Section 2

Tipping point impacts

Section lead coordinating authors:

Jesse F. Abrams, Steven J. Lade, Jonathan F. Donges and Joshua E. Buxton

Reviewers:

Luke Kemp, Richard Mann, Michael Mäs, Coleen Vogel

Contents

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.

Chapter 2.1 Tipping point impacts

Introduction

Authors: Steven J. Lade, Jesse F. Abrams, Sirkku Juhola, Viktoria Spaiser

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.

Chapter 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.

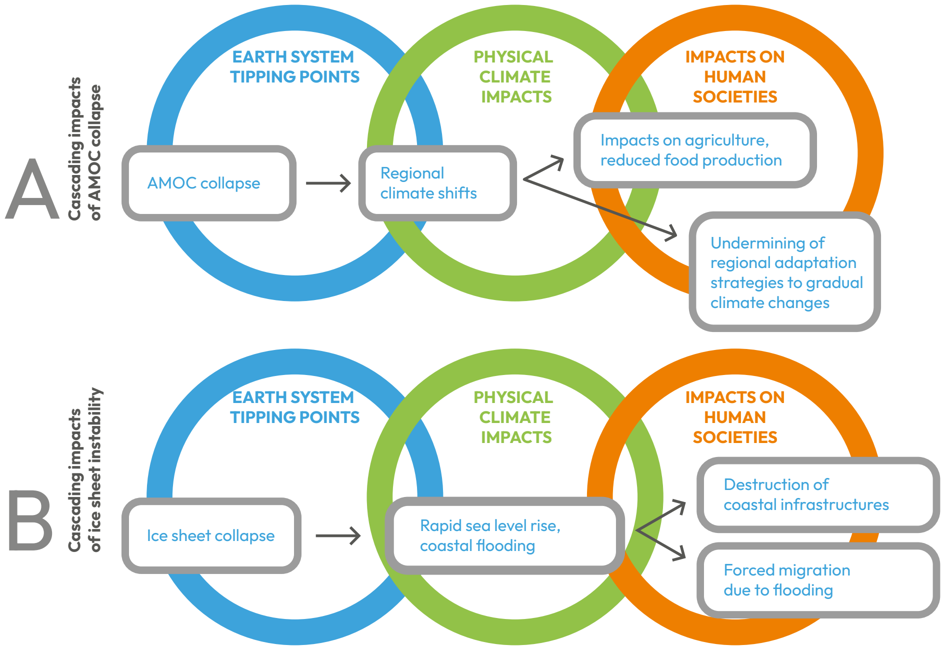

Figure 2.2.1: Selected impact pathways of negative Earth system tipping points. a) Cascading impacts of AMOC collapse, b) cascading impacts of ice sheet instability.

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.

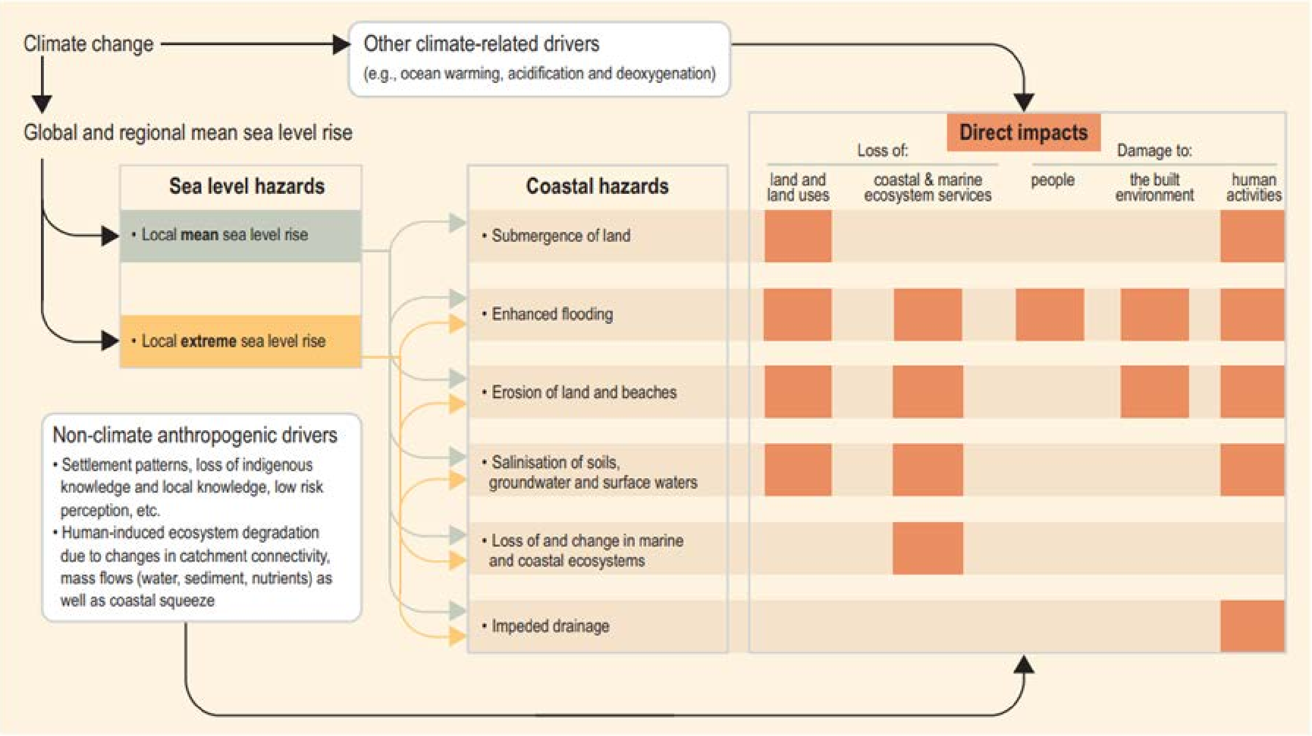

Figure 2.2.2: Cascading impacts of rising sea levels across systems, reproduced from Oppenheimer et al., 2019. Sea level rise and consequent impacts could be accelerated by crossing tipping points in ice sheets or the AMOC.

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).

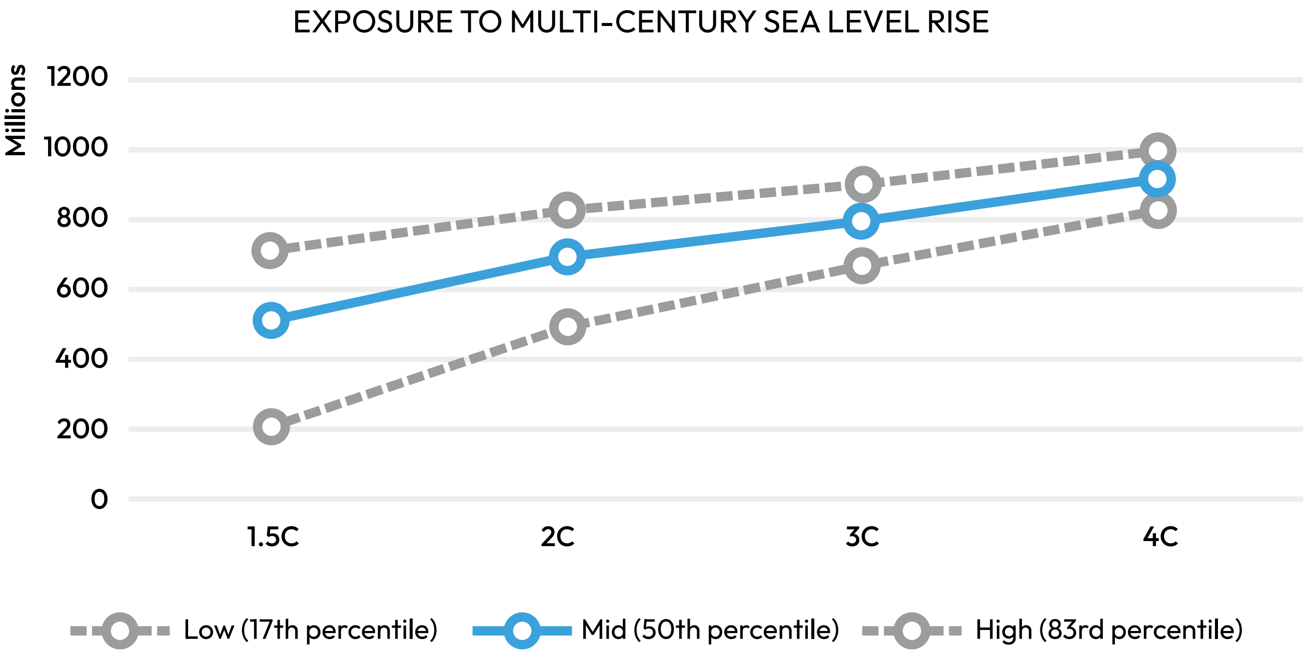

Figure 2.2.3: Projected number of people exposed to multi-centennial sea level rise including the impacts of cryosphere tipping points under a global mean temperature rise stabilised at 1.5°C, 2°C, 3°C and 4°C global warming, with population at 2010 levels Data source (Rockström et al., 2023).

