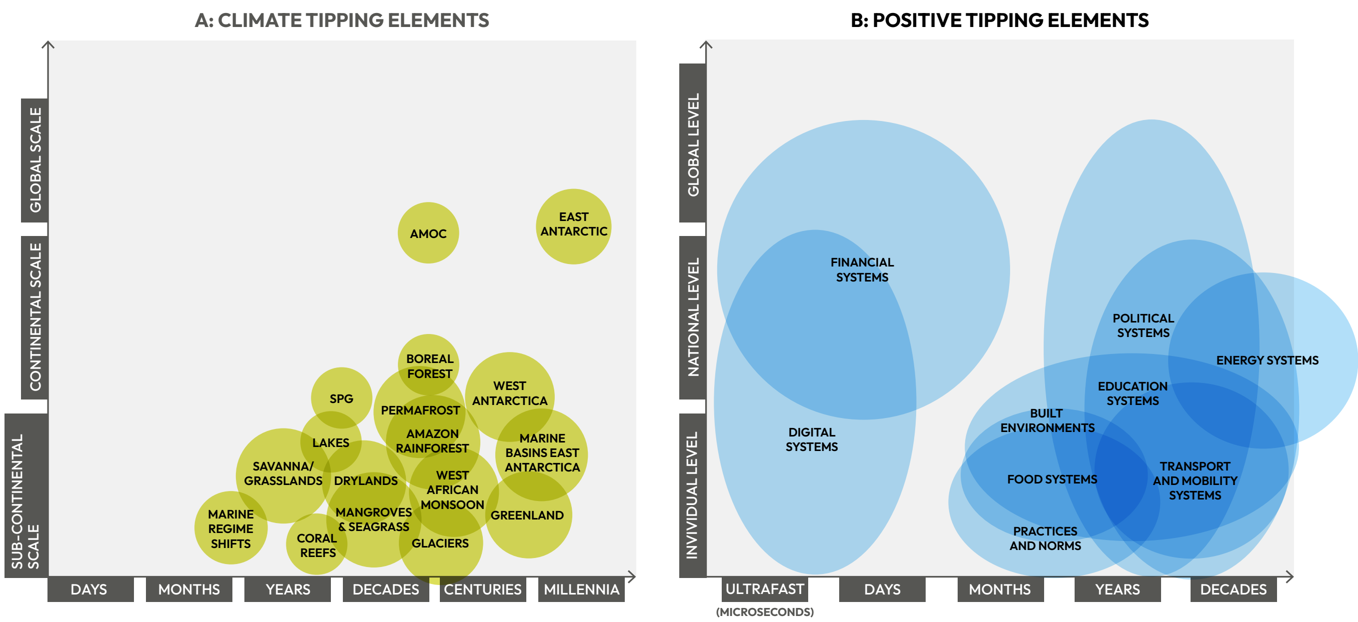

Figure 4.2.2: Typical spatial and temporal scales to illustrate climate and positive tipping elements (adapted from Winkelmann et al., 2022).

Human systems and their tipping points are also, in some ways, more difficult to define and measure than those of the Earth system (Winkelmann et al., 2022; Stadelmann-Steffen et al., 2021). Investigations of ESTPs have built strong empirical foundations based on natural laws, and on data on prior system states going back millions of years (palaeoclimatology). Quantitative units of measurement similar to those used for ESTPs are sometimes used to identify PTPs in technology and economics. But it is more difficult, and contentious, to assert tipping points for other, less-quantifiable systems concerned with change in human behaviours, practices, values and political systems. It is often not possible to identify a single parameter, mechanism or point that triggers tipping in human (social) systems, but rather multiple tipping dynamics that together trigger rapid and fundamental system change (Stadelmann-Steffen et al., 2021). In many cases, the study of tipping points in human systems has tended to rely on literature synthesis, case studies and expert elicitation to determine:

- **Historical precedents** – for example the shift from fossil fuels to renewables in electricity generation (4.3.1), or the Green Revolution (4.3.3).
- The key **characteristics** of the system.
- **Boundaries that distinguish** PTPs from other more established theories of societal change (Milkoreit, 2022). See Box 2.2.1 below.

Box 2.2.1. Positive tipping points for sustainability are characterised by:

- A transformative change in the human components of linked social-ecological systems.
- Nonlinear, rapid change.
- Reinforcing feedback as the change mechanism.
- Limited reversibility.
- Desirability.
- Human agency.
- The intention to support decarbonisation and sustainability.
- Adapted from Milkoreit, 2022.

4.2.1.3 Not all systems have tipping points

PTP researchers and practitioners need to acknowledge that this is a very recent field of study that has yet to devise a formal, empirical way of distinguishing a system that is possible or likely to tip from one that isn't. Incorrectly asserting a PTP could lead to false optimism and damage the credibility of the PTP approach. It could also lead to wasted effort, resources and time trying to induce PTPs in a real-world system that is either incapable or highly unlikely to tip within a useful timeframe.

Sectors that have very high capital costs and very low replacement rates, sectors in which there are no obvious, strong, reinforcing feedbacks to drive change, or sectors in which there are strong dampening feedbacks to prevent change, may be poor candidates for PTP intervention. Hard-to-abate industries such as steel, chemicals and cement, and avoiding land use conversion (e.g. deforestation) are examples of sectors in which there is low confidence that PTPs may occur (Meldrum et al., 2023). We should expect powerful incumbents to strongly resist (i.e. dampening feedbacks) any intervention that attempts to destabilise existing systems/regimes (Kohler et al., 2019). It is therefore critical to identify and assess the relative strengths of reinforcing versus dampening feedback loops before asserting a potential tipping point. Assessing the **relative strengths of feedbacks** within and between multiple systems is also important for identifying potential tipping cascades (see Chapter 4.5).

4.2.1.4 PTP dynamics

This complexity of human systems makes it difficult to generalise about the process or dynamics of PTPs. Each system or subsystem is a unique and constantly changing arrangement of elements operating in its own spatial, temporal, social, ecological, economic, technological, political, legal and other contexts (Weber et al., 2023). Opportunities for PTPs may differ by geographical region or jurisdiction. For example, the use of mobile money for payments, banking and insurance has increased exponentially – following the classic S-curve of adoption – in many countries of the Global South (e.g. M-PESA in Kenya, adopted by 96 per cent of households within nine years of its launch). This is due to its accessibility and suitability for users in developing economies with little capital but high cash turnover and access to mobile phones. Access to M-PESA increases economic activity, financial resilience, saving and entrepreneurship, and is estimated to have lifted two per cent of Kenyans out of poverty between 2007 and 2014 (Suri and Jack, 2016). However, it is unlikely to disrupt the established banking systems in developed economies, where the majority of people have access to traditional banking services.

Despite the many different kinds of systems and contexts, positive tipping dynamics do exhibit common features and principles across systems and domains, as illustrated in Figure 4.2.3.

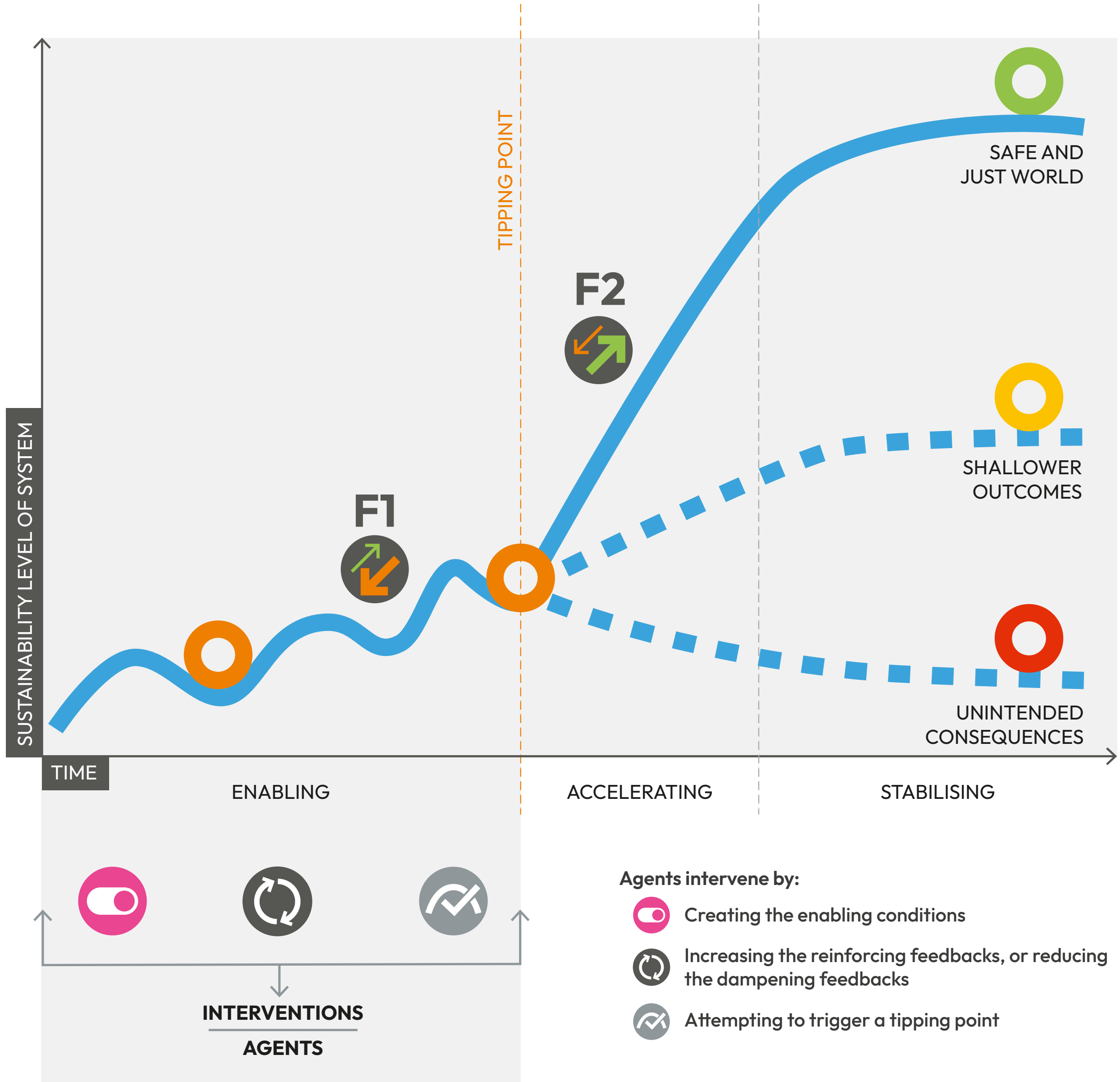

Figure 4.2.3: A conceptual framework for positive tipping points in human systems.

The current state of the target system is unsustainable. The desired outcome is consistent with a **safe and just world**. The process of positive tipping typically entails three different phases of **enabling, accelerating** and **stabilising**. To encourage the desired outcome, agents can strategically intervene to leverage change during the **enabling phase** in three ways, by: 1) Creating the **enabling conditions**; 2) Increasing the **reinforcing feedbacks** that increase the system's instability; or by decreasing the **dampening feedbacks** that maintain the system's stability; 3) Attempting to **trigger** a PTP. Once the **tipping point** has been crossed, the system enters an **accelerating phase** of nonlinear change dominated by **reinforcing feedbacks**, then **stabilises** again in a qualitatively different state. The primary characteristic of a tipping point is a shift in the balance of feedbacks: at **point F1**, prior to the tipping point, dampening feedbacks are dominant and system stability is maintained; at **point F2**, beyond the tipping point, reinforcing feedbacks are temporarily dominant and change accelerates exponentially. Other outcomes are also possible, including '**shallower**', less sustainable **outcomes**, and **unintended consequences**.

Mirroring the 'ascent' of sustainable innovations, PTPs also imply the 'descent' of incumbent, unsustainable systems (behaviours, practices, technologies and institutions). Whereas the tipping point for an innovative, sustainable solution marks the start of the accelerating, 'take-off' phase, it marks a 'cliff moment' of rapid descent for the incumbent system (Meldrum et al., 2023). Systems change might therefore be more accurately described as an 'x-curve', rather than the more familiar 'x-curve' (Loorbach et al., 2017).

The reverse, descending arm of the s-curve is composed of three phases – **destabilisation**, **breakdown** and **phase-out** – synchronous with the three phases of PTP dynamics. Interventions can be directed towards enabling or facilitating both of these processes (GSDR, 2023; Allen and Malekpour, 2023; Hebink et al., 2022).

We now examine the main PTP concepts in greater detail under the headings of agents, interventions, shallow and unintended consequences, and tipping cascades.

4.2.2 Agents

Human agency is the capacity of individuals or groups to change an outcome or course of events (Alsop et al., 2006; O'Brien, 2015). Agents (as policymakers, politicians, business leaders, activists, campaigners, artists, academics, investors, consumers or voters) can act, either intentionally or accidentally, individually or collectively, in ways that either assist or hinder social change (Newell et al., 2022; Gaupp, forthcoming). Individual and collective efficacy, or the belief that one's agency can avert threats or influence events, increases the motivation to act and enhances emotional wellbeing (Bandura, 1999; Feldman and Hart, 2016; Stern, 2018; Bostrom et al., 2019). Even small individual acts can lead to widespread collective effects – for example, the refusal of Rosa Parks to move bus seats in 1955, or the school strike initiated by Swedish teenager Greta Thunberg in 2018. Numerous studies and the history of social movements show that a committed and well-organised minority (between less than 3.5 per cent to 10 per cent of a population) can mobilise around a common aim long enough to exceed a critical threshold and transform a prevailing social structure – for example a social norm, law, institution or government (Chenoweth and Stephan, 2011; Xie et al., 2011; Rogers, 2010; Han, 2014; Marshall et al., 2018; Centola et al., 2018; Bolderdijk and Jans 2021; Constantino et al., 2022). Such social movements typically gestate in and benefit from 'free social spaces' (Törnberg, 2018) that protect them from the prevailing hegemony and actively cultivate and empower minority groups to challenge dominant agendas and narratives (Laybourn-Langton et al., 2021).

4.2.3 Interventions

As stated in Figure 4.2.3 and Table 4.2.1, agents can strategically intervene to encourage a PTP to emerge, by: a) creating enabling conditions; b) enhancing reinforcing feedbacks and neutralising dampening feedbacks; and c) providing the decisive trigger that pushes the system past its tipping point. Interventions can also be sequenced to create positive synergies – from innovation-oriented interventions that enjoy more political support to more controversial phase-out policies (Fesenfeld et al., 2022).

Table 4.2.1: Strategic interventions for triggering PTPs (Lenton et al., 2022). The three symbols correspond to those in Figure 4.2.3.

CREATE ENABLING CONDITIONS	INCREASE REINFORCING FEEDBACKS; REDUCE DAMPENING FEEDBACKS	TRIGGER POSITIVE TIPPING
Target smaller populations.	Social contagion.	Social innovation.
Change social network structure.	Increasing returns to adoption:	Technological innovation.
Provide information.	• Learning by doing	Ecological intervention.
Reduce price/cost.	• Economies of scale	Social ecological technologies
Improve performance and quality.	• Technological reinforcement	Policy intervention and public investment.
Increase desirability or symbolism.	Network effects.	Private investment and markets.
Improve accessibility.	Information cascades.	Public information.
Increase convenience.	Percolation.	Behavioural nudges.
Coordinate complementary technologies.	Co-evolution.	
	Ecological positive feedbacks.	
	Social-ecological positive feedbacks.	

4.2.3.1 Enabling conditions

Although the primary focus of attention might fall on the final, relatively insignificant input that triggers a tipping point, the reality is that many 'tippable' human systems first need concerted effort over a long period of time to generate the enabling conditions for transformative change to emerge (Lenton et al., 2022; Otto et al., 2020). For example, the cost of generating electricity using solar energy is now so low that capacity is expanding by more than 20 per cent per year (IEA, 2022). But this is the product of four decades of public investments, subsidies and other incentives. A new/niche technology, practice or behaviour needs to become more affordable, attractive, convenient, accessible, or morally acceptable than the established one before it becomes capable of displacing it. Generating these enabling conditions requires **strategically timed and targeted interventions appropriate to the system and focused on those elements that are most sensitive to change** (Mealy et al., 2023). For example, the widespread adoption of plant-based and planetary health diets likely requires a series of strategic interventions – labelling and other information schemes, changes in decision infrastructures, political advocacy, policy coalitions, financial and reskilling supports for the food industry, technological innovations, supply-chain restructuring, changes in dietary norms and habits, and so on – before such a major societal shift could emerge (Aschemann-Witzel and Schulze, 2023; Fesenfeld et al., 2022).

Most research, innovation and policy has until now focused on intervening in technological and economic domains – for example to enable a new renewable technology to achieve cost parity. However, PTPs in the socio-behavioural and political domains offer equally powerful opportunities for transformative change. For example, changing social norms could play a crucial role in enabling PTPs (Constantino et al., 2022; Schneider and van der Linden 2023). Social norms define acceptable behaviour and can change rapidly through a population. Two emerging examples that could prove pivotal to driving positive tipping points across multiple systems are **anti-fossil fuel norms** (Green, 2018), whereby fossil fuel use becomes socially unacceptable; and **norms that prioritise the avoidance of harm and sustainable sufficiency over material consumption** (Akenji et al., 2021; Newell et al., 2021; Haberl et al., 2020; Trebeck and Williams, 2019). In the political realm, policy can help create and spread new behavioural norms, for example by investing in infrastructural changes such as bike lanes (Yoeli et al., 2013; Nyborg et al., 2016; Lenton et al., 2022); or by strengthening climate education, arts and engagement that helps people imagine what a sustainable world would look like (Galafassi et al., 2018), and mobilises public support for greater action (Milkoreit, 2017; Stoddard et al., 2021; Plutzer et al., 2016; Otto et al., 2020; Bhowmik et al., 2020; Lenton et al., 2022).

Some PTP interventions are relatively straightforward and do not involve significant cost, innovation, social norm change, advocacy or diplomacy – for example, redirecting public procurement towards alternative proteins to help transform the food system (Meldrum et al., 2023). However, other potential interventions – for example, creating a global environmental court; removal of fossil fuel and animal product subsidies; a national or global network of deliberative mini-publics (DMPs) whose recommendations are fed into the policy system; or radical urban planning concepts such as 15-minute cities (4.3.2) (Otto et al., 2020, Moreno et al., 2021) – do involve significant cost, innovation, norm change, advocacy or diplomacy. For these more complex and radical interventions, a political process would first be needed to generate the coalitions and public support which, if successful, could then initiate a policy process. If this in turn is successful, the implemented policy may then transform the system and generate reinforcing feedbacks for further change (Figure 4.4.4). Positive tipping dynamics may therefore incorporate a **sequence of intermediary tipping points** on the way to the final goal or system state (Fesenfeld et al., 2022; Smith, 2023). Cross-cutting enablers in all domains may also be subject to their own tipping points.

4.2.3.2 Reinforcing feedbacks

As in natural systems, tipping points in human systems are driven by self-reinforcing (mathematically 'positive') feedbacks: an increase in a variable leads to a closed loop of causal consequences that further increase the same variable. For example, one person or organisation's decision to take the train rather than fly, or install solar panels, or pedestrianise a road, can increase the determination of others to do likewise. Such feedbacks are instrumental both in the enabling phase before a tipping point is reached and in the acceleration phase once a tipping point has passed (Figure 4.2.4). They can exist in any domain of human systems (social, economic, political and technological) and in their interactions with natural systems. For example, the self-reinforcing feedbacks of **economies of scale** and **learning by doing** have reduced the cost of solar PV and wind for energy generation to below that of coal power, with the result that most new power generation installed globally in 2022 was renewable (IEA, 2022).

Synergies between self-reinforcing feedbacks across multiple domains can help policymakers further enable the conditions for positive tipping (Fesenfeld et al., 2022, Pahle, 2018). Fesenfeld et al., (2022) highlight that synergies between policy-induced technological and behavioural changes can create self-reinforcing feedbacks and political conditions for positive tipping. For example, the German Renewable Energy Sources Act (EEG) triggered synergistic feedback effects in financial investment, technological innovation and cost reductions of renewable energy (Schmidt and Sewerin, 2018). Other self-reinforcing feedbacks associated with such policy interventions include shifts in public opinion, social norms and practices in favour of renewable energy, which in turn can reduce political opposition and create windows of opportunity for more stringent policy options, such as carbon taxation (Figure 4.2.4) (Fesenfeld et al., 2022; Lockwood, 2013; Schmid et al., 2019). Building on this logic in socio-technical transitions research, Geels and Ayoub (2023) distinguished seven feedback loops between behaviours of different social actors and technological changes in tipping dynamics.

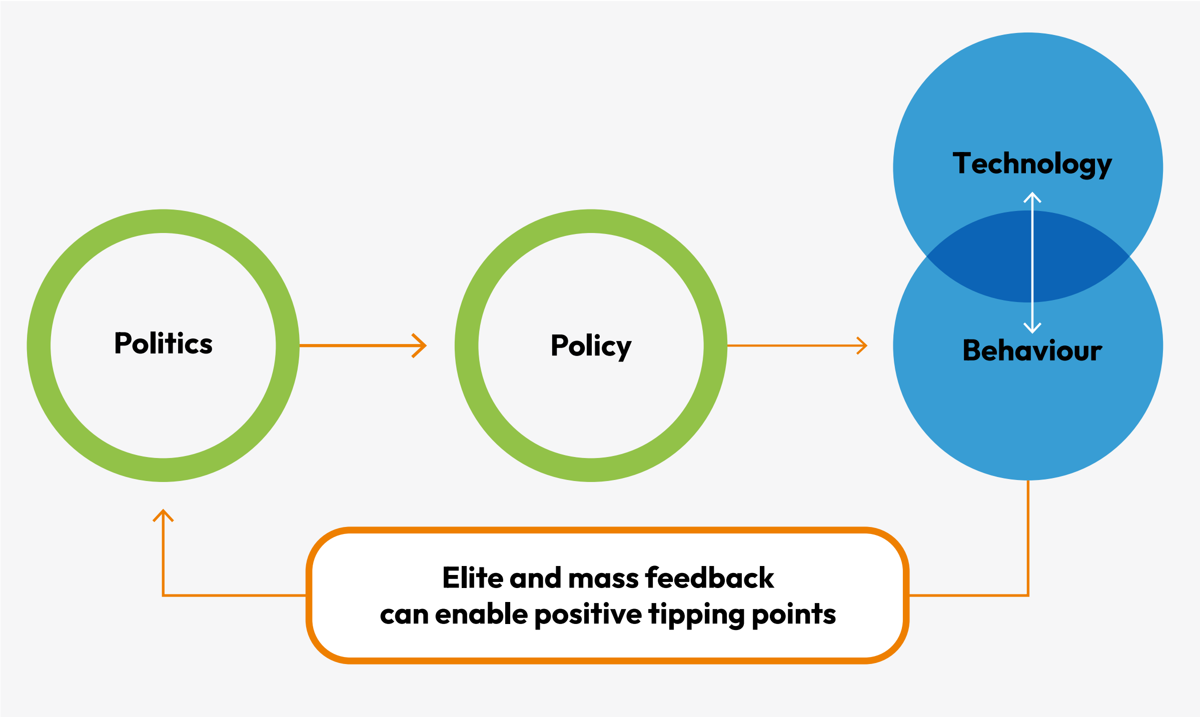

Figure 4.2.4: Reinforcing feedbacks from technological and behavioural changes can reduce existing barriers and enable PTPs (Fesenfeld et al., 2022).

Moreover, feedback and spillover effects between regions can play an important role in catalysing global change. For example, the German feed-in tariff created a first marketplace for solar PV panels that in turn has led to economies of scale in the production process of such panels in China. This has led to substantial cost reductions of solar panels so that PV became an attractive clean technology option at the global level. In turn, this has created a political momentum for change in other regions, such as China, the EU and US. In the transport sector, macro-economic modelling shows that mandates for switching to electric vehicles in major automobile markets such as China, the US or Europe can help to accelerate tipping points in other markets (Lam and Mercure, 2022).

4.2.3.3 Dampening feedbacks

As in natural systems, tipping points in human systems are prevented by dampening (or mathematically negative) feedbacks: a decrease in a variable leads to a closed loop of causal consequences that further decreases the same variable. Dampening feedbacks are system-stabilising forces. In the enabling phase, these forces – which in the case of human systems may be hegemonic political, social, discursive, economic, institutional or infrastructural – are typically still strong. They act as barriers to broader systems change. For example, in the political domain, the efforts of fossil fuel companies to obstruct, dilute, reverse or delay climate policy is well documented (Srivastav and Rafaty, 2022). In the socio-behavioural domain, a lack of trust or information, high perceived risk and uncertainty, institutional inertia, conformity, or ingrained habits may present barriers to people switching to more sustainable lifestyles (Rosenbloom et al., 2019; Constantino et al., 2022). Economic barriers to change may include high costs, supply-chain bottlenecks, or uncertainty surrounding future policy which delays new investment (Hamilton, 2009). In the technological domain, influential opposition may prevent the building of solar or wind farms. These and other forms of resistance, including system-preserving narratives based on excessive cost and over-regulation, should be expected to become more vocal and pervasive as system changes approach PTPs (Geels, 2014, Jost 2020).

A shift in the balance between dampening feedbacks (which maintain the status quo) and reinforcing feedbacks (which drive nonlinear change) can take a system out of its stable state and over a PTP, beyond which it enters an acceleration phase towards systemic transformation. Weakening the dampening (negative) feedbacks and/or strengthening the reinforcing (positive) feedbacks can bring a system closer to a PTP. The strategic sequencing of these interventions can also sometimes be important: for example, a policy process for radical change may first require a political process (4.4.2.4).

In this section of the report we focus exclusively on PTP systems. These are human (social) systems that **we want to tip** because this (in theory) leads to predominantly beneficial outcomes. We are not concerned with systems explored in Section 2.3 related to negative social tipping, where systemic change is unwanted because it leads to social harms such as war and social breakdown. Therefore, in this section alone, we can describe self-reinforcing feedbacks as being both normatively as well as mathematically 'positive'. Similarly, dampening feedbacks can be described as being both normatively and mathematically 'negative'.

4.2.3.4 Triggers of positive tipping

Any phenomenon that can be causally linked to a tipping point can be a trigger. This could be a deliberate social innovation, an investment or a policy intervention, strategically timed for maximum leverage or impact, and in awareness of the proximity of a tipping point thanks to early opportunity indicators (4.4.5). Alternatively, a trigger could be something incidental like a natural disaster or an epidemic, which causes a sudden shift in public attitudes and opens a window of opportunity for policy change. One example was the response of the German government to discontinue its nuclear power programme in the wake of the Fukushima tsunami disaster (Eder et al., 2023).

Mealy et al. (2023) argue that the most effective or 'sensitive' interventions should be executed when a system is close to tipping, the intervention thus acting as the decisive element or trigger. They propose a framework to help decision makers assess and prioritise interventions according to the assessment criteria, considerations and caveats presented in Table 4.2.2.

Table 4.2.2: A framework for prioritising 'sensitive interventions' close to a tipping point (Mealy et al., 2023).

Pillar	Key assessment elements	Other considerations and caveats
Trigger potential	**Criticality:** Does the intervention exploit a system that is close to a tipping point?	Does the intervention target a critical node in a network? Is this a critical point in time?
	Barriers: Are there barriers or resistance to the intervention, and can they be easily diffused?	Who stands to lose out from the intervention? Are there any other possible stumbling blocks or binding constraints?
	Lock-in and hysteresis: What prevents the change from being reversed?	Will a change in political leadership reverse the change? Does the intervention create path-dependency? Are actors in the system incentivised to keep the change in place?
Impact potential	**Size of impact:** Likely size of impact relative to cost of effort.	Size of impacts relative to costs can be difficult to quantify without a model that is able to capture nonlinear dynamics. However, rough estimates and expert opinion can also be useful (Lenton et al., 2008).
	Scales of impact: Potential to generate compounding change at greater scales.	Does the intervention lead to upward-scaling cascades across multiple system scales (e.g. sectors, geographies or social spheres? Does the intervention create synergies with other interventions, reinforcing the overall effect of change?
	Speed of impact: Timescale in which the intervention can be triggered and impacts realised.	Are the desired impacts likely to be realised at a time-scale relevant to address the problem (e.g. addressing climate change requires significant emissions reductions in the next few decades)
Risk potential	**Uncertainty:** What are the sources of uncertainty around the envisioned change process and associated impacts?	Are there examples where similar interventions have been tried in the past? Are there inherent sources of uncertainty that could put the viability of the intervention at risk?
	Unintended consequences: Could the intervention lead to impacts that are not intended or anticipated?	The risk of unintended consequences can be higher in complex systems that are sensitive to small changes in initial conditions or involve complex dynamics that are not well understood. Engaging with diverse groups of stakeholders can help bring to light unapparent unintended consequences.
	Trade-offs: Could the intervention or desired impacts cause adverse outcomes in other areas?	Are there any possibilities where the intervention or its impacts may create tensions or adverse impacts in other areas? If so, are there ways in which these trade-offs can be mitigated?

4.2.4 Shallow and unintended consequences

Interventions designed to induce positive tipping points towards safe and just Earth system boundaries can potentially lead to other outcomes that may be 'shallower' or insufficient (Pereira et al., 2023). Examples might include: changes to a system are not fully compatible with Earth system boundaries (ESBs); a social movement is assimilated into an existing power structure or regime before its aims are achieved; vested interests push for a suboptimal tipping point, for example the natural gas lobby pushing for hydrogen as the solution to future home heating when electric heat pumps are a far more efficient option. There may also be unintended consequences, which can negatively affect entire communities or regions. For example, in the rush to decarbonise transport and store electricity, the rising demand for lithium and cobalt for batteries can lead to heavily contaminated environments and shortage of drinking water surrounding mining communities, particularly in poorer countries. These areas have been labelled 'green sacrifice zones' because the environmental goods or services they provide also come with substantial costs (Zografos and Robbins, 2020; Hernandez and Newell, 2022). The report synthesis explores these risks, ethics and justice issues in more detail.

The speed of system change can be in tension or conflict with the 'depth' of positive change (Anderson et al., 2023; Newell et al., 2022; Skjølsvold and Coenen, 2021). The depth of change represents the extent to which the system is transformed into one that is sustainable or compatible with ESBs. The speed of transformation represents the time taken for the system to accelerate beyond its tipping point and re-establish itself in a new, qualitatively different stable state. These two forces are in tension when, for example, a sense of urgency to decarbonise as fast as possible leads to the further entrenchment of inequalities and injustices if policymakers are forced to rely on incumbent firms and investors to redesign systems in their own interests (Newell et al., 2022). The enabling conditions as outlined above must therefore consider policy architectures and forms of social engagement that neutralise these tensions.

4.2.5 Tipping cascades

A positive tipping cascade occurs when one tipping point triggers at least one other in a domino effect or chain reaction (Sharpe and Lenton, 2020). This can happen wherever tipping points occur – either in subsystems, where they can help accelerate change in a larger system, or across coupled systems (Chan et al., 2020). Coupled systems may be between domains, sectors, institutions and/or countries. The resulting overall multi-system impact of the initial change is larger than the initial impact as a consequence of reinforcing feedbacks and other secondary effects within and across systems, which is also referred to as **spiral scaling** (Newell et al., 2021; Geels and Ayoub, 2023). As elaborated in Chapter 4.4, some systems that have the potential for tipping can also be thought of and utilised as cross-cutting enablers of tipping in other systems. For example, there may be tipping points in the uptake of new electricity storage systems, digital technologies, social norms, political coalitions, or systems of finance; these can also be used, individually or in combination, as strategic interventions to enable tipping points in other systems. When designed to trigger a positive tipping cascade, such interventions are referred to as **super-leverage points** (Meldrum et al., 2023). As examples, economies of scale in the production of renewable energies can lead to tipping points in the adoption of electric vehicles, and thereby foster innovations in industry and agriculture; mandating Zero-Emission Vehicles can accelerate this process and create positive synergies with other potential super-leverage points, such as mandating green ammonia for use in fertiliser production. Cheaper renewable power reduces the cost of running electrolysers and reduces costs of green ammonia in fertiliser production. This, in turn, can lead to economies of scale in green hydrogen supply chains and bring down the cost of green hydrogen for use in several other sectors. To use a non-technological example, a social movement like Fridays for Future could create positive tipping cascades across sectors and jurisdictions if, for example, a series of school strikes were to inspire a general strike of workers organised by the trade union movement and professional associations.

In subsequent chapters we illustrate the practical application of this framework with empirically evidenced case studies in the sectoral systems of energy, transport, food and land use (see Chapter 4.3). We also investigate cross-cutting enablers of PTPs in socio-behavioural, political and financial systems, digitalisation and early opportunity indicators (see Chapter 4.4). The chapter after that (see Chapter 4.5) is a more detailed investigation of positive tipping cascades in a range of human systems.

4.3 Positive tipping points in energy, transport and food systems

Authors: Tom Powell, Steve R. Smith, Caroline Zimm

This chapter takes a closer look at sectoral systems – energy, transport, food and land use. These sectors are key to accelerating decarbonisation, reducing short-lived climate forcer (SLCF) emissions including methane emissions, and enhancing biodiversity. The Intergovernmental Panel on Climate Change (IPCC) most recent assessment report (AR6) emphasises the need for rapid transformation in these sectoral systems. Successful mitigation pathways in the SSP scenarios require changes at least consistent with the best-case scenarios for past technological, behavioural or institutional change, and often depend on unprecedented rates of change. The feasibility of decarbonisation is shaped by barriers and enabling conditions across technological, economic, social-behavioural, political and ecological dimensions. These enabling conditions are context-dependent, but are essential prerequisites for propelling the fast technology and behavioural change required to achieve net-zero CO_2 emissions by mid-century.

In each sectoral system, we examine existing or potential PTPs, drawing on case studies and other research. Much previous focus has been given to tipping points in the technological domain, for example the substitution of fossil fuels for renewable energy sources, or of battery electric vehicles (BEVs) for those powered by internal combustion engines (ICEs). For these PTPs, reinforcing feedbacks associated with economies of scale, learning by doing and technological reinforcement are instrumental in driving down costs of low-carbon innovations and making them attractive to users. The Breakthrough Effect report summarised 10 potential positive tipping points across high-emitting sectors, and potential super-leverage points that could trigger positive tipping cascades. This subsection does not aim to replicate that work.

The Breakthrough Effect report and other studies have tended to focus on the mechanisms that enable low-carbon technologies to compete on economic terms, while acknowledging that important enabling conditions in other domains may also need to be satisfied. In reality, **positive tipping dynamics likely involve strong feedbacks between technological, behavioural, political and economic processes**, all of which can be important in enabling tipping into a new regime (Geels and Ayoub, 2023). Here we take a complementary focus to consider multiple other enabling conditions including, for example, how norms and behaviours or political processes can change to accelerate uptake of low-carbon technologies or other practices.

Likewise, previous work has largely focused on supply-side substitutions for the highest-emitting technologies or industrial processes. Markets for these technologies are, of course, determined by interactions between supply and demand. Thus, to better understand the conditions in which these markets might tip into new states, we also broaden the focus to consider the role of demand-side changes in enabling positive tipping points. While supply-side substitutions can drive powerful emissions reductions, they may not be sufficient, or efficient enough on their own, to meet climate goals. For example, cities are responsible for 70 per cent of global carbon emissions and two-thirds of energy use; thus, measures that transform energy use and transport in urban environments can have powerful mitigating effects (Winkler et al,. 2023) which reinforce efforts to decarbonise energy sources. We therefore also explore the potential for discreet PTPs in reducing or changing demand itself.

In this respect, an **avoid-shift-improve logic (ASI)** (Creutzig et al., 2022) is helpful in structuring actions, as the three types of action each have potential to reinforce the others by amplifying their effects. **Avoiding** aims at refraining from harmful activities or products – reducing unnecessary consumption, possibly by redesigning service-provisioning systems. **Shifting** describes a change to a less-harmful activity or product – a switch to efficient and cleaner technologies and service-provisioning systems. With **improving**, the product or activity becomes better in terms of environmental performance – the efficiency in an existing technology is improved.

Arguably the greatest overall positive impact is often achieved by avoiding the activity or product in the first place, and embracing the concept of **sufficiency** (Princen, 2005; Newell et al., 2021; Trebeck and Williams, 2019). However, in a global political economy that prioritises consumption-based economic growth, improving and shifting actions receive the lion's share of government and business support. Shifting tends to deliver less overall positive impact, with improving delivering the least. Hence, an inherent hierarchy within these approaches exist. While **improve** options are not sufficient to tip systems to a decarbonised state alone, they are an important enabler and amplifier of options that can. Any increase in efficiency reduces the need for **avoid** and **shift** activities. Similarly, smaller resource systems following **avoid** or **shift** interventions, need fewer **improve** actions to tip (Figure 4.3.1).

The different approaches and related measures can and should be combined – they are not mutually exclusive. While some are characterised by individual or collective behaviour change on the demand side, others are dominated by novel technology or facilitated by revamping underlying structures of a system. Typically, **avoid** and **shift** options require larger changes in social practices and in the broader socio-technical system.

Options where both behavioural and technological change is required or that require a substantial change in social and user practices are typically more difficult to realise and thus difficult as a starting point for tipping dynamics (Geels et al 2018).

The respective roles of avoiding (sufficiency), shifting (substitution) and improving (efficiency) also depend on the relative importance of behavioural and technological changes for enabling positive tipping in a particular sector (Fesenfeld et al., 2022). For instance, the widespread adoption of more plant-based diets is likely to depend on a combination of technological and behavioural changes along food supply chains and careful sequencing and synergies between **avoid**, **shift**, and **improve** interventions (4.3.3)

We use this logic to describe and organise interventions in this section and use these labels.

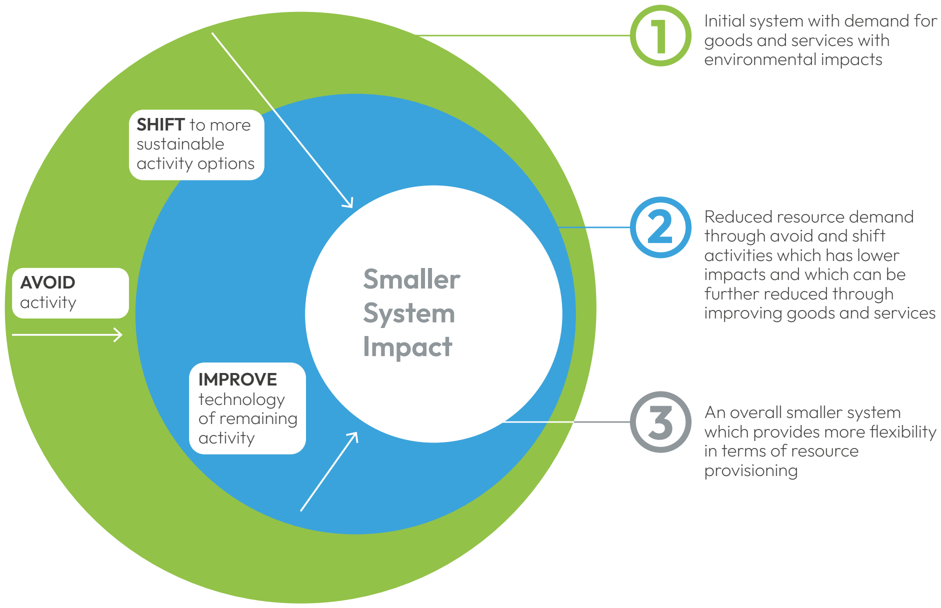

Figure 4.3.1: The avoid-shift-improve logic and how it connects to the overall system size which needs to tip. Systems are shaped by demand and supply options.

4.3.1 Energy systems

Authors: Floor Alkemade, Bart de Bruin, Francesco Pasimeni, Leila Niamir, Robert Wade, Franziska Mey, Johan Lilliestam, Raphaela Maier

Summary

The tipping dynamics in wind and solar power create potential for cascading effects to energy demand sectors, including household energy demand. These most likely start with shift actions and adoption of household-scale batteries and heat pumps. Key enablers are strong regulations incentivising reductions in demand and setting minimum efficiency levels for buildings and appliances. While there is evidence of spillovers to more environmentally friendly behaviour, the extent of these and the key leverage points present a knowledge gap. Moreover, these behavioural feedback loops require strong additional policy support to 'make them stick'.

Key messages

- For many countries the power sector has recently passed a tipping point in which the declining price of renewable electricity supply is reinforcing exponential growth, with over 80 per cent of new electricity generation in 2022 being solar and wind.
- Fast growth and declining price in renewable electricity supply is driving social tipping in the electricity system, as shown in the uptake of EVs, PV or heat pump systems and interactions between them.
- Reducing energy demand by identifying options to avoid energy-intensive activities, shifting to less energy-intensive activities and improving energy service efficiency can accelerate decarbonisation of the energy system.

Recommendations

- Further foster clean energy technology development and diffusion worldwide, especially in emerging markets.
- Enable positive tipping points in the adoption of novel technologies (shift and improve) and behaviours (avoid) with strong regulations that incentivise demand reductions.
- Set minimum efficiency levels for buildings and appliances.
- Encourage much-needed research on evidence of spillovers from one to more environmentally friendly behaviours and how to enable such spillovers.
- Implement strong additional policy support for behavioural feedback loops to 'make them stick'.

4.3.1.1 Introduction

The goal of energy systems is to provide energy services to end users. The main energy uses are for heat and electricity in industry and buildings and for transport (4.3.2). The industrial, residential and transport sectors together account for 70 per cent of the total global electricity consumption in 2019, and these sectors also are responsible for approximately 60 per cent of the worldwide carbon dioxide (CO_2) emissions (IEA, 2021a, IEA, 2023a). The decarbonisation of the energy system is a key driver of overall decarbonisation efforts. Energy systems are socio-technical systems; they consist of the technologies that generate energy and convert and deliver this energy to end users, but also of the actors and institutions that perform and govern these tasks. Within energy systems, the subsystems that can undergo tipping dynamics can be found in technologies, but also in social systems when actors and institutions change demand patterns (Geels, 2023).