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.

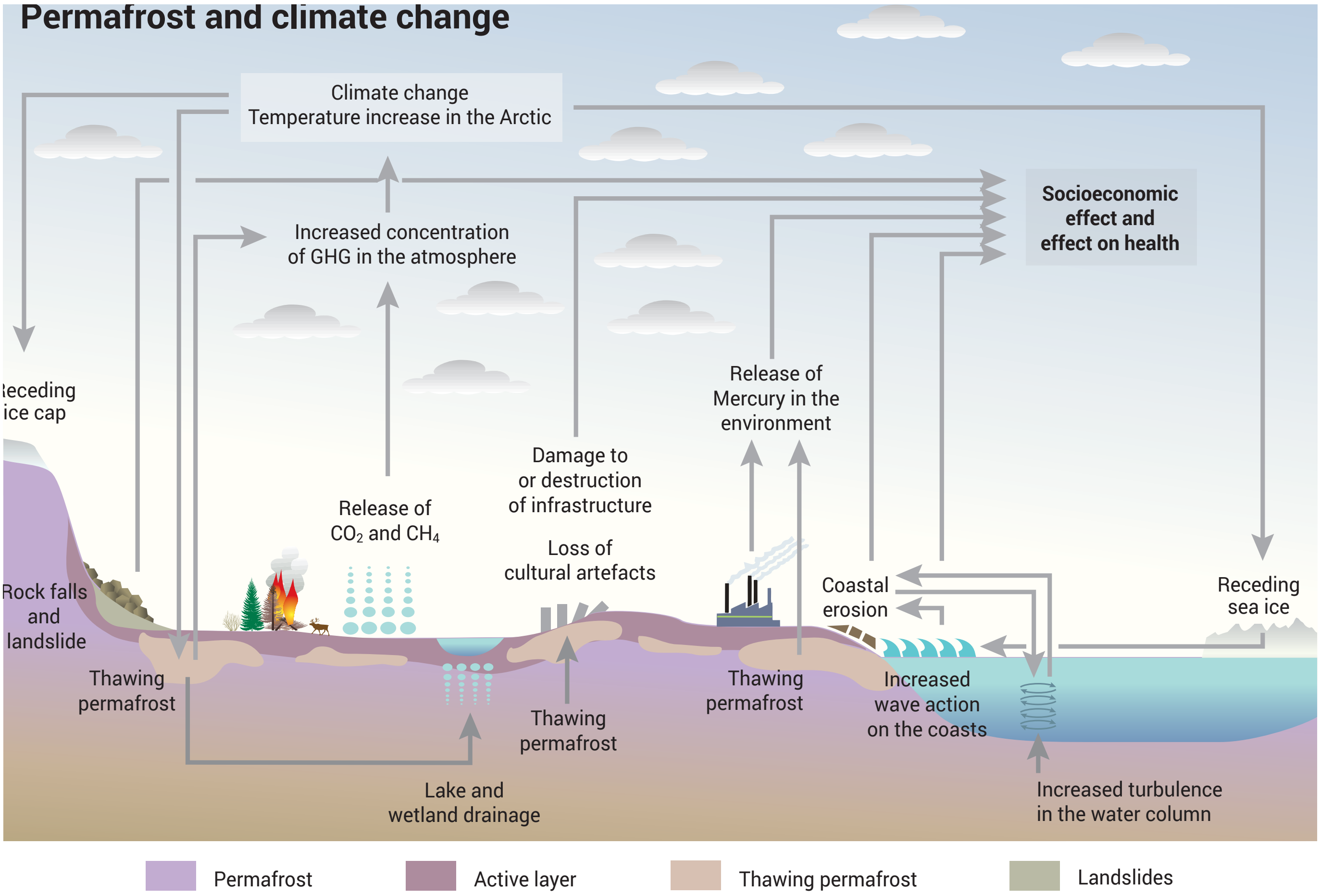

Figure 2.2.4: Permafrost changes under climate change and subsequent effects on environment and society (https://www.grida.no/resources/13348). Credit to Riccardo Pravettoni and Philippe Rekacewicz.

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.

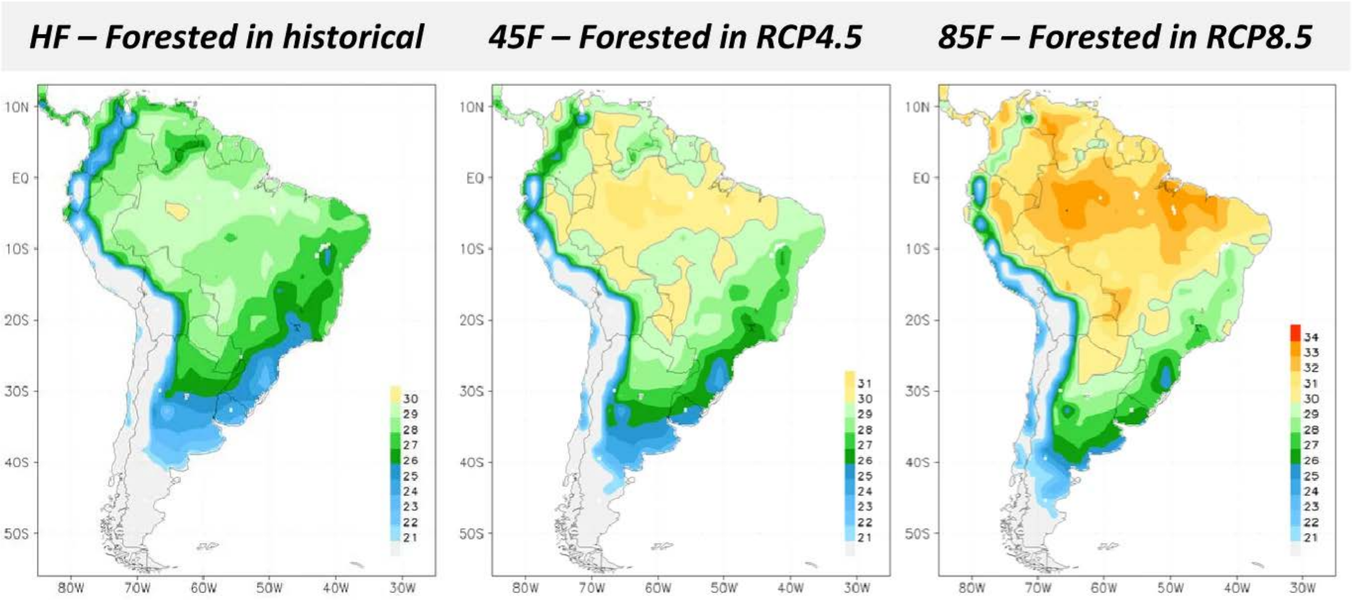

Figure 2.2.5: Projected impacts of Amazon forest loss on heat stress risk, quantified with Wet Bulb Globe Temperature (WBGT) in °C, in a climate simulation with the BESM-OA2.5 model driven by the RCP4.5 scenario. Reproduced from De Oliviera et al. (2021)

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.

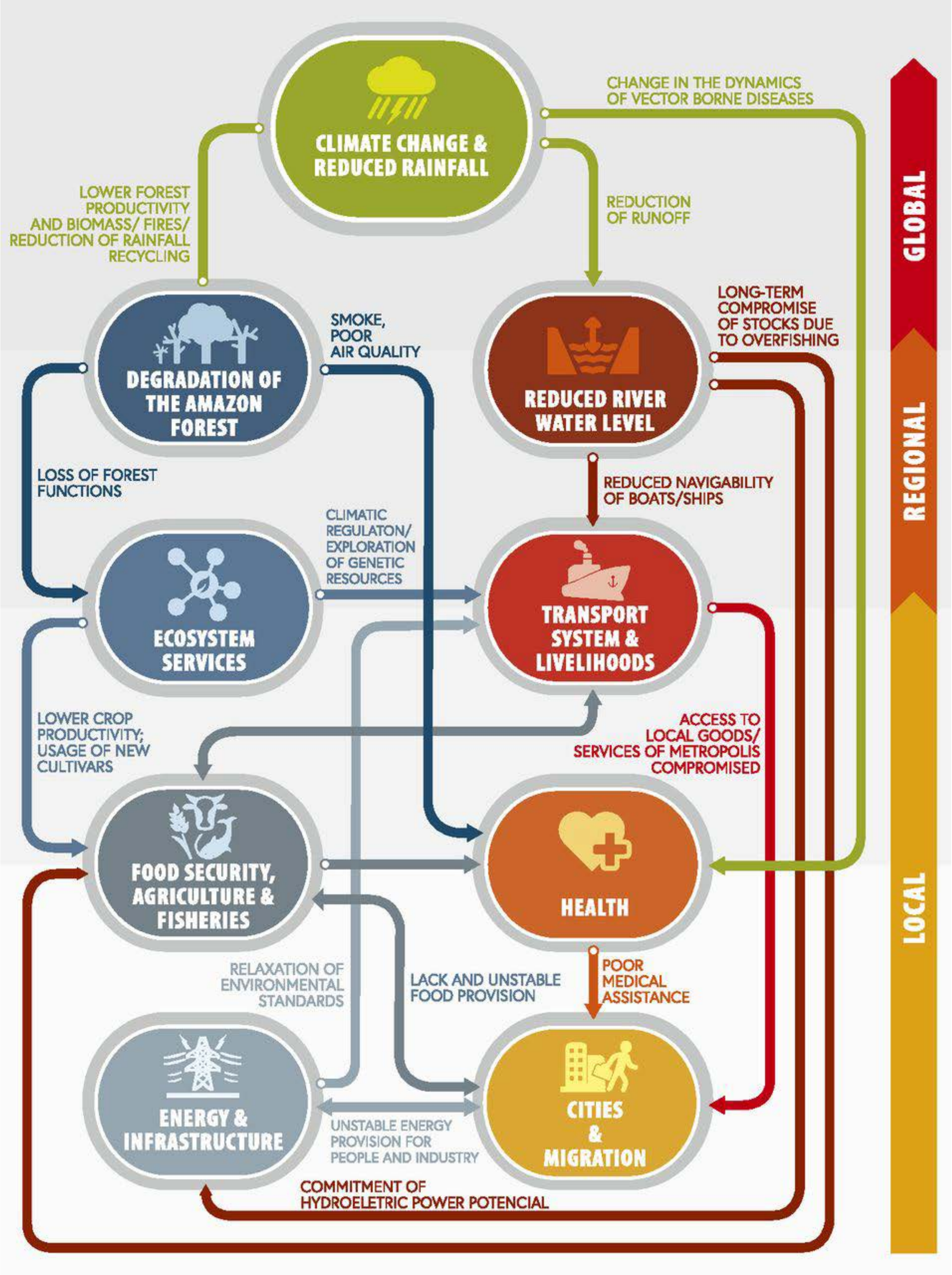

Figure 2.2.6: Socioeconomic impacts of Amazon dieback. Reproduced from Lapola et al., (2018).

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).

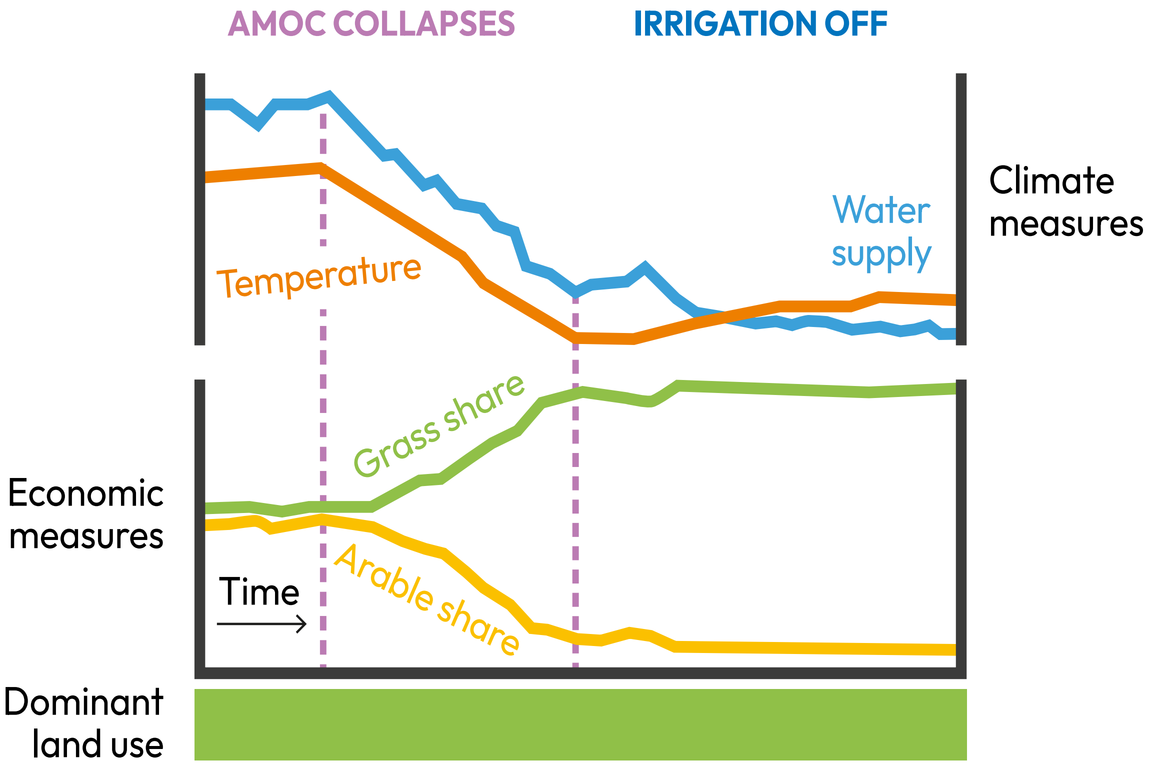

Figure 2.2.7: Impact of AMOC collapse on UK water supply and arable crops (Ritchie et al., 2020).

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).

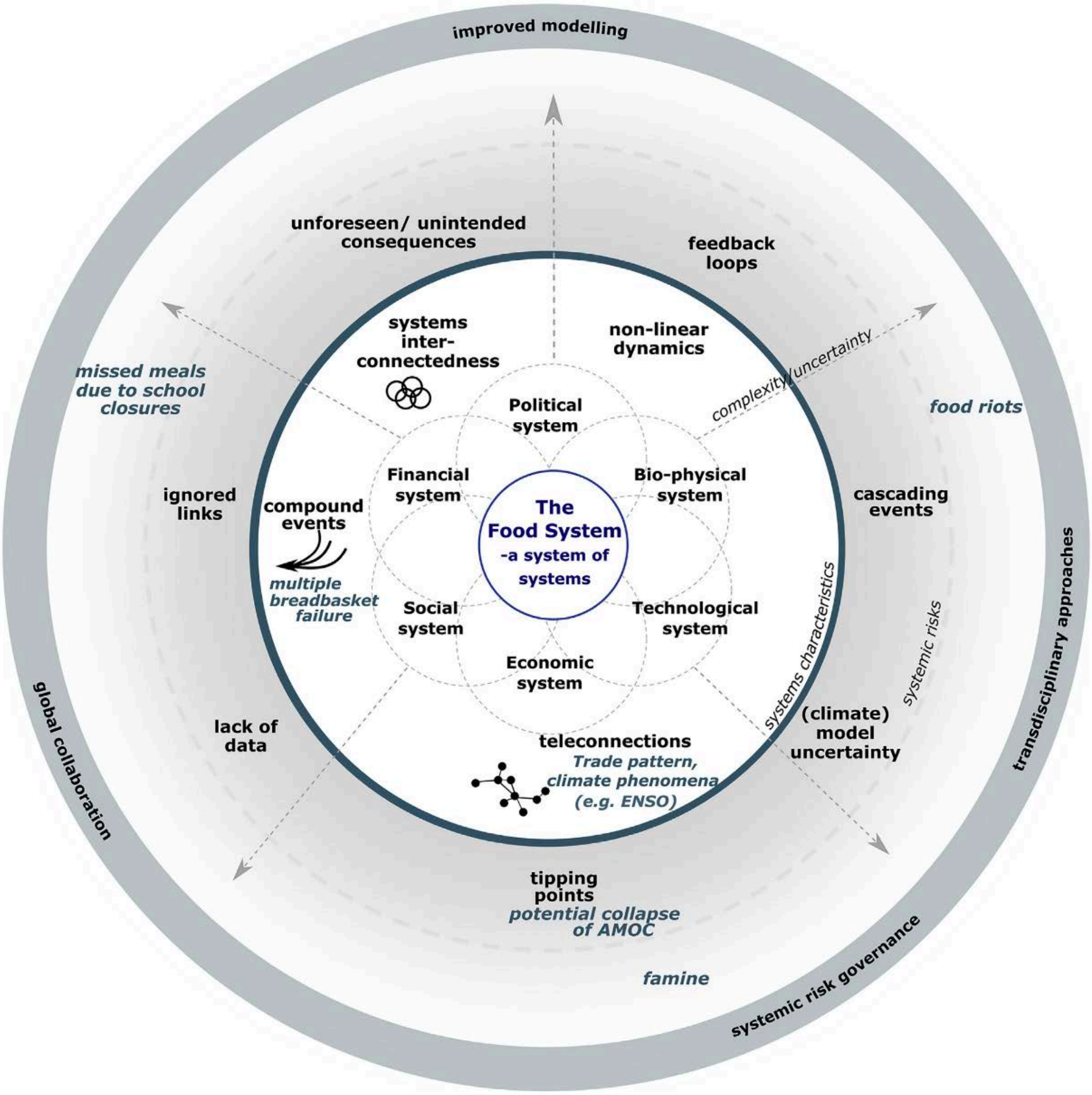

Figure 2.2.8: The complexity of the global food system and its inherent systematic characteristics. Reproduced from Gaupp (2020).