Most consideration of tipping dynamics in energy systems concerns the price performance of different technologies (Otto et al., 2020; Sharpe and Lenton, 2021; Meldrum et al., 2023). Cost-parity has been reached and exceeded in many regions in a 'new-for-new' comparison of energy generation from wind and solar, versus incumbent fossil fuel generation, with the majority of new installed capacity in 2022 being renewable (IEA, 2022a; IRENA, 2023). In OECD countries, the resulting fast growth in wind and solar generation capacity has led to a reduction in fossil fuel demand in the electricity production, but not globally, as other nations increased fossil fuel demand (IEA, 2021b; OurWorldInData, 2022). Renewable energy generation sometimes faces curtailment and the mismatch of renewable supply with energy demand slows down replacement of fossil fuels, which benefit from their incumbent position. This shows that economic tipping points alone are not sufficient to realise rapid decarbonisation. Below, we explore how the tipping dynamics in wind and solar technology may initiate further positive tipping in the energy system, and we touch upon what this means for coal-intensive regions (Box 4.3.2) and we investigate advances relevant for industry (Box 4.3.2).

4.3.1.2 Fast growth in renewable electricity supply drives social tipping in the energy system

Cost reductions in renewable generation technologies like wind energy and solar photovoltaics (PV) have been much faster than predicted. Renewables are now among the cheapest electricity generation options (Haegel et al., 2019; IRENA, 2022a; IRENA, 2022b).

For wind and solar energy generation, the main reinforcing feedbacks that created these tipping dynamics are cost reduction and performance improvements through investment in research and development, learning-by-doing and economies of scale, leading to more deployment and, in turn, to more learning and price reduction.

(Sharpe and Lenton 2022; Kavlak et al., 2018, Nemet and Greene, 2022). The German feed-in tariff for renewables discussed in 4.2.1 was historically an enabling condition for a positive tipping point in the solar PV sector (Otto et al., 2020; Clark et al., 2021). Moreover, markets are still expanding as performance improvements make the technology attractive to a wider range of users. As a result of these technological improvements and cost reductions, renewable generation is increasingly possible in locations where wind or sun conditions are less favourable. The exponential growth of offshore wind power in the North Sea (Drummond et al., 2021; Geels and Ayoub, 2023) and the increasing attention for floating solar (Karimirad et al., 2021; Pouran et al., 2022) illustrates this. Renewable energy generation coupled with battery storage is expected to reach cost parity compared to power generation from natural gas in the near future, if it has not done so already (Meldrum et al., 2023), as battery costs are driven down by the growing electric vehicle industry, further enhancing the competitiveness of renewables with fossil fuels.

The cost-performance feedback loop is the main, but not the only, feedback driving the tipping dynamics for wind and solar. For instance, there is evidence for social contagion in the diffusion of rooftop solar PV, which is typically clustered in space where people are more likely to adopt when people nearby also have adopted (Graziano and Gillingham, 2015; van der Kam et al., 2018). This suggests that their diffusion is partly a social process influenced by, for example, **observability**, **trialability**, and **word-of-mouth** (Rogers, 2003) and **social comparison** (Bergquist et al., 2023).

Another reinforcing feedback loop stems from policy interactions, whereby policy creates legitimacy and new interests, leading to increased lobbying and support for policy (Roberts et al., 2018; Meckling, 2019; Rosenbloom et al., 2019; Sewerin et al., 2020). Further, strong pro-environment policies may incentivise firms towards more RandD and innovation, thereby expanding industrial sectors for low-carbon technologies. In this way, public opinion may also increase support and acceptance for new low-carbon technologies, increasing pressure on policymakers in creating goals and strategies for a more sustainable society (Geels and Ayoub, 2023).

Sources of dampening feedbacks, lock-in and path-dependence of fossil fuel-based energy systems include energy infrastructures, technologies and institutions (Köhler et al., 2019). These can directly hinder the decarbonisation of the energy system through existing standards and resistance from incumbents and vested interests. Indirectly, the availability of cheap energy has stimulated demand for energy-intensive goods and services. Similarly, the high return on fossil fuel investments and the assessment of renewables as risky require policy attention to stimulate the move of capital from fossil to renewables (Pauw et al, 2022, 4.4.4). As an example, in the early 2000s, the UK government provided initial capital grants to boost offshore wind demonstration projects, resulting in a game changer into the overall offshore sector. This has, in turn, built confidence among financial investors, easing access to resources for project developers (i.e. lower interest rates) (Kern et al,. 2014; Geels and Ayoub, 2023).

Social dynamics can lead to reinforcing feedbacks but may also create dampening feedbacks when they mobilise opposition and a lack of societal support for larger-scale solar and onshore wind farms (Devine-Wright, 2007; Klok et al., 2023; Windemer, 2023). Cost-competitiveness is not a sufficient indicator to predict support for technologies for which the main public concerns are about spatial/visual impacts, health and safety, and questions of fairness.

Policy for positive social tipping can seek to strengthen reinforcing feedbacks and reduce dampening feedbacks. The policy-relevant timescales of the energy system vary from months to decades. Energy infrastructures are typically built for a lifespan of around 40 years, and changing these infrastructures takes place on the timescale of months to years. Once built, they contribute to stabilising the system state and are a source of path dependence and lock-in. In contrast, some demand-side behaviour changes are quite swift. An example is the substantial energy demand reduction in Europe in the winter 2022/2023, resulting from concerns about high energy prices and the war in Ukraine. A key policy challenge is how to make the new behaviour 'stick'.

4.3.1.3 Positive tipping dynamics that build on the fast growth in wind and solar technologies and services

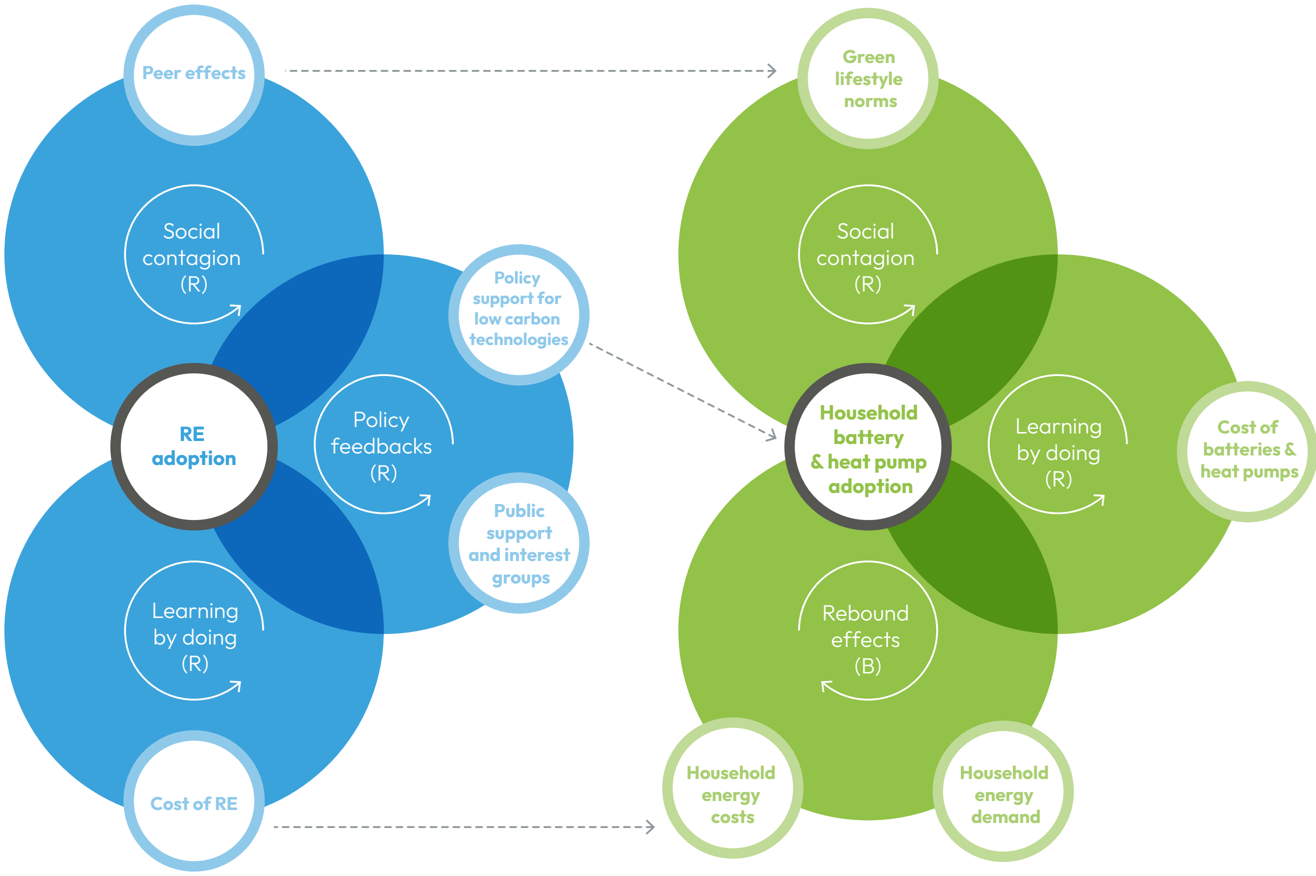

Figure 4.3.2: Cascading effects from renewable energy supply to household energy demand. The feedbacks that led to the strong growth in distributed renewable energy supply, can also strengthen the feedbacks that help reduce household energy demand when policy support is in place. R = reinforcing feedback, B = balancing/dampening feedback.

Two further significant developments are needed to transform the energy system. Firstly, while for many regions renewable energy potential exceeds demand, a fast energy transition faces constraints regarding the availability and sustainable sourcing of materials and personnel (Wang et al., 2023). Most scenarios therefore envision a reduction of demand where the demand for energy should be brought in line with what can be sustainably produced in the short term. Indeed, reducing energy demand is key in 1.5°C pathways (Koide et al., 2021). Reduction in energy use is thus widely regarded as a key pillar of decarbonisation in wealthy countries. At the same time, energy access and service provision will need to grow for many less-developed countries, and for poor people everywhere to ensure decent living standards and wellbeing (IPCC, 2022a). Although we observe a decoupling of energy demand and income in some places, in general household energy demand grows with income. Pro-environmental attitudes and behaviour have also been correlated with income, further complicating the challenge of how to reduce income inequality and material and energy consumption to sustainable sufficiency levels (Du et al., 2022). Moreover, individuals with high socio-economic status (top 10 per cent) are responsible for a large share of emissions (IPCC, 2022b; IEA, 2021b). These individuals could have a large positive impact when they reduce GHG emissions, becoming role models of low-carbon lifestyles, investing in low-carbon businesses, and advocating for stringent climate policies (Creutzig, et al., 2022). Such approaches are also discussed in the context of energy justice and equitable energy demand reduction (Büchs et al., 2023).

Second, when no low-cost zero-emission energy sources, like waste heat, are available, the energy system should electrify. In addition, but beyond the scope of this section, attractive technological alternatives like green hydrogen should be developed for hard-to-electrify demand (4.3.2).

To identify possible tipping dynamics and tipping elements in energy systems, we follow the avoid, shift, improve (ASI) logic (Creutzig et al., 2022, 4.3.1). While improve options are not sufficient to tip the energy system to a decarbonised state, they are an important enabler for options that can. Moreover, they may have important health co-benefits and reduce the material needs of the energy system. Any increase in efficiency reduces the need for avoid and shift activities. More generally, the different options often co-occur. While avoid options have the largest mitigation potential, they often need to be flanked with shift and improve options to be attractive. For example, when people switch from natural gas heating to heat pumps, good insulation (improve) is a condition.

Avoid options reduce unnecessary energy consumption. Changes in the energy behaviour of individuals can make a large contribution, specifically when supported by changes in the broader socio-technical system ranging from subsidies to norms for energy-efficient housing to educational and information campaigns (Nisa et al., 2019; Niamir et al., 2020). More specifically, social tipping of energy consumption by individuals, households or organisations is conditioned by a range of factors such as social and cultural norms, ownership and control of resources, technology accessibility, infrastructure design and services availability, social network structures, and organisational resources (Steg et al., 2018). Because of the relationship between income and energy use (Richmond and Kaufmann, 2006), a rebound effect may occur when technologically induced demand reductions lead to a higher budget and more energy demand (Newell et al., 2021; van den Bergh, 2011; Sorrell et al., 2020). While there is some empirical evidence for such a rebound effect (Berner et al., 2022; Brockway et al., 2021; Stern, 2020) – making decoupling of energy demand more difficult – decoupling has been observed in several Organisation for Economic Co-operation and Development (OECD) countries in recent years.

Digitalisation and AI can play a key role in avoiding unnecessary energy demand (Wilson et al., 2020; Giotitsas et al., 2022., see 4.4.4). At the individual and household level, lifestyle changes regarding energy demand, including turning down the thermostat and reducing the demand for hot tap water (shorter showers), are effective strategies (Roy et al., 2012; Creutzig et al., 2016; Ivanova et al., 2020). These are most effective when combined with policy support and shift and improve measures. More specifically, digital technologies are key to better match renewable supply with demand to prevent curtailments and grid congestion (load shifting and balancing) but have not yet reached widespread diffusion.

Higher prices (and temperatures) lead to reduced energy demand for heating. Natural gas consumption in the EU and in the period August-November 2022 decreased by 20 per cent compared to the average gas consumption for the same months in the previous five years (Eurostat, 2022). However, this also came with increased levels of energy poverty, particularly affecting low-income households in badly insulated homes (IEA, 2023b). Interestingly the high prices also triggered and opened the opportunity for sufficiency-based energy price interventions in the form of price ceilings for gas and electricity in response to the energy crises in the winter of 2022-2023.

When the demand reductions stem from changes in norms or behaviours with a sustainability motive, the risks of rebound effects are lower. Interestingly, **pro-environmental behaviours also induce other pro-environmental behaviours**, so changes in behaviour in mobility or food may spill over to energy behaviours (Steg and Vlek, 2009; Steg, 2023). The adoption of household PV for environmental reasons may thus induce other pro-environmental behaviours. As an example, evidence for Austria shows that the adoption of PV and electric vehicles are correlated (Cohen et al., 2019). When the new behaviour becomes common and the norm starts to shift, this also increases the **political feasibility of strict regulation**. There is, for example, public support for measures like incentives towards renewable technology and a ban on least energy-efficient household appliances (Poortinga et al., 2020).However, there is also evidence that these spillover effects are insufficient for the substantial lifestyle changes that are needed (Thøgersen and Crompton 2009; Truelove et al., 2016).

Empirical studies show that informing people about the energy conservation behaviours of their neighbours combined with the public labelling of energy conservation behaviour as desirable, can lead to significant reductions in energy consumption (Göckertiz, 2010; Allcot, 2011; Horne and Kennedy, 2017; Bonan, 2020). A key takeaway from these studies is that a relatively weak form of sanctioning (e.g., approval and disapproval of particular behaviour by using thumbs up/down or positive and negative 'smileys'), already has a modest positive effect on energy savings. Peer effects in social network structures can provide inhibiting or supporting conditions for the diffusion of energy conservation practices, depending on the structure of the network and the type of activity (Wolske et al., 2020).

If avoiding energy use is undesirable from a wellbeing perspective, then shifting the way this activity is done (or finding an alternative means to the same goal) is key. For electricity use, the decarbonisation of the energy system, driven by the cost reductions in wind and solar, is a large driver. Such reductions are more likely in smaller and more modular technologies (Wilson et al., 2020). Other small and modular technologies that may reach cost parity in the short term are household batteries and heat pumps (Meldrum et al., 2023). Household batteries are specifically attractive in places where feed-in tariffs for solar energy into the grid are much lower than the tariffs for energy from the grid (4.5.2).

The large-scale adoption of household batteries may influence the decarbonisation of the energy system in two ways: first, it reduces curtailment of household PV generation, better matching renewable energy supply with demand. Second, it reduces grid congestion during peaks in solar generation. Currently, in several countries, this congestion is a barrier to further grid integration of renewables. To stimulate demand to synchronise with the availability of renewable energy supply, utilities are offering dynamic tariffs that discriminate between time of use and sometimes also location of use (Nicolson et al., 2018; Freier and Loessl, 2022). These developments then further improve the attractiveness of household batteries.

The electrification of heating is a second technology that benefits from the fast decarbonisation of the electricity supply. For heat demand, which is often met by natural gas boilers (based on IEA, 2022b analysis, natural gas accounts for 42 per cent of global heating energy demand, with a 40 per cent share of the heating mix in the European Union and over 60 per cent in the US), the shift to low-carbon heat sources requires changes in technologies and infrastructure in houses, commercial buildings and neighbourhoods. When low-carbon heat sources like waste heat are available, this is a preferred option. When this is not the case, electrification of heating demand through heat pumps can lead to a large reduction in energy demand.

Here, important enablers are increased insulation (also to reduce overall heat demand) and increased renewable electricity supply. But, barriers are the lack of technologies for heat storage, the cumbersome installation process, and the high upfront installation costs. Supported by regulation and policy incentives, the demand for heat pumps is increasing fast in several countries (IEA, 2022c), providing further opportunities for cost and performance improvements through learning by doing. A more radical and politically challenging behavioural change would be to provide incentives to live in smaller homes or to have higher occupancy per dwelling, for example in planning decisions.

The cascading effect described above can contribute to energy demand reduction in rich countries. The declining cost of solar has also led to the development of solar home systems for energy-poor areas in the Global South, where off-grid solar technologies are estimated to be the least costly and most viable way to electrify the majority of those who lack access to electricity (IEA1, IEA2). Reliable access to electricity can unlock a cascade of benefits including access to cooking, cooling or heating, refrigeration for storing foods and medicines, lighting, power for agriculture, irrigation and other economic activities, and access to communications, banking and information. It plays a critical role in healthcare, sanitation and resilient livelihoods (PIDG report). A key barrier for enabling widespread deployment of solar power in the Global South is the high cost of capital in these economies – however, threshold and network effects in financial systems exist which could unlock investment (4.4.3.4). While in many of these countries the potential for solar energy, and for such systems to contribute to wellbeing, is large, the way they are packaged can fail to fit with local needs (Groenewoudt et al., 2020). Learning-by-doing is likely to play a key role in accelerating deployment, alongside continued support by international policy and investment to realise the potential benefits of solar at scale and develop local energy markets.

Box 4.3.1 Just energy transitions – tipping in coal- and carbon-intensive regions?

The socioeconomic transitions of coal- and carbon-intensive regions have raised concern for just transitions focusing on labour market opportunities. Essen and Duisburg in the German Ruhr Region, for example, have advanced in this transition process (>30 years) in different ways. Both cities experienced incremental changes in their demographic, economic and political trajectories. We can also identify a bifurcation in the cities' visions and their narrative development: Essen envisions a green, sustainable future, whereas Duisburg remains devoted to its industrial storyline. Neither of the cities have crossed a tipping point in the hard quantitative indicators (e.g. unemployment rate, GDP) yet the narrative change may indicate a significant and qualitative shift in the long term: if the cities embark on different trajectories now, this will likely result in stronger social and economic differences in the future. Maybe seen from a few decades into the future, the period around 2020 can be identified as a tipping period in one or both cities.

Successful examples exist where renewable energy stepped in when the fossil fuel industry declined. In Denmark, Esbjerg was a major port for the oil and gas industry. It was specifically targeted by the Danish Government to be a major beneficiary of the new offshore wind sector. Today, one in nine jobs (5,000 in total) in Esbjerg is related to wind power. The town received dedicated policy support for just transition which can be replicated elsewhere. Offshore wind has been revitalising communities in the North East of England that were left behind when coal mines closed in the 1980s. Offshore wind development now offers high-skill level jobs and opportunities for economic development and export-oriented local supply chains through investment in local facilities and communities. The UK is the largest off-shore wind power market in Europe. For just energy transitions benefiting communities, local value-creation will be key.

Box 4.3.2 Decarbonising the steel sector

The global steel industry is responsible for 7 per cent of greenhouse gas emissions (OurWorldinData, 2023) and needs to decarbonise quickly, by adopting low-carbon technologies instead of blast furnaces. Three scales are relevant here: the whole global steel industry, individual steel companies, and their specific production facilities. The ultimate goal is to see a tipping point at the global scale, which means a significant decrease in emissions across the industry. This will only happen when specific companies or facilities tip first. When some pioneering companies decide to switch to low-carbon technologies, it could set off a chain reaction. Currently, 11 full-scale green hydrogen DRI steel plants are planned to be operational by 2030, and once around 6 per cent of steel plants make this change, the prices of these technologies is expected to drop, making them more accessible to others, and emissions will start to decrease. Carbon pricing or equivalent subsidy can accelerate the point at which green steel becomes competitive with fossil fuel-based production (Meldrum et al., 2023). This process takes time, but it is crucial for the long-term goal.

How to trigger tipping points at the individual company level is the more urgent concern, in order to enable this wider tipping point. This happens when a company decides to commit to a net-zero pathway by using low-carbon technologies instead of fossil-based practices. The evidence for a potential tipping point is even stronger when the decision is backed by concrete plans for technology implementation and investment in new infrastructure.

One example is voestalpine, an Austrian steelmaker that decided to reduce emissions by replacing parts of its blast furnace process with green hydrogen-based direct reduction and electric arc furnaces (voestalpine, 2023a). This move shows the beginning of a positive feedback loop, pushing the company further along the path to net-zero emissions when new technologies become more common.

Political and economic factors also play a role. EU and national policies, such as the emission trading system, put pressure on companies to reduce emissions. When customers demand low-carbon steel products, it drives innovation and motivates steelmakers to provide more low-carbon options. These factors can trigger tipping, pushing the industry closer to the net-zero goal.

4.3.2 Transport and mobility systems

Authors: Luis Martinez, Leila Niamir, Aneeque Javaid, Keith Smith, Joshua E. Buxton, Aileen Lam, Caroline Zimm, Tom Powell

Summary

The transport sector is one of the most difficult to decarbonise, currently still relying almost entirely on fossil fuels for individual motorised transport. While individual technologies such as electric vehicles (EVs) show promising acceleration in their diffusion to support decarbonisation of this sector, transport demand is ever increasing. Merely switching to a new technology for passenger vehicles will not transform our mobility in a sufficiently sustainable manner as other externalities will prevail and material demand will remain high. Aiming to avoid demand for material-intensive mobility and shifting to more active modes of transport play a key role in transforming this sector. Examples of successful initiatives that moved towards more active mobility modes, such as walking and cycling, and higher-capacity technologies, are given with a focus on passenger mobility in cities. Bus Rapid Transit Systems are low cost and high impact and have been replicated in some cases both in Global North and Global South contexts. An example of how freight transport could be transformed is also given.

Key messages

- There is an urgent need for a large-scale tipping point in transport demand as demand for freight and personal transport continues to increase, with diverse negative impacts.
- EVs show evidence of passing or approaching tipping points in major markets including China and Europe, following the pioneering example of Norway.
- There are encouraging localised examples of tipping points in urban mobility, a decrease in individual motorised transport, and a shift to more active transport modes which can be upscaled.
- Decarbonisation in the sector will not happen without a behavioural adaptation of society to a new consumption and growth paradigm.

Recommendations

- Policymakers need to prioritise integrated planning to enable tipping in transport, foremost regional planning for public transport and active travel infrastructure to avoid material-intensive individual mobility.
- Policymakers need to steer the transition of the transport sector with tools such as zero emission vehicle mandates, which can induce EV tipping points across markets.

4.3.2.1 Introduction

The transport sector faces enormous challenges in meeting the decarbonisation targets in the following decades. Transportation worldwide is responsible for 23 per cent of global GHG emissions (ITF, 2023), still relying heavily on fossil fuels (91 per cent) (IEA, 2023). Its emissions are growing and it is the slowest sector to transform and adapt to a new reality (Creutzig et al., 2015), with infrastructure and vehicle fleets supporting lock-ins and path dependency. Freight (46 per cent of transport emissions) and passenger transport (54 per cent) are closely linked with the global economy and perceived wellbeing. This raises the question of how perceived wellbeing can be decoupled from unsustainable modes of mobility.

Interventions or policies in the transport sector that could allow moving towards decarbonisation and provide a smoother and more robust pathway rely on the avoid-shift-improve framework (Creutzig et al., 2022). Figure 4.3.3 presents the current system of policies and investment that needs to be inverted to increase the attractiveness of sustainable transport and public transport against car dependency, urban sprawl and long-distance travel. For transport systems, **avoid** focuses on measures that could help reduce demand for mobility by adapting consumption and activity patterns. **Shift** looks at the possibility of moving demand from carbon-intensive modes to cleaner zero-emission alternatives (e.g. public transport, biking, battery electric vehicles). And **improve** aims at increasing efficiency by meeting the same demand, yet reducing emissions through improving vehicle performance or promoting cleaner energy sources. Most recent measures and policies put in place or which have been promoted strongly for the next decades focus on the latter.

Improving the efficiency of vehicles, such as switching from internal combustion engines to EVs (4.3.2.2.), which have significantly lower lifetime emissions (Knobloch et al.,2020) (see Chapter 4.6), will contribute to achieve the decarbonisation targets and interfere less with how markets and society operates as underlying structures only have to adjust a little, but it will not be enough and also omits other externalities (e.g. traffic, material requirements). The challenge resides in the recent technological improvements that enhanced vehicle efficiency, reduced costs and generated more induced demand for mobility and transport than the CO_2 they mitigated. Energy demand for passenger transport can be lowered by up to 73 per cent when combining **avoid** and **shift** approaches, achieving several co-benefits and improving wellbeing simultaneously (Arz and Krumm, 2023). Combined with **improve** options for the remaining part, urgently needed decarbonisation could be achieved in time.

For this reason, this chapter will also discuss enabling conditions to tip the transport system and transport-related policy measures and innovations that could significantly bring down transport emissions and promote other sustainability concerns, such as liveability and resource-use efficiency, in the coming decades.

First, this chapter looks at passenger transport, summarising current understanding of the EV transition and then focusing on avoid and shift solutions in urban areas. Next, the chapter provides examples of technological advances that could transform freight transport. The examples are scalable and come with several opportunities for reinforcing feedbacks.

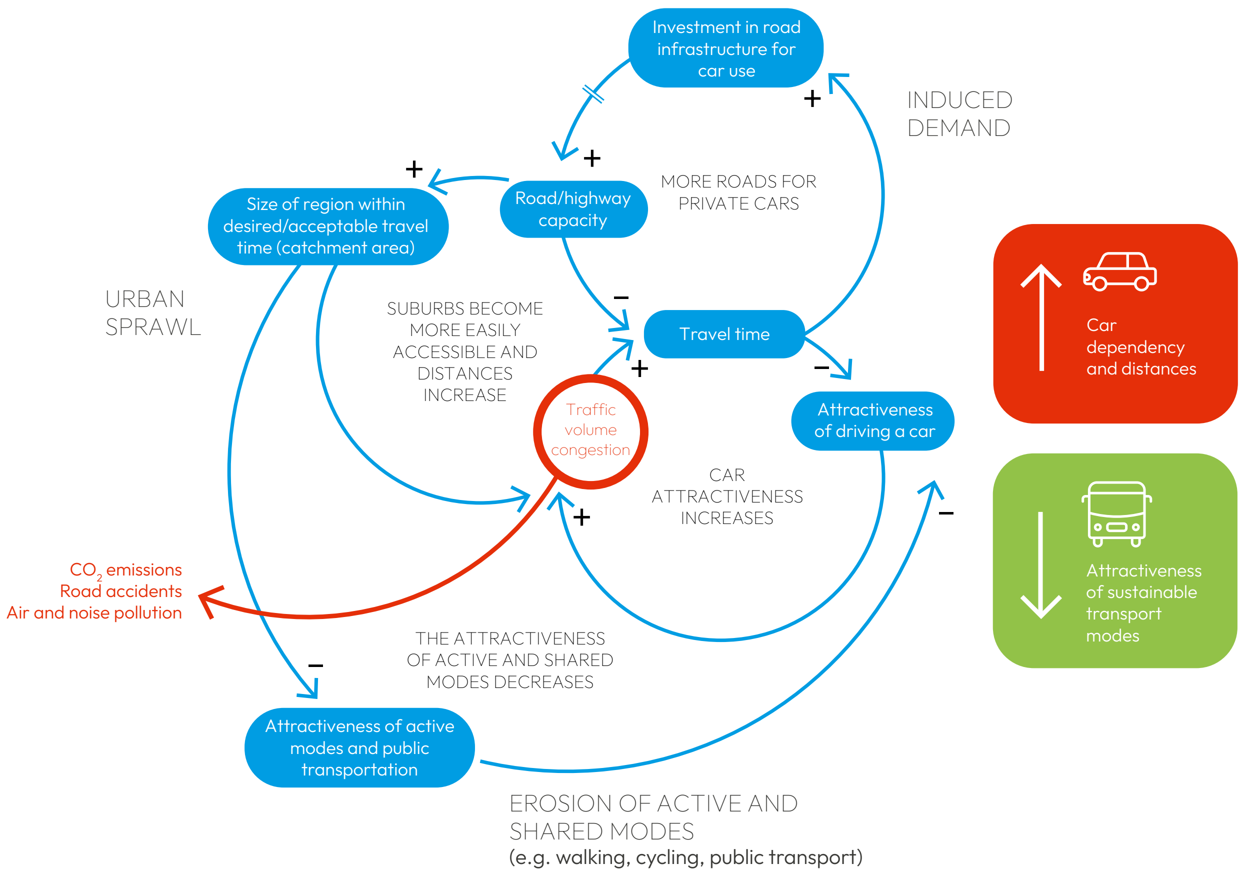

Figure 4.3.3: Causal loop relation of the vicious cycle of urban expansion and related transport regimes that need to be broken to reduce car dependency and increase attractiveness of sustainable transport modes. Higher urban sprawls increases the attractiveness of private cars and more roads for cars, which again leads to more sprawl and car ownership. Source: OECD, 2021

4.3.2.2 Improving passenger transport with the transition to electric vehicles

Sales of EVs, including battery electric vehicles (BEVs) and hybrid electric vehicles (HEVs), have increased rapidly in many national markets. Consequently, market share of internal combustion engine vehicles (ICEVs) has been declining in North America, Europe and Asia as EVs have further diffused. This regime shift in Europe and Asia has been rapid, with the two markets appearing to have undergone a tipping point, and EVs on track to rapidly capture more than 50 per cent of market share. So far however, the EV transition in North America does not appear to have reached a tipping point (Figure 4.3.4).

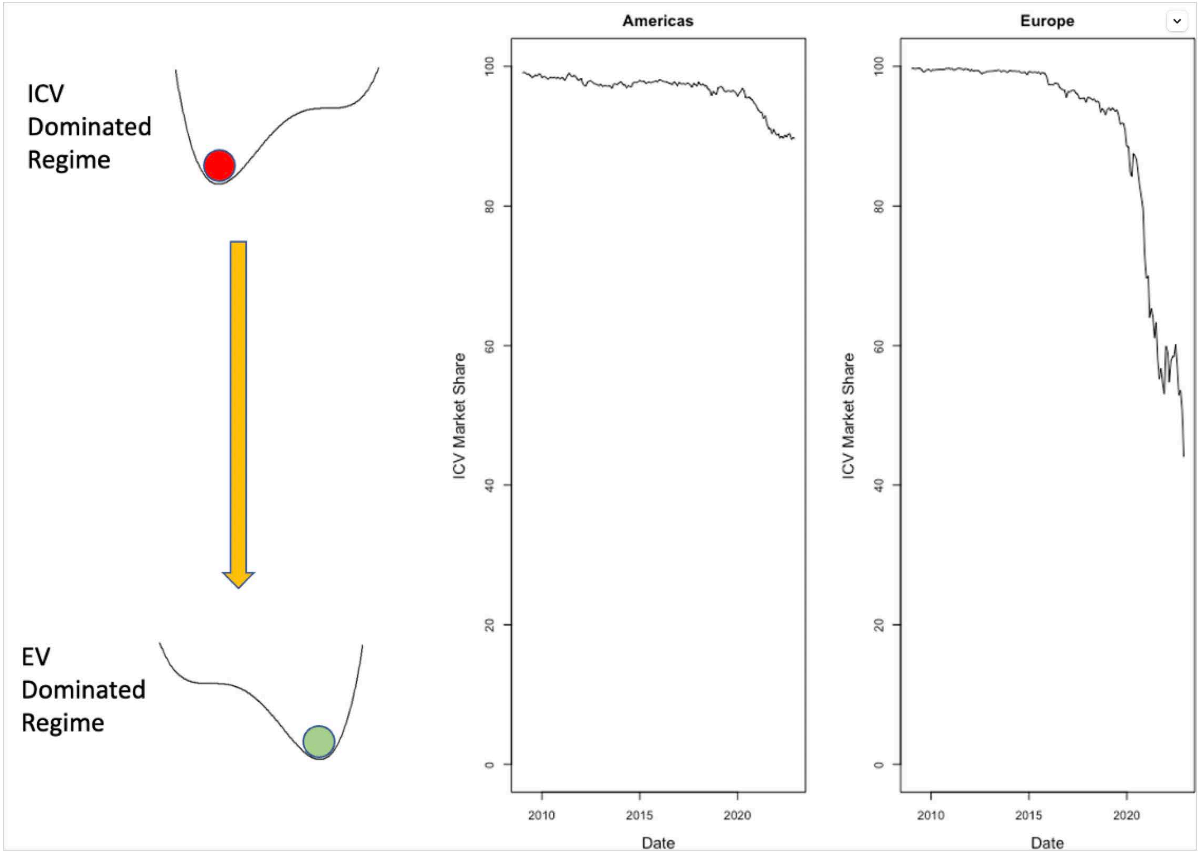

Figure 4.3.4: *I*CEV Market Share in the Europe, Asia and the USA, alongside a cartoon representing the alternate ICV dominated and EV dominated stable regimes which may exist.

Drivers of change

The EV tipping point has been enabled by factors involving technological innovation and economic developments, but also changes in policy intervention and public perception (Geels and Ayoub, 2023). There is a link between the unit volume of technology produced and the cost of production (i.e. learning rates), as has been demonstrated for solar PV and wind production (Way et al., 2022). The reduction in cost of production is driven by the reinforcing feedbacks of economies of scale and learning-by-doing.

This reduction in cost, as well as improvements in the technology, makes the technology more attractive and accessible to those who may purchase it, thus creating a positive feedback loop which can drive the rapid deployment of these technologies (Sharpe and Lenton, 2021; Farmer and Lafond, 2016; Lam and Mercure, 2022). BEVs have already passed tipping points in price parity of ownership with ICEVs in EU and Chinese markets, and are likely to do so in other key markets of the US and India by the mid to late-2020s (Figure 4.3.5). In most markets, tipping points for price parity at the point of purchase are also likely to be crossed before the end of the decade (Lam and Mercure, 2022).

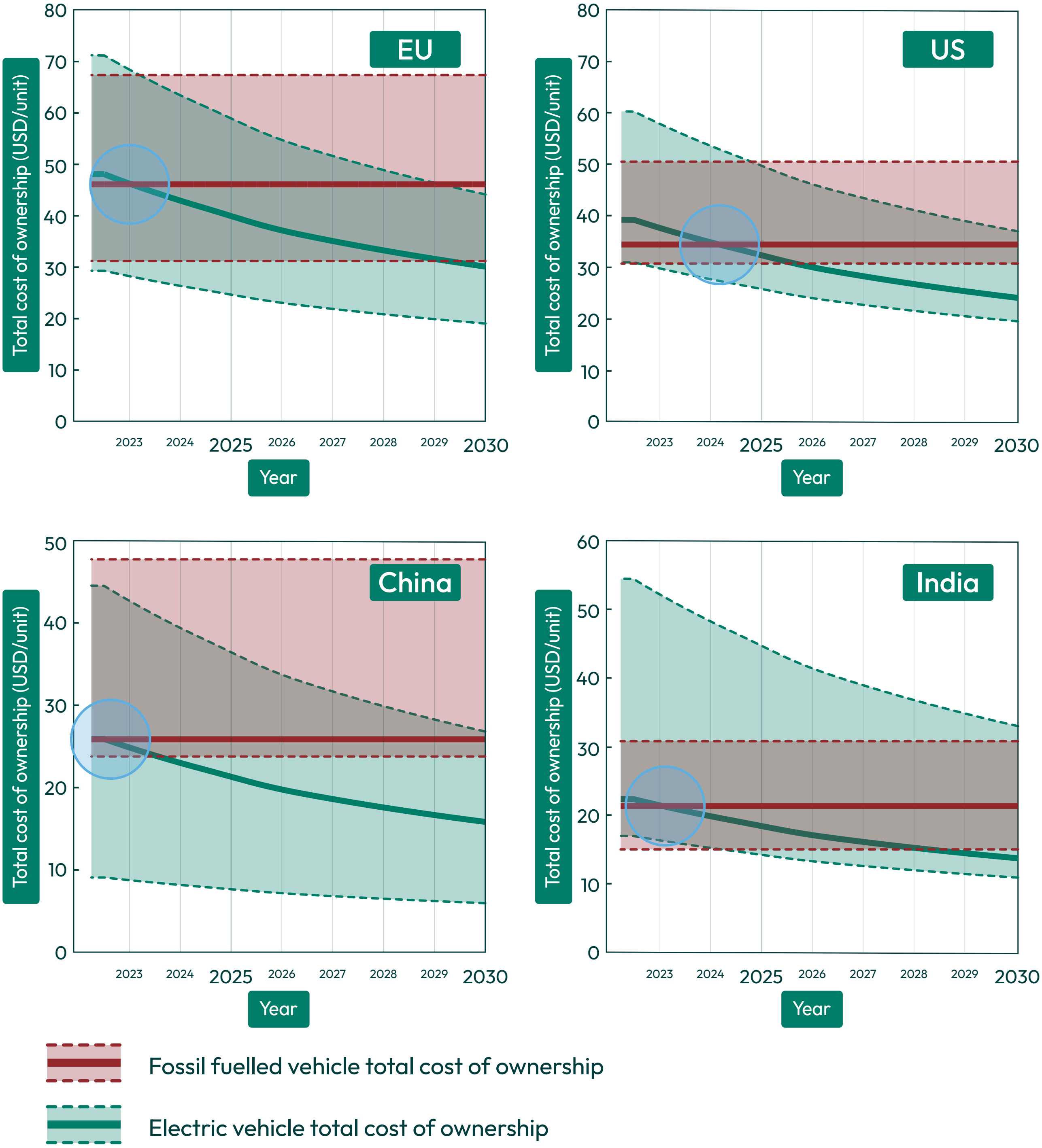

Fig 4.3.5: Tipping points for the cost of BEV ownership relative to ICEVs in major global markets. Source: Lam and Mercure, 2022

The key remaining barriers to adoption are (perceived) average driving range and battery charging time, and deployment of charging infrastructure. Range and charging time are continually improving, driven by the same reinforcing feedbacks as drive down overall costs, with the average range of new BEVs increasing 9 per cent per year from 2015-2021, however they are still some way off performance parity with ICEVs (Meldrum et al., 2022). Installation of public EV charging infrastructure is still lagging in many key markets, but is accelerating in leading countries.

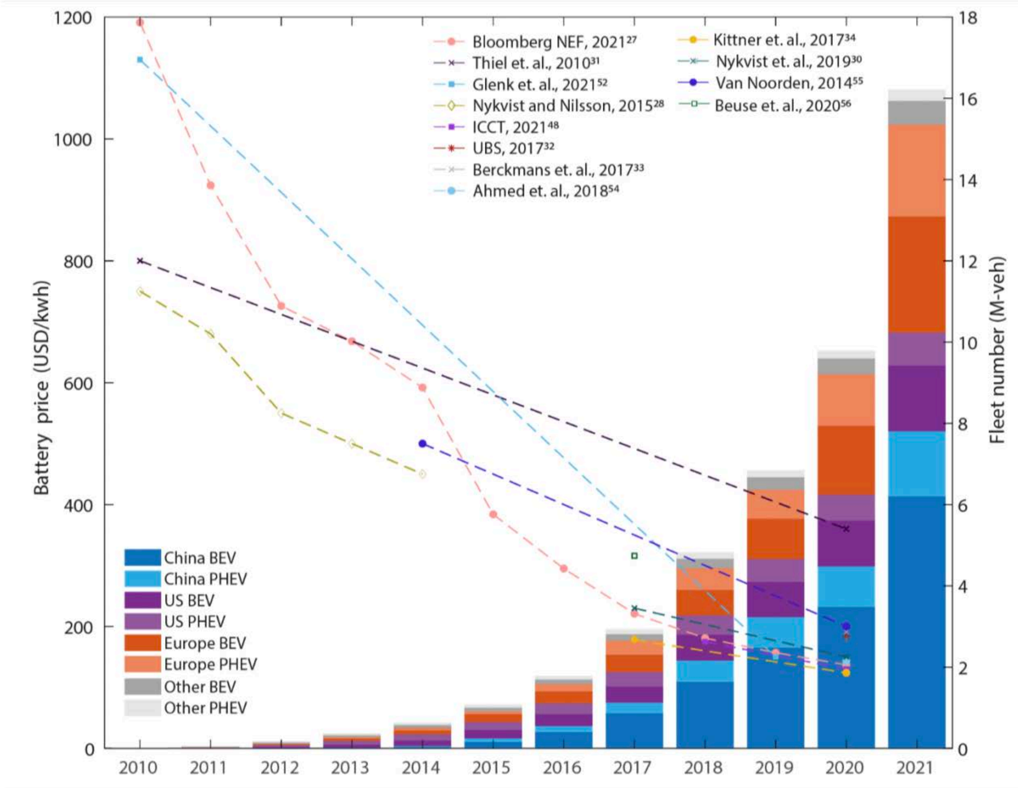

Figure 4.3.6: Exponential growth of sales of BEV and PHEV in China, US and Europe and the corresponding decline in battery price. Source: Lam and Mercure, 2022

As sales in EVs and PHEVs have increased since 2010 across three of the major global markets, the price of batteries has also declined (Figure 4.3.6). It is possible that, as EVs become widespread, this trend will continue; although some questions remain around mineral price volatility and how this will affect battery prices. Deployment of charging infrastructure is also growing exponentially, keeping pace with growth in EV sales (IEA).