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.

Chapter 2.3 Negative social tipping points

Authors: Viktoria Spaiser, Jürgen Scheffran, Uche T. Okpara, Weisi Guo, Florian Krampe, Sara M. Constantino, Ricardo Safra de Campos, Patricia Pinho, Taha Yasseri, Tabitha Watson, Daniel Godfrey, Hugues Chenet, Avit Bhowmik, John T. Bruun

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.

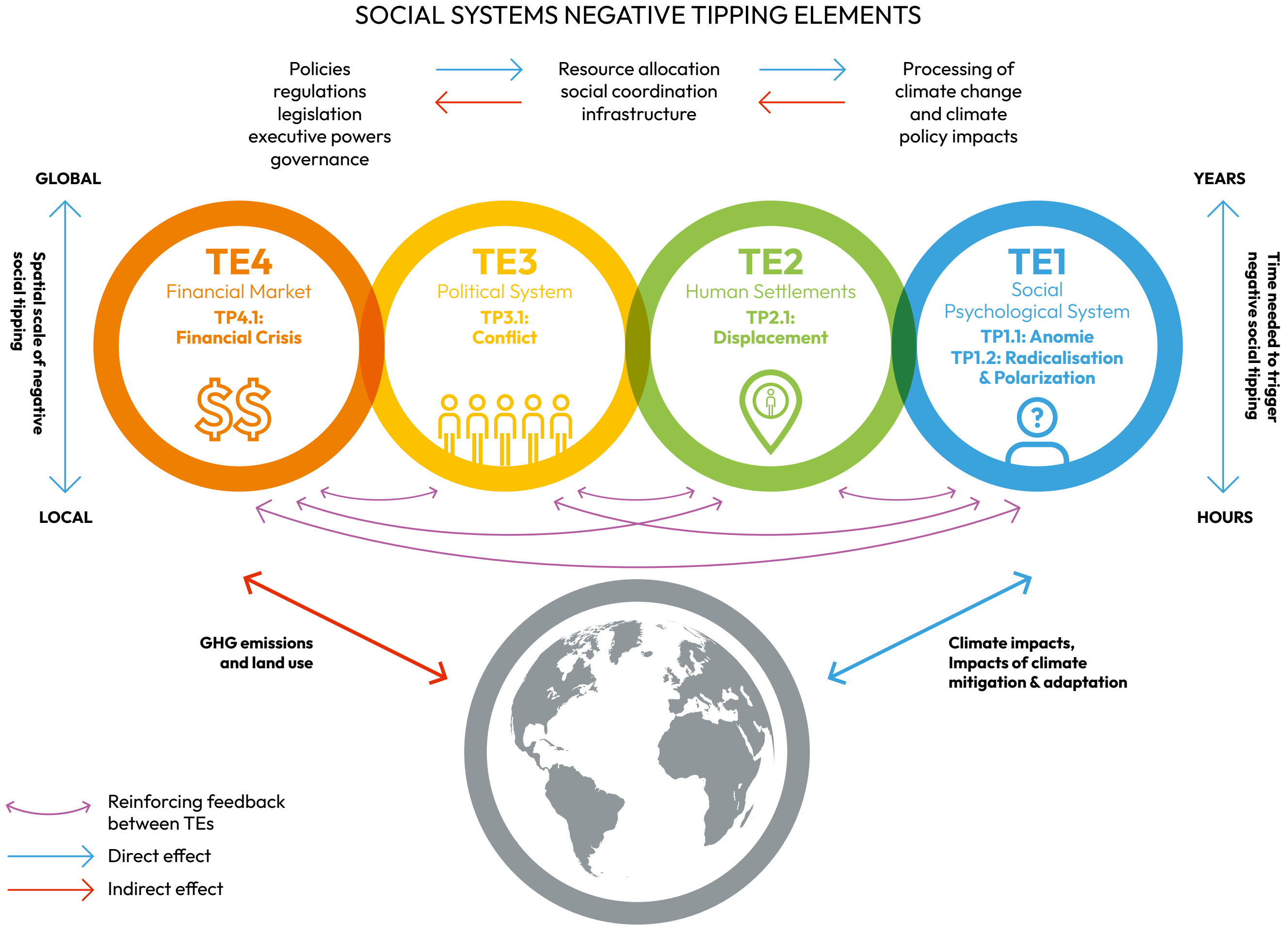

Figure 2.3.1: Tipping elements (TE) and associated negative social tipping processes (TP) with the potential to further destabilise the world–Earth system. The processes they represent unfold across levels of social structure on different time- and spatial scales. Tipping in all tipping elements can 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); HamidehH 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.

2.3.2.3 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).

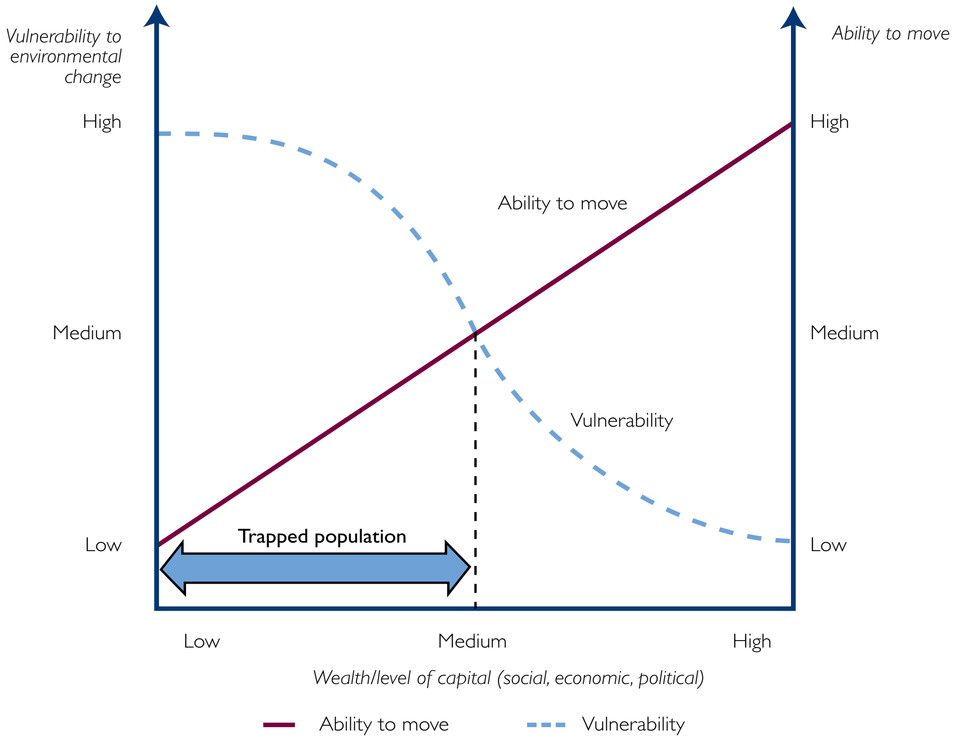

Figure 2.3.3: Mobility as a function of vulnerability and economic resources (Source: Foresight 2011).

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.

Chapter 2.4 Cascades of tipping in impacts

Authors: Sirkku Juhola, Juan Rocha, Jana Sillmann, Ashleigh Basel, Sara M. Constantino, Alessandro C.W. Craparo, Graeme S. Cumming, Jonathan F. Donges, Tatiana Filatova, Alexandra Malmström, Vidur Mithal, Jürgen Scheffran, Heidi Tuhkanen, Tabitha Watson

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.