Policy interventions can also assist in the diffusion of new technologies by reducing cost or mandating changes. Norway has become a classic case study of the successful transition from ICEVs to EVs, having been the first country to make this switch. One factor in driving this change was a tax system which ensured that EVs were cheaper than comparable ICEV models (Sharpe and Lenton, 2021), thus making them more attractive to consumers and leading to a rapid diffusion. Zero-emissions mandates at national and state level ensure a reduction of ICEVs within fleets and are likely the most cost-effective policy to drive the transition and contribute to this EV transition (Bhardwaj et al., 2022,; Lam et al., 2023). Due to the internationally connected nature of the automotive sector, EV mandates in major markets could induce, or bring forward, EV tipping points in other markets due to reduced sales prices (Lam and Mercure, 2022).

The effects of the EV tipping point are unlikely to be isolated just to the automotive transport sector. EV deployment will lead to an extensive charging network and is likely to have a significant impact on battery capacity, with consequences for renewable energy storage and production (Meldrum et al,. 2023). These cascading effects are discussed further in Chapter 4.5.

As indicated, improving transport modes alone will not be sufficient as this does not tackle the overall system size, including material needs, traffic and so forth. Tipping in shifting transport modes and avoiding travel are needed.

4.3.2.3 Shifting to enhanced active mobility

Shifting to walking and cycling is known as active mobility and known as active mobility or **non-motorised transport** (NMT), significantly increases human wellbeing and health through lifestyle changes, where individuals engage in physical exercises and enhance social cohesion, a reinforcing feedback that can lead to more demand in NMT (Hanson and Jones, 2015; UNEP, 2018; Marques et al., 2020; Mansoor et al., 2015). Such a shift can be enhanced through different enabling conditions, with prominent examples following here.

Appropriate infrastructure (Figure 4.3.7), including protected pedestrian and bike pathways, can support much greater localised active travel (IPCC 2022; Creutzig et al., 2022; Brand et al., 2021; Neves and Brand, 2019; Zhang et al., 2018) and, together with more compact urban design, can reduce urban GHG emissions by around 25 per cent. In addition, e-bikes and e-scooters have seen accelerating uptake and could unleash huge future potential in cities' mobility, leading to reduced congestion and emission reductions (Asensio et al.,2022).

Cities with cycling strategies, such as Copenhagen and Amsterdam, show how to prioritise non-motorized transport. In its dedicated cycling plan, Amsterdam prioritises cycling through infrastructure and regulations which strives to 1) keep bicycle traffic flowing smoothly; 2) improve bicycle parking; and 3) encouraging considerate cycling (Pucher and Buehler, 2007). Amsterdam is a safe and bike-friendly city, where even toddlers and older people use bikes as the most accessible mode of transport (Feddes and de Lange, 2019). Studies show that cycling is distributed evenly across all income groups for all trip purposes, that cycling rates fall only slightly with age, and that Dutch and Danish women cycle as often as men (Pucher and Buehler, 2007).

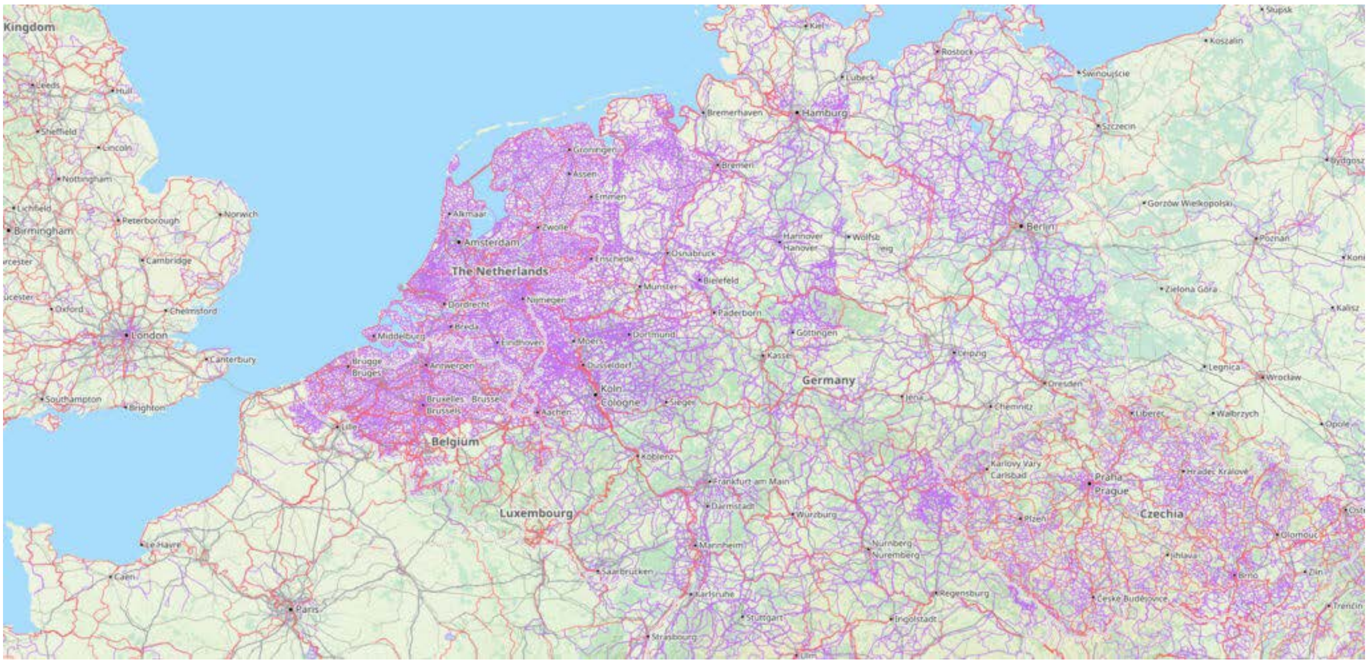

Figure 4.3.7: Bicycle path density In the Netherlands and neighbouring countries. (Open cycle map)

Active mobility narratives differ in the Global South context (Mansoor et al., 2022). More than 75 per cent of total daily trips made by Africa's low-income population are made by walking, compared with 45 per cent by more affluent groups (African Commute, 2018). Ethiopia, Kenya, Uganda and South Africa have set up policies to increase non-motorised transport recognition and accessibility, aiming to create a safe and comfortable environment for pedestrians and cyclists (Nairobi Metropolitan Services, 2020; City of Cape Town, 2005, 2017, 2020, 2021), and also aiming to improve air quality in cities. Replication across more regions and cities could lead to several positive feedbacks.

COVID-19 lockdowns have spurred significant trends in urban mobility, with several reinforcing feedbacks: a rapid expansion in 'pop-up' (temporary) urban cycling infrastructure (Becker et al., 2022; Creutzig et al., 2022; Kraus and Koch, 2021), electronic communications replacing many work and personal travel requirements (4.4.5); and revitalised local active transport and e-micro mobility (Goetsch and Quiros, 2020; Newman, 2020; Department of Transport UK, 2021; SLoCaT, 2021). The challenge so far has been the 'stickiness' of these changes in the longer term.

Infrastructure and policy design are two key enablers of positive tipping points for active mobility adoption. Peer effects, then, can add on positive and wished feedbacks to accelerate behavioural change (4.4.1). Combining infrastructural enablers, such as compact cities that avoid lengthy trips (Box 4.3.3), fair streets (which feature more space, design and services for walking, bikes and other micro-mobility) and bike/scooter-sharing schemes, with social enablers such as bike training, actions to generate a new culture (Jittrapirom et al., 2023) and policy design (e.g. carbon pricing, subsidies) (Matteoli et al., 2010), get us to the positive tipping point faster. The estimation of infrastructural and social tipping points vary and strongly depend on geographical, environmental, cultural and political context. One key variable is policy readiness: the availability of worked-out detailed policy plans that advance modal shift ready to be implemented when an opportunity occurs (Creutzig et al., 2022).

There are several success cases worldwide in achieving significant changes in mobility patterns and its externalities, the case of Pontevedra in Spain (Box 4.3.3) being one of the most notable for its vehicle restriction policy. **Vehicle restriction schemes** set a 'cordon' (i.e. a low-emission zone: usually a city centre or a whole city) restricting access for a subset of the vehicle fleet for specific periods or uses to reduce congestion, traffic speeds and/or pollution, and provide better access to non-motorised mobility modes.

Dampening feedbacks of such policies – even if only temporary – are related to social acceptability and the backlash this change can bring when the desire to own a car is spurred. This regulatory instrument can be categorised as shift to move mobility towards cleaner transport modes (Cloke and Layfield, 1996).

Box 4.3.3. Changing urban mobility – the case of Pontevedra,

Pontevedra in Spain, a city of around 100,000 inhabitants, stands out as a successful implementation of emission reduction in the transport sector in the Global North. Surface parking was removed and traffic calmed across the city, limiting speeds to 30km/h, adapting the pavement to slower speeds, and reducing traffic segregation with priority to pedestrians and cyclists as well as introducing roundabouts. The town developed walking maps (Figure 4.3.8) similar to metro maps to help people move quickly and promote active mobility. The impact of reduced mobility externalities, such as traffic, noise and pollution, has been immense and aligned with a solid public acceptance of the measures and improvement of the city's economy and vitality. Since 1996, CO_2 emissions have been reduced by over 70 per cent (~88 per cent downtown and ~47 per cent expansion area) Nieuwenhuijsen et al., 2023; Jimenez-Espada et al., 2023).

Pontevedra succeeded in changing the urban landscape, converting the car to a guest in the city and not the main actor, increasing liveability, revitalising the economy and positively affecting local population dynamics, as well as reversing the population loss of previous decades. The elements that created enabling conditions of this positive tipping point were the political courage of the mayor, technical and expert assistance to convert the whole city into a reduced traffic zone, the involvement of citizens in decision making and the design of the final solutions, with intense workshops to help people adapt their lifestyle and downgrade private cars in the priority of city space use. **Spain**

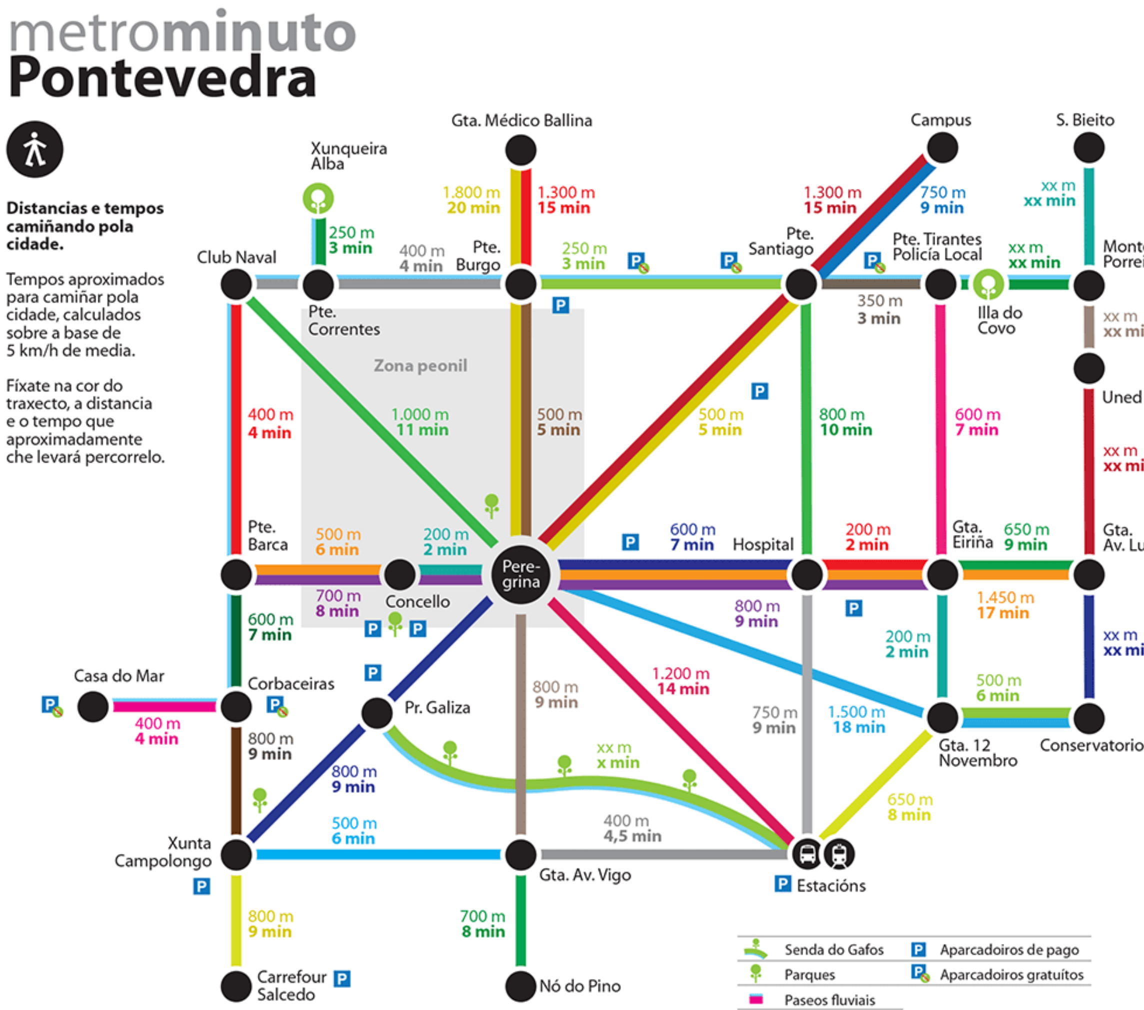

Figure 4.3.8: Tipping to active mobility by turning perspectives and providing tools to the population. A schematic walking map of the city of Pontevedra showing the distances and walking times to reach different places in the city.. (Source: https://metrominuto.pontevedra.gal/es/#features)

The level of success seen in Pontevedra (Box 4.3.3), which treated private cars without any differentiation, has yet to be achieved elsewhere, where lack of alignment of political will, consistency, technical support and citizens' involvement prevail. Implementation with partial plate-control systems to differentiate between user groups does not work, as cities including Athens, Milan, Oslo, Paris, London and Rome have shown. These partial restrictions are mainly aimed at air quality control and reduction in CO_2 emissions (Kuss and Nicholas, 2022). The policies were limited to certain types of vehicles or times of the day or certain number plates allowed to circulate for certain days of the week. These policies differ significantly in ambition and achieved impacts compared to Pontevedra.

In the Global South, several cities, such as Beijing, Jakarta, Mexico City and Bogota, have successfully implemented partial vehicle restriction programmes. With air quality improvement being the primary goal, CO_2 reduction and transformation of the mobility behaviour are perceived as a co-benefit but not the primary objective of the measures.

To achieve the radical change needed for a paradigm shift in urban mobility habits, public institutions need to provide firm and consistent political leadership and ensure public participatory processes, as well as smart land use, with high densities (>4000 inhabitants per sq km) and land use mixtures to allow inhabitants to use non-motorised mobility for most of their activity (e.g. compact or 15-minute cities). The municipality in Pontevedra implemented its public space management in less than one year. To replicate it in more cities and of different sizes will require tailoring to unique challenges while preserving the idea of reducing the hierarchical role of private cars in urban mobility.

Another example of change facilitation in urban transport is the concept of **Mobility as a Service (MaaS)**. By supplying a wide range of personal transport services, including bike and car-sharing, car rental, underground, rail and bus, through a single digital customer interface, MaaS can alter travel behaviour and demand (more details in 4.4.5.). A full implementation of this concept at the urban scale, linked with other measures such as vehicle restriction schemes, can be a game changer of the urban ecosystem and allow people to have better life quality by reducing costs, urban space devoted to cars, pollution and other externalities. The development of this concept will also be linked to the advance of infrastructure development, urban transport services diversification (4.3.2.4) and business models that provide users with more sustainable options.

4.3.2.4 Enhanced heavy capacity public transport networks

To cover longer distances, cities need alternative approaches to active mobility options. Bus Rapid Transit (BRT) systems have features similar to light rail or metro systems and are thus faster, more reliable and convenient than regular bus services. The main attractiveness of BRTs lies in the low cost compared to rail-based transit systems while providing relatively high mobility services (e.g. right-of-way, reduced congestion and accessibility of more distant stops). Yet, taking the decision to invest in such a public transit system remains risky for policymakers as the benefits are dispersed across many people over time and upfront investment remains high. Operational BRT systems, ideally from nearby or socio-economic and geographically similar cities, must be available as examples to learn from. Once a pool of such BRT systems exists, the likelihood of other cities adopting the approach increases. Such a demonstration effect in the diffusion of innovations shows how important successful fore-runner projects are for fundamental transformations – especially for large-scale infrastructure projects which systematically change a city's mobility system in the long term.

Box 4.3.4. Curitiba's Bus Rapid Transit System – an example to learn from

Curitiba, Brazil, was an innovator in developing its BRT system. Like other developing cities, Curitiba's initial master plans relied on cars to satisfy the growing mobility needs of its population. However, from the 1960s onwards, a fear of the ever-increasing resources needed to satisfy the demands for automobile-oriented mobility led city policymakers to embrace a public transit-oriented growth model to provide good, reliable public transit options at manageable costs for a city with limited means.

Curitiba's bus system is hierarchical, with the BRT system running along the city's main arteries connected by feeder buses spread across the city. This star-like structure enables public transit while preserving access to green areas and parks, simultaneously achieving climate mitigation and adaptation objectives (Pierer and Creutzig, 2019). It has been popular and effective in generating a modal shift away from cars to public transit (28 per cent of users previously travelled by car), with an estimated reduction of about 27 million car trips per year. Citizens from across the income spectrum use the system and have greater mobility. In Curitiba, about 30 per cent less fuel per capita is used compared to other cities in Brazil, resulting in one of the lowest rates of ambient air pollution in the country and lower transport-related GHG emissions. A reduction of traffic crashes compared to similar cities could be attributed to the BRT as it has led to more compact urban growth and increased land value around BRT lanes and stations (Lindau et al., 2010).

This contagion effect has been shown for BRT systems (Kitzmann et al., 2022): Following Curitiba's successful example (Box 4.3.4), several cities developed early BRT-like systems. Initially cities in neighbouring countries in Latin America followed a typical spatial diffusion pattern. This changed with the introduction and subsequent popularity of Bogota TransMilenio, which inspired cities across the globe to adopt BRT systems. Further momentum was created by systems springing up in Guangzhou in China, Ahmedabad in India, and Istanbul in Turkey. The popularity of BRTs is not limited to low and middle-income countries; cities in the European Union (e.g. Bus-VAO in Madrid, Spain) and the US and Canada (e.g. Metro Rapid in Los Angeles or B-Lines in Vancouver) have also adopted BRT systems modelled on the early pioneers in Latin American cities. Given the differences in quality attributes among the systems as well as the overall traffic and socio-cultural situation in cities where BRT has been implemented, not all of them are successful, with the system in Delhi, India being a prominent example of a poorly implemented system that has been rolled back due to opposition from certain sections of the population (Kathuria et al., 2015).

Globally there is evidence that implementing BRT systems leads to a significant increase in public transport usage and modal shift of up to 30 per cent at city level, with users preferring it over standard buses, creating a more satisfied customer base that is less likely to abandon it once private vehicles are an option. BRT stations often facilitate transit-oriented development with increased residential and business densities, a diversity of land uses and, thus, shorter distances to trip destinations. These systems are also associated with greater mobility for disadvantaged groups, especially women, for example in Lahore, Pakistan.. There is enormous potential for large public transit infrastructure to bring about a shift in female mobility in cities of the Global South.

Beyond BRT, examples of rail-based systems' disruptive effects on urban mobility can also be found in the Global North (e.g. Porto, Portugal) and Global South (e.g. Johannesburg, South Africa) (Curtis and Scheurer, 2019). Both cases showed a huge emission reduction potential by producing a strong **shift** towards cleaner public transport, reducing private car use, and **improve** by increasing transport efficiency by increased load factors, and cleaner energy use.

As with active mobility, the introduction of such public transport systems can make people rethink their (future) choice of using private vehicles for their mobility needs, impacting also inter-city and long-distance travel. Transport-related choices are influenced by social norms (4.4.1): with an increasing number of people relying on public transport (or active mobility) for their mobility needs, their peers are motivated to adopt similar behaviour. With this combination of changes in individual-level habitual choices and social norms, infrastructure developments can change societal attitudes towards sustainable mobility (4.4.1). Like in the positive feedback loop for individual motorised transport (Figure 4.3.3), once sustainable mobility infrastructure is introduced, more people rely on this infrastructure, thus creating demand for increased spending on this infrastructure and greater accountability to ensure policymakers meet these demands.

Globally, there is large potential for shifting urban mobility to options of public transport systems and active mobility. This has not yet been harnessed, with tipping lacking at large scale, but several successful examples exist which could be replicated if the enabling conditions were in place.

4.3.2.5 Positive tipping points in other transport systems

This chapter has focused on individual transport and tipping in urban contexts. Inter-city or long-distance passenger or freight transport and related indications of tipping opportunities have been discussed elsewhere previously (Meldrum et al., 2023).

A tipping point for electrification of heavy-duty road transport (i.e. freight), responsible for three per cent of global emissions, is a more distant prospect than that for EVs as it depends on considerable development in battery technology and charging infrastructure deployment to become competitive on cost. Once price parity is reached, however, tipping is very likely due to the strong economic incentives for business to reduce distribution costs. Strong policy to support development of charging infrastructure is likely to accelerate tipping. Other systemic changes can also play a powerful role in avoiding freight emissions by increasing efficiency, which would further reduce the costs of electrification (e.g. Box 4.3.5).

In aviation, tipping to using synthetic, power-to-liquid (PtL) fuels is a possibility, dependent on significantly reducing the costs of production to be competitive with fossil fuels. This requires considerable investment in development as PtL fuels are currently nearly four times the price of kerosene jet fuel. Reaching a tipping point likely depends on a mixture of regulation with carbon pricing and/or subsidy; policy support is currently emerging in the US and EU, and may help to drive cost reductions and scaling. Opportunities for tipping cascades related to green ammonia and fertilisers exist for the shipping sector (Meldrum et al., 2023) (4.3.3. and Chapter 4.5).

Box 4.3.5. Asset sharing and digital platforms to tip freight transport

Asset sharing is a resource-sharing concept in road freight that facilitates available volume or weight capacity in trucks to other companies by a common data platform that contains routing plans and can match requests and available supply, aiming to optimise load factors. Digital information and communications technologies (ICTs) and the creation of common data platforms facilitated this concept (4.4.5) and several pilot case studies have shown the huge potential for companies, especially if distributing goods with no special transport requirements (e.g. temperature control) (Ballot and Fontane, 2010).

From an environmental point of view, sharing assets can increase logistic efficiencies – for instance, by increasing the occupancy rate of vehicles. Shifts towards less carbon-intensive modes are also possible, where bundling several companies' freight creates a viable traffic flow. Ultimately, improvements that lead to load consolidation can reduce the number of trips required to deliver products and reduce the emissions linked to logistics activities. Reductions in emissions can be very significant, as shown in trial studies in the UK, with up to 40 per cent savings (Wang et al., 2015). Other studies, such as the EU-funded CO^3 project - Collaboration Concepts for Co-modality - found savings from horizontal collaboration to be above 15 per cent. A partial collaboration project modelled the impacts of multilateral co-operation on CO_2 emissions to be around 14 per cent. In Belgium, a collaboration between three firms could lead to a 25 per cent reduction of the number of delivery trips (Vanovermeire et al., 2014). Countries in the Global South have also already promoted some trials in urban contexts, such as Bogota, where a collaborative network of shared delivery routes and depot infrastructure was identified as having a 25 per cent CO_2-saving potential. Other urban consolidation studies showed a huge potential for shared assets in cost savings (approximately 50 per cent) as well as CO_2 emissions (40 per cent) (Nataraj et al., 2019).

Most of the trials and initial platforms so far have been from private initiatives, but governments may consider appropriate competition regulations to facilitate such asset sharing towards a Physical Internet (PI). This concept is an open, shared global logistics system based on a physical application of the principles of the digital internet. Individual logistics networks would no longer be operated by one transport service provider, but rather by one global transport network using shared hubs. Competition among companies would focus on products rather than logistics and supply-chain extent and efficiency. Such a system would require new standardised modular packaging units, standard protocols and tools, and shared logistics and digital assets. The change in logistics systems is still nascent and trials are emerging. Regulatory frameworks are needed for a full-scale implementation globally and locally, providing incentives or penalties for inefficient or uncooperative behaviours that lead to additional use of resources. PI could disrupt the entire existing logistics chain, providing a positive tipping opportunity.

4.3.3 Food systems

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Summary

Transforming the food system is critically important to meeting Paris Agreement targets, protecting biodiversity and achieving the Sustainable Development Goals (SDGs). Three key leverage points to mitigate food system impacts are illustrated by case studies: **reducing consumption of livestock products** by shifting to more sustainable diets; **avoiding food loss and waste**; and **restoring critical ecosystem service provision** through improved farming practices.

For dietary change, shifting behavioural norms and consumer experiences in high- and middle-income countries is key, and can be accelerated by policy choices and public procurement that increases exposure to low-livestock meal options. A positive tipping point in attractiveness and affordability of alternative proteins can help to accelerate this shift. Diffusion of alternative business models and income-sources for livestock and feed producers, e.g. in agri-photovoltaics, can also accelerate changes in livestock supply chains. To reduce food loss and waste, coordinated action by public and private initiatives can create reinforcing feedback and have transformative effects. To change farming practices, policy certainty and robust markets for ecosystem services can incentivise farmers to change, but strong information networks are critical.

For climate vulnerable people in the Global South, this shift can lead to social-ecological reinforcing feedbacks that build social, economic and ecological capital. Together, these leverage points offer opportunities to reduce pressure on natural ecosystems, restore natural carbon sinks and increase social justice. Strengthening deliberative food system governance, science-policy interface and effective sequencing of policy can help to accelerate transformation.

Key messages

- There are strong synergies between key leverage points for achieving climate goals, biodiversity protection and other SDGs. These leverage points are avoiding food loss and waste, shifting to more plant-based diets, improving alternatives to animal products, and shifting to agro-ecological farming.
- Triggering food system positive tipping points could be encouraged by a greater focus on adaptive and deliberative governance, a stronger science-policy interface, science-based targets and strategic policy design and sequencing to help support those who might otherwise be 'losers' in positive tipping points, such as livestock farmers.
- The key leverage points require coordinated political and social action to change norms, accelerate innovation, disrupt dampening feedbacks and provide incentives.

Recommendations

- Combine and sequence private and public interventions to create nonlinear reductions in food loss and waste. Examples include consumer apps and nudging in public cafeterias, supermarkets and restaurants and regulatory and incentive instruments that target retailers as central actors in the food supply chain, fostering reinforcing feedbacks.
- Focus on policy synergies along the supply chain (i.e. nudges, public procurement standards and innovation-oriented measures) to foster demand-side shifts in public cafeterias, restaurants, and supermarkets towards more plant-based diets, while providing incentives to producers and processors to shift towards plant-based food production.
- Integrate policies that foster innovation and diffusion of alternatives to animal products to drive positive tipping points through cost reduction, improved availability and quality, and social norm shifts.
- Make agroecological practices or alternative land uses economically attractive to farmers by diversifying business models through well-regulated markets for payments-for-ecosystem-services (including carbon), or other innovations like Agri-PV. Reducing administrative burden (e.g. via satellite-based and outcome-based subsidies), and offering compensation schemes can also reduce barriers and political backlash.
- Focus policies incentivising production-shift, new emission-pricing (e.g., nitrogen surplus fees and methane emission trading), phase-out and compensation schemes on large producers in key regions (e.g. regions and farms with excessive nitrogen pollution or organic soils). New revenues from emission pricing should be used to support most affected regions and low-income groups (e.g., via reducing VAT rates on plant-based food), foster innovation in alternative proteins, and create additional income sources for farmers. This can help to negotiate a feasible, efficient, effective, and just transition package.

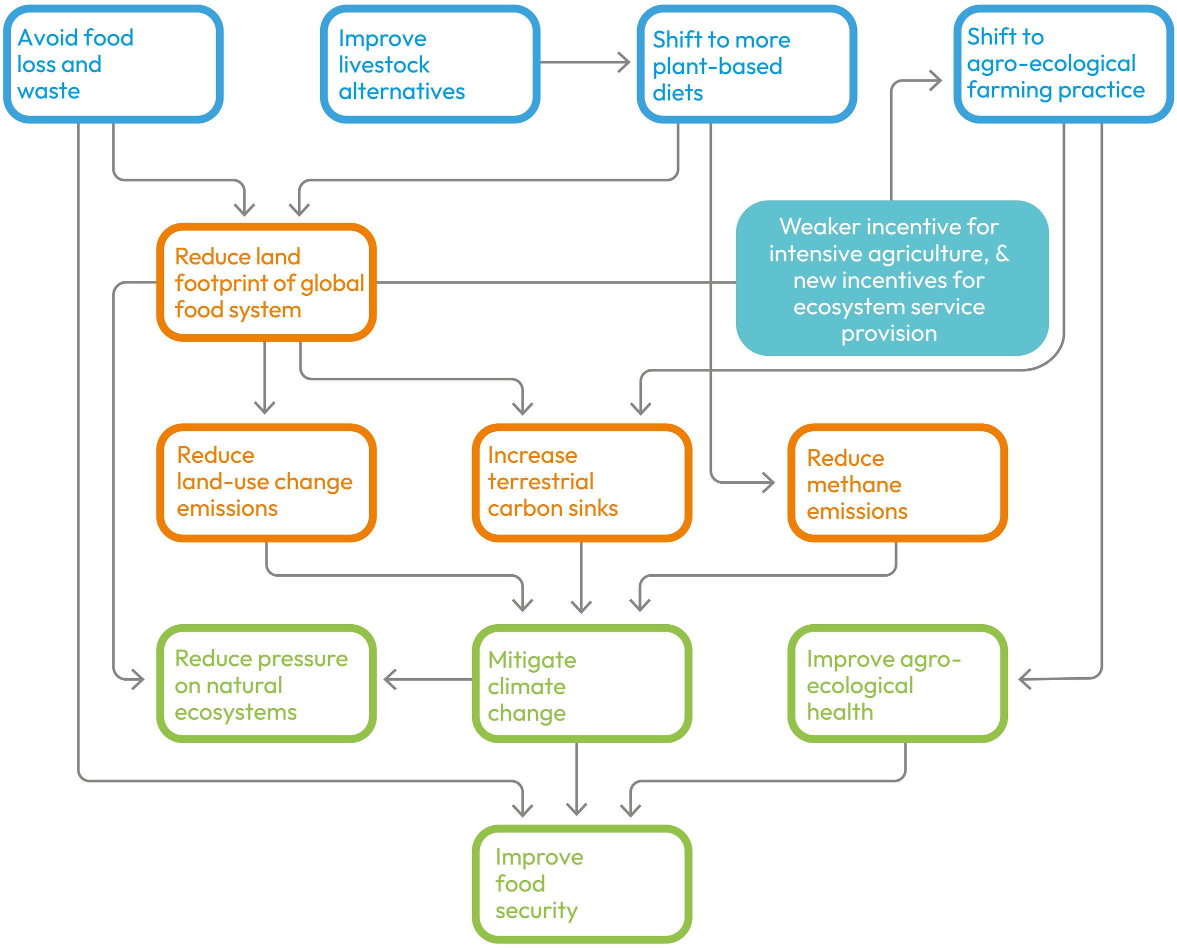

Figure 4.3.9: Avoiding food loss and waste, shifting to more plant-based diets and improving farming practice through agro-ecological approaches are key leverage points which can interact to produce a cascade of benefits for natural ecosystems, climate change mitigation and food security.

4.3.3.1 Introduction

Globally, food production is responsible for about 25–30 per cent of anthropogenic greenhouse gas emissions and is a major driver of biodiversity loss via land use change, degradation and deforestation (Ritchie,Rosado and Roser, 2002; Ritchie, 2021; Poore and Nemecek, 2018). Moreover, the food system-related emissions of short-lived climate pollutants such as methane (Fesenfeld, Schmidt, and Schrode, 2018) and agriculture-driven tropical deforestation (Pendrill et al., 2022) can accelerate tipping points in the Earth system, such as the dieback of the Amazon rainforest (Armstrong McKay et al., 2022). Production of animal products is a key driver of these impacts, via their own land use and methane emissions, and via the additional feed required to produce them in intensive systems (Pendrill et al., 2022; Poore and Nemecek, 2018; Springmann et al., 2018).

The food system is not only a direct cause of the global climate and ecological crises, but is itself profoundly affected by them; globalised value chains are under increasing pressure, threatening food security and political stability worldwide (Pörtner et al., 2023). Diverse crises in the past three years, such as the COVID-19 pandemic and the Russian war in Ukraine have led to food price inflation and challenged the resilience of the global food system (Bai et al., 2022; Bogmans, Pescatori, and Prifti 2022; Sperling et al., 2020). The wave of anti-government protests, uprisings and violent conflicts that began in 2010, collectively known as the 'Arab Spring', may also have been triggered by food prices (2.4.4.4).

Defining priority targets for food system transformation in line with the SDGs, Paris and Biodiversity Agreement

Sustainable transformation of food and land use systems is urgent to comply with the Paris Agreement (UNFCCC, 2016), and is also required to meet multiple international goals beyond this, including the SDGs (UN, 2015) and the Kunming-Montreal Biodiversity Agreement (Ainsworth, 2022; Allievi et al., 2019; Niles et al., 2018; United Nations, 2019). While in the short term certain trade-offs may exist between environmental, social and economic goals (Scherer et al., 2018), there are many positive synergies (Creutzig et al., 2022, Doelman et al., 2022) which can enhance reinforcing feedbacks; and trade-offs can be minimised by focusing on key priority targets and leverage points in food systems (Kroll, Warchold, and Pradhan, 2019). For example, avoiding food loss and waste and shifting to more plant-based diets and agro-ecological farming practices are key leverage points.

Accelerating positive change

The pace of progress is not sufficient, but positive tipping points may be able to unlock rapid and cascading change to accelerate transformation of food and land use systems (Pharo et al., 2021; Lenton et al., 2022; Fesenfeld. P. et al., 2022). The food system is a complex web of interactions across scales and sectors; from local scales between ecosystems, producers and communities, up to global scales between the biosphere, international markets, and technologies. As well as technological innovation, social norms and culture are important drivers and barriers for behavioural change across the food system. And the policy landscape, including taxes, subsidies and regulations, plays a key role at all scales (Fesenfeld et al., 2023; Pharo et al., 2021). All these interactions can be part of self-reinforcing feedback loops which can drive change for a more sustainable food system.

Many food system elements can have further cross-sector interactions – for example with energy and transport systems, which can generate either dampening or reinforcing feedbacks. Production of ammonia for fertiliser, for instance, is a globally significant energy use, currently contributing between 2 per cent and 5 per cent of greenhouse gas emissions; however, ammonia production has potential as an early market for green hydrogen (Box 4.3.6), which could in turn help to generate economies of scale that enhance its viability in other sectors (as discussed in Chapter 4.5 and in Meldrum et al,. 2023). Such cross-sectoral spillovers and cost reductions in technological learning, such as agri-photovoltaics and green-ammonia, can be mutually reinforcing and lead to potential tipping cascades (Fesenfeld L. et al., 2023; Meldrum et al,. 2023).

Box 4.3.6. A tipping point for green ammonia

Production of ammonia using renewable electricity, or 'green ammonia', is expected to be a significant lever for decarbonising fertiliser production, with at least 10 projects either operational or coming online in the near future (Meldrum et al,. 2023. Green ammonia production takes advantage of existing learning curves and rapid expansion in renewable energy deployment, and is also subject to a learning curve of its own. As the sector scales, a learning rate of up to 18 per cent cost reduction per doubling of output is expected (IRENA, 2020), and in turn lower costs are likely to drive greater deployment. Price parity with 'grey ammonia' is likely to represent a tipping point, and could be accelerated to be achievable this decade by a carbon price or equivalent subsidy of around $100 per ton CO_2. It should also be noted that, in addition to improving ammonia production, emissions from fertiliser use can also be avoided by up to 70 per cent by optimising fertiliser use through practices such as improved crop rotation, precision application and dietary shifts (Systemiq, 2022).

Deliberate, rapid transformation of the global food system is not a novel idea. The Green Revolution (Box 4.3.7) comprised a set of initiatives launched in 1965-1966 with the aim of enhancing agricultural production and ensuring food security in the face of a growing world population. This concerted effort demonstrated remarkable success in reducing malnutrition and hunger, though it also led to inequalities and unintended consequences that remain important today.

Box 4.3.7. Historic case study for tipping points in the food system: The Green Revolution

The 'Green Revolution' describes initiatives launched in 1965-1966 that aimed to enhance agricultural production and ensure food security in the face of a growing world population. These included the introduction and widespread adoption of new agricultural technologies and practices such as high-yield crop varieties, synthetic fertilisers and pesticides, the expansion of irrigated land, and mechanisation. The Green Revolution also had a strong political dimension. Governments made boosting agricultural production a priority and coupled public policies supporting farmers with technology development to address hunger and malnutrition with great success. Yields grew substantially in the subsequent decades, resulting in nonlinear increases in agricultural productivity. In the 50 years since the beginning of the Green Revolution, the global population doubled from 3.5 billion to 7 billion people, while cultivated land expanded by a mere 12 per cent (Alston and Pardey, 2014; De Schutter, 2017).

The Green Revolution had broad implications for the food system. It sparked a transformation in farming practices, from traditional subsistence farming to intensive, industrialised agriculture, dominated by economies of scale. This was accompanied by changes in land use patterns, water management strategies and consolidation of agricultural supply chains. The Green Revolution served as a catalyst for innovation in agricultural research and development, and led to the establishment of dedicated institutions and funding mechanisms for research and innovation. It also fostered collaboration between scientists, policymakers, and farmers, building information cascades which disseminate agricultural knowledge and technologies.

While the Green Revolution brought about nonlinear increases in productivity, it also raised concerns about its sustainability. Since 1990, the rate of agricultural productivity growth has notably slowed (Alston and Pardey, 2014), suggesting the possibility of reaching a plateau in productivity in high- and middle-income countries.

Widespread use of synthetic inputs and the focus on monoculture farming has led to environmental degradation, soil erosion, loss of biodiversity and increased vulnerability to pests and diseases. Increasingly subsidised food production, which did not internalise external costs, also led to increased food waste and loss and allowed widespread adoption of diets that are inconsistent with human and planetary health. For instance, substantial subsidies directed towards major grain producers have resulted in the availability of large quantities of low-cost feed inputs for meat production. This, in turn, has fostered an overconsumption of meat in many affluent countries (Hawkes, 2006;De Schutter, 2017).

Increasing use of new technologies and fertilisers also led to growing demand for capital and ultimately created more market concentration. Large retailers had an increasing preference for sourcing from prominent wholesalers and processing firms, resulting in 'mutually reinforcing dual consolidation' (Farina et al., 2005). These self-reinforcing feedback mechanisms contributed to the concentration of power and resources within food production and distribution chains as global supply chains expanded (Gibbon, 2005). In turn, larger market players could exercise increasing political influence, shaping the way agricultural subsidies were tailored to specific types of producers, products and production methods.

The Green Revolution stands as an example of a tipping point in the transformation of the food system. It revolutionised agricultural practices, boosted productivity and alleviated hunger and poverty on a global scale. However, it also demonstrates how tipping points can lead to suboptimal 'shallower' and unintended consequences that are not compatible with safe and just Earth system boundaries.

Many questions remain when it comes to positive tipping dynamics in food system transformation: How can the potential trade-offs between social, economic and environmental goals for food system transformation be reduced and synergies leveraged? Which specific goals should be prioritised to minimise these trade-offs and accelerate food system transformation? And what are the most promising leverage points to take advantage of these synergies across different regions of the world to enable positive tipping points in line with these goals? Tackling this major challenge is only possible when taking a holistic systems-thinking approach that accounts for the different elements in the food system rather than focusing only on agricultural production or food consumption (Poore and Nemecek, 2018; Gaupp, 2020).

Here we outline overarching priority goals for food system transformation in line with the SDGs, Paris Agreement and Biodiversity Agreement, and discuss historic and ongoing tipping dynamics in food system transformation with illustrative case studies. These goals are based on **avoiding** unnecessary GHG emissions and biodiversity loss by reducing food loss and waste; **shifting** to more plant-based diets and agro-ecological farming practices that enable farmland to store more carbon, support more biodiversity and provide other ecosystem services; and **improving** the availability of plant-based and other sustainable protein sources. These targets should thus be key priorities for decision makers (Lee et al., 2019; Frank et al., 2021).

4.3.3.2 Avoiding food loss and waste

Avoiding the emissions and environmental degradation associated with food loss and waste along the entire supply chain represents a key lever in global food system transformation. About one third of all the food produced worldwide for human consumption is lost or wasted annually (Pharo et al., 2021; Mokrane et al., 2023); 14 per cent after the harvest and before it gets to retail (FAO, 2019), and 17 per cent percent at retail, in food-service and by consumers (UNEP, 2021).

If food loss and waste were a country, it would be the world's third-biggest greenhouse gas emitter, after the US and China, responsible for 8 per cent of global anthropogenic greenhouse gas emissions.

(Food and Agriculture Organization of the United Nations, 2015, Melchior and Garot, 2019; Sethi et al., 2020). Similarly, that lost and wasted food consumes about a quarter of the freshwater used per year in agriculture (Kummu et al., 2012) and makes a major contribution to deforestation, land use change and land degradation. At the same time, food security remains a big problem, threatening 828 million people (World Food Programme, 2022). Halving per capita global food waste at retail and by consumers, and reducing losses in production and supply chains, is a target of the SDGs (United Nations Framework Convention on Climate Change, 2022).

France provides an example of how to successfully address this challenge (Box 4.3.8). A combination of private and public interventions in the country have led to nonlinear reductions in food loss and waste and reinforcing feedback in the form of economies of scale, changed social norms and public opinion, and new coalitions that can enable positive tipping points.

Box 4.3.8. France: Combining private and public interventions to reduce food loss and waste

France's strategy comprises private initiatives by large retailers (e.g. supermarket chain Carrefour, which has a 20 per cent market share) and NGOs (e.g. Phenix), but also a national political pact to fight food waste. This strategy led to nonlinear reductions in food loss and waste, and feedback that can enable positive tipping points.

When it was first introduced in 1998, the national law to fight food waste only included tax incentives for supermarkets that donated food (Corréard, 2023), but since 2016 it has become a regulatory instrument, and supermarkets that fail to donate their food can be penalised. This evolution of the pact was partially made possible by the emergence of various private initiatives between 1998 and 2016, among others Too Good To Go (TGTG) (Corréard, 2023). Novel digital platforms and apps like TGTG have made it easier to connect customers to restaurants and stores that have leftover food (Vo-Thanh et al. 2021). Those platforms have undergone nonlinear adoption and diffusion processes via network effects (Too Good To Go, 2023) and offered economic opportunities to reduce food loss and waste. Research shows that such private initiatives can create positive political feedback by increasing the public salience of the food loss and waste issue and the demand for more stringent public food waste regulation (Fesenfeld, Rudolph, and Bernauer, 2022).

The main objective of the pact is to cut food waste by 50 per cent between 2013 and 2025, implying a five per cent reduction annually and was initially focused on retailers. Although they are only directly responsible for five per cent of food waste, retailers connect production and consumption and thus can have feedback effects in both directions (Albizzati et al., 2019; Schönberger, Styles, and Galvez Martos, 2013). Retailers' central role in the supply chain can therefore be considered a strategic intervention to trigger nonlinear change in the area of food loss and waste reduction. For example, retailers can create reinforcing feedback by altering social norms and behaviours of both consumers and producers, and can create economies of scale for innovations to reduce food loss and waste. In turn, this can also enable favourable conditions for policy change and spillovers across countries.

Overall, France's strategy achieved a rapid reduction in food waste and loss and garnered positive international feedback. For instance, a food waste reduction of 18 per cent was measured at 20 agroindustrial test sites during nine months in 2018 (Agence de la transition écologique [ADEME] 2018). In the distribution sector, a 7,000-ton increase in food donations between 2016 and 2018 was measured by the French Federation of Food Banks (Melchior and Garot, 2019). Moreover, France served as a pioneer in this policy field and had a role model effect on Finland, Sweden, Peru and Malaysia, who all introduced similar policies (Melchior and Garot, 2019).

4.3.3.3 Shifting towards more plant-based diets

Reducing consumption of livestock products is the single most powerful leverage point for shrinking the environmental footprint of agriculture and food systems (including Land use changes). Reducing demand for unsustainable foods, especially in middle- and high-income countries (for example, shifting towards more plant-based diets can have a significant impact on GHG emissions and biodiversity loss, as well as having strong synergies with improving public health.) The planetary health diet (PHD) is one proposal for an idealised reference diet that, if adopted, could feed a global population of 10bn in 2050, would significantly reduce the number of deaths from poor nutrition and would be environmentally sustainable (Willett et al., 2019).

Dietary shifts require changes of normative consumer beliefs and behaviours, agricultural practices and policy. Changes to norms are nonlinear and dynamic – the more people who subscribe to a belief or behaviour, the more norms become visible and the more attractive the behaviour becomes to subsequent subscribers, creating a positive feedback loop (Figure 4.3.10) (Sparkman and Walton, 2017). Current norms in many countries hold that eating meat is tasty, ethical and normal. However, there are signs of changing beliefs (Dagevos and Voordouw, 2013). For instance, from 2008 to 2019 the UK has seen a 17 per cent decrease in meat consumption and worldwide participation in 'Veganuary' rose from just 1,280 in 2015 to 628,000 in 2022 (Veganuary, 2022).

Agency – the belief that an individual's change in dietary preferences will make a difference on a global scale and might encourage others to do so as well – is another element that can accelerate this change (Gaupp, Constantino, and Pereira, 2023). This belief may be driven by intrinsic motivation to try new, healthier food choices or a moral obligation to reduce animal suffering and/or environmental impacts, but can also be affected and amplified by socio-economic factors such as the influence of peers or exposure to media and information campaigns that advertise healthy eating. The non-linear spread of the GemüseAckerdemie, a non-profit organisation that focuses on establishing school gardens, fostering cooking skills, and dietary shifts in schools around Germany, Austria and Switzerland is an example for creating such reinforcing feedbacks. This rapidly growing project diffuses social norms, sustainable food knowledge, gardening and cooking capacities among children, parents and cooks in the schools and beyond.

Experimental evidence shows norm changes can be accelerated by targeted nudging interventions, in which public procurement can play a powerful role. For example, a 2017 study of choice-architecture interventions examined the effect of increased availability of vegetarian meals in public cafeterias (Garnett et al., 2019). The study showed that increasing the proportion of vegetarian meals to 50 per cent of all meals offered across a number of trial cafeterias increased vegetarian sales by 40.8 per cent to 78.8 per cent. Moreover, the experiment had little effect on total sales and profit and therefore was an economically viable option for businesses.

The dampening feedback of habitual food choices can be disrupted by choice-architecture interventions, while informational cascades and social contagion of norms work to reinforce willingness to try alternative, more sustainable diets. This works in synergy with the improvement of the alternative protein market, through feedback mechanisms such as economies of scale and learning by doing. In China and the US, a recent study shows that positive user experience is the most important predictor of an individual's intentions to reduce meat consumption and support meat-reduction policies (Fesenfeld et al., 2023), but that this choice was also affected both by social norms and exposure to information.

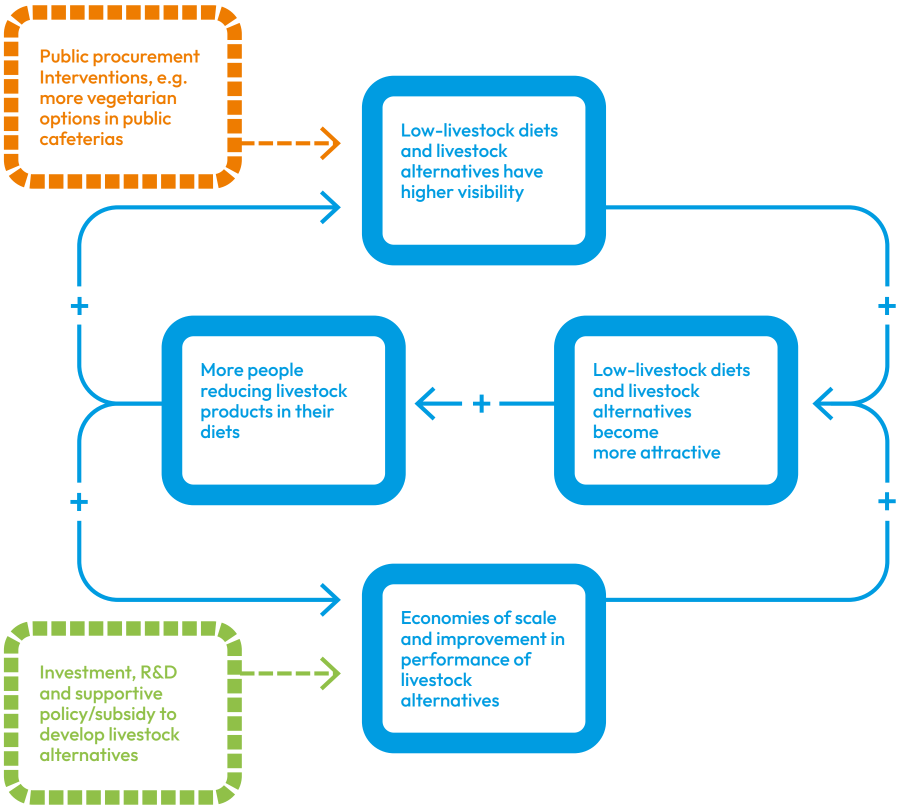

Figure 4.3.10: *Positive feedbacks can drive changes in dietary norms, both through social feedbacks that drive consumer beliefs and behaviours (above), and through increasing returns to adoption which drive improvements and economies of scale in livestock alternatives (below), making them more attractive and affordable. These feedbacks can amplify one another. Examples are given of interventions that can strengthen these feedbacks.*

4.3.3.4 Improving alternatives to animal products

Alternatives to animal products, such as plant-based, fermentation, or cultivated meat substitutes, can help accelerate dietary shift as they provide a (partial) substitution of meat and dairy in forms that are more familiar to consumers (Ritchie, Reay, and Higgins, 2018). In a report on UK and European meat and dairy alternatives, three key barriers to change were highlighted: high prices, unsatisfactory user experiences and limited availability (Geijer, 2020).

Price parity is an important factor of the uptake of meat and dairy alternatives.

Animal products and feed still receive substantially more subsidies in many countries (Vallone et al., 2023; Good Food Institute, 2022). Despite differences in subsidies, large retailers, like Lidl, start to announce price parity between meat alternatives and animal products (Vegconomist 2023).

The UK leads in Europe for price parity and subsequently has the highest purchase and consumption rates of alternatives to meat and milk. Feedback mechanisms contributing to price parity (Figure 4.3.10), such as economies of scale and learning, are evident in the increase of sales and investment over the past 10 years. In the UK and EU, sales of meat substitute products increased from €625m- €1381m (2010-2019), and globally investment in plant-based companies has increased nonlinearly from $23m to $2.1bn (2010-2020). In the US, the meat substitute market has grown exponentially, growing by 54 per cent between 2018 and 2021, an increase in growth rates that was three times faster than that of animal-based products, and plant-based alternatives were expected to reach price-parity soon (Meldrum et al., 2023). Such market developments also create positive feedback in technological learning and investments, which further decrease prices, and signal to retailers, consumers and policymakers a dynamic change. This can create new norms and interest group coalitions.

Targeted policy support, such as the Danish Fund for Plant-based Foods (Good Food Institute, 2021) and procurement standards for public cafeterias, can further accelerate shifts towards sustainable diets (Fesenfeld, 2023; The Food and Land Use Coalition, 2021) and create cross-sectoral spillovers (Meldrum et al, 2023). Promoting a combination of innovations along the supply-chain, such as agri-photovoltaics and alternative proteins, cannot only accelerate technology diffusion but also positively affect acceptance among potential transition losers such as . feed producers by offering them new income sources (Box 4.3.9). Transparency criteria of ecological and health impacts of alternative proteins can foster innovation in and the growth of healthy and sustainable products. Such innovation-oriented and green-industrial policies can lead to economies of scale by fostering technological learning, rapid reduction in costs of clean alternatives, and improvement in their performance (Fesenfeld, 2023; Barrett et al., 2020; Herrero et al., 2020). In turn, this can generate nonlinear political, economic and social feedback dynamics that can accelerate transition (Fesenfeld et al., 2022; The Food and Land Use Coalition, 2021).

Deliberative and participatory governance approaches, such as the German Commission on the Future of Agriculture or the Swiss Citizens' Assembly on Food Policy, can support the design and implementation of such policies to foster dietary shifts (Fesenfeld, Candle, and Gaupp, 2023). The large support of stakeholder groups and representative citizen samples can help to indicate that there is more room for political actions to alter diets than often assumed. For instance, the German Commission on the Future of Agriculture, composed of the central stakeholder groups in German food policymaking across the supply chain, supported policies to internalise the external costs of food products, alter food taxes, subsidies and change public procurement rules to shift towards a planetary health diet. It also highlighted that dietary changes will affect businesses in livestock farming and that respective restructuring in the sector requires cost compensation and planning certainty that is enshrined in law. In the Swiss Citizens' Assembly on Food Policy, a randomly selected, representative sample of 100 people discussed different options to transform the food system in line with the SDGs and produced recommendations for more sustainable food policy (SDSN, 2022). For example, they recommended adopting a carbon tax on climate-damaging food products and altering public procurement rules to foster sustainable diets.

4.3.3.5 Shifting farming practice

A shift in methods of agricultural production is needed to drive positive social, economic and environmental outcomes for farming (Pharo et al.,2019) and increase the resilience of food production to climate change and other shocks (UNFCCC, 2022). The current agrifood system's dependence on a small number of monoculture crops with high chemical inputs, GHG emissions and freshwater use are central to its impacts on the Earth system. Half of the world's habitable land is used for agriculture (OWD, 2019); thus the methods used to manage this land and ensure its productivity have global impacts.

Land-based CO_2 removal, including in agroecosystems, offers huge potential for climate mitigation. The '4 per 1,000' initiative aims to increase carbon storage in topsoils by 0.4 per cent per year globally, with the aim of offsetting a significant portion of anthropogenic GHG emissions. Both the Breakthrough Agenda (IEA, IRENA, and UNFCCC, 2022a) and the Sharm-el-Sheikh Adaptation Agenda (UNFCCC, 2022) set transformation of agriculture as a key priority and target for climate finance, with the combined aim of making climate-resilient, sustainable agriculture the most attractive and widely adopted option for farmers everywhere by 2030.

Development and adoption of a suite of agro-ecological or 'regenerative' farming practices are central to these goals, along with innovation for precision agriculture. These usually emphasise reduced tillage, crop rotation, integrated crop and livestock management and incorporation of perennial crops and trees into farming systems. Agro-ecological farming aims to restore soil health and increase agrobiodiversity and ecosystem service provision, including carbon sequestration, while reducing chemical inputs via increased nutrient recycling and precision application.

A transition to sustainable and resilient farming practices is relevant at all scales and regions (boxes 4.3.9 and 4.3.10), but the urgency is particularly acute for smallholder and subsistence farmers to adapt to increasing climate vulnerability and food insecurity. Hundreds of millions of smallholder farmers are increasingly vulnerable to climate change and are approaching the limits of adaptation for the models of farming on which their livelihoods depend (Morton, 2007). For many subsistence farmers, current Green Revolution farming practices come with costly dependence on chemical inputs like fertilisers and pesticides, or irrigation systems. Often overuse of fertilisers in these farms has caused soil degradation, and reduced water quality and biodiversity. This can drive a vicious cycle of degrading reinforcing feedbacks, where farmers are locked in a cycle of increasing input requirements, increasing indebtedness, and decreasing productivity (The Food and Land Use Coalition, 2021). Accelerating a transition therefore requires breaking this cycle of feedbacks, and strengthening positive feedbacks associated with agro-ecological health and farmer livelihoods.

In Sub-Saharan Africa, around 80 per cent of farms are subsistence smallholdings of less than one hectare (OECD, 2016), operating on degraded land and with minimal capital assets. In this region alone, 50 per cent adoption of regenerative agriculture could lead to a 30 per cent reduction of soil erosion, 60 per cent increase in water infiltration, >20 per cent increase in soil nitrogen and 20 per cent increase in soil carbon, adding ~$70bn gross value per year for farmers. Similar benefits are already driving widespread adoption of regenerative agriculture in both East Africa and areas of India, including certain practices being mandated at state level in Sikkim and Andhra Pradesh (The Food and Land Use Coalition, 2021).

Smallholder farmers have strong social networks which encourage social contagion, and small individual farm sizes which can foster high learning rates. This makes them strong candidates for driving a tipping point in farming practices.

To enable widespread adoption, regenerative farming practices must:

- Offer a more economically attractive livelihood for small-scale farmers (i.e. by reducing inputs or labour costs or through access to subsidies or other incentives).
- Perform better than current practices, through higher yielding or more diverse, nutritious or resilient crops.
- Become a part of prevailing cultural and social norms.

Farmers must also be able to access:

- Markets for crops produced with regenerative methods.
- Information and knowledge networks that enable them to assess the benefits of shifting, and support them to learn new farming practices.

Access to finance can incentivise practices that increase productivity and resilience while reducing emissions and protecting natural habitats (IEA, IRENA, and UNFCCC 2022); as such the Breakthrough Agenda recommends that access to international climate finance by smallholder farmers needs to sharply increase (Meldrum et al., 2023). Multiple mechanisms exist for this, but one model already driving innovation is the Voluntary Carbon Market (VCM). Through established monitoring protocols and verification standards, carbon sequestered in biomass and soils can be accredited and sold on an open market to buyers looking to offset carbon emissions. Payment for carbon credits can help to fulfil the enabling conditions above by offering farmers incentive payments or access to markets for a 'virtual' carbon crop in addition to conventional crops, helping them to build diversified and more resilient livelihoods (Box 4.3.9). Globally, VCMs have been growing exponentially, at a compound annual rate of over 30 per cent from 2016-2021 (World Bank, 2022), with the value of carbon credit retirements close to US$1bn and expected to grow to 15 times that by 2030. Recent developments have questioned the credibility of credits generated through 'reduced deforestation', which are qualitatively different from credits produced via actively sequestering carbon in vegetation or soils (Balmford et al., 2023). This has served to increase demand for credits based on sequestration, and those with demonstrable social co-benefits.

In countries where industrial agriculture predominates, similar mechanisms for paying land managers for provision and improvement of ecosystem services remain an effective tool. In these systems, high levels of subsidy have considerable influence over the structure of farm business models and the choices available for land management. Diversifying income streams is often attractive for farmers as it offers resilience in the face of marginal livelihoods and volatile markets (Box 4.3.10). Research in the UK suggests that, given incentive structures that make agro-ecological practices economically viable, and confidence in long-term government commitment to agri-environmental policies, farmers are prepared to shift practice accordingly (Guilbert et al., 2022). However, powerful dampening feedbacks also exist in the agro-industrial sector (Daugbjerg, 2011), and it is not clear whether potential for tipping dynamics exist, as opposed to linear change.

Box 4.3.9: Voluntary carbon markets drive agroforestry adoption in East Africa and India

The International Small Group and Tree Planting Programme (TIST) supports access to voluntary carbon markets to incentivise tree planting by smallholder farmers in Kenya, Uganda, Tanzania and India, with the goal of maximising benefits for participating farmers (TIST Program, 2023). Since its inception in 1999, it has grown rapidly through a mixture of grassroots activity, social contagion and targeted expansion (Emmanuel O. Benjamin and Blum, 2015), to include more than 170,000 participants (TIST Program, 2023). TIST members have planted more than 23m trees and own the rights to verified carbon credits generated by measuring their growth. Small incentive payments are made until trees are large enough to qualify for carbon credit verification, and these appear sufficient to offset the opportunity cost of committing to tree planting (Emmanuel O. Benjamin and Sauer, 2018).

Once planted, trees provide multiple co-benefits to farmers (De Giusti, Kristjanson, and Rufino, 2019) including fuelwood, animal fodder, fruit or nut crops, shade, and soil stabilisation. These benefits generate strong social-ecological reinforcing feedbacks, providing motivation for trees to be maintained over many years. The greening impact of TIST tree-planting is visible at landscape scales, and can be seen to extend beyond individual tree-groves to neighbouring land (Buxton et al., 2021), potentially strengthening these feedbacks. Regular meetings, training and visits by extension officers to measure tree-growth ensure accountability and transparency, and generate strong social feedbacks.

TIST's organisational structure is inherently scalable, and designed to facilitate sharing experience, information and training, both vertically and horizontally. Coupled with a culture of learning by doing, this means that best practices and innovations, including for other regenerative farming practices, can be spread rapidly (Masiga, Yankel, and Iberre, 2012). Rotating leadership throughout the programme structure, with equal leadership for women and men, facilitates social capital which further enhances the programme outcomes (Marshall, 2022), including ensuring economic empowerment for participants (both male and female) (Emmanuel O Benjamin, Ola, and Buchenrieder, 2018) which in turn enables greater investment in farming, education and health (Benjamin, Blum, and Punt, 2016), bringing further benefits aligned with multiple SDGs (OECD, 2020).

Growth in African-origin carbon credits slightly exceeds the global average growth rate in VCMs, with credits based on agriculture, soil sequestration, forestry and land use attracting the highest prices (two to four times the global average) (ACMI report). However, it is estimated that Africa currently generates only ~2 per cent of its annual potential for carbon credits, with potential to generate around US$50bn by 2030. This represents a powerful opportunity to leverage the feedbacks demonstrated in TIST and other programmes.

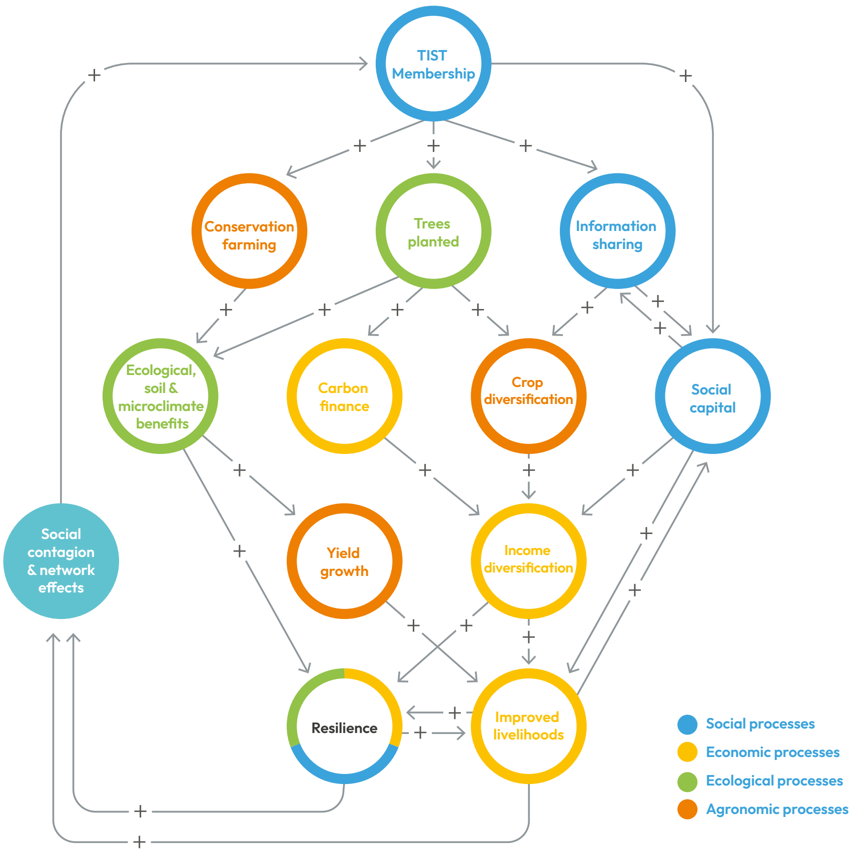

Figure 4.3.11: Positive feedbacks initiated by the TIST programme that increase capability of farmers, support them to access and benefit from voluntary carbon markets and improve the performance of their farms relative to the vicious cycle of degradation and vulnerability presented by the status quo.

4.3.3.6 Food system tipping points have important feedbacks for protecting nature

Together, widespread adoption of sustainable diets, the reduction of food loss and waste, and the sustainable use of land can work in synergy with one another to reduce GHG emissions, especially methane, and meet SDG targets for food security and sustainable livelihoods (Figure 4.3.9). Critically, they also have powerful synergies for protecting nature, including critically vulnerable carbon sinks and biodiversity hotspots like the Amazon.

Both reducing food loss and waste and changing towards planetary health diets can significantly reduce the global land area required for food production, despite growing populations, and open opportunities for nature recovery, including land-based CO_2 removal (Powell and Lenton, 2012; Meldrum et al, 2023). This could help reduce focus on maximising yields in intensive agriculture, and open opportunities to **shift** farming practice through incentives for diversifying farm business models to include ecosystem service provision, with the aim of restoring ecological health and function to agrifood systems.

Growing markets for natural capital and payments for ecosystem services, supported by strong policy and incentive frameworks to support agro-ecological farming and nature-based solutions, can make alternative models of land-management economically viable by creating economies of scale, and weaken economic incentives for environmentally degrading practices, including intensive livestock production. The rapid growth in voluntary carbon markets globally (close to US$1bn in 2021) demonstrates this potential, and these and other natural capital markets are seen as key pathways for directing climate finance, with significant recent commitments made by the EU (EU Parliament, 2023) and African leaders (Nairobi declaration, 2023). Recently, important critiques have been made of the transparency and effectiveness of credits for **avoided** emissions (e.g. West et al., 2023), and warnings of the risks of inappropriate (e.g. tree planting in African grasslands) (Bond et al., 2019) or poorly implemented carbon removal initiatives. These are undermining confidence in carbon markets and present a critical incentive for the evolution of more robust, transparent and accountable mechanisms to direct finance to appropriate solutions. Key to this is also ensuring benefits from these markets are accessible to communities and Indigenous peoples, who are key to ensuring sustainable land use transitions in much of the world. Reducing deforestation and supporting regeneration of natural vegetation can reduce annual net GHG emissions by more than 5GtCO2e by 2030, and more than 8GtCO2e by 2050, while contributing to halting and reversing biodiversity decline, and all while delivering a possible net economic gain of US$895bn per year by 2030, and US$1.3tn per year by 2050 (The Food and Land Use Coalition, 2021).

Shifts in values and norms which can accelerate tipping towards planetary health diets are also likely to be tightly linked, and therefore mutually reinforcing, to those which build demand for 'deforestation-free' products or which can demonstrate strong credentials for supporting conservation and Indigenous rights. These shifts can be accelerated by development of robust and transparent mechanisms for verifying and labelling provenance, and further strengthened by public and private-sector commitments to deforestation-free supply chains (The Food and Land Use Coalition, 2021).

4.3.3.7 Strategic interventions to enable positive tipping points in food systems

Box 4.3.10. Embracing new technologies and compensation schemes to support farmers and incentivize shifts towards more plant-based food and 'regenerative' farming.

Current subsidies in many countries, such as in the EU and US, incentivise farmers to not embrace regenerative farming practices and produce animal products and feed rather than plant-based food for human consumption. (Vallone et al, 2023). While demand-side shifts and clear market signals are an important lever for shifting towards more plant-based food production, it is important to incentivise and support farmers in shifting towards more plant-based food production. For example, targeted innovation policies could support the scaling of agri-photovoltaics in combination with the production of plant-based food to offer farmers a new income source when shifting their business model from feed or animal products towards plant-based food production (Fesenfeld et al., 2022).

Innovation and rapid reductions in the costs of such new technologies at the nexus of the energy and food systems can also help to reduce climate adaptation costs for farmers by protecting plants against extreme weather events. Moreover, in some regions and for some crops, new technologies such as agri-photovoltaics can increase overall land productivity by up to 70 per cent (Weselek et al., 2019; Tormer and Aschemann-Witzel, 2023). Other technologies, such as smart and precision-farming tools, can also reduce the costs and environmental burden of plant-based food production and thus help farmers to shift production (Finger et al., 2019; Walter et al., 2017; Finger, 2023). Here, targeted financial support and on-the-ground consultancy are important to foster the uptake and diffusion of such technologies. Focusing on farmers that act as important nodes in social networks and regions can be very effective to foster social contagion and innovation diffusion.

Novel satellite and result-based payment schemes can substantially reduce the administrative burden for farmers and thus resistance to more environmentally friendly and plant-based food production methods. Rapid improvements and economies of scale in digital farming technologies and high-resolution remote-sensing technologies thus offer new opportunities for accelerating transformation towards more sustainable farming methods, such as agroforestry (Teraski Hart et al.,2023). Moreover, the use of bio-char or other carbon-sequestering practices in plant-based food production and the potential integration into carbon markets can offer new income to farmers and increase their production resilience, and thus lower their risks when switching towards plant-based food production.

Targeted compensation schemes, especially designed to switch production of large feed and animal product producers with high environmental footprints, are another important measure to reduce resistance against production shifts towards plant-based food and regenerative farming. Focusing incentives for production-shift, emission-pricing (e.g. nitrogen surplus fee, methane emission trading), phase-out and compensation schemes on large producers in key regions (e.g. regions and farms with excessive nitrogen pollution or organic soils) is particularly promising because it reduces the number of affected farmers, can facilitate the negotiation process between farmers and governments, foster network effects and create positive political feedback (e.g. reduce backlash from smaller, unaffected farms). Using new revenues from emission pricing to support most affected regions and low-income groups (e.g., via reduce VAT rates on plant-based food), foster innovation, and create alternative income sources can reduce opposition. This can open a window of opportunity for more fundamental changes in agricultural subsidies that are also needed for accelerated food system transformation.

Box 4.3.11. Packaging and sequencing policies along the supply chain that focus on transformation opportunities: The example of the Danish Plant-based Fund

Importantly, production-focused policies that target farmers (Box 4.3.10) should be smartly combined and sequenced with policies along the entire supply chain that foster demand-side shifts and provide a clear signal for a growing plant-based food market. Such measures can include public procurement standards, innovation subsidies for the development and scaling of alternatives to animal products, and nudges in supermarkets and restaurants, but also consumer-sided price instruments such as tax reductions on plant-based foods or new pricing instruments for emission-intensive food products. The combination and sequencing of different policies not only increases the effectiveness but also the feasibility of policy change, by creating enabling conditions (e.g. shifting social norms and increasing public support for transformative policies) and reinforcing feedback (e.g. creating economies of scale in plant-based and alternative protein supply chains) (Fesenfeld et al., 2022).

The Danish Plant-based Fund is an example of a recent policy change that takes a packaging approach and integrates measures along the supply chain by focusing on the opportunities of food system transformation. The new policy involves funds for plant-based food product development and marketing, plant-based eco-schemes that pay premiums to farmers who grow plant protein crops for human consumption. A programme to promote environmental technologies targeting innovations in plant-based food-processing facilities and a strategy and projects to develop 'green proteins', particularly proteins produced from fermentation and cultured meat. It also includes an action plan to promote plant-based foods and dietary shifts (e.g. via nudging in public canteens, restaurants, supermarkets, etc). Importantly, the establishment of the fund involved deliberation among key (partially opposing) stakeholder groups, such as environmental NGOs and farmer associations, and inputs from scientists focusing stakeholders' attention on the opportunities of shifts towards plant-based food.

This strategic approach to policy design and framing might function as a best-practice case and be diffused to other countries and regions to create the enabling conditions (e.g. norm shifts and increased support) and reinforcing feedbacks (e.g. economies of scale) to accelerate food system transformation.

These examples show that positive tipping points in food and land use systems are possible, but that they are rarely a 'manna from heaven' and need an enabling environment and strategic decision making in politics, civil society and business. Decision makers need to take care of unintended negative effects and strategically design interventions to enable positive tipping. Based on existing scientific synthesis work (Fesenfeld, 2023, Fesenfeld et al., 2023; SAPEA, 2023; Galli et al., 2020; The Food and Land Use Coalition, 2021) we propose key interventions that can help to create enabling conditions for positive tipping points in food systems (Fesenfeld, Candle, and Gaupp, 2023):

1. **Strengthening adaptive and deliberative food system governance**
   Expanding beyond a narrow agricultural policy framework to encompass a comprehensive food system governance approach presents avenues for the involvement of new stakeholders and the potential to create reinforcing feedback via belief-updating and information cascades. This is particularly the case as, from a food system rather than a pure agricultural policy perspective, new actors enter the policymaking space, form novel coalitions and exchange information. Embracing inclusive and deliberative governance approaches, such as food policy councils and citizens' assemblies, at the regional, national and international levels can support such feedback and increase the input and output legitimacy of more ambitious policy change, such as **avoid measures** related to a fundamental repurposing of agricultural subsidies and new emission prices. Engaging diverse stakeholders in joint scenario development and multilateral negotiation processes can overcome political and implementation hurdles of such policy change by offering room for negotiating more integrated policy packages that compensate losers and open new business opportunities.
   a. **Strengthening the food system science-policy interface and science-based targets**
      Strengthening the knowledge and capacities of stakeholders is important for creating reinforcing feedback such as changes in norms and the creation of economies of scale. For an improved science-policy interface, several key actions can be taken:
   b. **Integrate research and data from various disciplines and sectors**, such as agriculture, food consumption, ecology, justice, food security and health, spanning different parts and levels of the food system.
   c. **Assess and provide knowledge in a transparent and independent manner**, ensuring credibility and reliability. Furthermore, independent policy progress monitoring can also create the enabling conditions for sudden policy changes (e.g. the UK Climate Change Committee (Carter and Jacobs, 2014).
2. **Develop science-based targets for policymakers and other key stakeholders** (e.g. businesses) can help to diffuse norms and trigger accelerated action. The nonlinear spread and adoption rate of the science-based target initiative is an example of how improved science-policy interfaces can lead to reinforcing feedback (Ramdorai, Delivanis, and Simons 2023).
3. **Strengthening policy sequencing, policy packaging and framing**
   Public and private decision makers can strategically combine policy framing, sequencing and packaging to create positive feedback loops and overcome political, social, technological and economic barriers to food system transformation (Fesenfeld, 2023). This positive political feedback can enable policies aimed at decline-oriented reforms, such as fundamental changes to existing non-sustainable subsidies, or the implementation of emission pricing schemes. In order to ensure a just and feasible transition, policy packaging becomes crucial to increase policy effectiveness and potentially compensate those adversely affected by the transition (SAPEA, 2023; Fesenfeld et al., 2020). This can increase fairness and facilitate broader stakeholder and public support.

   Initiatives by private companies (as outlined in the case studies above) can also lead to nonlinear changes and feedback to public policies. Framing policies around plant-based foods (rather than meat) and the opportunities of transformation (e.g. the Danish Plant-based Fund) can reduce political backlash. Moreover, policies adopted in one country can create spillovers to other jurisdictions and create positive feedback loops in these contexts (see examples of French Food Waste Legislation above). To increase the likelihood of such cascading effects, policymakers at the local, national, and international levels should engage in policy experimentation, which facilitates learning, feedback and diffusion.

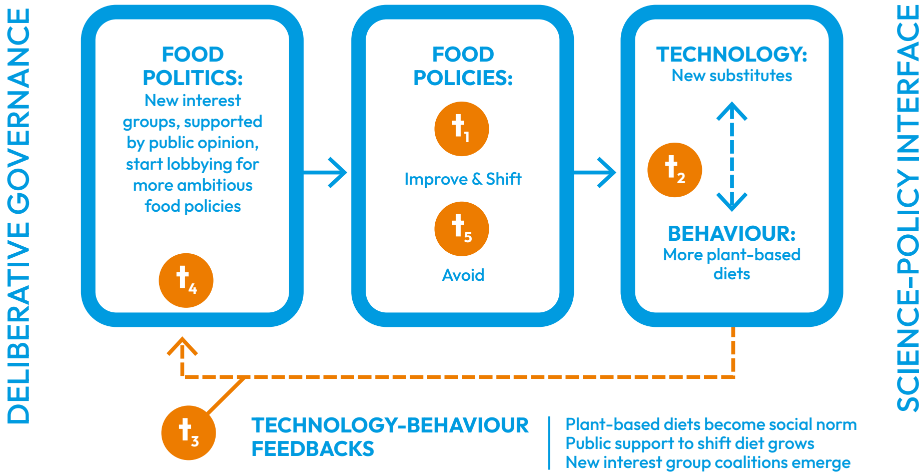

Figure 4.3.12: It is crucial to create the enabling conditions and reinforcing feedbacks to accelerate food system transformation by taking a systemic perspective and focusing on the opportunities for change. Building on examples like the Danish Plant-based Fund (Box 4.3.11) illustrates how the strengthening of deliberative governance, science-policy interface and strategic policy sequencing, design and framing can create the enabling conditions (e.g. changes in social networks, norms, product accessibility, quality and price) and lead to reinforcing technology-behaviour feedback (e.g. economies of scale, social contagion, information cascades) that reduce barriers for triggering positive tipping points. For example, deliberative forms of governance and stakeholder exchange focusing on the opportunities of change can enable in t1 (first phase) the adoption of improve and shift-oriented policies, such as the Danish Plant-based Fund. In t2 (second phase), such policies can then foster innovations and positive synergies between technological change (e.g. in meat substitutes) and behavioural change (e.g. supporting dietary change in cafeterias). Strengthening the science-policy interface can enhance policy impact and accelerate such technology-behaviour changes. In t3 (third phase), technological-behaviour changes can lead to reinforcing feedback, e.g. altering social norms, public opinion and interest group coalitions. In t4 (fourth phase), this can create the enabling conditions for changes in food politics and enable in t5 (fifth phase) the adoption of more ambitious avoid measures (e.g. new emission pricing instruments) that can trigger positive tipping points. The figure is based on (Fesenfeld et al., (2022)).

4.4 Cross-cutting enablers of positive tipping points

4.4.1 Socio-behavioural systems

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Summary

This chapter explores changes in socio-behavioural systems that provide important enabling factors and feedbacks for the positive tipping points described across Section 4. In addition, socio-behavioural systems can themselves be tipped, usually driven by complex contagion processes along extended social networks. Changes in social norms are often key drivers for social-behavioural systems, as they define acceptable behaviour, both in consumption domain and in the civic and political domains. Social movements are the main actors, seeding complex contagion of new social norms. However, social movements rely on allies and sympathisers for complex contagion to spread across social networks. Policymakers can also help to establish new social norms through policies that favour behaviours prescribed by new social norms. The chapter also describes the role that education can play in empowering actors to become agents of change.

Key messages

- Changes in socio-behavioural systems often precede and fuel political and technical changes and can exhibit tipping dynamics through social contagion processes.
- Social movements can initiate tipping in social-behavioural systems by shifting social norms, but to be successful they need an extended network of allies and sympathisers.
- New social norms that could beneficially transform society include anti-fossil fuel norms and sufficiency norms. However, replacing deeply entrenched values and norms around consumerism in favour of sustainable sufficiency would be extremely difficult.

Recommendations

- Accelerate the spread of desired new norms and behaviours through coordinated policies such as fossil-fuel phase-out, post-carbon infrastructure investment and policies that make desired behaviours the most affordable, visible and convenient option.
- Provide 'free social spaces' for social movements to gestate, and for members of such movements to build their networks and learn from each other.
- Equip social actors to become effective seeders of social contagion of new social norms through enhanced capability and efficacy.

4.4.1.1 Introduction

Social and behavioural change are key forces that can drive social tipping. Socio-behavioural systems encompass social norms, behaviours and lifestyles, communities and their cultures, and institutions. More than 65 per cent of global GHG emissions come directly or indirectly from household consumption (Ivanova et al., 2016). According to the IPCC, demand-side mitigation could reduce the total GHG emissions by 40-70 per cent compared to the baseline scenario emissions by 2050 (Creutzig et al., 2022). Demand-side mitigation (see Chapter 4.3) refers to changes in technology choices, consumption, behaviour, lifestyles, coupled production-consumption infrastructures and service provision (Creutzig et al., 2018).

A host of consumer behaviours have significant environmental impacts – for example, mobility choices, including decisions about whether and how often to fly; food waste; diet; and home weatherisation and electrification. However, there are other socio-behavioural changes with the potential to be highly impactful. Civic and political actions, including voting behaviours but also participation in social movements and boycotts, can have large impacts through their effects on policy and politics (4.4.2). Discussing climate change with one's peers can increase their concern about climate change and willingness to support mitigation policies, and potentially contribute to collective action (Geiger and Swim, 2016). Finally, there are also many socially reinforced beliefs that may be important to overcome or replace in order to shift societies towards more sustainable consumption patterns (e.g. consumerism, individualism).

Research has identified the aspects of lifestyles that support limiting global warming to 1.5°C and the required demand-side mitigation measures, see Figure 4.4.1 (Akenji et al., 2021). Addressing carbon inequality is crucial though, with the richest 10 per cent globally accounting for nearly half of all CO_2 emissions, indicating that significant carbon cuts must be made by affluent individuals through measures like carbon budget policies, luxury-focused carbon taxes, and the spread of sufficiency norms, especially among the wealthy (Kenner, 2019; Gössling and Humpe, 2023; Duscha et al., 2018; Rammelt et al., 2022; Oswald et al., 2023, IPCC 2023, Büchs et al., 2023; see Chapter 4.6). Social norms directly affect behaviours and lifestyles by defining what behaviours are appropriate in different contexts. What is considered appropriate is often linked to moral principles – what is considered right or wrong in a society (Buckholtz and Marois, 2012; Nyborg, 2018) – and can vary both across and within societies. People often behave according to social expectations for myriad reasons, including an intrinsic desire to belong and concerns that norm transgressions could lead to social exclusion (Constantino et al., 2022; Schneider and van der Linden, 2023). Changing norms hence translates into behavioural change by denormalising one behaviour and normalising another – e.g. denormalising investing in fossil fuel companies and normalising divestment (4.4.4).

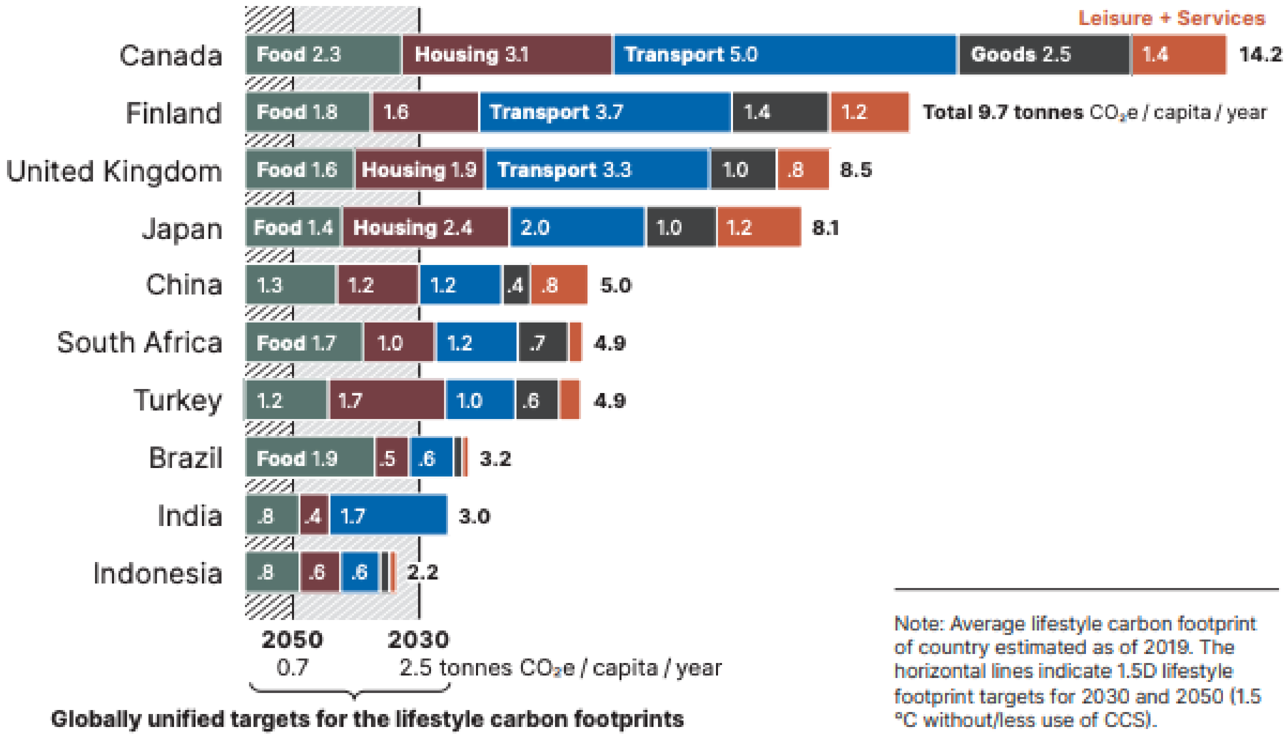

Figure 4.4.1: Per capita average carbon footprint and its breakdown for selected countries Source: Akenji et al., 2021.