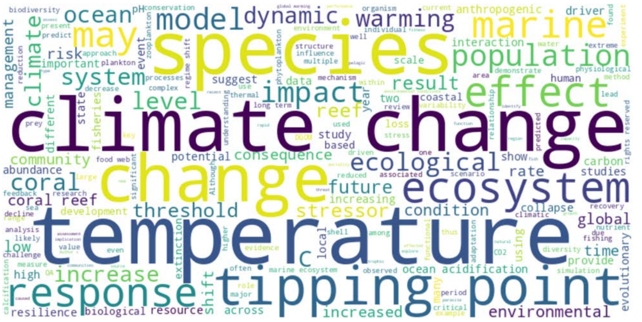

Figure 2.4.1: Climate change tipping points

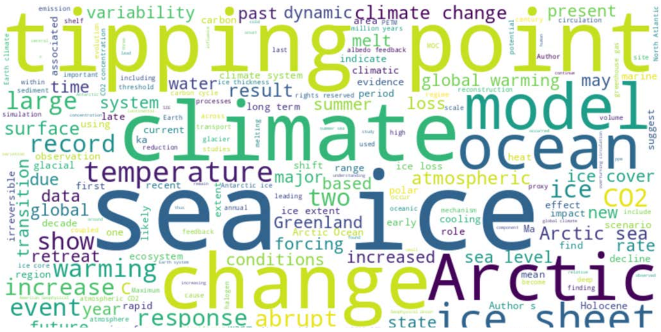

Figure 2.4.2: Ice arctic sea seaice

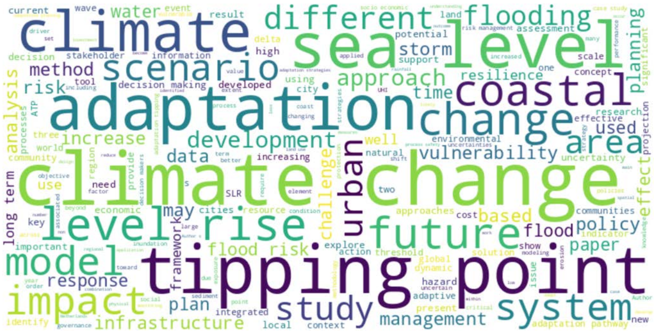

Figure 2.4.3: Adaptation coastal flood rise

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.

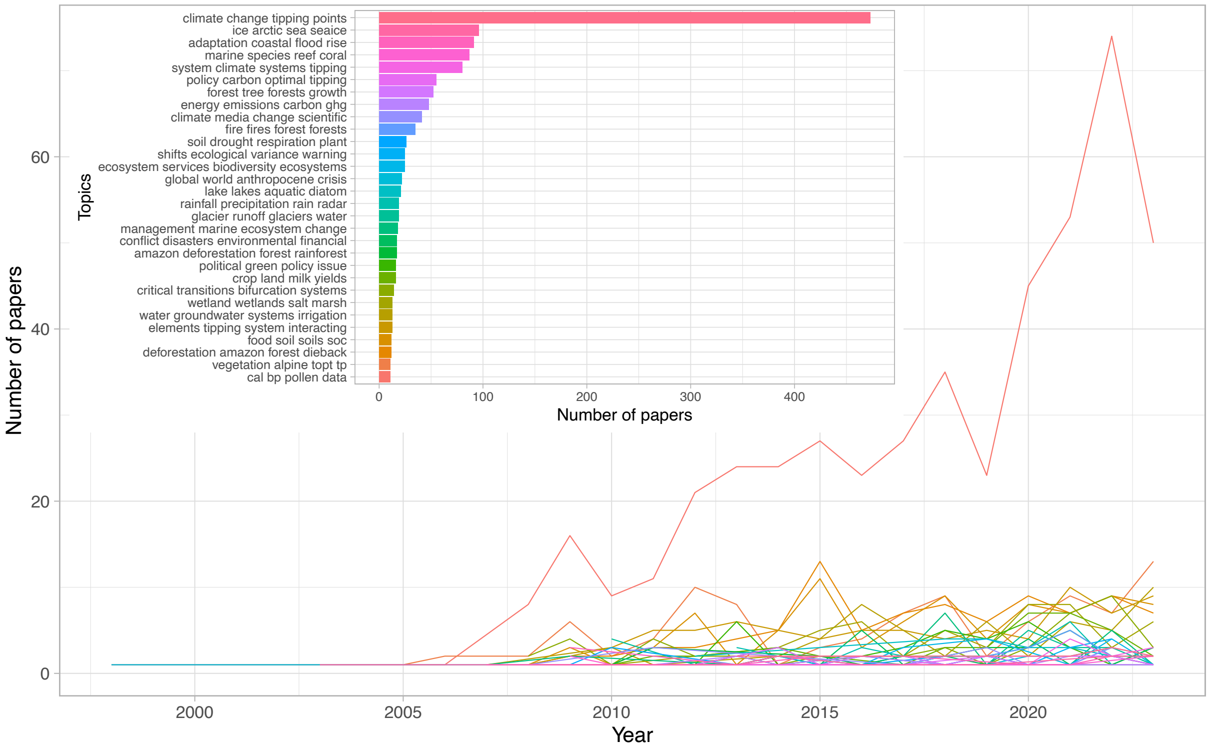

Figure 2.4.5: Unique topic clusters generated using BERTopic ranked by the associated volume of publications within each, and the temporal dynamics thereof.

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.

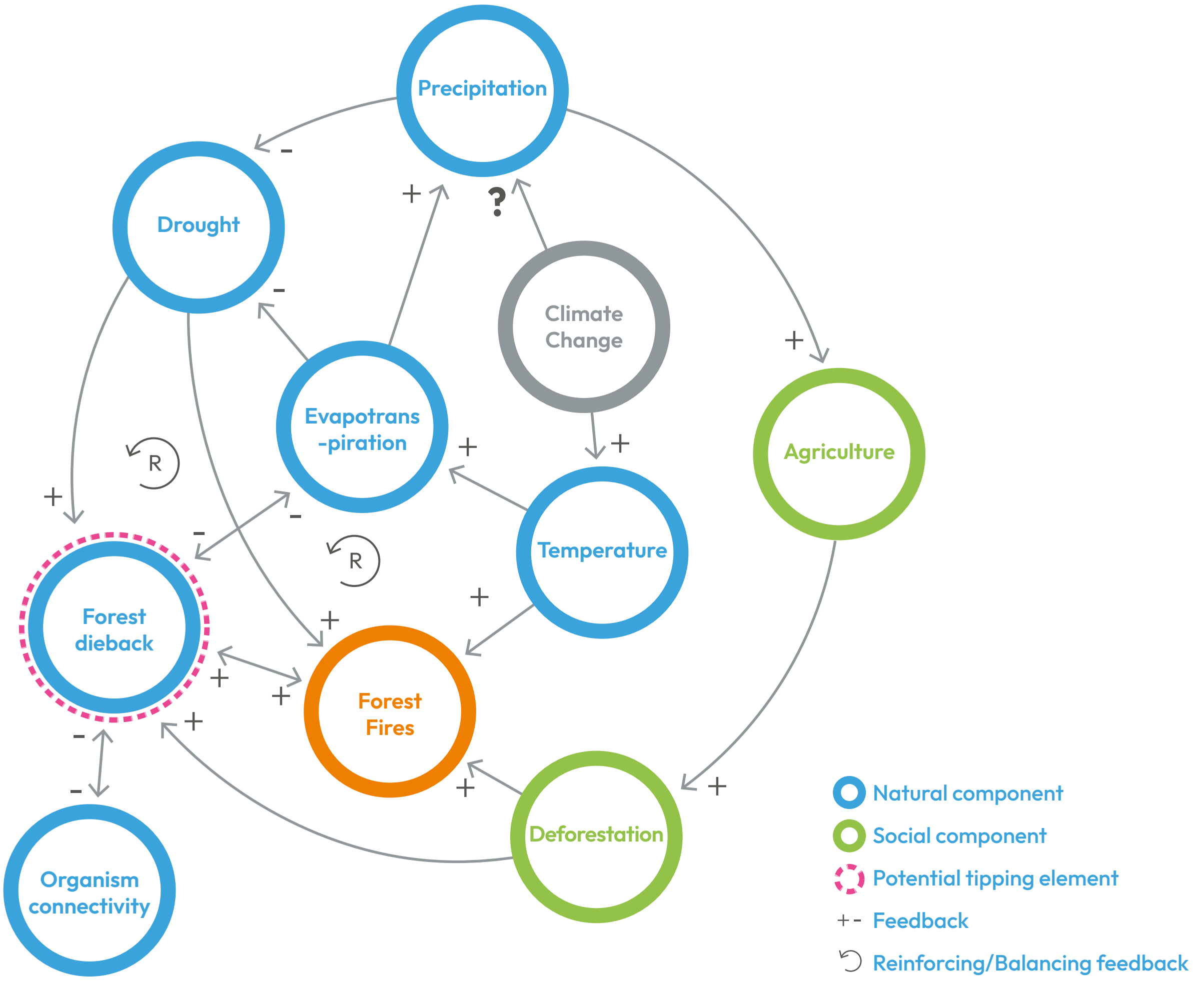

Figure 2.4.6: Tipping cascades in the Amazon rainforest.

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.

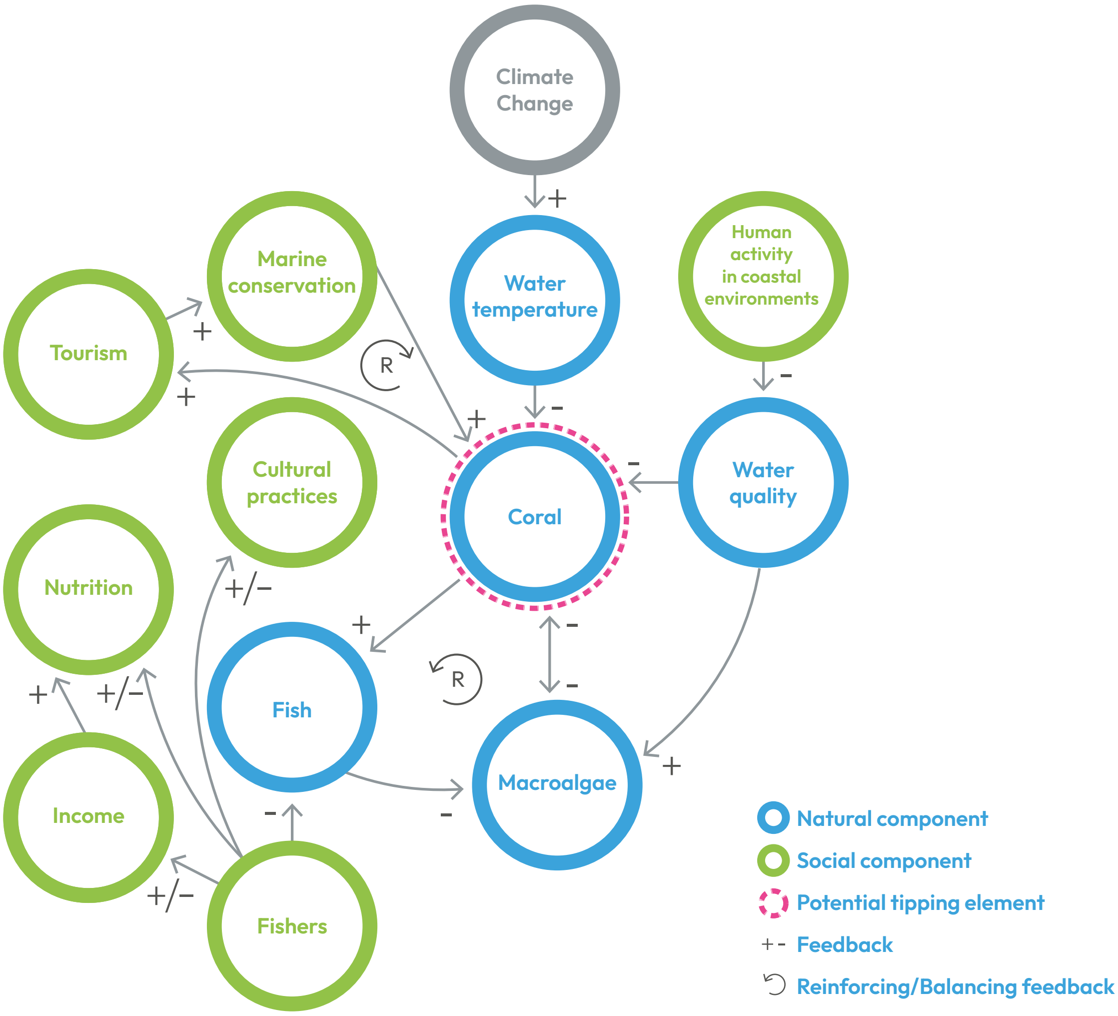

Figure 2.4.7: Tipping cascades in coral reefs and small-scale fisheries.

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.

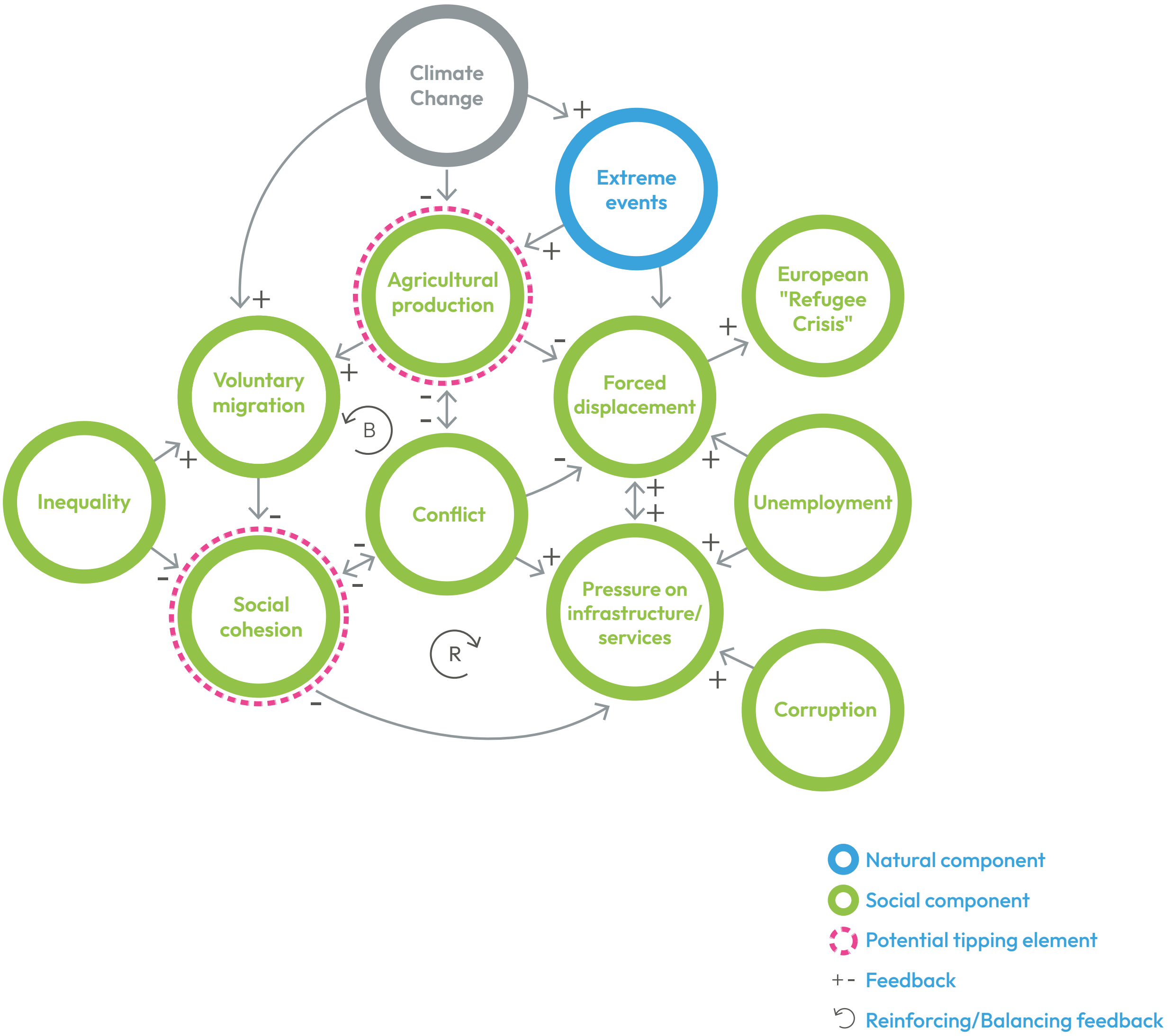

Figure 2.4.8: Tipping cascades in migration.

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).