4.4.1.2 Social norms facilitate tipping and can themselves tip

Carbon lock-ins depend in part on and reinforce social norms linked with petrocultures (belief systems around entitlement to cheap, abundant energy provided by fossil fuels to feed consumerist lifestyles, see Wilson et al., 2017; Daggett, 2018). Decarbonisation requires disrupting carbon lock-ins and the socio-behavioural foundations that uphold them (Bernstein and Hoffmann, 2018). Such a disruption could come from the large-scale adoption of anti-fossil fuel norms, which convey the inappropriateness of behaviours that require the extraction or consumption of fossil fuels (Green, 2018; Blondeel, 2019). Social norms also affect policies, as they inform which policies are likely to have significant public support. Change in civic and political behaviour facilitates changes in policies, as politicians would be given a clear mandate for decarbonisation and regenerative policies (Stokes, 2015; Willis, 2018; see 4.4.2).

Research suggests that one important element in the social system that can tip are social norms and the behaviours, beliefs and practices they prescribe. Other elements that are important, such as social identities and values, typically change more slowly. New social norms, ideas or behaviours can spread through complex contagion processes across social networks (Guilbeault et al., 2018; Fink et al., 2021; Becken et al., 2021) – i.e. an individual is likely to adopt a new norm, idea or behaviour if a certain number of their peers have adopted it. Complex contagion processes can lead to social tipping (Wiedermann et al., 2020; Xie et al., 2021), including in the context of climate change (Bury et al., 2019). This means the contagion of a new norm, idea or behaviour spreads initially gradually and slowly until a critical threshold (critical number of early adopters) is reached and the contagion becomes self-reinforcing, causing transition of the social system towards a new state (a new norm, behaviour).

Complex contagion is influenced by factors such as similarity of interacting individuals, the resonance of new norms with existing values and norms and the feasibility of prescribed behaviours (Guilbeault et al., 2018; Woodly, 2015; de Lanauze and Siadou-Martin, 2019; Schaumberg and Skowronek, 2022; Nyborg et al., 2016; Kaaronen and Strelkovskii, 2020). Networks characterised by clusters of strong local ties can facilitate and accelerate complex contagion (O'Sullivan et al., 201; Centola et al., 2018).

4.4.1.3 Social movements as norm entrepreneurs

Socio-behavioural change has to begin somewhere. For example, actors committed to an alternative norm or behaviour may be able to seed complex contagion. Social movements and civil society groups can be such initiators, and often have been in the past. For instance, the abolitionist movement was crucial for abolishing slave trade and slavery (Oldfield, 2013).

Social movements create social change by creating new norms, practices or beliefs, denormalising the status quo and bringing particular issues to the attention of the public.

(Nardini et al., 2020; Pathak et al., 2022). Such movements are particularly powerful when they can integrate their identity and the new norm, i.e. when they become the change they want to see in the world (Smith et al., 2014). Climate movements were identified as one among 10 main drivers to achieve (deep) decarbonisation by 2050 by triggering disruptive change through a range of actions, including campaigning, protest, climate litigation, boycotts and civil disobedience (Muñoz et al., 2018; Wasow, 2020; Engels et al., 2023; Nisbett and Spaiser, 2023).

Social movements must strike a balance between publicity and alienating the public, though (Zhou, 2016), as the successful seeding of complex contagion relies on diverse allies, who can reinforce and multiply the messages of the movement, by introducing it to communities lying outside a movement's direct spheres of social influence (Nardini et al., 2020; Nisbett and Spaiser, 2023). Together, social movements and their supportive sympathisers can reach the 'sweet spot' (around 10,000) in scaling social change (Bhowmik et al., 2020) through a ripple effect (Figure 4.4.2).

Some research suggests that the threshold for social movement mobilisation necessary to achieve broader social change can range between 3.5 per cent and 25 per cent of the population (Chenoweth and Stephan, 2011; Centola et al., 2018); however, these estimates have a lot of uncertainty and are likely to be context specific. For example, the research conducted by Chenoweth and Stephan (2011) analysed 323 country cases and found that when at least 3.5 per cent of the population actively participated in non-violent civil disobedience, their political demands were successful. However, none of these cases involved a Western liberal democracy, and all involved regime change, not system-wide transformation to a post-carbon economy.

There is also evidence that mundane features of many societies, such as the diversity of preferences and beliefs, how interdependent the culture is, and whether there are in- and out-group dynamics or strong social identity groups, have implications for whether and how social change spreads through social networks (Ehret et al., 2022; Constantino et al., 2022). Relatedly, a wider, diverse network of allies is often crucial for social movements to take hold.

Generally speaking, social movements emerge and create social change often through individuals with a strong urge to 'change the world', who inspire others around them, creating a vocal minority that can transcend the collective action problem (failure of a group of individuals to achieve common good), particularly when presented with a sufficiently large and certain threat requiring collective response (Ronzoni, 2019; Barrett and Dannenberg, 2014). Through traditional and new digital media, the movement spreads to other locations and communities. Grassroots groups coordinate their activities and actions, building a networked, international social movement with multiple leaders that mobilise key stakeholders and the public (Figure 4.4.2). As we will discuss in 4.4.3, once social movements have successfully mobilised a committed, well-organised minority (activists and allies/sympathisers) around a common cause they can affect political change.

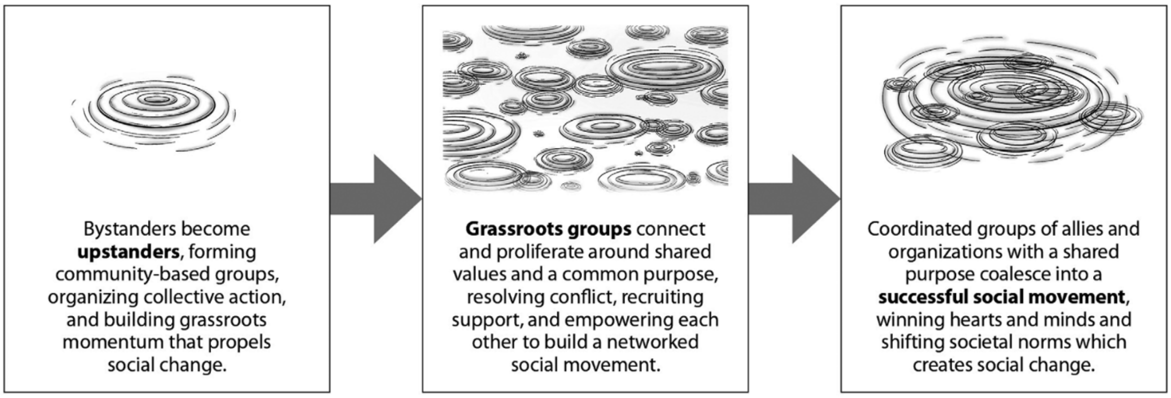

Figure 4.4.2: Ripple effect of social movements (Source: Nardini et al., 2020).

Changes in social norms are often contentious. New norms challenge existing norms and behaviours and the privileges and power structures that underpin them. This inevitably provokes resistance and backlash from those benefiting from existing norms and behaviours (Bloomfield and Scott, 2017), or whose social identities and values are closely aligned with them. It is therefore not surprising that research has identified a surge in denial and climate action delay arguments as well as a backlash against climate movements that challenge business-as-usual (Lamb et al., 2020; Falkenberg et al., 2022; Vowles and Hultman 2022; Nisbett and Spaiser, 2023). As has been noted earlier in this report, forces trying to preserve the current state of the system are likely to increase as we approach a tipping point. Despite the backlash, some new norms, like the anti-fossil fuel norms, have nevertheless been able to gain increasing traction (Harvey, 2023).

4.4.1.4 Policies that facilitate tipping in social norms

For socio-behavioural change, policymakers are also important, as policies can have a great impact on shifting norms, behaviours and practices. For instance, the law banning smoking in closed public spaces has shifted society from a state where most smokers were inconsiderate to non-smokers, to a new equilibrium in which a large share of smokers are considerate, even in unregulated spaces (Nyborg and Rege., 2003). Policymakers can support the propagation of anti-fossil fuel norms by making political decisions that explicitly signal the end of the fossil fuel era, for instance by withdrawing from all oil extraction activities, as Denmark did in 2020, or mandating a ban on petrol/diesel car sales, as the UK did from 2030 (now put back to 2035).

Additionally, governance interventions increase the visibility of certain behaviours and can help to establish emerging norms and the behaviours they prescribe.

Behaviours that are easily observable (e.g. smoking, mask wearing) may be more likely to show tipping dynamics due to the more prominent role of social norms and sanctioning in guiding those behaviours (Nyborg et al., 2016). Policies can explicitly increase visibility of desired behaviours. A study showed that making a behaviour observable tripled compliance, outperforming even cash incentives (Yoeli et al., 2013; Shrum, 2021). Moreover, as far as targeting companies is concerned, regulatory climate shaming (e.g. through rankings, ratings, labelling, company reporting, lists or online databases based on corporate climate performance) can be quite effective. (Yadin, 2023).

Many climate-relevant behaviours are perfectly visible though, such as driving a petrol-fuelled car versus cycling or walking. In such cases, governance interventions must look for ways to break self-fulfilling expectations (Nyborg et al., 2016) – i.e. people need to believe that others will take up cycling or walking and policies can provide reasons for people to change their expectations. Costly public investments, like bicycle lanes, can change expectations about which behaviours are likely to prevail as they signal that incentives (and potentially social norms) have changed for everyone (Nyborg et al., 2016, see 4.3.3). Usually, several social, economic and other feedbacks are present and can dominate to various degrees.

Transitioning to new behaviours is often costly, particularly in terms of upfront costs. Behaviour and lifestyle changes are influenced by norms, but also by perceived and actual action control – i.e. people can only adopt behaviours that are possible and salient (Ajzen and Fishbein, 2005; Fritsche et al., 2018). Hence, if reinforcing social feedbacks (e.g. anti-fossil fuel norms) are present or emerging but dominated by disincentives (e.g. costs), policy can modify the latter through taxes, carbon fees with dividends, subsidies, or infrastructure investments (Nyborg et al., 2016; Stiglitz et al., 2017).

4.4.1.5 The role of climate education and engagement

Strengthening climate education and engagement is another enabling intervention (Otto et al., 2020, see Figure 4.4.3). Since climate issues are complex and deeply intertwined with unsustainable development and cultural change, an education system that facilitates transformative learning processes and fosters collective engagement to enable agency for transformation, is fundamental for triggering PTPs (Macintyre et al., 2018). In the long term, climate action-oriented education can foster empowerment and agency (Stoknes, 2015; Tannenbaum, 2015; Colvin et al., 2019), increasing competence by providing facts and strategies for behavioural change (Hertwig and Grüne-Yanoff, 2017) and instigating sustainable lifestyles and career pathways, widespread engagement and action.

Education can also create rapid changes by connecting school classes with local transformation actors, such as farmers, entrepreneurs and non governmental organisations (NGOs). For example, school farms in the UK are fostering students' engagement with learning while facilitating sustainability practices among local farmers. Such processes create learning feedbacks across students and local transformation actors creating networks of positive tipping agents. Education can thus also enhance self-efficacy or agency for rapid social change by actively engaging students in real-world climate action projects and providing soft skills which translate into collective efficacy for society (Lenton, 2020; 2022; Centola and Macy, 2007;Centola 2018; Törnberg 2018).

A population size of around 10,000 people has been shown to be a 'sweet spot' scale for accelerating social learning between students, parents and peers (Bhowmik et al., 2020). Intervening via education at this scale can trigger social learning through multiple loops and can thus trigger multi-level interactions across formal and informal institutions and state and non-state actors (Pahl-Wostl et al., 2009). And finally, education can promote 'active hope' for young people suffering eco-anxiety and climate trauma by involving them in activities that shape the future they hope for (Macy and Johnstone, 2012). This empowers them to become potential seeders of positive social tipping processes, for example through climate activism.

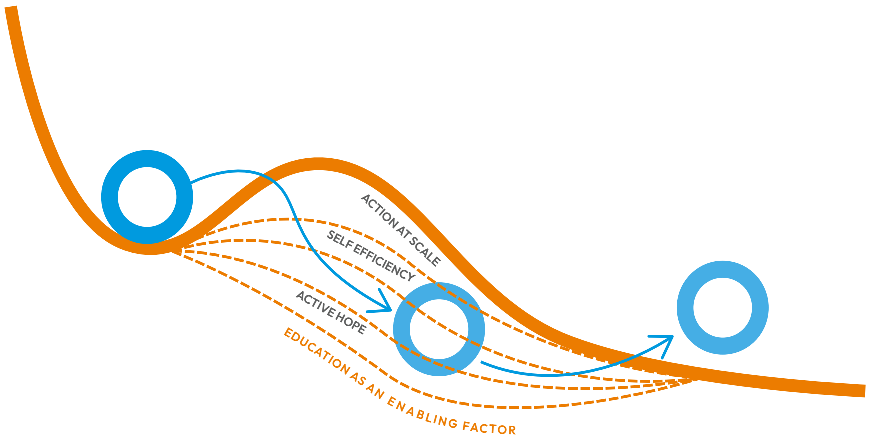

Figure 4.4.3: How education can enable social tipping through triggering action at scale, self efficacy and active hope.

Box 4.4.1: POSITIVE TIPPING POINTS IN INFORMATION AND KNOWLEDGE SYSTEMS

In information and knowledge systems (Cash et al., 2003), a positive tipping point happens when information previously considered 'noise' or irrelevant (Ollinaho, 2016) becomes a meaningful signal (O'Brien and Klein 2017; O'Brien 2020) that can trigger fundamental changes in social norms, behaviours and lifestyles consistent with Earth system boundaries (Rockström et al., 2023). The tipping occurs when a sufficiently large number of people recognise and act upon the information.

Broadly speaking, human information and knowledge systems (HIKS) (Tàbara and Chabay, 2013) comprise both the agents and the mediating mechanisms that generate, store, select and interpret information and turn it into actionable knowledge. Examples of HIKS include economic instruments such as market prices that indicate the current value of things, from commodities to countries; written, oral and computer languages, technologies and libraries; education and research institutions; and other information providers, including social media, that frame and render information salient. HIKS may be understood as **foundational systems influencing how humans interact with each other and the natural world.** As such, they are a core part of the enabling or constraining conditions that can accelerate or restrain cultural and structural transformations towards sustainability.

The capacity to reinterpret information previously dismissed as irrelevant 'noise' into meaningful information worthy of action requires higher-order individual and social learning abilities. New knowledge and beliefs replace those that are no longer fit for purpose. At the societal level, the consequences of a tipping point in HIKS can reorient all forms of human endeavour, from scientific research to technology innovation to governance (Ollinago, 2016).

The regenerative sustainability paradigm (Tàbara 2023; Fazey et al., 2020) describes how positive tipping points could emerge in multiple HIKS. This paradigm calls for the dissolution of the dominant worldview that disregards existential ESTP risks, in favour of a new restorative one that prioritises a thriving human future (Tàbara 2023; Fazey et al., 2020). Such a paradigm would establish new HIKs to help guide sectors towards sustainable pathways, for example HIKS on regenerative food and agriculture.

4.4.2 Political systems

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Summary

In this subchapter we discuss the role of the political domain, both as an enabler of positive tipping within social systems and as a system that can itself be tipped. Political systems can enable change through new policies, investments and discourses. These measures can amplify positive feedbacks and enable new system trajectories, solidifying transformations and making them difficult to reverse. Political systems can also be tipped, either via internal, self-reinforcing dynamics or as a result of acute events (e.g. crises that change the priorities of the electorate). Tipping dynamics within the political system include abrupt changes in politics (e.g. change of leaders), policies (e.g. new laws and regulations), or polity (e.g. introduction of new political institutions). Social movements, civil society and strong interest groups can entrench the status quo or be an instigator of change in political systems.

Key messages

- Political systems often reinforce existing social orders, but political action is crucial for significant and sustained progress towards sustainability.
- Political interventions – such as policy and public investments – can support early change, create positive feedback loops and enable positive tipping in key subsystems.
- Political systems, despite being resistant to change, can also be tipped.
- Civil society and social movements can build broad coalitions and mobilise the public, facilitating new policies and the tipping of incumbent political systems.

Recommendations

- Pursue policies to facilitate positive social tipping through increasing returns, compensating losses, and building the autonomy and capacity of agents for change.
- Build international climate clubs to facilitate climate leadership and unlock deeper and broader global climate cooperation that can be amplified by international organisations.

4.4.2.1 Introduction

Political systems involve complex networks of actors embedded within various institutional settings and operating across multiple scales, from hyper-local to global. This complex arrangement of governing institutions has been described as a **climate change regime complex**, as opposed to a comprehensive and integrated regime, and is characterised by loosely interdependent elements that are sometimes conflicting and sometimes reinforcing (Keohane and Victor, 2010). The political regime determines the set of rules and power structure regulating the operation of a government or institutions. Political actors shape and are constrained by the rules and regulations in their particular spheres (e.g. municipal, state, national), and by pressure from their constituents, advocacy coalitions and other interest groups. The political sphere can enable tipping in other subsystems, for example through the introduction of new policies or investments, and can itself tip, resulting in new policy goals, political leaders or regimes. At the same time, political systems can also be conservative forces, sometimes by design, often resisting change and reinforcing existing social orders, power structures and dominant practices.

Political systems as tipping elements have received relatively limited attention in the literature on social tipping and detailed knowledge of the specific mechanisms, feedbacks and temporal and spatial scales are limited. Given the complexity of the political sphere, especially when it comes to the governance of climate change and ESTPs, it may be impossible to detect the exact *point* of tipping and more fruitful to examine tipping *dynamics*, including enabling conditions and feedbacks, and locating the most 'sensitive points' at which to intervene (Mealy et al., 2023; Farmer et al., 2019; Geels and Ayoub, 2023). For example, the policy feedback literature suggests that new technology firms (e.g. offshore wind or electric vehicles) can use their growing lobbying power to shape public policies. Strategic policies and investments can in turn support and reinforce the development of these new technologies and strengthen markets, especially at early stages of a transition, when there are greater costs or risks (Geels and Ayoub, 2023). New technologies and associated markets can create new coalitions that in turn change policy goals and alliances, as well as public discourse. Similarly, public attention can create pressure on policymakers to introduce, remove or strengthen policies or investments. These dynamics are discussed in more detail below.

4.4.2.2 Political systems can enable (or dampen) social tipping

The political system is a key cross-cutting force in driving or preventing rapid social change. Political systems and institutional settings can be drivers of rapid, nonlinear change in other subsystems (e.g. transition to renewable energy) by setting the rules and regulations that govern society but also by providing capital to different sectors, building out the capacity of relevant agencies, incentivising investment of private capital, investing in public goods such as research and development into new, risky or underprovided technologies, subsidising 'desirable' goods or taxing 'undesirable' ones, or through the discourse they promote and public education and communication efforts, which can in turn create new social norms. The state can thus play an 'entrepreneurial' role by facilitating technological breakthroughs and transformative innovation (Mazzucato, 2011, 2015).

Innovation-focused public interventions can act as enablers of social tipping by fostering technological progress and workforce development, potentially altering public sentiment and increasing political will for sustainable policies, while ensuring a just transition and addressing opposition to change through compensation for those adversely affected. The impacts of such public interventions can be both direct and indirect. For example, the Inflation Reduction Act in the US, which includes $369bn in funding to tackle climate change, much of it directed at renewable energy investments, is also driving indirect change and positive feedbacks by catalysing private-sector investments, the development of new, cheaper green technologies, and policymaking in other countries. This echoes related work, which shows that the adoption of carbon pricing in one country can explain its subsequent adoption in others (Linsenmeier et al., 2023).

Indeed, networked or polycentric forms of governance may support rapid social change by creating interdependence across locations and the potential for positive feedbacks as new innovations and policies take hold (Chapin, 2021). For example, cities involved in programmes such as ICLEI and C40 Cities have come together around the goal of sustainability, deliberately creating global city networks to foster rapid social change through policy experimentation, capacity building and the diffusion of information and innovations." (Bhowmik et al., 2020).

Political systems can of course also dampen feedbacks, limit climate action and reinforce the status quo – as is evident in sizeable fossil fuel subsidies and tax credits, limited renewable energy infrastructure, and lack of a meaningful carbon tax across countries. This may happen in part because of the checks and balances built into democratic systems, but also because those in power serve limited terms and so focus on shorter-term outcomes in their policymaking, have an incentive to respond to present constituents rather than future generations or populations in other locations, often have vested interests in current systems, including fossil fuel-based energy systems, and face intense lobbying from the oil and gas industry, among others (Köhler et al., 2019; Besley and Persson, 2022). Further, politicians may perceive constituents to have limited desire for climate policy (Kneuer, 2012; Stokes, 2016; Willis, 2018) due to widespread misperceptions of public sentiment and large silent majorities and vocal dissenting minorities (Mildenberger and Tingley, 2019). Different institutional forms or regimes determine the distribution of power between government, businesses and publics, and incentivise different coalition-building strategies and policy-shaping efforts (Meckling and Karplus, 2023).

Political systems can thus enable or impede rapid social change and positive social tipping in other subsystems. Ultimately, **climate politics are distributive politics**, resulting in political battles over who reaps the benefits and who bears the costs of climate policy (Meckling and Karplus, 2023). Strategic policy design should thus include both measures to **enable desired change** in key subsystems, such as the renewable energy sector, and to **mitigate impeding factors**, including backlash from key constituents, as enumerated below.

1. Identify policies with concentrated benefits but diffuse costs. Rooftop solar panel subsidies, for example, have concentrated benefits for homeowners and solar panel manufacturers and installers, while the costs are spread across taxpayers.
2. Link climate policy with popular and salient issues. The expansion of renewable energy production through wind and solar, for example, reduces the dependence on fossil fuels and Green House Gases (GHG) emissions but also increases energy independence and security.
3. Combine policies that impose visible/concentrated costs with compensation mechanisms that create visible/concentrated benefits. Carbon fee and dividend schemes, for example, require companies to pay a fee based on their emissions, which is returned to the public in the form of dividends or rebates, compensating for higher prices. Another example is strategic workforce training and placement for those left structurally unemployed due to a transition away from fossil fuels.
4. Ensure policy durability by building positive feedbacks and path dependencies into the policy design. Sequence when benefits or costs are introduced, such as subsidising costs until new technologies take hold, and providing benefits to key political groups.
5. Ensure state capacity and autonomy to enforce policies. To accelerate the build-out of clean energy infrastructure, the capacity of permitting agencies to efficiently and effectively assess projects could be increased through larger staff, better training and more power to advance processes (Bozuwa and Mulvaney, 2023).

4.4.2.3 Political systems themselves can tip

The political sphere may itself constitute a tipping element. In political systems, tipping can occur at the level of policy, politics or polity and involves a complex arrangement of actors (Eder and Stadelmann-Steffen, 2023). For example, extreme events such as natural disasters or long-lasting crises such as the COVID-19 pandemic can change the political landscape by altering public perceptions and behaviour (Casoria et al., 2021), pressure on incumbents (Oliver and Reeves, 2015), and the process by which new measures are introduced (e.g. under disaster declarations), potentially opening windows of opportunity for the introduction of new policies, investments and discourse. Political regimes and policies can tip, as happened with the dissolution of the Soviet Union in 1991 (Kramer, 2022), as can political majorities and, ultimately, leadership. Indeed, this is one of the core principles of democracy: leadership can change rapidly as the priorities of constituents evolve (Eder and Stadelmann-Steffen, 2023; Yankelovich, 2006). However, while new governments may seek to quickly reverse policies introduced by prior governments, many actions, such as investments in large infrastructure projects (e.g. as needed for energy system transformation or nuclear phase-out), are characterised by strong path dependencies and lock-in of development pathways (Thacker et al., 2019) and can thus be considered nearly 'irreversible'. This inertia built into certain infrastructures, technologies, institutions and social norms can create carbon lock-in, but also has the potential to lock in low-emissions pathways (Urge-Vorsatz et al., 2018).

An example of tipping in policy that was driven by tipping in politics is Germany's rapid phase-out of nuclear energy following the Fukushima Daiichi nuclear disaster (Eder and Stadelmann-Steffen, 2023). While this example is largely negative when assessed in terms of emissions and climate goals, it is nonetheless an illustrative example of tipping in politics. In Germany, rapid changes in sentiment among the public and the governing majority (the CDU-FDP coalition in Germany) led to the rapid phase-out of nuclear energy, including the shutting down of several operating power plants. In Switzerland, in contrast, while a political majority also showed signs of tipping towards nuclear phase-out, the decision was gradual. These differences have been attributed to Germany's 'critical state' prior to Fukushima, due to the public's scepticism towards nuclear energy since the Chernobyl meltdown in 1986, and a well-established anti-nuclear movement. They also point to differences in the institutional context. In Germany, the CDU-FDP government coalition held a parliamentary majority and abruptly changed its position. Conversely, in Switzerland compromises and coalitions had to be formed in parliament to phase out nuclear energy.

4.4.2.4 Civil society and political tipping: The role of social movements and coalition formation

To date, most countries have taken relatively modest action on climate change. This has been the case for a host of reasons, including those mentioned in section 4.2.3.3 on dampening effects. One reason for the lack of political will to fight climate change stems from policymakers' beliefs (including in non-democratic regimes) that they lack the mandate for drastic climate policies (Kneuer 2012; Stokes, 2015; Willis 2018). Indeed, research has shown that there are substantial misperceptions among political actors regarding the policy preferences of their constituents, including underestimation of support for a carbon tax (Mildenberger and Tingley, 2019). Civic and political behaviour, including voting behaviour, diverse forms of political participation and the emergence of effective social movements, increases the visibility of public preferences, puts pressure on incumbents to take action on climate change, and can even lead to new leadership (Kuran, 1989). For instance, the German Energiewende/EEG law, which was crucial for initiating the global solar power boom (see Chapter 4.2), would not have been possible without social change in German society, which brought the Green Party into government in 1998 (Hake et al., 2015). Similarly, the CFC ban to protect the ozone layer was also facilitated by shifts in social norms, mass boycotts of products containing CFCs, and public demand for laws banning chlorofluorocarbons (CFC) (Stadelmann-Steffen et al., 2021).

Civil society plays a crucial role in creating enabling conditions for political tipping. Successful social movements, such as the transnational abolitionist movement, played a huge role in shifting societal perceptions and norms and ultimately effecting political change by advocating for the moral unacceptability of slavery. They did so through publications, public education, public responses to arguments, appealing to opponents' values, placing actors of change in core institutions, mass petitioning, litigation, supporting slavery victims and boycotting slave-produced goods, and through leading by example (e.g. former slave owners freeing slaves) (Oldfield, 2013). Crucially, the movement understood the need to create links with policymakers and the importance of building political coalitions. They also made use of litigation, using progressive national law to advance their cause. A similar strategy is increasingly adopted by climate movements. For example, in the Youth plaintiffs in Held vs. State of Montana (US) Climate Case, a judge ruled in August 2023 that it is against the constitution for a state to fail to consider climate change when approving new fossil fuel projects. The national law referenced in this case was the right of state residents (in this case the young plaintiffs) to a clean and healthy environment, including a stable climate. The interplay of national law and civil society enforcing accountability could be a powerful driver for political and social change.

Key challenges for social movements in the longer term include maintaining the authenticity of the message, the commitment and the mutual trust of the base of support, while also leveraging the connections and resources of the wider political network and coalition (Newell, 2015). In democratic countries, coalitions for radical policy change are unlikely to succeed until politicians are first emboldened by the political legitimacy of a broad, popular mandate (DNZ, 2021; Newell, Daley, and Twena, 2021; Willis, 2020). Advocacy for radical change therefore begins in social movements and proceeds, over years and decades, to build coalitions to persuade 'the changeable people…' (Commissioner Tim Kasser, quoted in Newell et al., 2021, p.43).

Although a simple, linear sequence may be of limited use in describing the interdependent complexities of rapid social change, it could be argued that it typically begins with the problem/issue, proceeding with a political process, and ultimately becoming a policy process (Smith, 2022), as summarised in Figure 4.4.4.

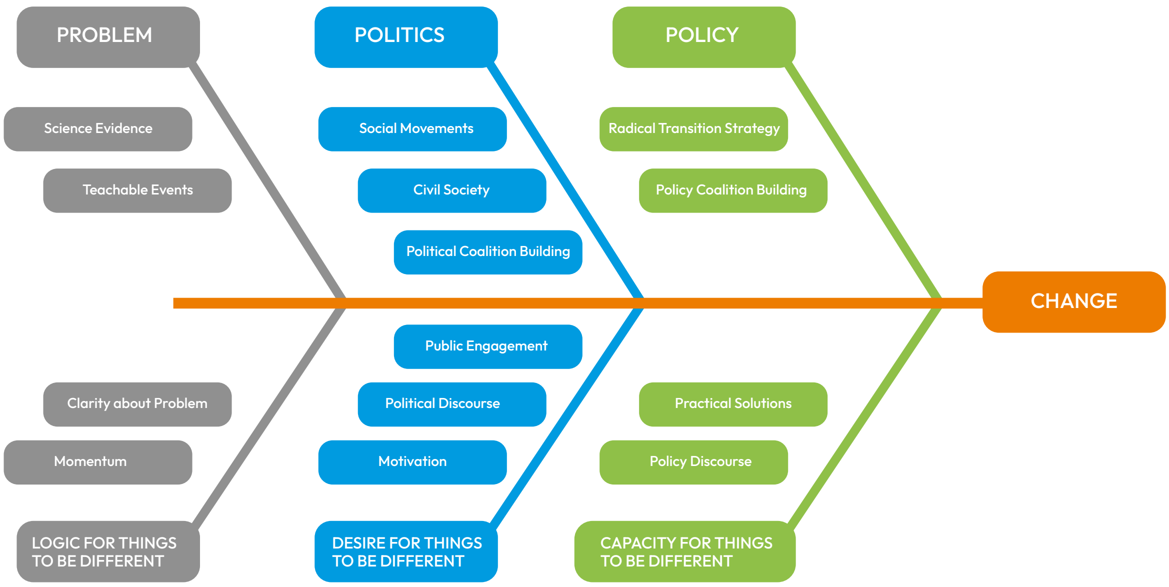

Figure 4.4.4: Sequence of rapid social change.

4.4.2.5 International climate governance and the diffusion of political change

Achieving global climate targets requires some degree of international cooperation, but a key question is how many cooperators are needed at the outset to sustain and increase decarbonisation goals over time. For many years, international climate negotiations under the United Nations Framework Convention on Climate Change (UNFCCC) were predicated on a consensus model, which resulted in weak agreements (e.g. the Kyoto Protocol). Even the Paris Agreement can be regarded as weak, as it outlines a strong set of collective goals (e.g. limit the rise of global temperatures to well below 2°C) but leaves countries largely free to choose the actions needed to meet them (Sharpe, 2023) with limited mechanisms to hold them accountable to their pledges.

Recent work emphasises that **broad consensus may not be the only or most promising pathway** to addressing climate change. To date, global cooperation has been insufficient and difficult to enforce, and none of the world's largest emitters are on target to meet the goals of the Paris Agreement (Carbon Tracker). Many have argued that the lack of cooperation may stem from concerns about free-riding or from the view that addressing climate-change is a zero-sum game (Barrett 2003), made worse by the presence of catastrophic tipping points with uncertain thresholds (Barrett and Dannenberg, 2014). However, addressing climate change is in the interest of certain countries, regardless of whether all countries cooperate (Mildenberger and Aklin, 2020). For example, certain countries may have strong domestic constituencies committed to climate action (e.g. a concerned public or special interest groups and lobbying groups), which may drive their leaders to take mitigative action regardless of whether other countries act. Other countries may face greater exposure to unmitigated climate change and may thus choose to act, or to come together to pressure other countries to take action, as has happened with the Small Island Developing States (SIDS) and the establishment of the Loss and Damage Fund at COP27.

Pioneering states and small-group coalitions may be able to catalyse virtuous cycles of cooperation on climate change due to three features of mitigation efforts that challenge the zero-sum game view (Hale, 2020):

1. **Shared benefits**: Investments in public goods, such as mitigation of GHG emissions, can also confer private benefits.
2. **Diverse preferences**: Different countries attach varying levels of importance to mitigation, which means that some countries will take action despite inaction by others.
3. **Increasing returns**: Previous mitigation efforts enhance the benefits and decrease the costs of future actions through a positive feedback mechanism.

One way to increase ambition is thus through the creation of climate clubs – i.e. a small group of countries committed to ambitious climate goals and deeper cooperation that might involve sectoral agreements and corporate partners. Climate clubs can act as 'tipping sets' which, by switching to a more desirable equilibrium state, can lead others to follow (Grimalda et al., 2022; Heal and Kunreuther, 2011). A few key countries, especially large emitters, working together to speed up the development of green technologies coupled with well-designed broad-based market mechanisms could help accelerate global progress on climate change (Sharpe, 2023). Additionally, such climate clubs can concentrate negotiation power (Meckling and Karplus, 2023) and can be crucial for establishing new norms such as anti-fossil fuel norms (Green, 2018; van Asselt and Green, 2022; Meckling and Karplus, 2023; Linsenmeier et al., 2023). International institutions can in turn amplify this cycle through information sharing, capacity building and the elevation of certain norms (Park, 2006; Meckling and Karplus, 2023).

International norms have been described as evolving according to a patterned 'life cycle' (Finnemore and Sikkink, 1998). Norm entrepreneurs convince states to adopt norms that they deem desirable or appropriate – e.g. the conceptualisation of climate change as an issue of justice and fairness (Mitchell and Carpenter, 2019). If a critical mass adopts the new norm, this can, under certain conditions, create a tipping point after which it spreads, eventually becoming institutionalised. For example, in recent years, SIDS have acted as agenda- and norm-setters in international climate negotiations (Corbett et al., 2019; Constantino et al., 2023). A global coalition of 132 co-sponsoring countries and a global campaign with more than 1,500 civil society organisations in 130 countries formed around Vanuatu's call in 2019 for climate justice. This movement led to the 2023 adoption by consensus of a historic resolution to seek an advisory opinion from the International Court of Justice (ICJ) on the obligations of governments to protect human rights threatened by climate change under international law during the 77th session of the United Nations General Assembly (Vanuatu ICJ Initiative, 2023).

International law can also serve as a trigger for positive social tipping. One example is the introduction of formalised human rights laws, which spread to over 100 countries in three decades (Kim, 2013). In the context of Earth system tipping, a transnational network is advocating for the inclusion of ecocide, defined by an Independent Expert Panel (2021) as "unlawful or wanton acts committed with knowledge that there is a substantial likelihood of severe and either widespread or long-term damage to the environment being caused by those acts", as the 'fifth core crime' in the ICC (International Criminal Court) Statute. As Robinson (2022) argues, including ecocide as the fifth core international crime, or even an international ecocide convention, would "provide stronger penal sanctions, stigmatisation, jurisdictional reach, and commitments to prosecute in relation to the worst environmental crimes. But perhaps an even greater value of the crime is its 'expressive function': reframing massive environmental wrongdoing not as a mere regulatory infraction, but rather as one of the gravest crimes warranting international concern". Such an international law would be a strong signal, shifting expectations and hence social and global norms. It is notable that the International Corporate Governance Network (ICGN), a global investor-led network, called for criminalising ecocide during COP26 (2021) to channel international finances away from ecologically destructive practices.

In summary, political systems can **enable** or **impede** positive social tipping in other key subsystems, and can also **be tipped**. However, political systems are complex, ranging across local to global scales and varying in type of regime, and contingent. Additional research is needed to understand how they tip under different conditions. In this chapter, rather than focusing on identifying exact tipping points, we have focused on highlighting political enabling factors that may help initiate or amplify change in other subsystems, and addressed impeding factors, introducing some key historical and present examples in energy systems transitions. We have also identified mechanisms by which different components of political systems may themselves tip, and the role of social movements in bringing these changes about. This review is by no means comprehensive, and we expect many insights to come from ongoing and novel research efforts into this crucial component of rapid societal change.

4.4.3 Financial systems

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Summary

As of today, the financial sector is fuelling an economy currently on a trajectory towards ~3°C by 2100. Leveraging the tipping elements inherent in financial markets will be critical to direct the economies onto a net-zero emission trajectory compatible with the 1.5°C-2°C goal of the Paris Agreement. Taken together, the mechanisms we describe in this section highlight the positive tipping points that can be triggered within the financial system and emphasise the necessity of policy interventions to activate and capitalise on these dynamics. The financial system must assume a central role in expediting the shift towards a net-zero carbon economy. For this, the alignment of expectations between investors and policymakers is key, requiring clear transition plans and strategies. Utilisation of public finance, reduction of capital costs and attainment of low-carbon investment thresholds in the Global South and Global North are also indispensable to ensure capital allocation towards where it is most needed. Coordination will be essential to foster implementation of robust financial regulations along with industrial and climate policy. The identification of critical intervention points can lead to the amplification of sustainable investments, mitigate risks and foster transformative changes in the practices of the financial sector.

Key messages

- The financial system must assume a central role in accelerating the shift towards a net-zero carbon economy.
- Policy interventions can activate nonlinear changes to enable transformative shifts within and beyond the financial sector, capitalising on these dynamics.

Recommendations

- The role of the financial system in the transition to a net-zero economy must be clearly articulated and aligned to an industrial strategy. The rules and regulations governing the system can be adjusted accordingly.
- Public finance and policy support should be used to mitigate market uncertainty and encourage private investment, particularly to developing economies. Policy mixes that combine state-based and market-based instruments can initiate virtuous circles that drive innovation and reduce the overall need for public investment.
- Prudent regulatory and financial supervision tools should be used to facilitate a managed decline in fossil fuel lending. Coordinated planning through institutions like the Net Zero Banking Alliance could help manage the transition in debt and equity markets.

4.4.3.1 Introduction

The transition to a net-zero carbon economy relies on financial markets adopting sustainable practices to unlock low-carbon opportunities, accelerate emissions reduction and nature conservation efforts, and mitigate societal and financial risks associated with carbon-stranded assets. The financial system must both finance the 'green' (the desirable) and stop financing the 'dirty' (the undesirable), while managing financial risk-adjusted returns as its primary function (fiduciary duty). However financial markets tend to replicate by default the economy as it is, as they do not a priori 'have a plan' for the economy, whether high or low carbon. The existing economic framework largely operates within an accumulation paradigm driven by search for short-term profits, inadequate climate policy and unclear industrial priorities at both national and international levels. In this context, perpetuating historical patterns is still the best way to ensure profitability. Driven by backward-looking, climate-blind indicators and ignoring the complexity and systemic impacts of their investments on the environment (Chenet et al., 2021; Crona et al., 2021), financial actors are still allocating capital to fossil fuel assets, consolidating and even creating new carbon lock-ins (FTM, 2023), thereby constructing their own exposure to future climate-related financial risk. However, it is now clear that those investments are not 'needed' from an energy-demand perspective (IEA, 2023a).

To be effective at accelerating the transition, financial markets need to be forced to move beyond their conventional emphasis on financial risk and return, short-term horizons, prevailing market rules and operations, and would need to integrate systemic sustainability considerations into regulation and market practices across the entire financial chain (including investors, financers, financial services, rating agencies and more). Progress thus far does not match the needed pace and depth of transformation. It has been essentially limited to reframing (such as addressing climate-related financial risk), repackaging (as seen in the case of green bonds) and disclosure (with the establishment of the Task Force on Climate-Related Disclosures (TCFD) and similar initiatives), and has not yet led to a significant reallocation of financial capital at global scale. However, **the potential exists for swift and nonlinear changes that can drive transformative shifts within and beyond the financial sector**. In this way, the financial system can be an enabler of positive tipping points in other sectoral systems, in the 'real economy', and may itself exhibit tipping point behaviours.

On the positive side, the financial sector's engagement with climate change has nevertheless undergone a significant evolution over the last decade. Key milestones, such as the 2015 Paris Agreement and Mark Carney's (former Bank of England Governor) influential speech on climate-related financial risks, have catalysed a new discourse connecting finance and climate change and prompting financial actors to embark on a different path (Farmer et al., 2019). The formation of voluntary initiatives like the private-led Glasgow Financial Alliance for Net Zero (GFANZ) and the central bank-led Network of Central Banks and Supervisors for Greening the Financial System (NGFS), exemplifies the growing commitment of financial entities, from private institutions to public authorities, to align themselves with climate targets beyond their traditional perimeter. While not yet having led to transformative actions, these coalitions in their respective domains aim to achieve net-zero carbon emissions by 2050, which questions the role of finance in addressing the challenges posed by climate change – either by challenging the historical role and responsibilities of financial institutions vis-à-vis invested and financed companies, or through renewed approaches to financial supervision, credit and monetary policy (Chenet 2023; Lamperti et al., 2021).