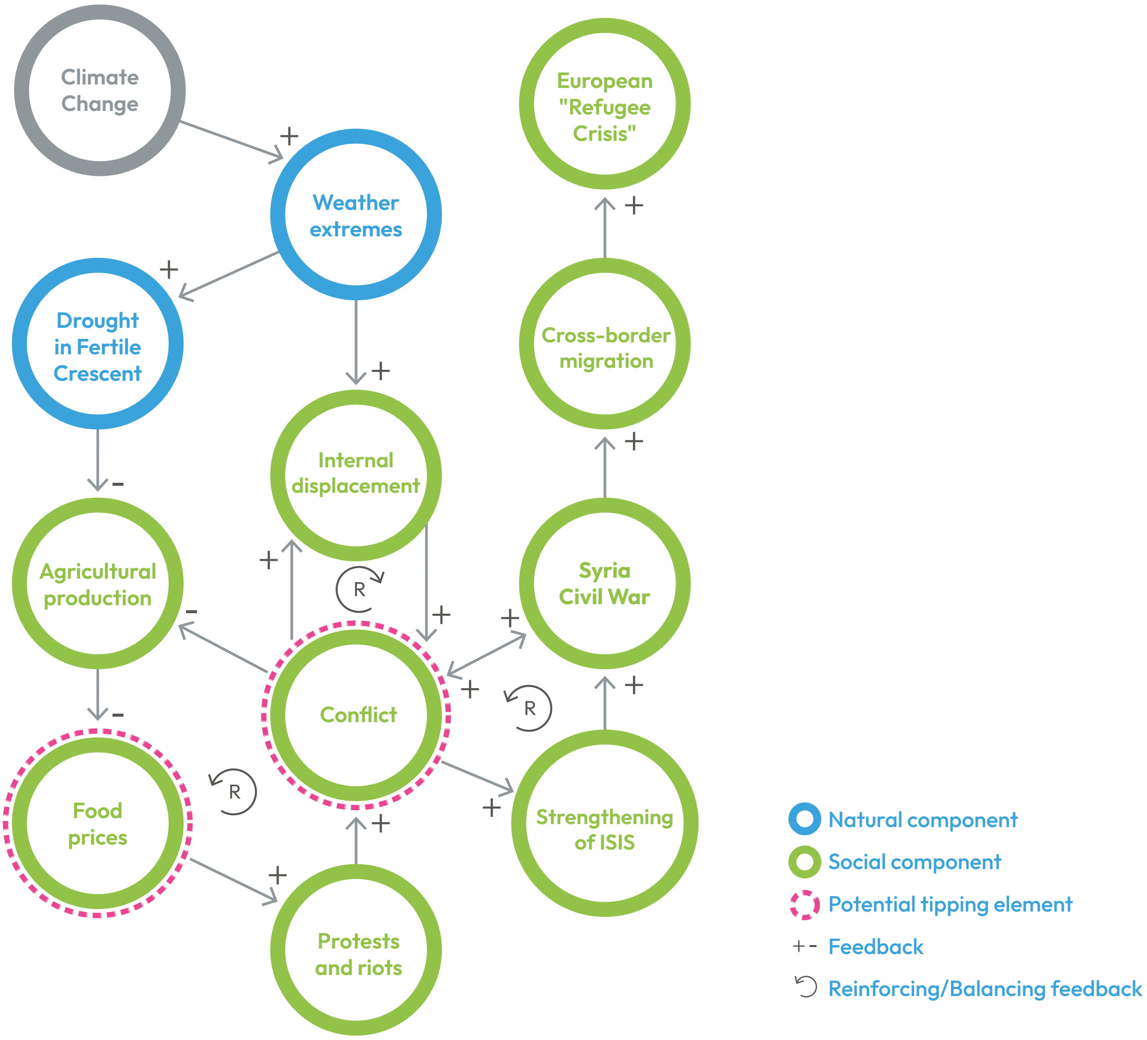

Figure 2.4.9: Tipping cascades in the Arab Spring.

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).

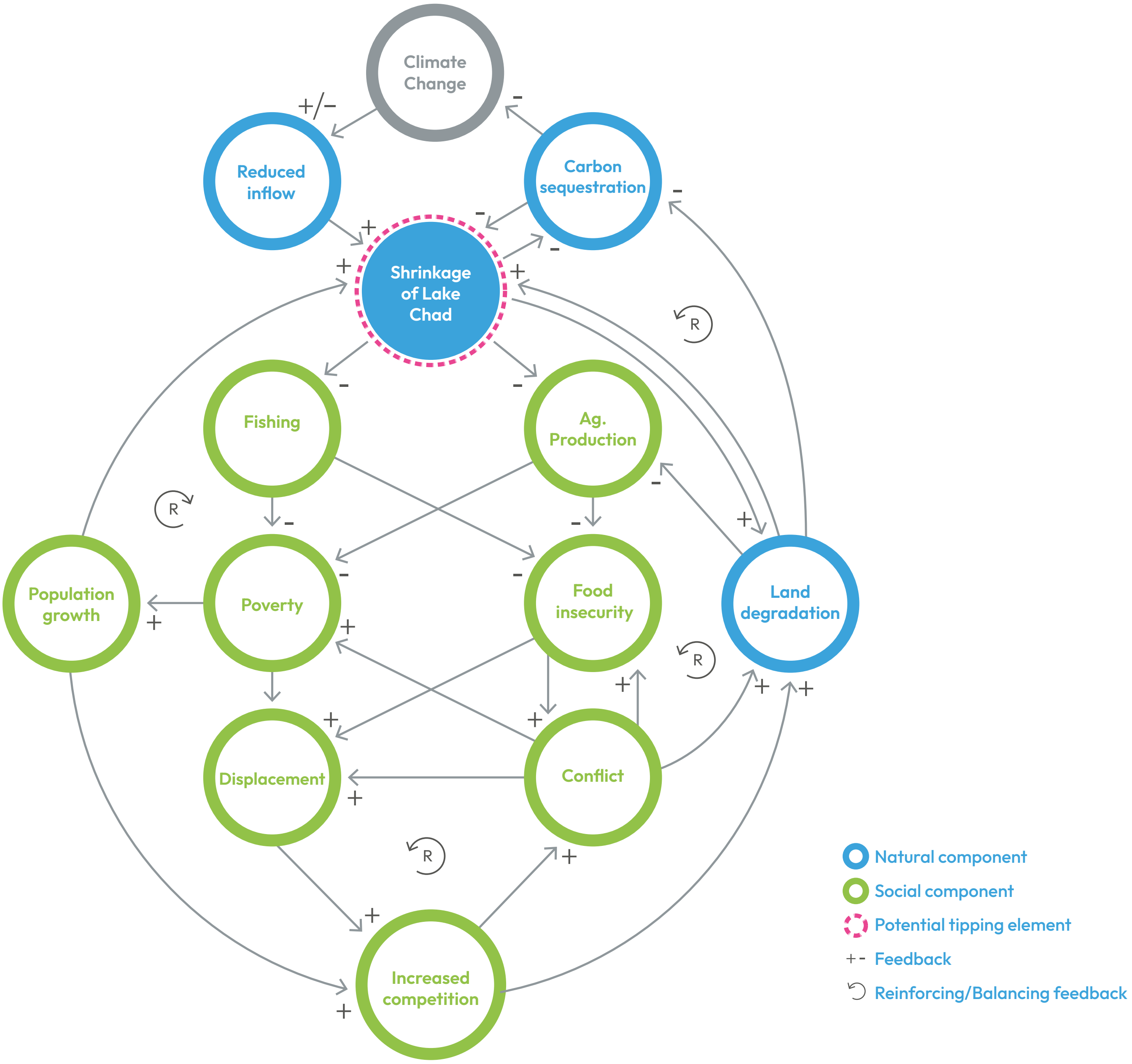

Figure 2.4.10: Tipping cascades in Lake Chad.

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.

Chapter 2.5 Early warning of tipping points in impacts

Authors: P. Krishna Krishnamurthy, Isaiah Farahbakhsh, Chris Bauch, Madhur Anand, Joshua B. Fisher, Richard J. Choularton, Viktoria Spaiser

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.

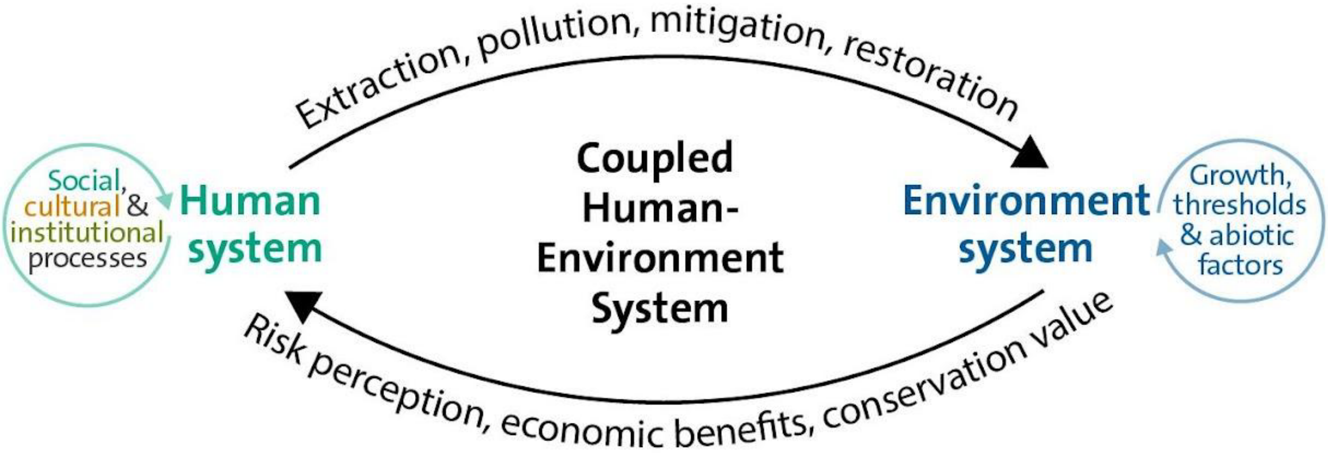

Figure 2.5.1: An illustration of key feedbacks in coupled social-ecological systems. Identifying tipping points in social-ecological systems is a difficult task because of the complex feedback loops and response of social systems. However, recent examples in the literature have shown how social-ecological 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.