These shifts have the potential to surpass crucial thresholds or tipping points, where a small change can trigger a larger, irreversible transformation, with feedback effects acting as amplifiers. By influencing the allocation of capital to different sectors or activities, the financial system has the power to affect the evolution and composition of the real economy. Often, the financial system has functioned to amplify oscillations, whether positive or negative, through reinforcing feedback mechanisms such as the financial accelerator, contagion, bank runs and assets' fire sales (Bernanke et al., 1999; Delli Gatti et al., 2010). However, finance doesn't just magnify economic shocks – it may also assume a crucial role in enabling technological revolutions (Perez, 2003). Financial actors – and public investors most prominently (Mazzucato, 2013) – actively contribute to the advancement and implementation of innovative technologies, extending their involvement beyond simply providing funds. In fact, they often take part in the management of the innovation process, assuming the role of financial entrepreneurs and 'picking winners', while other mechanisms can also operate concurrently. For instance, once a particular path is established, it can lead to a self-reinforcing cycle where the initial choice gains momentum and becomes increasingly difficult to change (Arthur, 1989). **Finance, thus has the capacity to expedite or impede the dissemination of new products and technologies**, particularly those of utmost importance for the transition to a low-carbon future.

4.4.3.2 Feedbacks between public and private finance

Public finance plays a pivotal role in stimulating new investment by encouraging private investors to follow suit (Mazzucato, 2013). This is not only due to the substantial amount of funding provided by public actors, such as public investment banks and governmental agencies, but also to the quality of financing schemes they offer. Public financing, with its long-term time horizons, favourable repayment conditions, and support services, resembles the role of financial entrepreneurs (Perez, 2003).

By minimising risks associated with investments and supporting specific technological trajectories, public finance can mitigate market uncertainty, potentially enabling tipping points in the financing of low-carbon projects and assets (Campiglio and Lamperti, 2021; Mazzucato and Semieniuk, 2018). However, adequate policy support, such as mission-oriented industrial policies, is essential to facilitate these tipping dynamics.

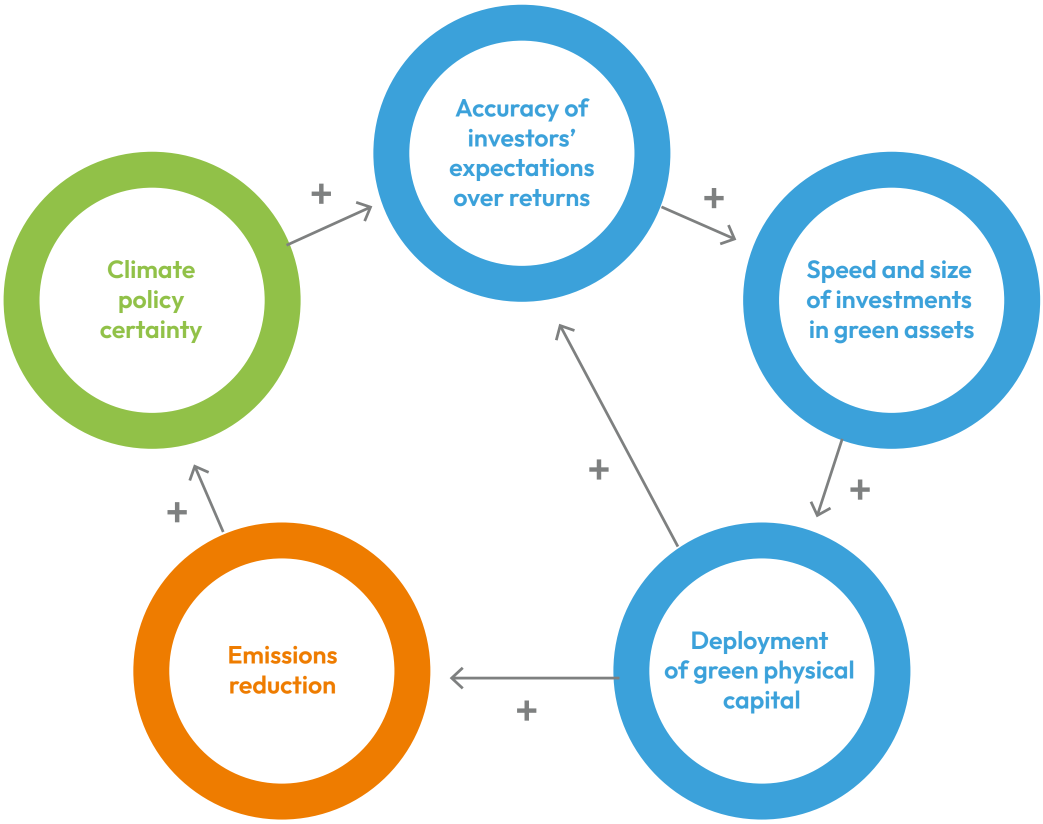


Figure 4.4.5: The figure shows the set of self-reinforcing mechanisms and feedback loops occurring in the process between climate policy certainty and deployment of green physical capital. Expectation alignment creates a positive feedback which can be triggered and sustained by certainty in climate policy. The + symbol indicates a positive effect.

Expectation alignment on the timing and speed of the transition is an additional tipping element that can scale up sustainable investment (Campiglio and Lamperti, 2021; Campiglio et al., 2023; see Figure 4.4.6). Uncertainty about the future prospects of low-carbon assets and unclear information about the strength of climate policy can lead to conservative wait-and-see approaches among investors, especially private ones. However, certainty regarding future climate policy schedules can signal the long-term trajectory of the economy, establishing a positive correlation between macroeconomic performance and the returns of low-carbon assets. For example, the public Contracts for Difference scheme in the UK provided policy certainty on low-carbon electricity generation and triggered large private investments, expanding the stock of offshore wind capacity and lowering power generation costs well below conventional sources. Further, the alignment of beliefs can coordinate and shift the strategies of long-term institutional investors, transforming low-carbon investment from diversification assets to strategic ones and increasing the risk of carbon-intensive assets. Clear and trustworthy climate policy is key for such an alignment to occur. This shift would reduce the cost of capital for low-carbon firms, facilitate their growth, and create a virtuous feedback loop of low-carbon investment.

4.4.3.3 Strategic policy intervention

Two finance-related interventions identified by Farmer et al., (2019) include financial disclosure and the early identification of combinations of new technologies to invest in. Such actions can be interpreted as small **kicks** that can initiate behavioural changes or endogenous shifts in the system's dynamics. Changes in accounting standards and disclosure requirements can significantly alter the value of fossil assets, limiting the development of new projects, reducing committed emissions and thus facilitating the transformation of the energy industry (Le Ravalec et al., 2022; Rambaud and Chenet, 2021). Additionally, low-carbon technologies, given their capital-intensive nature, are subject to much higher investment risk than fossil fuel-based incumbents (Schmidt, 2014). Such risk needs to be managed and/or diversified. Hence, focusing resources on specific technological complementarities (e.g. solar PV and energy storage) as early as possible, rather than investing across a broad range of options, can accelerate the development and deployment of novel and unproven technologies. This **concentration of resources and identification of complementarities reduces uncertainty** surrounding new technologies and enhances the spread of related knowledge and experience.

The utilisation of policy mixes that incorporate a combination of command-and-control and market-based instruments can be likened to kicks that yield positive outcomes for the transition to a net-zero carbon economy (Robalino and Lempert, 2000). Recent advancements in modelling have demonstrated that these policy combinations have the potential to initiate a virtuous cycle, driving technological development, reducing the overall need for public investment, and simultaneously stimulating employment and economic growth (Wieners et al., 2023; Lamperti et al., 2020; Lamperti and Roventini, 2022; Stern and Stiglitz, 2023). Moreover, such positive feedback loops significantly lessen the reliance on carbon taxes by decreasing their intensity. As a result, this enhances their political acceptability and potentially triggers another tipping element.

4.4.3.4 Accelerating renewables investment in the Global South

While issues related to finance are central for the Global South in the face of climate change, these countries are essentially ignored by 'sustainable finance' due to the limited role of financial markets in their economies. **In developing economies, policy support can help to overcome climate investment traps due to high costs of accessing finance** (Ameli et al., 2021).

Financial constraints, including underdeveloped capital markets and limited capital stock, prevent these countries from obtaining sufficient funds for low-carbon investments. This creates a self-reinforcing cycle where high risk-perceptions lead to increased capital costs, delaying the transition to cleaner energy systems and carbon emission reductions. Climate change impacts exacerbate the situation, causing adverse impacts on production systems, economic output, unemployment, and political stability (figure 4.4.6).

To address this challenge, a reinforcing feedback cycle has the potential to function in the opposite (desirable) direction with the right changes in action. For instance, appropriate policies that reduce capital costs can act as tipping elements in facilitating the low-carbon transition. Measures like credit guarantee schemes can shift risk away from private investors, resulting in lower capital costs. This would enable developing economies to achieve higher levels of low-carbon electricity deployment and faster emissions reduction in the order of a decade earlier than without such reductions (Ameli et al., 2021).

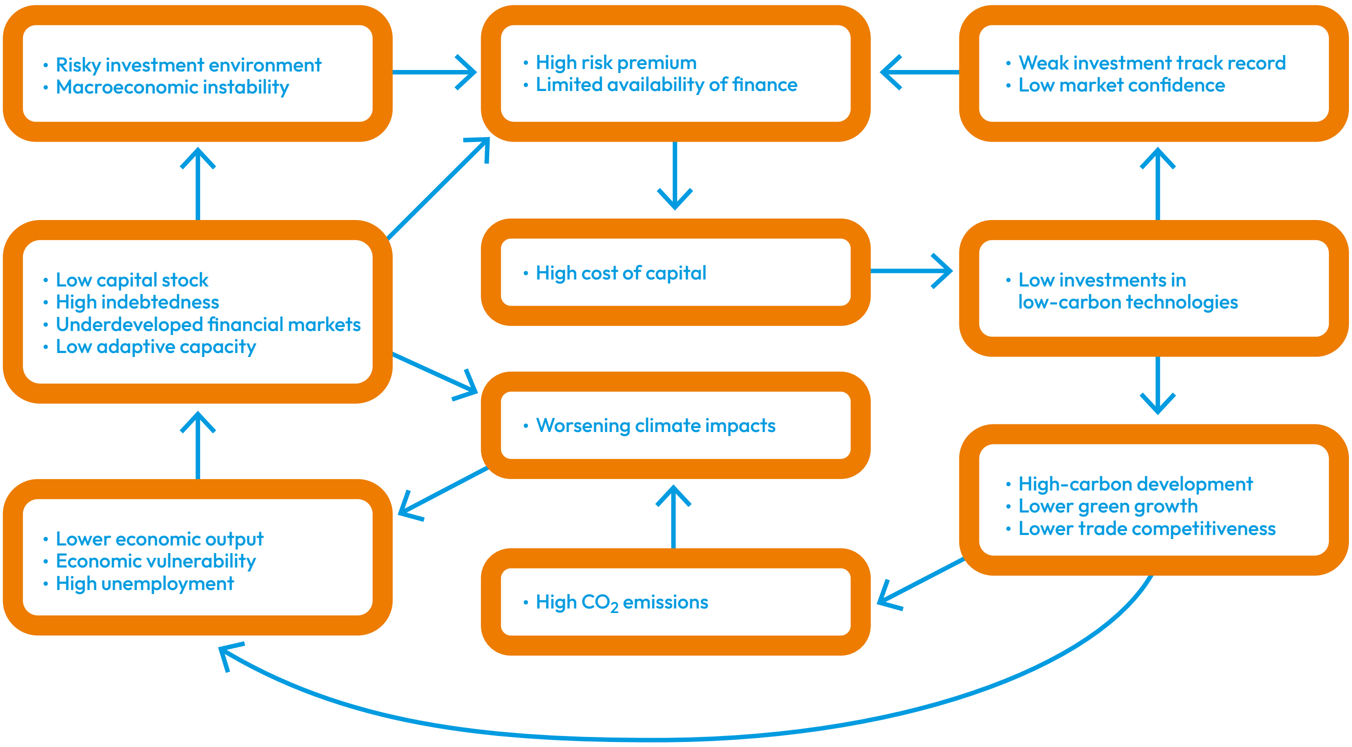
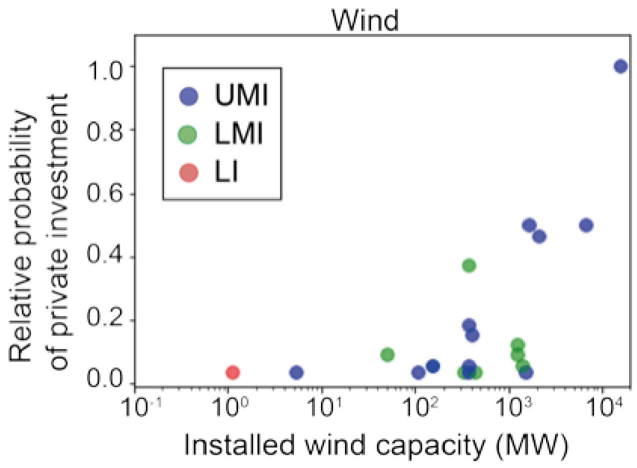


Figure 4.4.6: The figure shows the set of self-reinforcing mechanisms and feedback loops occurring in developing economies characterised by the high cost of capital and limited track records in renewable investments. The strength of these links is strongly linked to local conditions implying that the set of self-reinforcing mechanisms could be exacerbated (or less relevant) in some economies.

Additionally, the flow of international capital into renewable projects in developing countries is influenced by path-dependency, creating a tipping element in the scaling up of renewable investments (Rickman et al., 2023a). Countries with a track record of renewable investments are more likely to attract future investments, leading to positive feedback loops within renewable energy markets (Figure 4.4.6). As countries build a track record in renewables, market confidence grows, bringing down financing costs and attracting further investments in a virtuous cycle. Indeed, there is a nonlinear relationship between the probability of private investment and a country's track record in renewables (Rickman et al., 2023a).

Once a significant capacity base of around 1GW (of wind or solar) is installed, a tipping point is reached and the attractiveness of a market for new investment increases sharply (Figure 4.4.7). However, this also results in an 'investment lock-in, where historical inequalities in financing across countries and income groups persist over time. To escape this investment lock-in, **developing countries must mobilise sustained investment to build a renewables track record that can attract private finance at scale**. Low-income developing countries often fall below this threshold, highlighting the need for sustained investment in holistic energy roadmaps to unlock private finance. Innovative financial and policy mechanisms that target the evolution of a renewables sector can initiate path-dependent flows from private sources and leverage tipping elements in the renewable finance ecosystem.



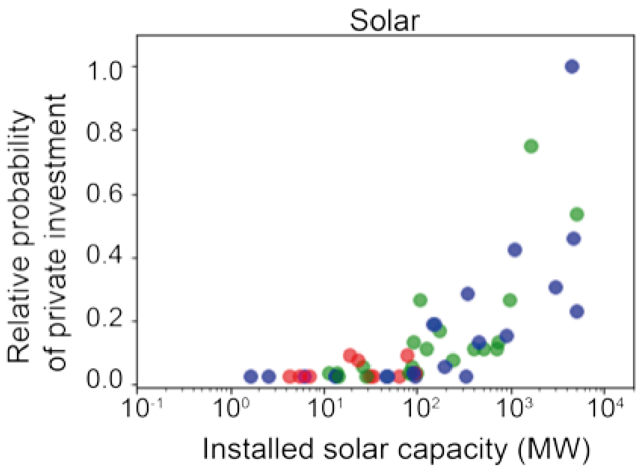


Figure 4.4.7: Empirical relationship between relative probability of private investment and installed wind and solar capacity (Rickman et al., 2023a). Plots show the relative probability of private investment for each country in the post-Paris Agreement period against installed capacity as of 2019, using IEA statistics. Probabilities are normalised against the country with the highest probability of private investment (wind: Brazil, solar: Mexico). Upper middle income (UMI), lower middle income (LMI) and low income (LI).

4.4.3.5 Tipping points in financing of fossil fuels

Over the last decade, the notions of **carbon bubble** and **stranded assets** have been at the core of the attention of financial institutions involved in the fossil fuel sector. Additionally, theoretical modelling reveals tipping elements in the global network of banks which supply debt to the fossil fuel industry (Rickman et al., 2023b). While fossil fuel debt markets are resilient to the unregulated phase-out of capital, the introduction of capital requirements rules (e.g. setting limits on banks' fossil fuel investments based on their capital reserves) can trigger a rapid contraction of fossil fuel debt flows.

The tipping point depends on the stringency of rules and can be reached sooner if large banks lead the phase-out. Appropriate capital requirements rules, developed by standard-setting bodies and regulators, can facilitate a managed and smooth decline in fossil fuel lending. Banks should also coordinate transition plans through alliances like the Net Zero Banking Alliance to enhance their collective impact on debt markets.

4.4.4. Digitalisation

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Summary

Digital technologies have the potential to support decarbonisation and promote positive tipping points (PTPs)in all sectors and countries. Digitalisation has many possible applications that can accelerate socio-economic transformations towards a post-carbon, regenerative society. Taking three examples from earlier sector analyses – teleworking, Mobility-as-a-Service (MaaS) and smart homes – we show that establishing supportive systemic structures and action to limit rebound effects are needed to harness the positive impact potential of digital technologies. These systemic structures rely on targeted regulations and public policy to establish enabling conditions and avoid the risk of unsustainable impacts. Digital technologies can act as **multipliers of change** because they can unlock and promote broader economic and social benefits alongside efficiency gains.

Key messages

- Digital technologies are already helping enable positive tipping points for renewable electricity and light road transport – they push energy efficiency, enable an electricity system anchored on renewable electricity and allow much higher asset utilisation – and they are likely to be part of prospective positive tipping points in other sectors.
- Given their pervasive and disruptive nature, digital technologies have the potential to be **leverage points**, promoting positive tipping in all sectors, as well as **super-leverage points**, capable of catalysing tipping cascades across multiple sectors and promoting the creation of inclusive economies and societies characterised by high wellbeing.
- Policies are needed to **govern** the digital revolution, with the aim of harnessing the potential enabling role of digital technologies with respect to positive tipping points and cascades towards climate mitigation, and more broadly to sustainable development.

Recommendations

- Use a public policy framework that prohibits or limits environmental degradation while promoting the purposeful use of digital technologies as an enabler of positive tipping points and positive tipping cascades.
- Implement rules and regulations to ensure that the benefits of digitalisation do not accrue to specific parts of societies, or to specific countries, but are diffused and used to harness their mitigation potential in key sectors across user groups.
- The public sector needs to invest in capacity building, including the development of skills for the purposeful use of digital technology and the granting of access to the appropriate digital hardware, software and infrastructure,
- A culture of sustainability and purposeful action needs to be established.

4.4.4.1 Introduction

The digital revolution describes the major restructuring of all domains of social life and of the economy as firms and consumers take advantage of new digital technologies – i.e. ubiquitous connected consumer devices such as mobile phones (Grubler et al.,2018), global internet infrastructure and access (World Bank, 2014), computing devices, sensors and digital communication technologies (Verma et al., 2020). Digital technologies have extraordinary enabling powers: they provide access to information, contribute to forming preferences, modify demand choices, and change the way in which goods and services are provided and accessed (IEA 2017, Nakicenovic et al., 2018).

This subchapter discusses the enabling role that digital technologies and devices can play in the context of PTPs (Lenton et al., 2022). Addressing this topic is important given the lively debate on whether the digital revolution will contribute to the achievement of a low-carbon, sustainable future or whether the rapid diffusion of digital technologies will simply exacerbate existing economic and social inequalities both within and across countries (Nakicenovic et al., 2018; Nature, 2020). Indeed, the 'twin green and digital transformation' is increasingly referred to as a challenge of unprecedented breadth and depth, scale and speed (European Commission 2020; IPCC, 2022; Shukla et al., 2022; Verdolini, 2023).

Digitalisation has myriad possible applications that can be utilised to accelerate socio-economic transformations towards a post-carbon, regenerative society and we cannot cover all possible benefits. We focus on three specific examples: teleworking, MaaS and smart homes, given their relevance for the case studies presented in 4.3.1 and 4.3.2.3.

4.4.4.2 Conceptual underpinnings

Digital technologies have the potential to play two distinct positive roles in the context of the climate and sustainability transitions: they can act as enablers and multipliers of change. **Digital technologies** are **enablers of change** because they underpin the development of the next generation of large-scale, distributed, coordinated, renewable and smart systems by providing sophisticated techniques for controlling, monitoring, managing, optimising and balancing electricity supply and demand (see for instance IEA, 2017; Kangas et al., 2021; Giotitsas et al., 2022). They also contribute to energy efficiency, support energy demand management, promote platform-based sharing economies, and, in a more general sense, enable virtualisation and servitisation, with associated reductions in material inputs (Grubler et al.,2018; Royal Society, 2020; GESI, 2022).

In addition, digital technologies act as **multipliers of change** because they can unlock and promote broader economic and social benefits alongside-energy efficiency gains (Xu et al., 2022). These are often referred to as co-benefits of the energy transition. For instance, digital technologies increase the ability to access products and services, they increase competitiveness and go hand in hand with the up-skilling of the labour force, and the improvement of the quality of jobs. Xu et al. (2022), for instance, find human capital accumulation (measured in terms of educational attainment) as one of the mechanisms by which digitalisation helps reduce energy demand. Digital technologies also enable transformative agency through increased and improved coordination and the creation of digital spaces for action and interaction.

Given their pervasive and disruptive nature, digital technologies ave the potential to be used as strategic interventions or leverage points to enable positive tipping in all sectors as well as super-leverage points capable of catalysing tipping cascades across multiple sectors and promote the creation of inclusive economies and societies characterised by high wellbeing.

In this context, ensuring democratic access to knowledge systems and digital technologies, distributing rents from these knowledge systems fairly, and establishing a governance framework within which digital technologies can contribute to the public good, are strategic interventions to ensure that digitalisation can play its roles of enabler and multiplier of change and that its potential as a leverage point promoting **domain-specific PTPs** can unfold (Box 4.4.2).

Box 4.4.2. Potential risks of digital technologies for sustainable change

While digitalisation can enable positive sustainable change, an increasingly rich literature illustrates how digital technologies can also create significant risks for it (Creutzig et al., 2022; Verdolini, 2023). First, they themselves are energy-intensive and may contribute to increasing energy demand (Freitag et al., 2022). Indeed, the evidence on the energy efficiency (and low demand) potential resulting from digitalisation presents mixed results. Some studies, e.g. Li et al., 2023, show an inverse linear relationship as a function of income (GDP): lower-income countries benefit more in terms of improved energy intensity or reduced energy demand because digitalisation helps avoid or leapfrog existing inefficiencies.

Conversely, other studies (e.g. Xu et al., 2022) show a U-shaped relationship describing how lower and higher-income countries benefit more in terms of efficiency gains, while middle-income countries benefit less. In the latter, scale effects appear to outweigh efficiency gains. Second, they require an increasingly diverse set of material resources (such as rare earth elements) which are sometimes/often sourced from developing countries through unfair labour practices and which later turn into large piles of digital waste. Third, they can be used to increase social and behavioural control and to promote new consumption practices which put further strain on the Earth's resources. Fourth, their wider societal co-benefits do not necessarily accrue equally across countries, regions and sectors: they often are concentrated within the wealthiest individuals in the wealthiest economies.

The costs associated with digital technologies in terms of materials and digital waste weigh more on poorer countries (Creutzig et al., 2022). Digitalisation, and in particular AI, is accelerating the spread of misinformation and leads to further concentration of (economic) power by monopolising information and knowledge systems (Galaz et al., 2023). Misinformation and the concentration of power create conditions in which mistrust of dominant actors spreads to governance institutions more broadly. This set of factors, in turn, may erode support for stringent climate policies whose effective implementation depends on social consensus, too, hinders action for sustainability (2.3).

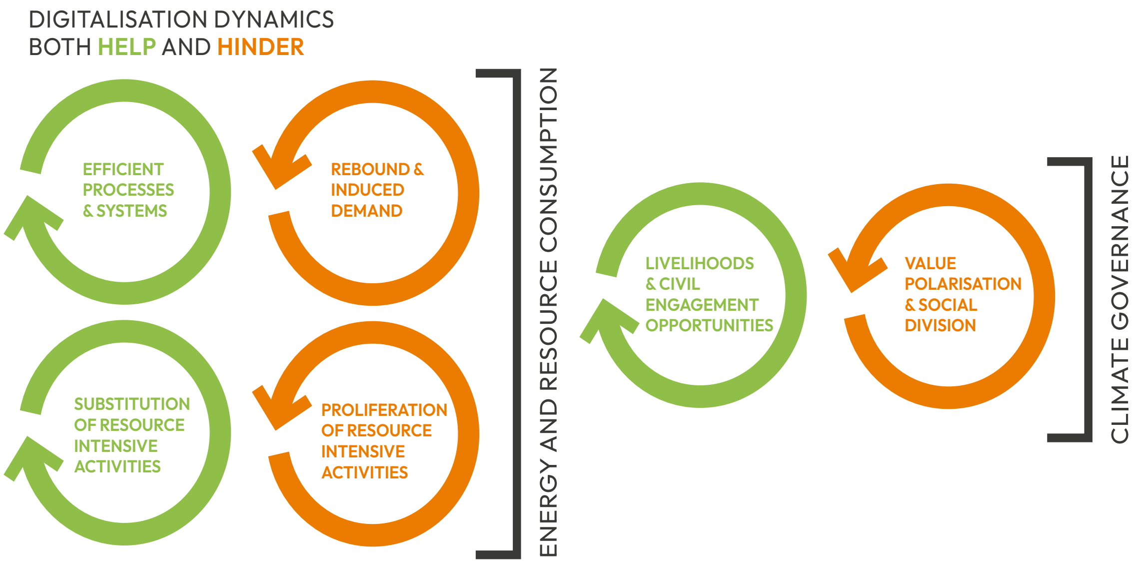

Figure 4.4.8: Illustrative representation of digitalisation impacts on resource use (left panel) and on governance institutions (right panel).

We present here illustrative examples of the transformative potential of digital technologies as enablers of PTPs on the basis of the **avoid, shift, improve framework** (Creutzig et al., 2022) in relation to teleworking, MaaS and smart homes.

4.4.4.3 Digital technologies and avoid options: Teleworking

Recent analysis, spurred by the forced use of telework during the COVID-19 pandemic, explores the potential emission reductions linked with remote working thanks to the availability of ICT and digital technologies such as computers, cloud services, and remote access to networks. Teleworking not only changes how people commute to work but also how and where they travel for their other everyday business (Bohman et al., 2021; Elldér, 2020). For workers, teleworking represents a chance for higher flexibility and autonomy and improved work/life balance; for employers, it often leads to reduced costs and increased employee productivity (European Parliament, 2021). At societal level, it is worth exploring how telework can be designed as an intervention within a policy package to successfully transform currently unsustainable transportation systems into sustainable ones that **avoid** GHG emissions and other impacts.

There is increasing evidence that teleworking affects both carbon emissions and spatial development (European Parliament, 2021). For the specific case of Austria, Heinfellner et al., (2020) argue that about 40 per cent of the workforce could potentially resort to telework, leading to about 1.4 per cent reduction in Austria's GHG emissions from passenger transport, net of rebound effects. Analysing data on the desirability of telework from a survey and through a focus group in a case study for Austria, Maier et al., (2022) conclude that telework might function as a potential positive tipping intervention to move passenger transport on to a low-carbon trajectory. The surveyed respondents showed high willingness to engage in telework and accept various incentives that support low-carbon mobility (personal agency).

However, only with attractive framework conditions (societal agency) will this personal willingness lead to tangible emission reductions. Key reinforcing feedbacks of teleworking as part of a broader tipping point to a lower-mobility paradigm go beyond the direct positive environmental impacts due to a decrease in traffic congestion and carbon emissions, and include (1) improving the mental wellbeing of workers by sparing them the stress of long journeys to and from work, (2) commuting time and travel costs savings and (3) long-lasting impact on the spatial distribution of work and economic activities away from city centres, to the benefit of peripheral geographical locations (e.g. suburbs) (European Parliament, 2021). This, in turn, would make working and living in peripheral areas more attractive and reduce pressure and environmental impacts associated with commuting and life in cities.

Yet, realising the full transformative potential of teleworking is conditional on the availability of digital work equipment (e.g. laptop, monitor, printer) and appropriate home office space, as well as access to a fast and stable internet connection and the ability to securely access documentation through either intranet or cloud services. For people to not only switch to teleworking but also transition to sustainable transportation modes, there is a need to establish supportive systemic structures. Telework should not be viewed as an isolated measure; it can unlock its full potential as a transformative intervention when integrated into a comprehensive policy package that includes incentives for low-carbon mobility.

Beneficial outcomes of telework for energy demand and GHG emissions are not a given. A systematic review of 39 pre-pandemic telework studies found evidence of increases in both non-work travel and home energy use (Hook et al., 2020). The telework PTP therefore requires ancillary action to limit rebound effects (more motorised travel, additional leisure travel) for example through higher fuel taxes and better parking management (Ceccato et al., 2022). In the longer term, teleworking may have an uncertain systemic effect on housing preferences, real estate markets, and (de)urbanisation should teleworkers seek to move out of cities and into larger homes.

Workers lacking access to appropriate digital devices, services and skills, as well as suitable domestic conditions, will have lower willingness or capacity to engage in telework practices, preventing the achievement of a PTP. Tackling the digital divide in its various forms therefore represents a sensitive intervention point to fully capitalise on the enabling potential of digital technologies supporting teleworking.

4.4.4.4 Digital technologies and shift options: Mobility-as-a-Service

Digital technologies underpin the diffusion of MaaS, namely the supply of a range of mobility services through a single digital customer interface. MaaS integrates different transport, information and payment services into a smooth and reliable customer experience. It can include traditional public transport, car, scooter or bike sharing and demand-responsive modes, allowing multi-modal, door-to-door travel using a single platform and potentially replacing the need for vehicle ownership (e.g. car, motorcycle, bicycle or scooter). MaaS therefore allows consumers to **shift** between different mobility options and, importantly, away from carbon-intensive options towards more sustainable modes of transportation, including public transport, active travel, micro-mobility and shared modes (OECD/ITF, 2020; Kamargianni et al., 2016).

MaaS is an emerging framework of transport systems. Several test cases can be found in Helsinki with an application called Whim developed by MaaS Global, which allows planning and using a cab, metro, light rail, bus, car or bicycle and paying with a QR code. In Vienna, the Wien Mobil app integrates public transportation, self-service bicycles, car-sharing, cabs, scooters and parking lots. In Djakarta, a case study demonstrated that shared motorcycle services improve mobility, but not GHG emissions (Suatmadi et al., 2019). Payment for public transport can be done in the application, yet there is no integrated multimodal fare between different operators in the platform. Similarly, Hannover developed an application called Mobility Shop, which provides access to public transport, car-sharing and cabs. The app assists with trip planning, and all mobility is paid with a monthly invoice automatically debited from a user's bank account.

The achievement of PTP's in the context of MaaS is linked to whole-system adoption, particularly in the context of moving towards less carbon-intensive modes, including micro-mobility and ridesharing efficiency. The value and utility of MaaS increases with its penetration rate. On the one hand, as more travellers resort to it, the value of using MaaS will increase for all users. In addition, it would also enhance non-user motivation to explore MaaS.

The high mitigation potential of MaaS in the transportation sector fundamentally depends on the ability of digital applications to reduce frictions and promote coordination. MaaS can reduce transport CO_2 emissions by encouraging modal shifts and changing vehicle ownership patterns.

Nevertheless, the results may only be limited once this model is sufficiently implemented to change lifestyles and social norms. Leveraging the benefits of MaaS options requires limiting rebound effects and problematic inefficient solutions by regulations and public policy (Creutzig et al., 2019). Some evidence of short-term impacts for partially implemented systems were assessed by the project MAASiFiE, showing a reduction of eight and a half per cent in emissions due to less car use and some promoted shift to other modes. Other co-benefits are the efficiency, affordability and accessibility for citizens.

The widespread development of MaaS hinges on the availability and reliability of digital devices and interfaces: providers need to be able to access integrated platforms under suitable rules governing competition, pricing and service provision; users need the ability to access requisite digital technologies and skills. Legislative, commercial, governance and technological changes are likely needed to establish MaaS successfully. Several organisational models for a MaaS market involve varying levels of involvement by public authorities.

Similar to the telework case, it therefore requires a public policy framework that both favours new MaaS options, directs outcomes towards public purpose (e.g. lower congestion and GHG emissions), ensures MaaS supports rather than cannibalises public transport, and also limits private motorised transport. MaaS PTP could be a central enabler of a wider strategy to dislodge the private car as the dominant and preferred mobility option, particularly in urban contexts. Resulting societal benefits could be large, but the transformation is socially and politically difficult.

4.4.4.5 Digital technologies and improve options: Smart homes

In smart homes, information and communication technologies (ICTs) are distributed throughout rooms, devices and systems (lighting, heating, energy management); they relay information to users and feed back users' or automated commands to manage the domestic environment (Wilson et al., 2020). Smart homes and smart devices play an important role in demand-side mitigation options: they are the end-use node of the smart energy system that allows consumers to **improve** the use of energy as well as utilities to respond to real-time flows of information on energy demand fed back by smart metres from millions of homes (Hargreaves and Wilson, 2017; Baydia et al., 2021). Thanks to digital devices and technologies, measures aimed at influencing habits through information provision and feedback on energy consumption can in theory result in substantial household energy savings (Jensen et al., 2016; Malmodin and Coroama, 2016; Nilsson et al., 2018). Notwithstanding this high potential, demonstrated energy savings from the limited number of studies on this topic appears to be relatively small but significant (BIT, 2017, Khanna et al., 2022). In the UK, for instance, data from a large-scale trial of smart metres and in-home displays in the UK demonstrated around three per cent energy reductions on average (AECOM, 2011). Potential savings (or 'shaving') during peak times can be more pronounced (Pratt and Erickson, 2020), particularly if linked in-home displays communicating usage and cost information to end-users enable utilities to charge for electricity at its marginal cost, providing a price signal to shift or curtail demand when supply is expensive or in short supply (Srivastava et al., 2018). Yet, households' appetite or capacity for reducing energy bills in response to information feedback and price incentives appears limited, and interest in information and price signals rapidly wears off and is subject to rebound effects that offset demand reductions (Azarova et al., 2020).

Embedding digital technologies and devices in homes turns them from 'passive' (i.e. non-responsive to network needs) end-user nodes in hub-to-spoke energy networks to 'active' (responsive, flexible and integrated) nodes in distributed energy networks. This switch supports the achievement of PTP's in the energy system, as it integrates significantly more renewable energy and faces increased challenges due to widespread electrification of all sectors and activities. This shift is enabled by digitalisation in the domestic environment, with emerging potential for AI applications to help accelerate positive trends (towards informed energy management without required user interventions, and control over distributed end-use, storage and generation resources throughout the building stock).

4.4.4.6 Other domains where digital technologies can enable positive tipping

The three specific applications discussed so far illustrate how digital technologies can enable PTPs and act as multipliers of societal change in the context of the ASI framework. Importantly, digitalisation has myriad possible applications that can be utilised to accelerate socio-economic transformations towards a post-carbon, regenerative society. Indeed, similar dynamics to those described above could be discussed with respect to other sectors and applications. For instance, digital technologies can contribute to avoiding food waste (4.3.4) and improving sustainable consumer practices in the food sector e.g. through digital provenance systems and blockchain-based certification. They can also avoid unnecessary energy demand (Wilson et al., 2020, also 4.3.2), promote pro-environmental behaviours as well as improved practices at the level of urban planning (Milojevic-Dupont and Creutzig, 2021) and favour asset sharing in freight transport (Box 4.3.4.). In the supply side of the energy sector, digital technologies are necessary for the large-scale deployment of smart grids and the integration of prosumers – that is, actors that both consume and produce energy. Other instances in which digital technologies could enable PTPs include:

- **Augmented democracy**, where digitalisation can facilitate inclusive, democratic and yet expert-informed political decision making from local to global (Satorras et al., 2020; Wellings et al., 2023; Nisbett et al. 2022);
- **Carbon/ecological footprint tracking** for individuals, organisations and companies, potentially linked to bank accounts and potentially augmented with conversational AI (Nerini et al., 2021; Wemyss et al., 2023; Nisbett and Spaiser 2023);
- **Digital twins simulations** for sustainable city planning, traffic monitoring systems, manufacturing, green transition planning, etc. (Xia et al., 2022; Bauer et al., 2021).

More generally, advances in digitalisation and AI can enhance our abilities to automate and optimise processes – e.g. coupling production processes such as green hydrogen production to fluctuating renewable energy production processes (Yang et al., 2022). The new generation of large-scale language models (LLMs, which underpin services like ChatGPT), combined with a human loop training iteration, can produce question-specific knowledge to citizens, starting from a curated compilation of the existing literature on planetary health and climate change (Debnath et al., 2023).

4.4.4.7 Strategic interventions

Digital technologies, devices and applications have the potential to support decarbonisation (Blanco et al., 2022) and promote PTPs in all sectors and countries. Yet, this enabling role does not arise independently. Strategic interventions can ensure that digitalisation becomes an enabler for, rather than a barrier to, sustainable change. Importantly, two types of strategies and policies are relevant in this respect. On the one hand, **framework policies need to ensure the social steering of digitalisation** so that its agenda is aligned with that of climate mitigation and more broadly to sustainable development. Second, **specific policies need to be tailored to respond to heterogenous challenges** across sectors as well as within and across countries. A specific challenge common across many sectors is efficiency-induced scale and rebound effects that increase overall levels of consumption if digitalisation makes accessing goods and services cheaper, easier, quicker or more convenient. Such scale and rebound effects would need to be recognised and appropriately dealt with in comprehensive climate policy packages.

4.4.5 Detecting 'early opportunity indicators' for positive tipping points

Authors: Joshua E. Buxton, Chris A. Boulton

Summary

Statistical signals that could provide early warning of Earth system tipping points may also be detectable for positive tipping points. Identifying such signals in key indicators for target systems could provide early indication of opportunities for (for example) policy intervention to accelerate tipping when the resilience of an incumbent system is weakening. They could also be used to monitor the impact of past or future interventions. Because positive tipping points (PTPs) involve complex interactions across different domains of society, it may be useful to assess multiple indicators spanning these dimensions. A case study in electric vehicles (EVs) demonstrates that 'early opportunity indicators' (EOIs) can be detected in market share of internal combustion engine vehicles (ICEVs) as they approach a tipping
point and lose majority market share to EVs. Similar signals can be observed in public interest in EVs, as expressed through advertisement views online.

Key messages

- 'Early opportunity indicators' in key variables can be detected for some positive tipping points.
- This approach could enhance opportunities for intervention to accelerate positive tipping points, or could be used to assess the impact of previous measures.

Recommendations

- Greater focus should be given to identifying potential early opportunity indicators in a range of sociotechnical and other systems that may be important targets for positive tipping points.
- Where possible, variables for EOIs should be chosen that represent more than one dimension of systemic change, for example by assessing sales data and public sentiment in parallel.

4.4.5.1 Predicting tipping points

In some circumstances, tipping points in climate and ecological systems may be preceded by specific statistical signals, termed **early warning signals** (EWS) (see Chapter 1.6). These provide some indication that a system is losing resilience and a self-propelling transition may be approaching. Chapter 2.5 discusses where these EWS may be applied to negative social-ecological tipping points, and here we expand upon this by considering how they may relate to **positive social tipping points** and illustrate this with a case study of the EV transition.

EWS are often observable as a consequence of **critical slowing down** (CSD), which occurs in a system as it loses resilience before a tipping point. When a resilient system with strong restorative feedbacks experiences some perturbation, it will return quickly to its equilibrium state (i.e. a healthy forest recovering from a drought). However, as the system loses resilience, these restorative feedbacks weaken, and the system takes longer to return to equilibrium following a shock. This changing response can be measured to indicate the system's resilience, by measuring the declining return rate (Wissel, 1984). This change can also be measured over time with an increase in the lag-1 autocorrelation (AR(1)), in addition to an expected increase in variance prior to a tipping point (see Chapters 1.6 and 2.5 for further details of this method and other EWS).

While measuring EWS with empirical data is most common in ecological and climate systems, it is not exclusive to these domains and a number of studies have applied this approach to alternate systems, such as health, economics and online social discourse (Dakos et al., 2023). In health sciences, attempts have been made to identify generic EWS prior to disease re-emergence (Proverbio et al., 2022). Several studies have attempted to detect EWS prior to economic shock events, with varying levels of success (Tan et al., 2014; Diks et al., 2019; Wen et al., 2018; See Chapter 2.5). Social media data has also been employed to detect EWS before transitions in online discourse (Pananos et al., 2017) and could be applied to online radicalisation (see Chapter 2.5). These studies often focus on negative shocks, where the shift occurring is to a less desirable alternate state, but it is also possible that these statistical indicators may be present prior to a rapid transition to a more desirable state.

As discussed in the rest of Section 4, positive tipping points may occur in different elements of social systems and across different nested scales. For example, in socio-technical systems, development of a technology may have positive feedback loops which allow it to scale rapidly, reduce in cost and improve in quality: thus becoming more accessible (Sharpe and Lenton, 2021; Farmer and Lafond, 2016; Lam and Mercure, 2022). Rapid changes in social behaviour or perspective may be required to enable this transition. In these complex systems it is likely that **social and technical change will be interlinked**, with each affecting the other. Consequently, for some systems it may be possible to measure changes in resilience within the social sub-system and in the technical or ecological sub-system. There are also likely to be **exogenous shocks** due to policy decisions or external economic factors which will show up in the system and may enable us to measure some element of its resilience. We sketch out these intersecting feedback loops as they may apply to the EV transition in Figure 4.4.8.

There are therefore two potential ways that we might measure the resilience of social systems; i) the **return rate** from a known perturbation or event or ii) the long-term **changes in the resilience** from a longer-term forcing on the system, which can be measured with AR(1). These approaches could be applied to multiple elements or indicators of these systems, either to detect **decreasing** resilience of an incumbent system, or to detect **increasing** resilience in a new, positive social or technological innovation. Here we refer to these indicators as EOIs.

4.4.5.2 Case study: Detecting early opportunity signals indicators in the electric vehicle transition

The transition to EVs has been widely discussed as approaching a tipping point in some countries, and having passed one in others (Meldrum et al,. 2023, see 4.3.2.2). By analysing sales data of EVs (including battery electric vehicles (BEVs) and hybrid electric vehicles (HEVs)), and internal-combustion engine vehicles (ICEVs), we can attempt to detect this transition by measuring the resilience of markets for both the incumbent and the new technology. The EV transition involves strong feedbacks between technological development that makes EVs more affordable, accessible and attractive, and changes in the social domain, including public interest in and perception of EVs (Figure 4.4.8). To understand this social dimension of the transition, we also consider the frequency with which people view EVs in the UK on AutoTrader, an online marketplace site (Boulton et al., 2023).

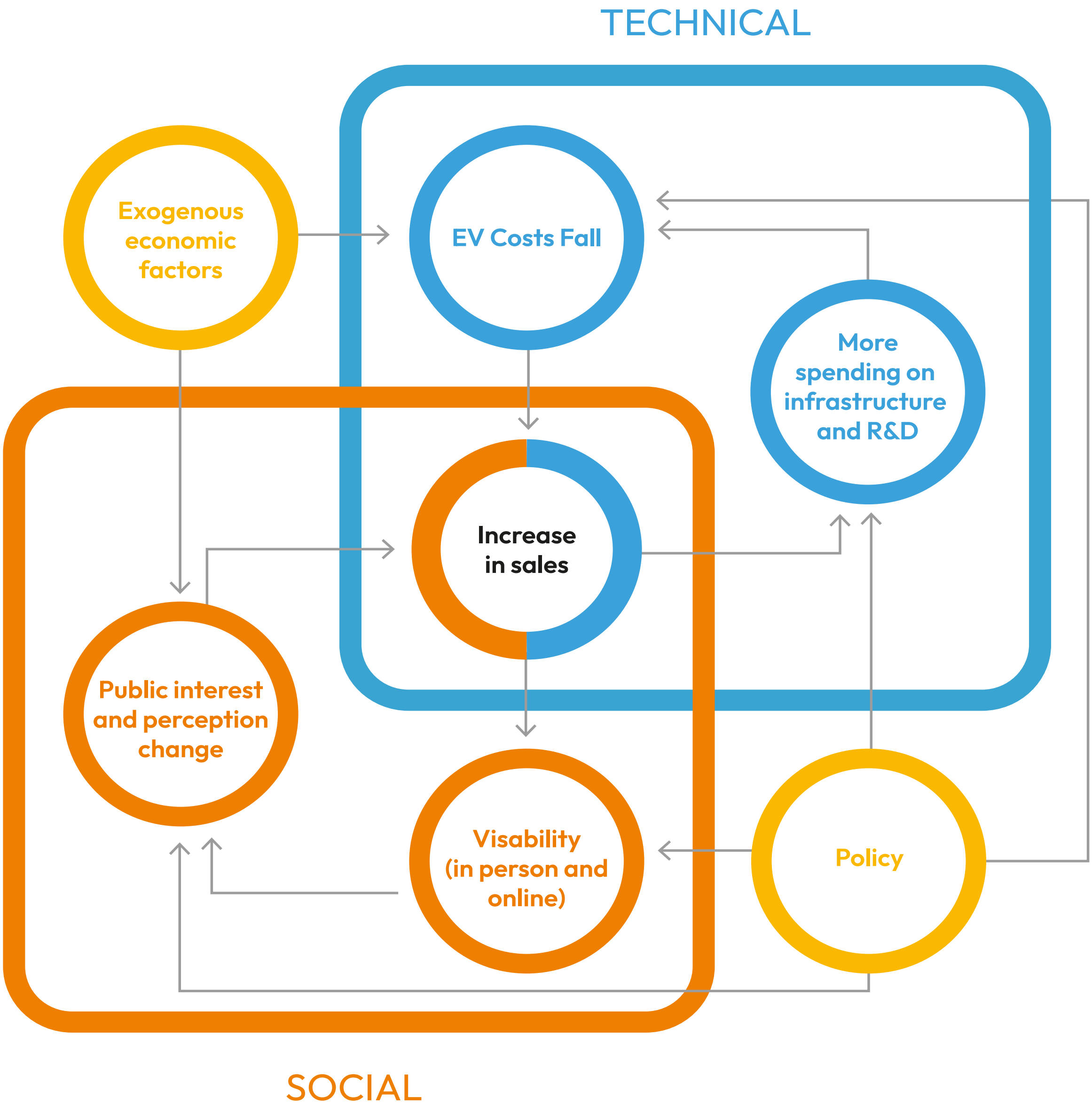

Figure 4.4.9: Simplified causal feedback loop of how the technical and social elements may interact within the EV transition.

Can we measure the resilience of the automotive industry?

If we consider the automotive industry as a complex system, consisting of an interconnected ecosystem of, among other things, production, sales and public preference and needs, then the question arises of whether we can measure the resilience of this system in a comparable way to a 'natural' ecosystem, such as a rainforest.

While numerous factors might affect the stability of this system, such as supply chain resilience, one simple metric is to consider the sales of vehicles. This can be affected by economic shocks, and recovery from shocks could provide an indication of the resilience of this system.

One such event is the 2008 financial crisis which, among other impacts, caused a rapid decline in vehicle sales across many major markets (Figure 4.4.9). For Denmark and the US, this perturbation caused an initial sharp decline in sales, which then recovered over subsequent years. The faster recovery rate of sales in Denmark suggests a more resilient market (and wider economy) than that of the US. Car sales in Greece also suffered because of the wider economic crisis caused by the 2008 financial crisis, and here there is no observable return, with the system tipping into an apparently alternate stable state of very low car sales; thus suggesting very little resilience prior to 2008. The effect of government intervention to support the automotive industry as a significant employer can be seen in Germany, where incentives provided a boost to sales in 2009. A similar scheme in the US resulted in a brief spike in sales that same year, however true recovery took longer, again suggesting lower resilience.

While this approach does not delve deeply into the underlying structure of the automotive industry and the fact that the 2008 financial crisis occurred as a different perturbation in different economies, it illustrates an approach to applying concepts of resilience from the natural sciences to broader socio-economic questions.

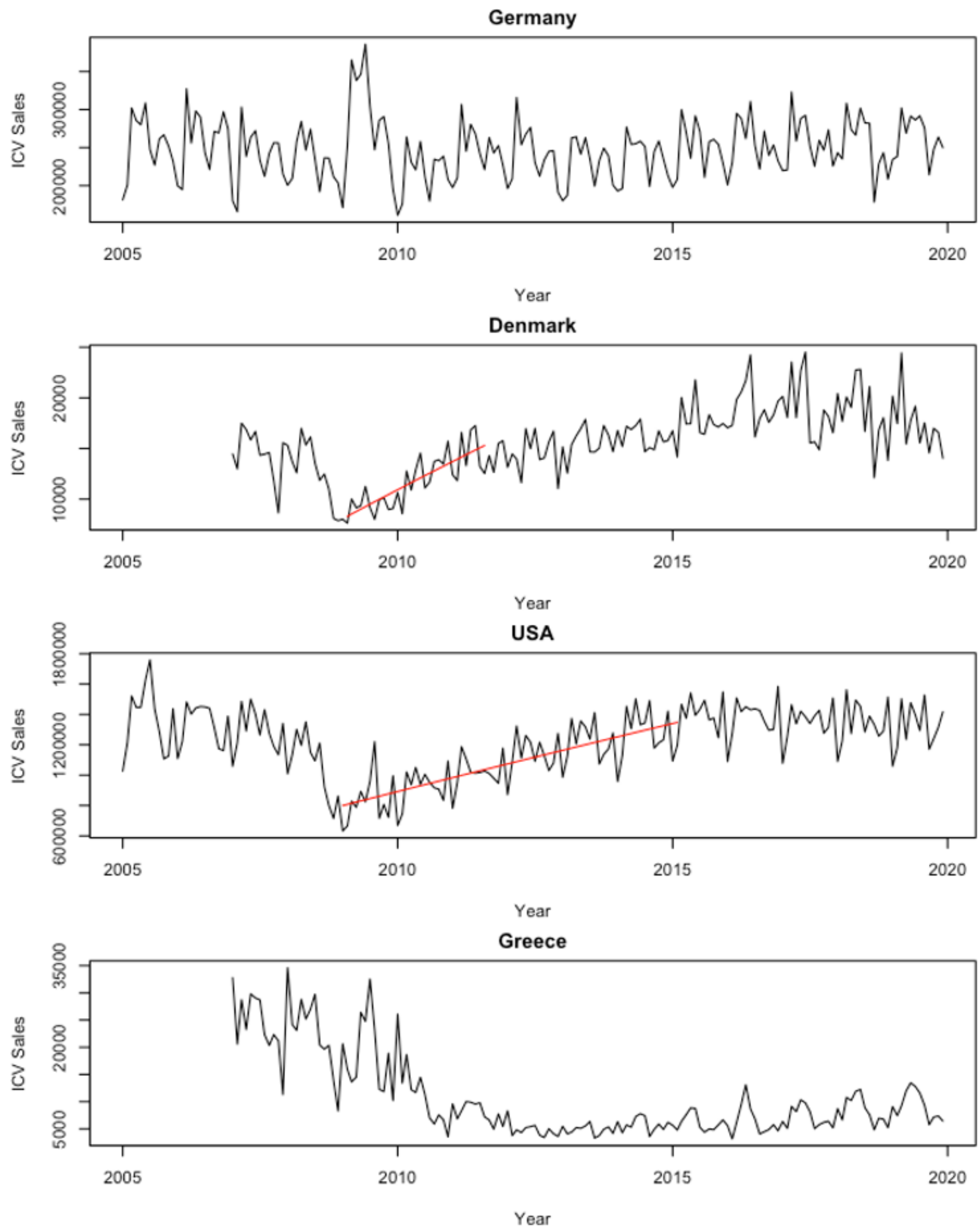

Figure 4.4.10: Sales of automotive vehicles in Germany, Denmark, US and Greece. Red lines in Denmark and USA show recovery from perturbation caused by the 2008 financial crisis. Data unavailable for Denmark and Greece prior to 2007.

4.4.5.3 Resilience change prior to the EV transition tipping point

To understand the changing resilience of the incumbent, ICEV-dominated, system prior to an EV tipping point, we can use the same approach to analyse **market share**, rather than total sales of ICEVs. In the UK, France, Germany and China, the market share underwent a gradual change from January 2009 to December 2019, with ICEVs losing ground, prior to a dramatic and abrupt change in 2020 caused by a surge in sales of EVs and PHEVs (Figure. 4.4.10). Conversely, the US has not yet experienced abrupt change, with ICEVs still accounting for the majority of sales.

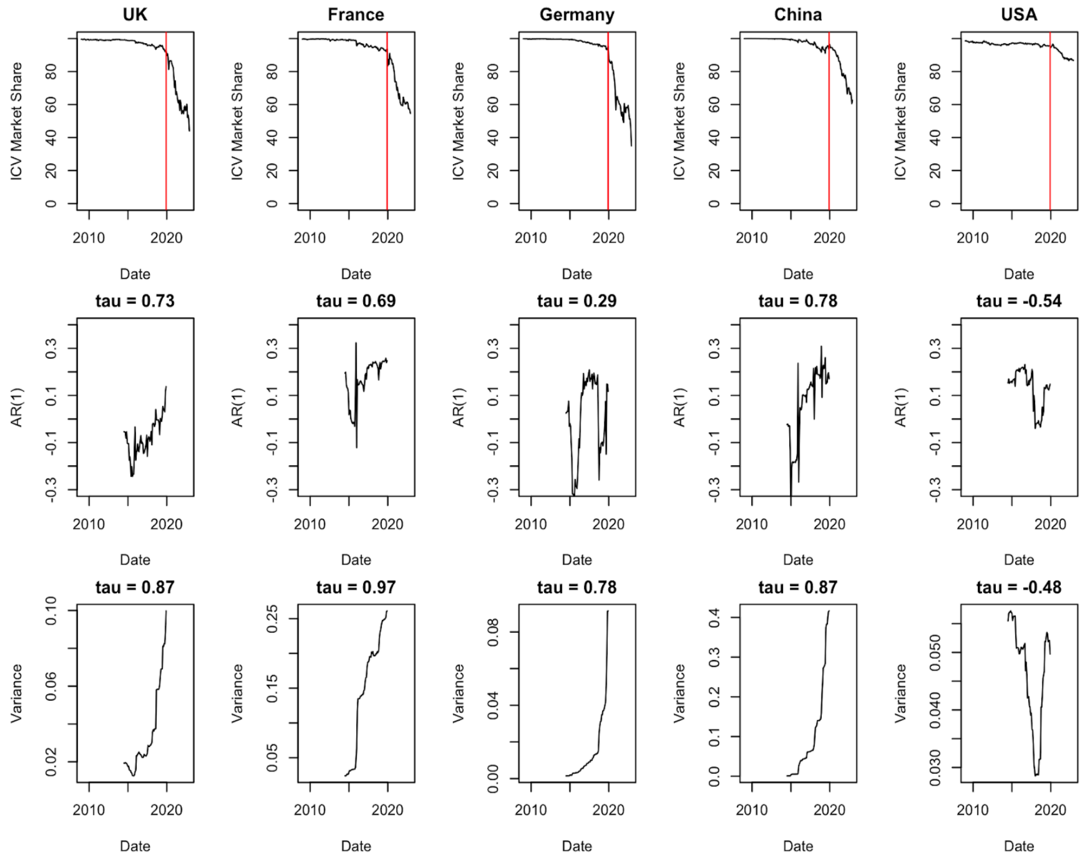

Figure 4.4.11: First row: Changes in ICEV market share in UK, France, Germany, China and US, with December 2019 marked with a red line. Second and third row: Change in AR(1) and variance for each of these countries suggesting a loss of resilience and approaching tipping point prior to the start of 2020. Positive mann-kendall tau trend values above plots imply significant positive trends in these indicators of resilience loss.

AR(1) and variance, as measured across a moving window, increase in three of the four markets that show a tipping point – UK, France and China – however the change in AR(1) is not convincing in Germany. In the US, which does not show this tipping point behaviour, the trend in AR(1) and variance is not positive, as we may expect.

Therefore for some of the markets that are currently experiencing an EV transition, the tipping point was preceded by changes in statistical measures that we observe in natural ecosystem tipping points. This suggests that these changes may be detectable prior to these socio-technical tipping points and could provide a way to monitor when social systems are losing resilience.

4.4.5.4 Changes detectable in other social data?

The attention EVs receive from the general public is a further possible indicator of change (Boulton et al., 2023). A time series of view share (proportion of advert views that are for EV cars rather than non-EV cars) on AutoTrader, a prominent UK website, shows that there has been a general increase in view share from 2018 up to July 2023 (Figure 4.4.11). Also clear is that, at certain times, spikes in attention can occur, a few days after which view share returns to normal.

These spikes in attention can be directly linked to specific external events:

I. **4th February, 2020:** The UK Government announces a ban on sale of new petrol vehicles by 2035;

II. **18th November, 2020:** The UK Government brings forward the ban on sale of new petrol vehicles to 2030;

III. **29th September, 2021:** Potential HGV driver shortage, leading to uncertainty about petrol availability, panic buying and fuel shortages in the UK;

IV. **10th March, 2022:** Spike in UK fuel prices associated with international fossil fuel volatility from Russian conflict in Ukraine;

V. **8th June, 2022:** Spike in UK fuel prices.

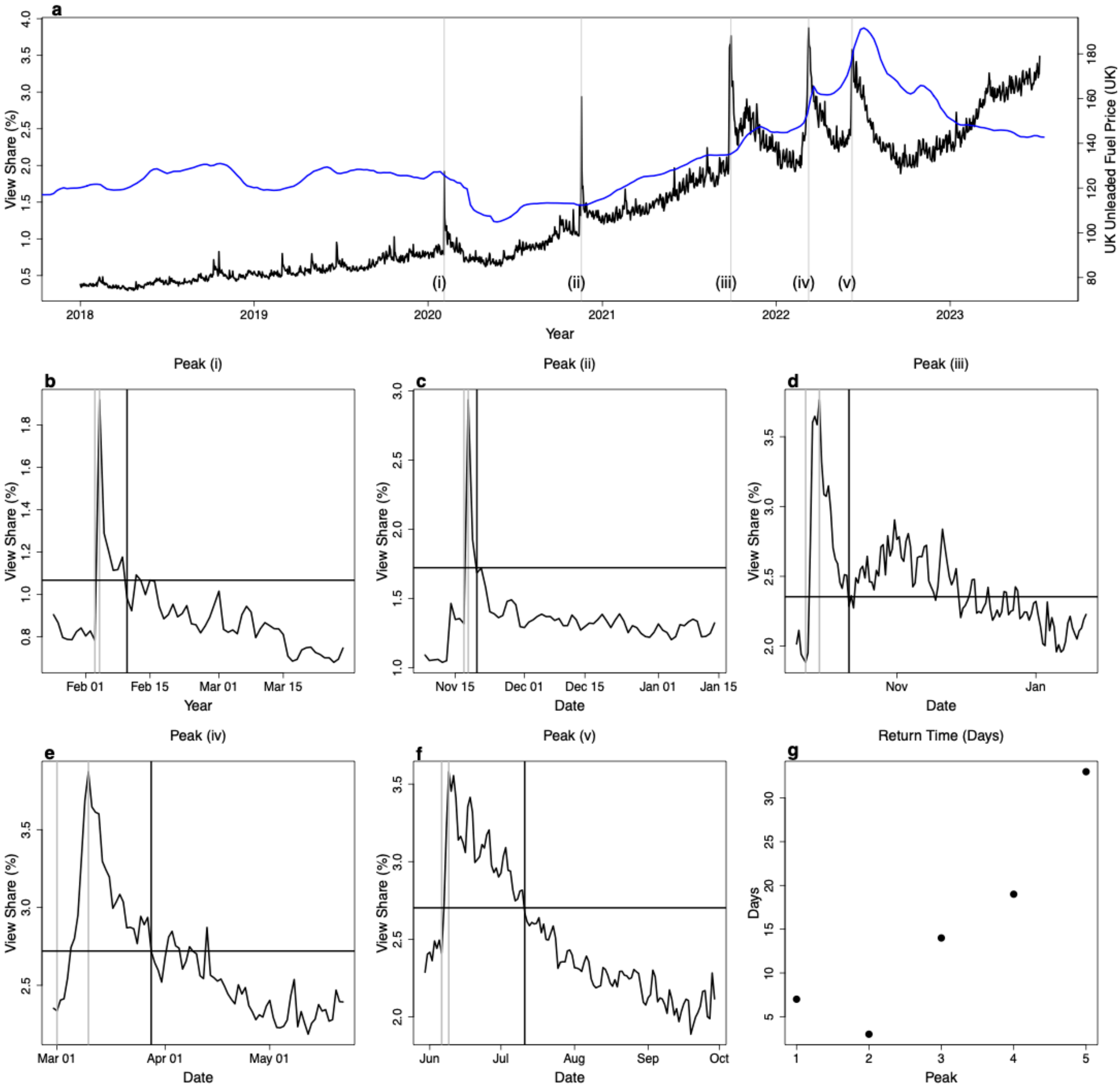

Figure 4.4.12: Measuring the return time from specific events as an EOI in view share of EVs (compared to non-EVs) on AutoTrader UK. (a) The time series of view share (black), alongside the weekly mean UK unleaded fuel price (blue). Marked in grey vertical lines (i-v) are specific external events detailed in the main text. (b)-(f) The return time from each event is calculated as the number of days it takes for the time series to decrease by 75% of the distance from the spike back to the pre-spike value. Dotted grey lines show the pre-spike and spike dates as vertical lines. The 75% value is shown as a horizontal black line, and the date this is reached by the vertical black line. (g) The number of days after the spike it took for the system to reach the 75% value for each spike.

We measure how long it takes for attention to return to 'normal' after each spike (i)-(v) as an early opportunity indicator (see Chapter 1.6 and 2.5), by determining how long it takes for a spike in attention to decay by 75 per cent. For each successive spike (Figure 4.4.11 b-f), there is a clear increase in the length of time it takes for decay to happen, i.e. for the system to return to 75 per cent of its pre-spike level (Figure 4.4.11 g), increasing by a factor of approximately six from point (i) in June 2020, to (v) in June 2022. This shows that the system is slowing down and the incumbent state of ICEV dominance is losing stability over time. Colloquially, one can imagine this increase in return time suggests that events are affecting the system more intensely, such that it takes longer for interest in EVs to die down after the event has passed and that this indicates the system is losing stability. Just as for market share in the sales data, we can also observe increases in AR(1) and variance in view share across the whole period (Figure 4.4.12).

Compared to sales data, this dataset provides the opportunity to measure actors' instantaneous reactions to events, as they do not have to interact with the system in such a strongly committed way such as buying a vehicle. As such, we are able to better determine people's interest using this novel dataset. These results imply that critical slowing down is occuring in the view share of EV adverts, and thus that a tipping point is being approached such that they may rapidly gain the majority of view share.

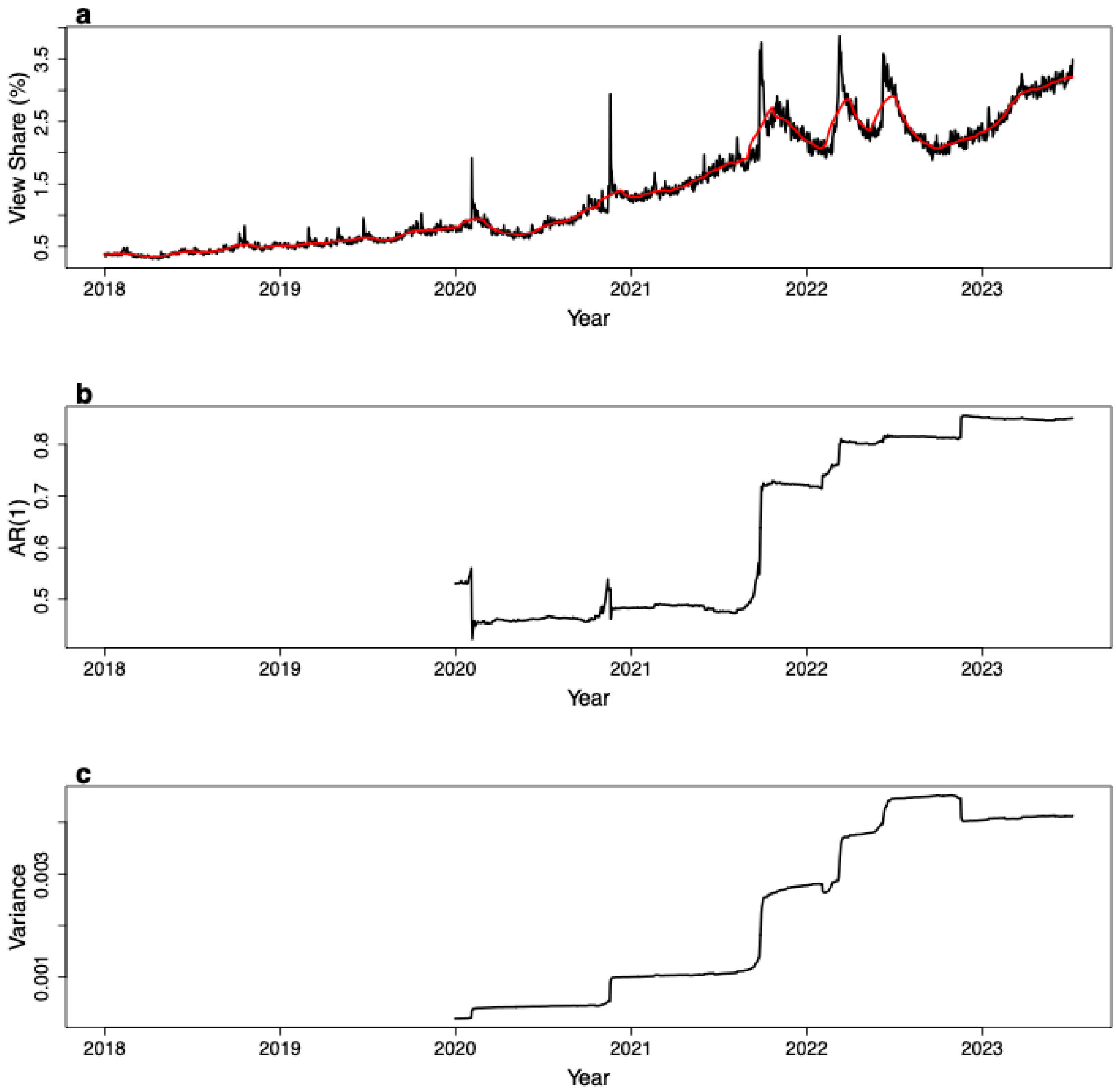

Figure 4.4.13: 'Early opportunity indicators on EV view share time series. (a) The time series of view share (black) and the smoothed version (red) used to detrend (calculated using a Kernal smoothing function with bandwidth equal to 50). (b) AR(1) calculated from the time series in (a) once it has been detrended using a moving window equal to two years (as described in Chapter 1.6) and plotted at the end of the window used to create it. (c) As in (b) but for variance.

4.4.5.5 Limitations

Attempting to detect EOI in social systems can encounter additional difficulties compared to ecological and climate systems (Chapters 1.6 and 2.5). Careful thought is required when considering other positive tipping points in order to decide which system elements should be monitored and which could show these EOI, as they are likely to be system dependent. The EV transition example is occurring as a substitution; this contains a market shift and some amount of behavioural change (4.3.2), therefore we consider sales and EV adverts. Other positive tipping points will not necessarily have a behavioural aspect, or alternatively may almost exclusively exist as a behavioural and values change. These would require a different framing and would likely be constrained by data availability. These methods require high temporal resolution data which matches the relevant timescale of the system and is sufficient in extent to precede the tipping point. It is uncommon for this data to be available for social systems and careful consideration must be given for which state variable should (and can) be measured in social systems.

Questions also remain about the timescales over which we could detect these changes in resilience and whether they would manifest early enough to offer a substantial lead time compared to other analysis methods, such as expert elicitation.

It is also possible that this resilience loss framing is not consistent across all social systems. One key difference between social and ecological systems is the question of agency; it is possible that people are able to self-correct or that interested actors may try to strengthen the feedbacks which keep a system within an 'undesirable' regime, and that some abrupt transitions may be too rapid (or exogenously caused) to be detectable with EOI. Some social tipping points may have obvious alternate states, such as substitution of an incumbent technology for a new, low-carbon innovation, however this may not always be the case, especially when considering cultural and behavioural changes, and the drivers and likelihoods of these alternate states will differ across countries and cultures.

4.4.5.6 Measuring progress – Early opportunity indicators in other sectors

We have discussed how one might apply EOIs to a socio-technical transition, using the EV transition as a case study. This approach seems to show some success and requires consideration of how we may apply it to other positive tipping points.

We propose that further work is required to investigate these indicators for other PTPs, in order to add value to existing work on determining when tipping points may happen. Some of these system changes may have a social element, such as consumer demand and preferences, and as such social data (where it exists) would be useful here; one such example could involve discourse around plant-based diets and meat alternatives. As well as exogenous drivers, some social tipping points may be strongly driven by network effects and social contagion, such as the agroforestry project TIST discussed in Chapter 4.3 (Box 4.3.9). Network-based statistics can aid in predicting tipping points (Lu et al., 2021; see before Chapter 1.6 for more details) and therefore investigating these networks' structures may explain if and why a tipping point is being approached or where contagion can be facilitated.

These indicators may be observed in datasets which measure different elements of the transition – in this case, ICEV sales and EV advert views. They can give some measure of the effect of external intervention and show how 'resilient' the undesirable status quo is, and therefore how easy or hard it may be to tip out of (in our case study, this is the incumbent ICEV regime). From the EV advert views, we can see that changes in the system response to external perturbations, such as policy announcements and economic factors, offer a way to detect the social response to these. One approach to utilising this is to measure the resilience of the existing (undesirable) regime and to monitor how it responds to interventions, with a system approaching a tipping point showing the largest effect from an intervention. They can therefore be conceived of as both a measure of 'progress' towards a goal, and also as an indicator of when a system is losing resilience and can therefore experience greater return on targeted efforts to push it towards a tipping point.

4.5 Positive tipping cascades

Authors: Sibel Eker, Jürgen Scheffran, Timothy M. Lenton, Caroline Zimm, Steven R. Smith, Deepthi Swamy, Tom Powell

Summary

Cascading effects through cross-system interactions is one of the biggest promises of positive tipping points to create rapid climate and sustainability action. Several channels exist through which a strategic input can trigger secondary impacts for a disproportionately large positive response. We need to balance positive and negative feedback loops across systems for managing cascades. There are various agents that can trigger cascades. We need early warning systems and empirical evidence, either based on observational data or simulations, on interventions that can trigger cascades towards and beyond a positive tipping point.

Key messages

- Cascading effects can occur across sociotechnical systems when one sector drives the cost of a shared technology down, or when the output of one sector provides a low cost input to others. Similar relationships exist across sociopolitical systems that amplify the impact of norm, behaviour and policy changes.
- Super-leverage points can exist where interventions can tip multiple systems across multiple sectors in a domino effect. Public authorities and non-governmental agents can both play a role in triggering cascades through super-leverage points.
- Governmental positive tipping interventions for rapid climate and sustainability action can benefit from the indirect influence of policies on society, such as norm-setting. Non-governmental positive tipping interventions can harness the influence of social change on policy, indicated by climate litigation, green voting, discourse change and civic action.
- Cascade management requires all actors from governments to industry and civil society to adopt a systems thinking approach.

Recommendations

- Government, business, finance and research sectors need a coordinated, ideally international, approach to designing and implementing strategies to activate super-leverage points.

  For example, to implement green ammonia blending mandates for fertiliser manufacturing could trigger a tipping point in demand for hydrogen electrolysers, which would reduce the production costs of green hydrogen, and thereby increase the economic viability of green hydrogen-based solutions in other sectors, including steel production and shipping.

4.5.1 Introduction

Positive tipping dynamics have been, or can potentially be, observed in various sociotechnical and environmental systems. Due to (sometimes) strong interconnections between these systems, a positive tipping intervention can lead to a sequence of secondary impacts across different systems (energy, finance, policy, etc) and scales (individual, national, international) and result in a much larger eventual impact. These cross-system interactions also create cascading feedback mechanisms that can further reinforce the positive feedbacks within those systems and accelerate the tipping dynamics, or vice versa. Therefore, identifying and managing such cascades is necessary to accelerate tipping dynamics and boost the effectiveness of positive tipping interventions towards rapid decarbonisation.

The Industrial Revolution in Britain (ca. 1760-1840) provides archetypal examples of cascading effects across the economy. High wages spurred innovation in the substitution of energy for labour; and innovation in cotton manufacturing triggered much wider applications of machines and the new modes of production. Increasing energy demand spurred innovation in resource extraction, in the energy-efficiency of steam engines, and in a transport network to move heavy materials (e.g. coal, iron). That transport network in turn expanded markets for both heavy and pre-existing lighter (organic) goods. Increasing demand for such goods from a growing middle class drove further investment in innovation, increasing productivity and maintaining economic growth.

This chapter describes key examples of cascading effects and feedback loops across various sociotechnical (e.g. energy, transport), social-ecological (e.g. agriculture) and socio-political systems. Besides a better understanding of the state and potential of positive tipping, this chapter sheds light on how such tipping dynamics can be triggered by civil society and the private sector, creating the constituency for government-led interventions, and can be managed by limiting negative cascades and inducing positive ones.

4.5.2 Cross-system interactions leading to cascades

The cross-system interactions within sociotechnical, socioecological and sociopolitical systems can lead to positive tipping cascades. Furthermore, the interactions across society, policy, technology and economy (Figure 4.5.1) can amplify these cascades. Historically, interacting political, technological and behavioural tipping elements such as the Montreal Protocol, development of non-Chlorofluorocarbon (CFCs) substitutes and public concerns over Ultra Violet (UV) radiation and skin cancer, led to a rapid phase-out of ozone-depleting chemicals (Stadelmann-Steffen et al., 2021).

In the near term, cascades across those systems can also lead to rapid decarbonisation. For instance, public procurement of sustainable food can accelerate norm and behaviour changes, enable the use of alternative agricultural practices, such as regenerative agriculture or green ammonia use, by reducing the land pressure, and (with the latter) can facilitate the decarbonisation of energy and transport systems by boosting the production of green hydrogen. Similarly, zero emission vehicle (ZEV) mandates are a strong leverage point due to cascading effects. As policies require manufacturers to ensure ZEVs account for rising proportion of their car sales, they overcome a constraint on supply in the transport sector, facilitate decarbonisation in the energy sector through innovation and raise the demand from the society. Versions of this policy have proved highly effective in California, China and the Canadian provinces of Quebec and British Columbia, combined with installation of charging stations.

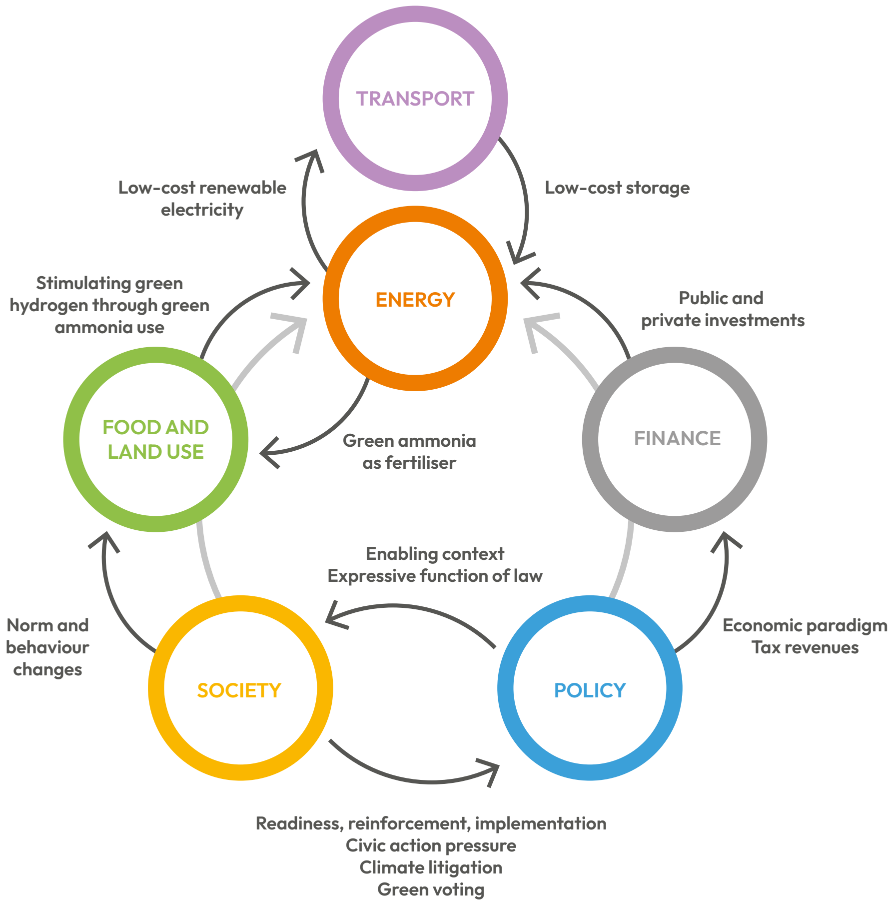

Figure 4.5.1: Overview of the cross-system interactions that can create positive tipping cascades.

Not only public authorities and governments, but many different agents can play a role in triggering the cascades. For instance, thought leaders and media can be pivotal in enhancing the visibility of a population already engaged in climate action, which determines not only the demand for low-carbon goods and services, but also increases the momentum of climate policies and the perceived risk of fossil fuel assets. When such policies and financial developments reduce the fossil fuel supply, the resulting lower costs of low-carbon technologies lead to more people taking climate action by choosing low-carbon options, and creating a reinforcing feedback loop of cross-system cascades (Eker and Wilson, 2022).

Below, we describe these interactions within and between the sociotechnical (energy, transport), socioecological (food and land use) and sociopolitical (society and policy, including finance) systems to highlight the role and ability of various agents in triggering cascades.

4.5.2.1. Cascading effects in sociotechnical systems

Across sociotechnical systems, cascading effects can occur when one sector drives the cost of a shared technology down, or when the output of one sector provides a low-cost input to others. Electricity is a general-purpose technology, and with renewable energy becoming the cheapest source of electricity generation (Way et al., 2022), there is the potential for economy-wide cascading consequences across the electricity sector, mobility and heating (Chapter 4.3). Low-cost renewable power combined with cheaper and longer-duration battery storage is making direct electrification highly attractive in some sectors of the economy (e.g. light-road transport) and more feasible in others (e.g. heavy-duty transport, short-haul shipping and aviation).

Specifically, passenger electric vehicles EVs represent the majority of projected demand for batteries, with estimates suggesting that they will account for ~70 per cent of total installed battery capacity by 2030. At the same time, wider deployment of EVs reduces the battery costs, further reducing the renewables' storage costs in the energy sector. (Meldrum et al, 2023) highlight that boosting EV adoption to 60 per cent of total global passenger vehicle sales by 2030 would increase the total volume of battery production by 10 times from current levels, while a continuation of the currently announced projects would increase the battery production capacity only fourfold from the current levels (IEA, 2023). Given current learning rates, this could drive a 60 per cent reduction in battery costs by 2030. As battery costs account for ~30 per cent of the total cost of renewable power, a 60 per cent reduction in them will bring forward cost parity points of new solar/wind plus storage with new or existing gas (or coal) power generation.

Cheaper batteries provide cost-effective electricity storage also to balance intermittent renewable energy supply and demand, encouraging homeowners to install batteries that charge at low rates during the night and provide power at times of peak demand during the day (4.3.1). Furthermore, declining costs of renewables boosts the use of heat pumps in residential heating, with higher demand for renewables in return (Meldrum et al., 2023). In the mobility sector, cheaper and better-performing batteries, as well as the advancing electric drivetrain technology, are increasing the competitiveness of electric trucks, bringing forward the point where they outcompete petrol or diesel trucks. Linked with advances in digitalisation, this spurs decentralisation of electricity generation (4.4.4 and 4.3.2).

The impact of cheaper electrolysers and renewable energy goes beyond the electricity sector, mobility and home energy, and creates new avenues for industries to decarbonise using green hydrogen and its derivatives. For instance, green ammonia (produced from hydrogen with renewable energy) can be used for agricultural fertilisers, shipping fuel and synthetic jet fuel in aviation. It can also be a storage option to facilitate load balancing in renewable electricity systems (Edmonds et al., 2022, Bouaboula et al., 2023). Green ammonia is already cost competitive in fertiliser production, thanks also to its low transport costs either through pipelines or shipping (IEA, 2019). With economies of scale and learning, progress in green ammonia use for fertilisers could bring down the cost of green hydrogen for use in several other sectors. For example, implementing a 25 per cent green ammonia blending mandate in fertiliser manufacturing could create demand for almost 100 GW of hydrogen electrolysers, which would reduce capital costs by ~70 per cent given current learning rates. This could unlock US$1.5/kg green hydrogen costs if accompanied by continued falls in the cost of clean electricity – helping to close the gap to cost parity or increase the economic viability of zero-emission solutions in other sectors including steel production and shipping.

4.5.2.2 Cascading effects in social-ecological systems

Food and land use is one of the key systems (4.3.3) that can create tipping dynamics for accelerated decarbonisation. Self-reinforcing feedback loops such as increasing returns and technological reinforcement can progressively push an inadequate into a more sustainable food system (Lenton et al., 2022; Fesenfeld L.P et al., 2022).

The role of society is considered a key driver of transformation in the food system, as widespread behaviour changes towards lower waste, sustainable diets and diversified protein sources can not only reduce the GHG emissions of the agriculture sector but also create synergies for achieving multiple SDGs, such as alleviating hunger, improving public health and averting biodiversity loss, and reducing the intensity of the tradeoffs between them (van Vuuren et al., 2018; Leclere et al., 2020; Obersteiner et al., 2016).

As dietary behaviour changes reduce land pressure, fertiliser consumption is expected to decline, and adoption of diversified and regenerative farming practices are expected to increase (Gosnell et al., 2019), as well as ecological restoration and associated carbon sequestration, leading to more rapid decarbonisation in agriculture (4.3.3.5). In climate vulnerable, low-income economies, these feedbacks can also drive diversification of livelihoods, new economic opportunities, and other social benefits (4.3.3.4). Social norms have been repeatedly shown to be a key driver of widespread dietary changes in model-based studies (Eliot, 2022; Eker et al., 2019). Public procurement of sustainable food is considered a strategic intervention to accelerate the adoption of new norms (GSDR, 2023), and food labelling and certification in alternative food networks (Lenton et al., 2022) is key for facilitating market penetration of alternative proteins. Therefore, such triggers in society and policy can have cascading impacts on intensified and accelerated transformation of food and land use systems.

4.5.2.3 Cascading effects in sociopolitical systems

The interaction between society and policy can be key to tipping global carbon emissions by creating cascading effects through individual action, social conformity, public discourse, climate policy and technological learning. For example, simulation results suggest that individual action is ineffectual unless the social credibility of costly behavioural change is high (Moore et al., (2022).

Society affects policy in multiple ways: First, adoption of niche technologies signals readiness for wider policy change; early cost reductions reinforce the policy ambition towards stimulating such technologies further; and coalitions of early adopters influence politics for more aggressive policy response (Schmidt and Sewerin, 2017). Societal readiness affects pro-environmental policies, especially on a local scale, as exemplified by different car-sharing policies of local authorities in the Netherlands (Meelen et al., 2019), different solar photovoltaic policies of German states (Dewald and Truffer, 2012), and the positive tipping dynamics observed in the UK's offshore wind production and EV sales due to policies following an increase in public concern and attention (Geels and Ayoub, 2023). Second, social movements affect policy, either in legislation or in agenda setting. Civic action preceding and during Conference of Parties (COP) (Carattini and Löschel, 2021) and resistance to local fossil fuel projects have been able to cancel or suspend such projects (Piggot, 2018; Temper et al., 2020) or create non-fossil fuel energy policies (Hielscher et al., 2022). In a third and fundamental way, society influences policy through the election of politicians and policymakers. In Europe and the US, for instance, public risk perception has resulted in green voting after extreme climate events (Hazlett and Mildenberger, 2020; Hoffmann et al., 2022), even though income and political identity play a strong mediating role. Therefore, society provides the political legitimacy and democratic mandate that policymakers need to support radical policy change (Willis, 2020; Smith, 2023).

Another socio-political phenomenon that can trigger a tipping cascade is the spike in climate litigation cases worldwide. Climate litigation describes administrative, judicial and other investigatory cases that raise issues of law related to climate change, and it reflects underlying sociocultural changes. Since 2015, climate litigation cases have more than doubled worldwide, surpassing 2,000 in May 2022 (and representing 25 per cent of all cases filed between 2020 and 2022) (Setzer and Higham, 2022). They reflect climate action from diverse citizens (e.g. children in Germany or the Netherlands, grandmothers in Switzerland, a Peruvian farmer against a German energy company) in various jurisdictions (against governments, banks and large corporations in emission-intensive sectors) to advance climate action or to challenge how and which climate policies are implemented.

Policies have a direct and significant impact on society by creating an enabling environment for the adoption of low-carbon technologies and behaviours through financial support, infrastructure design, regulations, standards and bans. For instance, subsidisation of low-carbon energy (Otto et al., 2020) or transport modes, and tax benefits of EVs (Sharpe and Lenton, 2021) are government-led positive tipping interventions that can accelerate the adoption of these technologies and create cascading effects on energy and transport systems (4.3.1 and 4.3.2). Moreover, policies have a secondary impact on society by signalling what is socially approved or disapproved and setting social norms (Hoff and Walsh, 2019), according to a mechanism called the 'expressive function of law' (McAdams, 2015; Sunstein, 1996). Several studies confirm the expressive function of law in other contexts, such as compulsory voting in Switzerland (Funk, 2007), legalising same-sex marriage in the US (Tankard and Paluck, 2017) and social-distancing policies during COVID-19 lockdowns in the UK (Galbiati et al., 2021).

The tipping of socio-political systems can also be triggered by public discourses that have cascading effects on public opinion, political priorities, policymaking, legitimacy, credibility, social norms, values and mobilisation (Dryzek, 1997; Dryzek, 2001; Bradford, 2016). For instance, the Nobel Peace Prize awarded to the Intergovernmental Panel on Climate Change (IPCC) and Al Gore in 2007 marked a tipping point in climate change discourse (Walsh, 2007), contributing to increased global awareness, strengthened political commitment, enhanced credibility for the IPCC, catalysed climate activism, and influenced future global agreements and sub-national actions (Schiermeier and Tollefson, 2007). Similarly, the Earthrise image taken by the Apollo 8 mission crew in 1968 (Poole, 2008) served as a tipping point contributing to a shift in public opinion and environmental awareness (Schroeder, 2009). This and similar images produce what is known as the 'overview effect' (Yaden et al., 2016), evoking a sense of awe and interconnectedness with Earth's systems and inspiring international cooperation in addressing environmental challenges (Logan, Berman, Berman and Prescott, 2020). Some have claimed that the photograph influenced environmental policy and institutions, including the creation of the Environmental Protection Agency (EPA) in the United States (Collins, Genet, and Christian, 2013). Reframing international climate policy from burden-sharing to win-win (Jaeger et al., 2012) is considered a key factor leading to the acceptance of the Paris Agreement, and such transformative win-win narratives in the economic, cultural and financial contexts can also accelerate climate action (Hinkel et al., 2020).

Policies can also create tipping cascades by affecting society through the political-economic system. The societal paradigm shift towards a global neoliberal capitalist economic system in the late 1970s is an intriguing example of a whole-society cascade of change. The crisis of Keynesianism in the late 1970s, the collapse of the Bretton Woods system, the oil price shocks, and trade union disputes, caused a shift in public opinion and provided the political opportunity for Neoliberalism, which used state power to expand the role of markets, competition, and individual responsibility in society. Prior to its ascendency, the Neoliberal project had spent 50 years developing a coherent philosophy, a compelling narrative, a detailed policy portfolio and a network of political support ready for favourable conditions to emerge (Davies and Gane, 2021; Newell, 2018; Brown, 2015; Mirowski and Plehwe, 2015; Burgin, 2012). The historical lessons to be learned in relation to society-wide tipping cascades include the importance of having a portfolio of policies and an effective advocacy coalition ready for a window of political opportunity.

Besides the broader economic system they create, the economic influence of policies on society can lead to positive or negative cascades in more specific ways. For instance, mechanisms like mitigation taxes may create new government revenue streams: a carbon price of $50 per tonne of CO_2 in 2030 is estimated to lead to a rise in government revenue amounting to approximately 1 per cent of GDP for several G20 nations, and significantly higher increases in some countries (IMF/OECD, 2021). On the other hand, as the economy moves away from fossil fuels, tax revenues from carbon-intensive industries and associated sectors such as tourism and agriculture are likely to shrink (Agarwal, et al., 2021; Bachner and Bednar-Friedl, 2018). For example, a climate policy package focused on long-term decarbonisation across the economy in India is estimated to reduce government fuel tax revenues by nearly US$70bn (2018) by 2050 (Swamy, Mitra, Agarwal, Mahajan and Orvis, 2022). The net impact on government revenues from such varied streams can have societal implications on education, infrastructure and healthcare expenditure, which are the means to tip society through awareness and an enabling environment.

4.5.3. Harnessing the power of cascades

Supporting positive cascades is a challenging task, in particular when considering the complex interaction with negative (undesirable) cascades in the human-earth system, which can disrupt positive cascades, but which in turn can help contain negative cascades. Therefore, the key elements of intervention design for positive tipping (4.2.3) to balance reinforcing and dampening feedback mechanisms to avoid unintended consequences are also instrumental in harnessing the power of cross-system cascades.

Integrated human-Earth system models capturing the feedback mechanisms that are identified as potential drivers of tipping dynamics can support understanding of the role of various feedback mechanisms, hence help intervention design for tipping cascades. Scientific literature contains several examples of modelling studies that explore positive tipping dynamics and interventions in specific contexts (Hochrainer-Stigler et al., 2020b; Niamir et al., 2020; Eker et al., 2019), using various methodologies such as system dynamics (top-down feedback perspective), agent-based modelling (behavioural rules) and social network analysis (spread of cascading events). An integrated modelling framework that captures the cascades across sociotechnical, socioecological and sociopolitical systems discussed above (4.5.1) is however still missing. Moreover, the complexity of integrated systems modelling might come at a cost of their interpretability and practical usefulness (Figure 4.5.2). Strong stakeholder engagement might be needed when designing modelling interfaces and scenarios, including dimensions of political economy, power, distribution and justice.

Participatory approaches are valuable not only in utilising models in decision support, but also in harnessing the power of cascades by establishing a shared understanding and systems thinking among multiple actors, as well as supporting cooperative governance.

Cooperative governance coordinates, regulates, manages and controls interdependent social and political relations among multiple actors, including coalitions and organisations of governmental, intergovernmental and non-governmental organisations, all pursuing their own goals and interests. To overcome collective action problems and the tragedy of the commons, various mechanisms offer promising signs of supporting positive tipping cascades: implementing co-benefits and co-evolution; neighbourhood collaboration; transnational initiatives like city networks; coordination of goals, efforts and actions for mitigation and adaptation; bottom-up participation complementary to top-down global negotiations; and regulations and norms. Identifying conflict potentials is important to prevent escalation towards a cycle of conflict and instead induce cycles of cooperation between stakeholders. This depends on the societal responses, involving adaptive agents following their motivations, capabilities and behavioural rules.

Governance of tipping cascades is facing tremendous uncertainties about natural and social impacts and responses (Franzke et al., 2022). Diverse sources of knowledge can help to contain this uncertainty, including scientific data and modelling as well as local and Indigenous knowledge based on experience, mobilised in participatory approaches and collective learning.

Agency benefits from constructive and mutually adaptive behaviour of agents to induce positive tipping cascades across the socio-technical, -ecological, economic, and -political system interactions.

The real difficulty and the major political effort, though, lies in getting to that point in the first place. In order to begin to understand how to get there, and to design and operationalise positive tipping across socio-political sectors, scales and institutions, we can start with understanding the ecologies and dynamics of the key actors and coalitions. We can then use systems thinking across all sectors, scales and research domains to create a shared understanding of how everyone – including local authorities, political parties, artists, NGOs, businesses, financial investors, trade unions, farmers, faith groups, academics, journalists, lawyers and social movement organisers – can contribute to rapid climate action by leveraging their role in positive tipping.

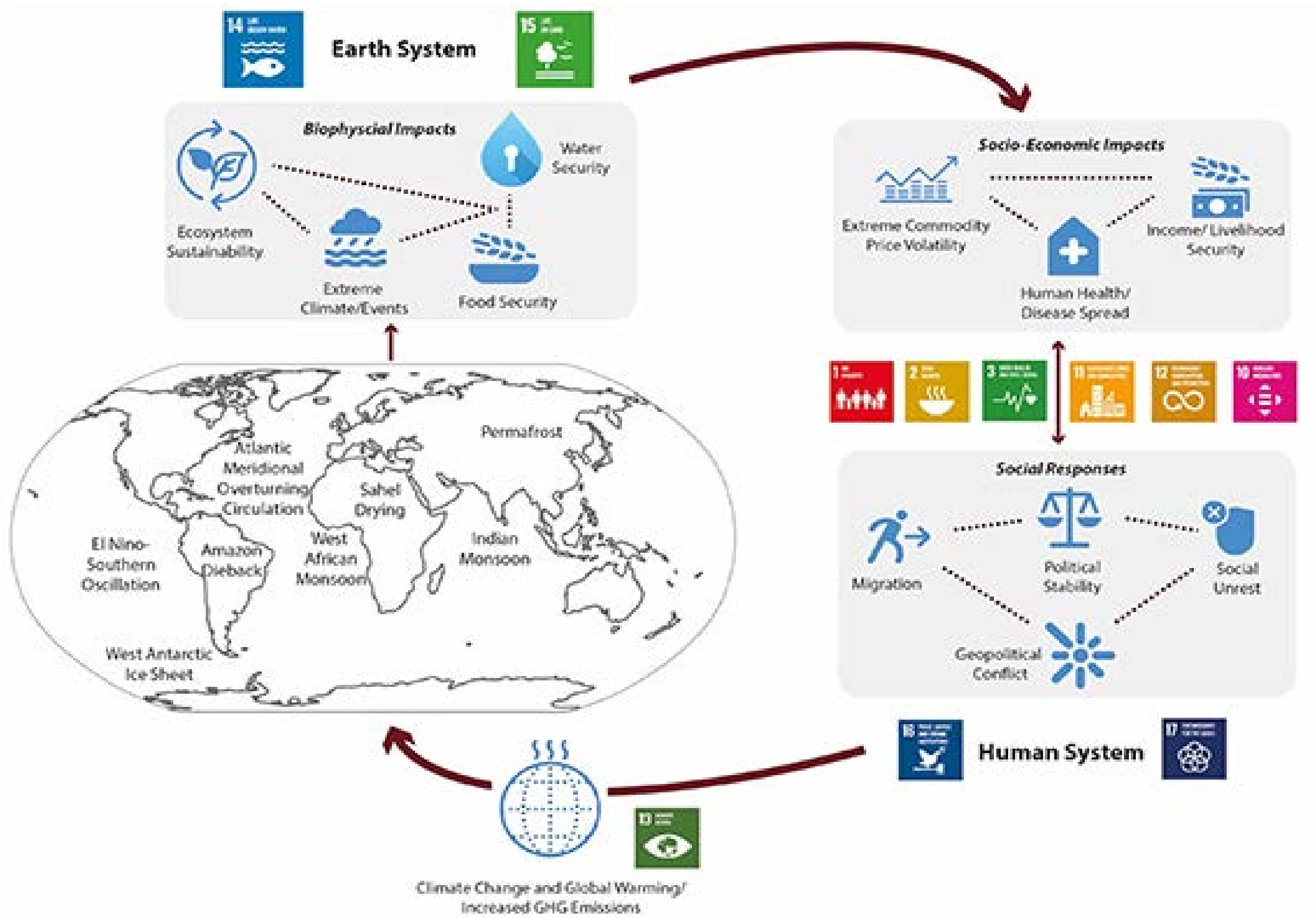

Figure 4.5.2: Possible interactions and cascades between the Earth system and the human system. Pathways can cascade into the human system inducing economic and social responses and potentially tip some social subsystems into a different state, such that they can increase or mitigate global warming and potentially affect further tipping elements via positive or negative feedbacks. More responses and interactions are likely than shown here which interact with the SDGs.(Franzke et al., 2022).

4.6 Risks, equity and justice in the governance of positive tipping points

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Summary

Earth system tipping points pose existential threats to current and future generations. Those least responsible for causing them are often most at risk. Positive tipping points (PTPs) have the potential to beneficially transform societies, but they carry their own risks. positive tipping points should not perpetuate or create unjust or inequitable outcomes. For example, in our urgency to transition to electric vehicles, the demand for more cobalt and lithium to produce batteries should not come at the expense of creating sacrifice zones and destroying communities elsewhere in the world. Consideration of what needs to change, who is being asked to change, where the change or its impacts will be felt, and by whom, are fundamental questions that require a level of reflexivity and systemic understanding in positive tipping point governance and other decision making.

All actors have a role to play in ensuring that risks, justice, equity and ethics are carefully considered prior to and during interventions. Enabling positive tipping point for radical transformation could benefit from more diverse perspectives to open up solutions, with a particular emphasis on the inclusion of marginalised voices. Taking a precautionary and systemic approach to positive tipping interventions and stepping back to explore all options, not just those appearing to offer a quick fix, should help ensure more socially just and environmentally sustainable outcomes.

Key messages

- Positive tipping point governance that prioritises justice, sufficiency and strong sustainability are the only realistic solutions left. These must be enacted without creating green sacrifice zones where people or places are foregone in the quest for sustainability solutions.
- Considerations of what needs to change, who is being asked to change, where the change or its impacts will be felt, and by whom, require a level of engagement, reflexivity, inclusiveness and systemic understanding.
- All actors can help ensure just and equitable change, especially regarding marginalised voices.

Recommendations

- Public and private finance must provide more supportive and inclusive investment.
- Business should be more proactive in lobbying for and co-creating a level of governance commensurate with the scale and speed of change required.
- Media and other influencers should be aware of political and power dynamics when framing positive tipping point messages.
- Positive tipping point researchers and practitioners must consider diversity and inclusivity and avoid unintended negative consequences when designing projects.

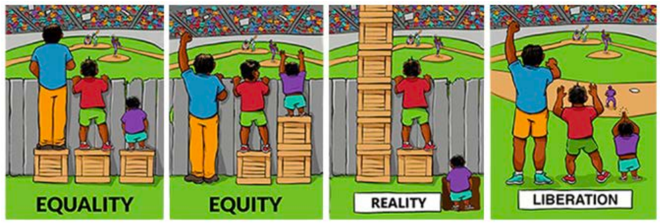

Image Credit: "Artist: Angus Maguire".

4.6.1 Introduction

Humanity faces unprecedented challenges, including climate change, biodiversity loss, inequality and poverty. The Earth system in which human history has played out is fast changing to 'a new climatic regime' (Latour, 2017). In response, diverse groups have called for transformative change, but this is not a simple, inevitable or apolitical process. Orienting complex systems onto more sustainable and socially just trajectories is messy and complicated. As history shows, there are 'dark sides' to transformations, including unintended consequences, losers as well as winners, and the potential for capture by vested interests (Blythe et al., 2018). These risks can be exacerbated in the context of PTPs because interventions designed for exponential and irreversible positive change also carry the risk of exponential and irreversible negative change. A **precautious, considered, systemic approach** is therefore necessary to understand the potential consequences and to whom they might apply. Governance approaches that prioritise climate and ecological stability, equity and justice must anticipate and take steps to avoid perverse outcomes and negative distributional impacts using compensatory and redistributive mechanisms. Trade-offs must be considered, and tough questions asked: What sacrifice zones are being created? Who is likely to occupy them? What forms of vulnerability are being experienced from change? Who is left behind? Here, we understand 'sacrifice zones' as places that include 'extractive zones' – territories, resources and communities that are viewed as extractable and commodifiable by coordinated forms of capitalism (Gómez-Barris, 2017).

Recent United Nations Framework Convention on Climate Change (UNFCC) climate summits have seen an increasing number of calls from climate justice campaigners and representatives of the Global South, including Small Island Developing States, for an acknowledgement of historical damage in the international response to climate change. These are articulated in calls for loss and damage compensation and for reparations (Huq et al., 2013). These calls are supported by the work of climate historians, decolonial critics and others. Together they assert that we cannot hope to agree on climate action if we do not address past injustices and the unequal access to decision making and resources that created the climate and ecological crisis and which continue to shape intergovernmental responses to it (Moore,2016, Yusoff, 2018, Ghosh, 2021, Bhambra and Newell, 2022). Discussions on tipping points, therefore, must emphasise the plight of the poorest and historically marginalised people, who also face the greatest risks, and must acknowledge the central role of the economy and politics in driving precarity. These past and present injustices create a need for the rebuilding of damaged trust and relationships. For many Indigenous peoples and local communities at the forefront of the climate and ecological crisis, these challenges have become a matter of survival (Gilio-Whitaker, 2019; Whyte 2021). Other important considerations include the rights of future generations and the potential for future harms (Rammelt et al., 2023) as well as a need to consider not just humans, but the rights of all species to exist on a healthy planet (Chapron et al., 2019).

4.6.2 What do we mean by equity and justice?

Earth system justice is conceptualised through multiple approaches to justice including, but not limited to, intragenerational, intergenerational and interspecies justice (Gupta et al., 2023). **Intragenerational justice** refers to relationships between humans rights now and includes justice between states (international), among people of different states (global), and between community members or citizens (communitarian). **Intergenerational justice** examines relationships across generations, such as the legacy of greenhouse gas (GHG) emissions for youth and future people and assumes that natural resources and environmental quality should be shared across generations (Tremmel, 2009). **Interspecies justice** refers more generally to the rights of nature and other species to co-existence on the planet (Harden-Davies et al., 2020) and also counters the idea of human exceptionalism as a lens for thinking through development impacts (Srinivasan and Kasturirangan, 2016). These frameworks can help design just responses to the shifts experienced as we near tipping points, or even help us avoid them all together.

In the context of addressing biophysical tipping points by attempting to enable positive social tipping, a justice lens is critical to ensure that past injustices are not perpetuated in the name of staying within planetary boundaries (Rockström et al., 2023). Attempts to address procedural justice (how processes are designed, who is involved), reparative justice (including recognition of wrongs, restoration where possible and compensation for negative impacts), and distributive justice (or equity) are complicated but important. An Earth system justice approach can promote the fair sharing and management of remaining ecological spaces (Gupta et al., 2022).

4.6.3 Governance of PTPs

Just as is the case for Earth system tipping points (ESTPs), there is no global forum, institution or any other initiative yet established to consider the governance of PTPs. Governance, as defined in Section 3, refers to the rules, regulations, norms and institutions that structure and guide collective behaviour and actions. In addition to state actors at various scales down to city and local government, governance also involves non-state actors from the private sector – business, finance and industry – and from civil society organisations and social movements, including those representing campaigns for environmental and social justice, faith groups and Indigenous peoples. There are well-established international institutions that have sustainability goals: for example, the United Nations Development Programme, the Organisation for Economic Cooperation and Development OECD, the World Economic Forum, and the C40 Cities network. But none of these specifically address the goals, resources or strategies for operationalising PTPs.

4.6.3.1 A polycentric approach to PTP governance

The primary objective of any future system of governance for ESTPs is **prevention**. In contrast, the primary objective of any future system of governance with respect to PTPs in human (social) systems is **promotion**. However, in common with and in coordination with ESTP governance, a clear and persuasive logic and agenda for action, political coalition-building, and a multi-scale or polycentric approach and framework is needed (Ostrom, 2010; Jordan et al., 2018). A **polycentric** system is a nested hierarchy of authorities from local to global scales. Each authority has a degree of independence to set and enforce rules. For example, a local authority might be responsible for community-owned energy or food cooperatives; a region might be responsible for new transport and energy infrastructure, or for supporting and reskilling workers in a just transition; each nation might continue being responsible for setting GHG emissions targets and implementing plans to meet them, as they are now. These authorities would also interact, learn from each other, and coordinate efforts to ensure that, collectively, the global goals – for example, net-zero (GHG) emissions by 2050, or 50 per cent fewer people in poverty by 2030 – are achieved (Elsässer et al., 2022).

4.6.3.2 Making the case for PTP governance

The case for inclusive global governance of PTPs needs to be made. Some might question the need, given that action is being taken without it: solar and wind power and battery technology are on exponential growth paths that will disrupt the global electricity sector within this decade (Bond et al., 2023; Nijsse et al., 2023); sales of Electric Vehicles (EVs) are growing exponentially in leading markets and approaching tipping points in others (Meldrum et al., 2023); the technology exists to transform the environmental performance of agriculture and food systems, for example in the use of green ammonia for fertilisers, or the manufacture of alternative proteins for food (Meldrum et al., 2023; FOLU 2021). The potential for some of these solutions to perpetuate inequitable and unjust outcomes, such as green sacrifice zones, should, however, be of great concern, building the argument for an **inclusive governance system** to ensure that risks are accounted for and that the marginalised have political voice and agency. There is also positive movement in climate commitments. Net-zero decarbonisation targets, which no country in the world was thinking about 10 years ago, have now either become legally binding or have been pledged in 96 countries, representing almost 80 per cent of global GHG emissions (WRI, 2023). Some countries have shown it is possible to reduce emissions while continuing to grow their economies – known as absolute decoupling – even taking offshored production into account (Ritchie, 2021). But the rate at which this is happening is still far too slow (Vogel and Hickel, 2023). Revisiting these approaches and **how they are governed with just PTPs in mind** is therefore necessary.

Others might accept the need for governance in principle, but argue that we currently do not have enough empirical evidence to meaningfully influence PTPs in many systems. In addition, some might question the feasibility of PTP governance. Sovereign actors have strong interests in accelerating the transition to a sustainable, post-carbon future – in theory, this is a positive-sum game that everyone can win, not a zero-sum game (Wright, 2001). So far, however, the system of governance that has developed is highly complex and cumbersome and has barely begun to consider tipping points in natural systems, let alone in human systems. Structural impediments like vested interests, perverse incentives, competitive market dynamics and legacies of colonialism all offer significant barriers that need to be overcome (Scoones et al., 2020, Ghosh, 2022). A recent assessment of the 17 United Nations Sustainable Development Goals (SDGs), which are meant to be achieved by 2030, concluded that none were on track. It calculated that, on current trends, the world in 2030 would have 575 million people living in extreme poverty, 600 million facing hunger, the +1.5°C 'safety limit' for global heating would be beyond reach, and gender equality would take another 300 years (United Nations, 2023).

We understand these reservations and complexities. Nevertheless, we believe that a global effort to accelerate systemic change – implied in a PTP's discourse – is urgently needed. This is not to claim that all action and progress requires global agreement – far from it. A lot has already been achieved at the national level and much more is possible through small group coalitions of nations and climate clubs (4.4.2.5). But some things do require global cooperation and governance, such as the 1.5°C/well-under-2°C limit of the Paris Agreement. Meeting that limit, justly and in time, will also require some global governance, cooperation and coordination of effort. We cannot avoid difficult, contentious decisions, and we do not have time to postpone them any longer. ESTPs are fast becoming a real threat, so the only way to prevent them is through transformative change, which may include successfully enabling PTPs. Incremental, linear change is no longer an option.

Inclusive global governance to promote PTPs is therefore necessary for essentially the same reason that it is necessary to prevent and adapt to ESTPs – because it requires collective action across diverse actors. Deep emissions cuts and climate-resilient development that prioritises risk reduction, equity and justice would be much easier to achieve with a level of global cooperation that creates 'a sense of collective responsibility and action' (Wiedmann et al., 2020, p. 7), as evidenced in global environmental agreements. This is a complex and delicate task that ultimately relies on finding an inclusive narrative that encourages ambition and enables action. However, the former 'peaceful and reassuring' (Bonneuil and Fressoz, 2016) narrative based on consensus, voluntary measures, efficiency gains and the gradual decoupling of emissions is insufficient to meet the globally agreed +1.5°C limit (Meinhauser et al., 2022). If we are serious about navigating towards a more just, equitable and sustainable future, radical solutions that prioritise staying within Earth system boundaries, implementing Earth system justice, ensuring sufficient, and strong sustainability are the only realistic solutions left (Gupta et al., 2023; Rockström et al., 2023 ; Newell et al., 2021; Trebeck and Williams, 2019; Raworth, 2017; Haberl et al., 2020; Steinberger, Lamb, and Sakai, 2020).

Looking just at the climate issue and the avoidance of 'negative' ESTPs, what matters for sustainability is the **aggregate amount** of GHG pollutants and other drivers/stressors **from all sources**, and the speed at which they can be safely and justly phased out. The development of new technologies, of net-zero policies, or of absolute decoupling, are important parts of that aim and, at least for richer countries, might be achievable without international cooperation. However, cooperation can accelerate these changes, as shown in economic modelling of Electric Vehicle (EV) mandates, for example (Lam and Mercure, 2022). The key question is whether collectively they can amount to deep enough, wide enough, or fast enough change. As previously mentioned in relation to energy systems, rapid growth in wind and solar capacities have led to a reduction in fossil fuel demand in Organization for Economic Cooperation and Development (OECD) countries, but not globally, as other nations have increased fossil fuel demand. Success is ultimately measured in terms of the speed at which we globally phase out GHG emissions and the extent (or 'depth') to which we apply principles of Earth system justice while doing so (Gupta et al., 2023). Following the X-curve framework, this requires rapidly transitioning away from the current energy system dependent on fossil fuels in an equitable fashion – a just transition – while rapidly transitioning towards an alternative system that is also more equitable and just and respects 'safe' Earth system boundaries.

4.6.3.3 Metaphorical scales of justice

Tensions between these two imperatives – the need for speed and for depth – support arguments for the governance of PTPs (Anderson et al., 2023). On the one hand, one might argue that since every additional tonne of GHG emissions adds to the toll in human lives, and every additional fraction of a degree of global heating multiplies threats, including the threat of ESTPs, then speed equals justice. On the other hand, if the speed of decarbonisation and the upscaling of technological change are the sole considerations, this offers carte blanche to the most powerful, dominant actors to restructure the new post-carbon economy in ways that maintain existing power, gender, and socioeconomic inequalities (Newell, Geels and Sovacool, 2022; Gabor, 2023).

In this scenario, while tipping points in technological innovations alone could conceivably save more lives, they could also squander a unique opportunity for greater inclusivity and 'depth' in the redesign of society along more equitable lines (Leach and Scoones, 2006). For example, instead of an energy system composed of a massively distributed network of community-owned and managed cooperatives offering very low-cost, secure energy, we may enter a post-carbon society in which a small number of oligopolistic energy suppliers continue to command a high price and reap extortionate profits (Stone et al., 2021; Hoffman and High-Pippert, 2005). One example that demonstrates governance that respects both the need for renewables and concern over ownerships and consolidation – speed as well as depth – can be found, for example, in Denmark, where there is a minimum requirement of 20 per cent community ownership of wind power (May and Diesendorf, 2018).

Using metaphorical scales of justice, some might judge that a rapid transition that saves more lives (speed) outweighs the benefits of a longer struggle for energy democracy (depth) – where, for the sake of argument, these are perceived to be mutually exclusive. But these and other competing claims for justice at least deserve due consideration. Governments themselves are highly unlikely to initiate action that disrupts dominant systems of power in which they are key players. Instead, governance that encompasses other, non-state actors, beginning with social movements and civil society, would be expected to initiate these forms of political struggle (Smith et al., 2020).

4.6.4 Blind spots, risks and unintended consequences

Climate policymakers and other influential actors tend to focus on the more technological, less politically risky or contentious aspects of climate governance (Patterson et al., 2018). Justice and ethical implications of policies and other actions also tend to be ignored, leading to blind spots in who loses and in the assumptions made when labelling change as 'positive'.

Whether in their eagerness to accelerate technological fixes, or a desire to maintain unanimity, momentum and political will, negotiators have sometimes been tempted to ignore or dismiss normative dimensions of climate policy and the possibility of unintended social consequences (Klinsky et al., 2017). However, all actors in the process – from scientists to world leaders – need to be careful to avoid today's solutions becoming tomorrow's harms. This is especially true when considering interventions designed to trigger exponential rates of positive social change or quick 'techno-fixes' (Sovacool, 2021). Solar radiation management is one such intervention that has already clearly been stated as not a feasible or just option for PTPs in this report, but there are other techno-fixes that could result in an equally exponential increase in unintended negative consequences. It is thus imperative that all actors take responsibility to include a justice framing, acknowledging potential risks, when referencing positive social tipping points as solutions to the ongoing climate and other social-ecological crises.

Some 'positive' interventions for climate impact mitigation and adaptation can also have unintended consequences and pose ethical challenges. In particular, they require careful consideration about what is 'positive' and about any attempt to intervene in systems that can never be fully understood.

4.6.4.1 Examples of negative consequences

An example of the risks associated with the quest for PTPs is the transition to a renewable energy economy that is driving the growing demand for batteries, solar panels and digital devices, all of which require mining of lithium, cobalt and other rare Earth minerals (Dutta et al., 2016). While this creates economic benefits for mining communities, it can also produce negative ecological, economic and social impacts in the near, medium and long-term (Soto, Hernandez and Newell, 2022; Manzetti and Mariasiu, 2015). The industrial mining sector has been accused of supporting state violence and corruption, polluting ecosystems and failing to relieve poverty, while the informal mining sector is known for ignoring occupational safety and health standards and human rights concerns (Calvão et al., 2021;Sovacool, 2019).

Other prominent examples of unintended consequences have been documented for a variety of cases linked to positive interventions for sustainability. Some large-scale renewable and bioenergy projects have resulted in significant local opposition (Cavicchi, 2018) and have resulted in the displacement of Indigenous peoples and local communities (UNPFII, 2023: Zurba and Bullock, 2020) as well as impacting small-scale fisheries (Beckensteiner et al., 2023). Other potential impacts of such renewable energy projects include deforestation (Kraxner et al., 2013), biodiversity losses (Pedroli, et al., 2013) and competition for land and water resources; which can also lead to food insecurity (Hasegawa et al., 2020). Decarbonisation of the built environment, particularly the housing stock, has resulted in health impacts from poor indoor air quality, and fuel poverty (Davies and Oreszczyn, 2012). Carbon offset markets have driven afforestation in open ecosystems, resulting in negative impacts on biodiversity, ecosystem function and livelihoods (Bond et al., 2019).

4.6.5 Winners and losers: sacrifice zones

PTP interventions that succeed in accelerating a reduction in GHG emissions by, for example, a switch to renewable electricity using batteries that require rare earth metals, or by expanding natural carbon sinks, could reduce access to food, livelihoods and land for vulnerable communities (Mehrabi et al., 2018). The tendency for PTPs to benefit some people while (intentionally or unintentionally) excluding others creates sacrifice zones.

Well-intentioned interventions have the potential to put severe pressure on lands held by Indigenous and marginalised communities and reshape their ecologies into 'green sacrifice zones' by reproducing a form of climate colonialism in the name of just transitions. (Zografos and Robbins, 2020).

Climate colonialism involves addressing the climate crisis through the continued domination of less powerful countries and peoples through initiatives that intensify foreign exploitation of their resources or undermine the sovereignty of Indigenous peoples and local communities (Sultana, 2022). Green sacrifice zones refer to 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 (Zografos and Robbins, 2020). Such sacrifice zones are not random, but carefully chosen within a power dynamic of colonial paradigms, worldviews and technologies that reduce life by equating it to a mere capitalist resource (Gómez-Barris, 2017).

The root causes of harm are often obscured when Western knowledge and technocratic interventions are prioritised over others, but there is an emerging governance of the impacts of loss and damage that need to be taken up by decision makers (Jackson et al., 2023). One critical aspect is to shift the focus away from individual action (Newell et al., 2021,) that places responsibility for change on those with least agency, and towards tackling the 'polluter elite' (Kenner, 2019; Wiedmann et al., 2020) and the infrastructure of high-impact sectors such as food and energy production, transport and housing that, combined, comprise about 75 per cent of total carbon footprints (Newell et al., 2021). In this, the PTP agenda could have a significant impact if it maintains reflection on who is being asked to change and why in order to drive nonlinear change.

4.6.6 Self-determination for the Global South

The capacity of the Global South and other marginalised communities to self-determine (make choices without the coercion of more powerful actors) has sometimes been undermined in diverse ways. Firstly, some commentators (e.g. Lyon and Maxwell, 2011) have argued that sustainability has been used as a cynical ploy: Western-led development frameworks and models have promised to uplift 'vulnerable' communities with payments for ecosystem services (Bottazzi et al., 2018), carbon trading and renewable energy projects, but which result in weakening or disregarding local structures and creating new structures and feedbacks that largely benefit developers. Evidence of the controversial impacts on local communities of Payment for Environmental Services (PES) has only recently become well known (Bottazzi et al., 2018). Although farmers have in some cases been willing to accept compensation for their nature conservation efforts in PES programmes (Geussens et al., 2019), such payments are often too little to cover their social and economic opportunity costs (Hayes et al., 2022; Vedeld et al., 2016). As a consequence, a system is created which promotes new forms of value (often monetary at the expense of other values), and which exacerbates existing inequalities and injustices and cultivates division within communities.

Creating a more decolonised future in the PTP or transformation landscape involves allowing local voices and capacities to surface in and by themselves (Scoones et al., 2015), to self-organise, self-determine and design changes as they see and need them (Rocha et al., 2022). By decolonial, we refer to the move away from the colonial worldview that anything differing from a Eurocentric worldview is inferior, marginal, irrelevant or dangerous (Santos, 2021) towards an appreciation of multiple temporalities, knowledges and praxes of living (emphasising the prefix 'de' rather than the prefix 'post') (Mignolo, 2021).

Supportive resources should also be chosen according to local needs and framings without stringent, unrealistic or exploitative terms and conditions. It is important to note that resources may come from various sources, ranging from development aid to compensation for historic damage (e.g. loss and damage payments due to historic GHG emissions), to payments for whatever international donors care about, such as investments in conservation projects.

Investment in a specific agenda for the 'global good' – for example, to avoid negative tipping points – cannot be undertaken at the expense of local needs without commensurate change in the behaviours of wealthy countries whose development has largely led to this crisis. (Hickel et al., 2022; Hickel and Slamersak, 2022).

As recommended by Obura et al., (2023), any positive changes in the human-nature discourse must uphold and respect local rights and voices, and as such enable agency to undertake the necessary changes.

With this in mind, there needs to be a deeper engagement to understand what kinds of information, knowledge and interventions can lead to PTPs that are truly equitable and spread the burden of change to those who have benefited most from the current system, rather than further marginalising the most vulnerable. Scientists, practitioners and their organisations who create decision making tools and solutions need to explicitly recognise the risks and trade-offs associated with them. The power dynamics of global models of carbon sequestration – for example, tree planting schemes – that impact local people and communities need to be carefully considered (Pereira et al., SI). It is of critical importance for researchers and practitioners working on positive and negative tipping points to reflect on how their findings might be used by other actors to drive agendas that aim to dismantle an unjust system (Engler and Engler, 2021). This requires a decolonisation of the solution space of what is needed to address tipping points. Space for alternatives that do not come from a Western-dominated perspective needs to be opened up and imaginations engaged (Pereira et al., SI; Yusoff and Gabrys 2011). In particular, there needs to be an openness to alternative economic models based on regeneration beyond growth.

4.6.7 Forms of equity and justice

Governance needs to go beyond over-simplistic, quantitative indicators, such as counting how many trees have been planted and where. It needs to acknowledge the rights, values, visions, knowledge and needs of local communities in policies: **recognitional equity**. It also needs to ensure an inclusive and participatory decision-making process: **procedural equity** (Bennett, 2022). Earth system, biodiversity and wellbeing outcomes (as well as potential harms) should be balanced: **distributional equity**. The interests of disadvantaged or marginalised groups need to be safeguarded, including nonhuman species and ecosystems: **environmental equity**. Leadership from, and participation with, local communities should be fostered and improved to allow local engagement in management activities: **management equity**. Emphasis should also be placed on qualitative factors such as equity and justice of protected areas: **contextual equity** (Pickering et al., 2022). Failing to address any of these dimensions may result in reproducing historical injustices and simply 'kick the tipping point down the road'.

4.6.8 Implications for practice

We close by recommending some practical implications for different change agents.

4.6.8.1 Policymakers

Governments must step up to address inequality through improved legal and fiscal policy (Green, 2021). Domestic fiscal policy needs to subsidise or compensate lower-income households for the higher costs that accompany regulations like carbon pricing, emissions trading and new standards. Failure to do so could set off a cascade of unintended consequences and increase poverty, inequality and other impacts like popular protest and political instability. Legal mechanisms to ensure procedural, reparative and distributive justice are also imperative. PTPs require intervening in complex systems that we do not fully understand. Policymaking therefore needs to become more flexible and anticipatory, and include the ability to correct for unintended consequences. Such anticipatory governance mechanisms could include ringfencing funding to support unintended consequences as well as ongoing review of policy interventions to assess their effectiveness and equity and allow for a change of direction if necessary. Policy and governance actors attracted to positive social tipping interventions should also recognise that research is constantly updating and so there is a need to be aware of hidden assumptions, biases and potential for backfires, rebounds and other unwelcome results (Sterman, 2002).

4.6.8.2 Finance

Investments need to guide sectors along more sustainable and equitable pathways rather than fuel unsustainable business models, working conditions and use of resources – for example through the coupling of public incentives and improved working conditions (Jouffray et al., 2019). Divesting from companies that are seen to be complicit in transgressing planetary boundaries, such as oil majors and powerful cattle lobby groups in the Brazilian Amazon (Piotrowski, 2019) has the potential to reshape the business environment towards more equitable practices. Another area where investments could leverage PTPs is in the shift away from car dependency, particularly for those living in densely populated metropolitan areas, whose health and life expectancy would benefit from improved air quality and pedestrian safety (Rionfrancos et al., 2023). 4.3.2 on transport and mobility systems discusses efforts to avoid demand for material-intensive mobility and shift to more active modes of travel. Finally, finance has the opportunity to redistribute money to vulnerable regions and intervention spaces like mitigation, adaptation, loss and damage, and biodiversity (4.4.3). Currently there is highly uneven access to credit and capital to bring about more transformative change. Such reconfiguration of finance flows needs to be undertaken with full consideration of the impact that such investments would have, not just on financial returns, but also on social and environmental outcomes.

4.6.8.3 Business

Businesses are part of social-ecological systems, not separate from them, and so business needs to recognise that the only way to avoid negative tipping points is through active interventions to change the current system. This requires strong regulation of the access and financial power that incumbents have over political systems to enable a space for transformative change. Businesses that want to be leaders in a more sustainable and equitable future should also encourage the redirection of financial resources towards enabling PTPs and away from sectors causing the most harm. For example, they should support moves to redirect the US$11m per minute currently being spent on fossil fuel subsidies towards improved access to renewable energy for poorer communities (McCulloch, 2023).

4.6.8.4 Media and discourse

Media, and all climate communicators, must be alert to the competing ideologies, values and systems of power that affect which messages are communicated and how that message is interpreted by different communities. This is particularly relevant in relation to the language of 'positive' and 'negative' tipping points, which can imply a universality of effect that is insensitive to the diverse experiences and responsibilities of different communities. Knowledge does not automatically lead to enlightened action (Norgaard, 2011). Certain facts and emphases – for example, emphasising the risks of climate breakdown rather than the co-benefits of climate action – may serve to further entrench dismissive perceptions of climate change (Bain et al., 2012). There is therefore a need to shift away from linear, 'information-deficit' models of communication towards values-inclusive, reflective and creative dialogues (Gaertner and Dovidio, 2014; Stirling, 2010). Communication strategies should be tailored to and co-produced with the communities they are seeking to engage (Wang et al., 2020). Media and communication organisations must not see themselves as neutral information transmitters, but as actors in a complex, nonlinear system that is entangled with issues of knowledge and power.

4.6.8.5 Researchers

More inclusive global research needs to be undertaken that reflects on the justice and risk aspects of tipping points. Scientists have an agenda-setting function and a breadth of expertise that will be invaluable in navigating the science-policy interface and solving complex problems like tipping points. Greater diversity in terms of cultural, religious, ethnic, gender, background and discipline of researchers is needed. Place-specific information and experience is often lacking as a lot of research is concentrated in high-income countries. In order to harness relevant positive tipping opportunities, researchers and practitioners need to understand diverse living realities and interact with actors outside of their professional 'bubbles' (Bentley et al., 2014).

Avoiding diverse harms requires a broad range of experience and expertise, and an acknowledgement of the need for plural approaches not only within academic disciplines, but also of diverse knowledge systems beyond academia.

(Tàbara et al., 2022). By being more mindful about inclusiveness, research can bring about more procedural justice into research through participatory co-design, action research and humility on the part of researchers. Diversity and inclusivity of research teams – within and beyond academia – are needed to help find solutions to tipping points that do not exacerbate existing inequities and inequalities.

4.6.8.6 Embrace creative co-production

The effectiveness of literature, film and art in promoting ethical responses to climate change is increasingly being recognised (James, 2015; Weik von Mossner 2017; Galafassi et al., 2018): 'The arts have an ability to communicate the vulnerability and sensitivity of climate issues that other channels may lack' (Holmes 2020, P.10). The arts also offer models for empowering communities to create their own narratives and contextualise tipping points in relation to their own systems of value. These can help to imagine and articulate alternative imaginaries of change: 'from what is to what if?' (Hopkins, 2019).

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Appendix 1: Glossary

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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.
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).
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.

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Section 1

Earth system tipping points

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Chapter 1.5 References

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Section 2

Tipping point impacts

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Section 3

Governance of Earth system tipping points

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Chapter 3.3

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Section 4

Positive tipping points in technology, economy and society

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Chapter Reference 4.6 Risks, equity and justice in the governance of positive tipping points

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