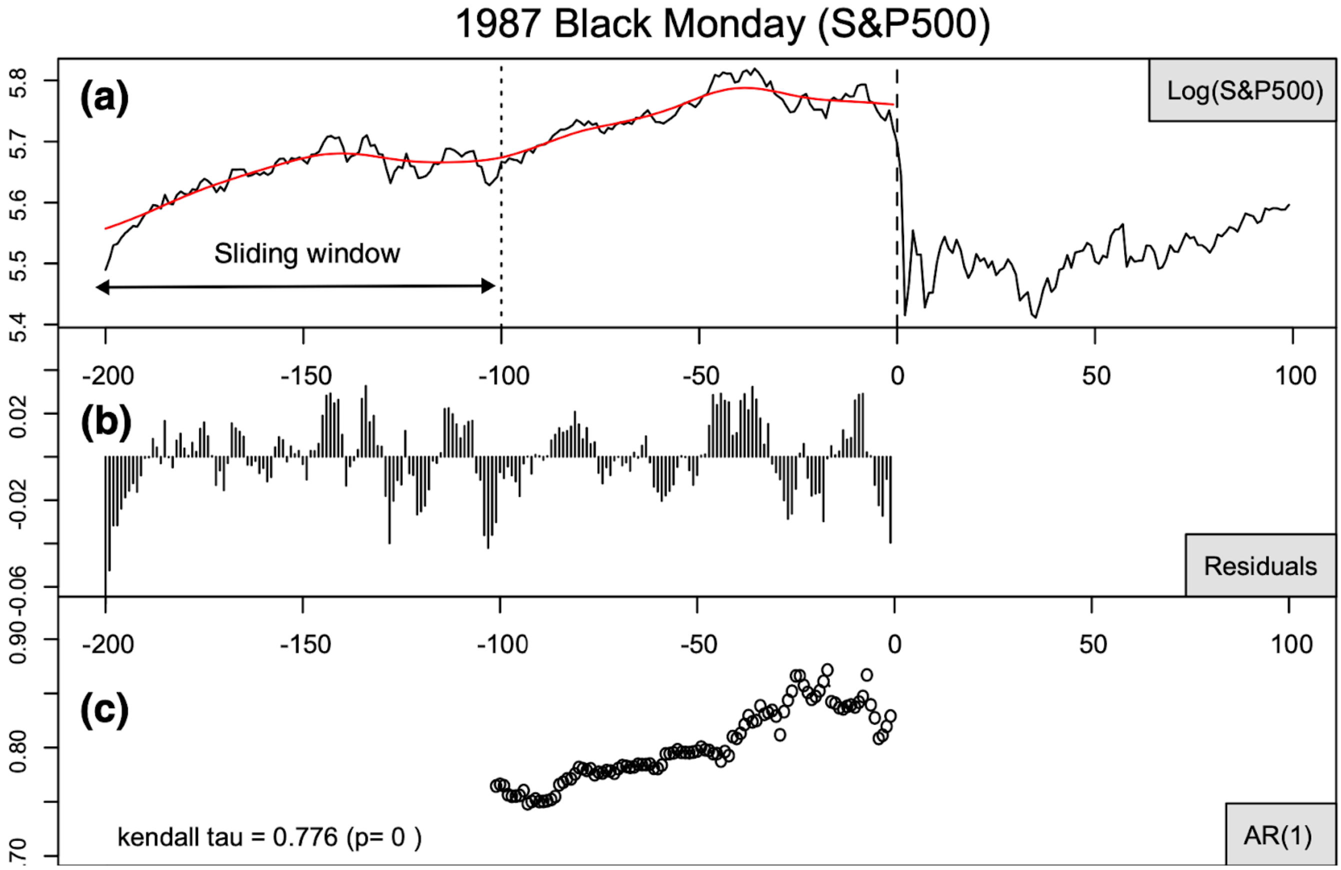

Figure 2.5.2: Early warning signals for financial time series data leading up to the 1987 Black Monday financial crisis. This analysis could also be performed on financial data directly related to resource extraction. Source Diks et al., 2019

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).

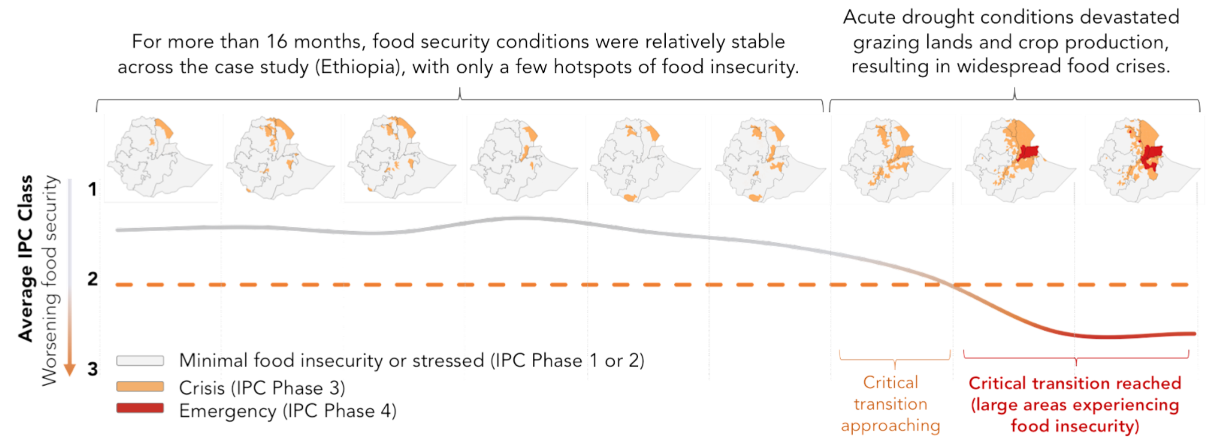

Figure 2.5.3: Example of a tipping point in the context of food security, showing the transition from stable food security conditions to a food crisis resulting from drought in Ethiopia. Source: Krishnamurthy et al., 2020

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).

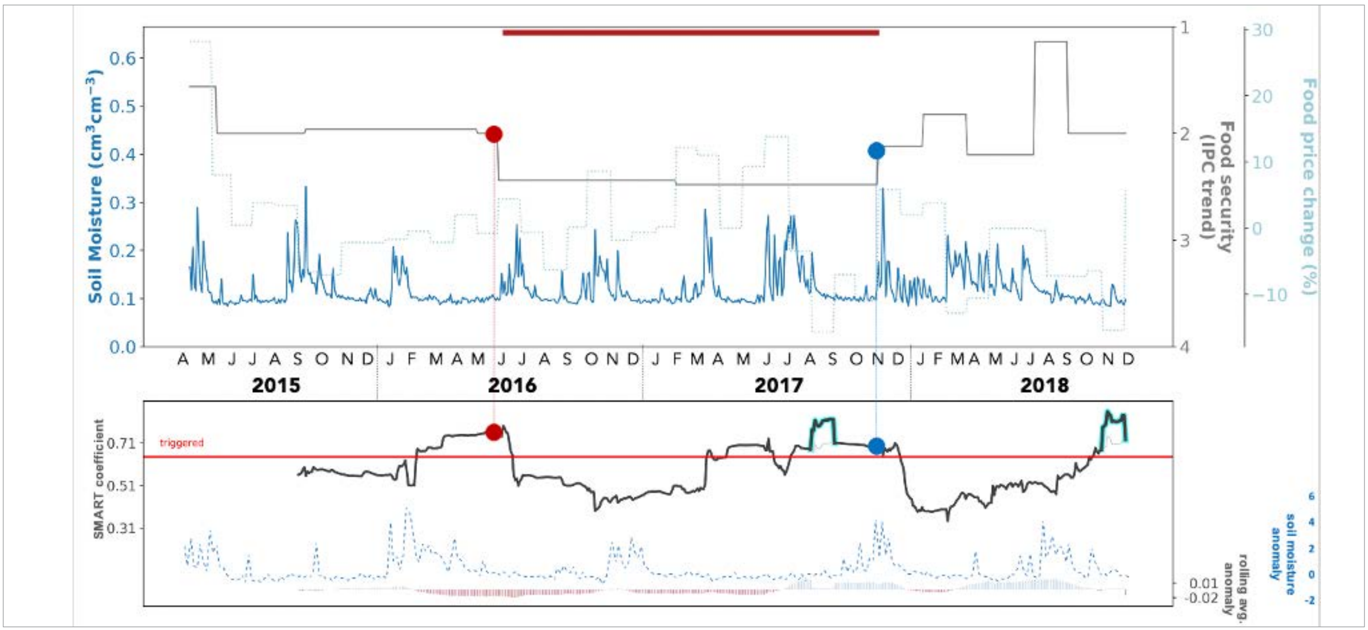

Figure 2.5.4: Data visualisation dashboard showing how food security transitions are detected with remotely sensed soil moisture data and food price data. Top panel: Integrated Food Security Phase Classification (IPC) (grey line), remotely sensed soil moisture from SMAP (solid blue line) and food price 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).

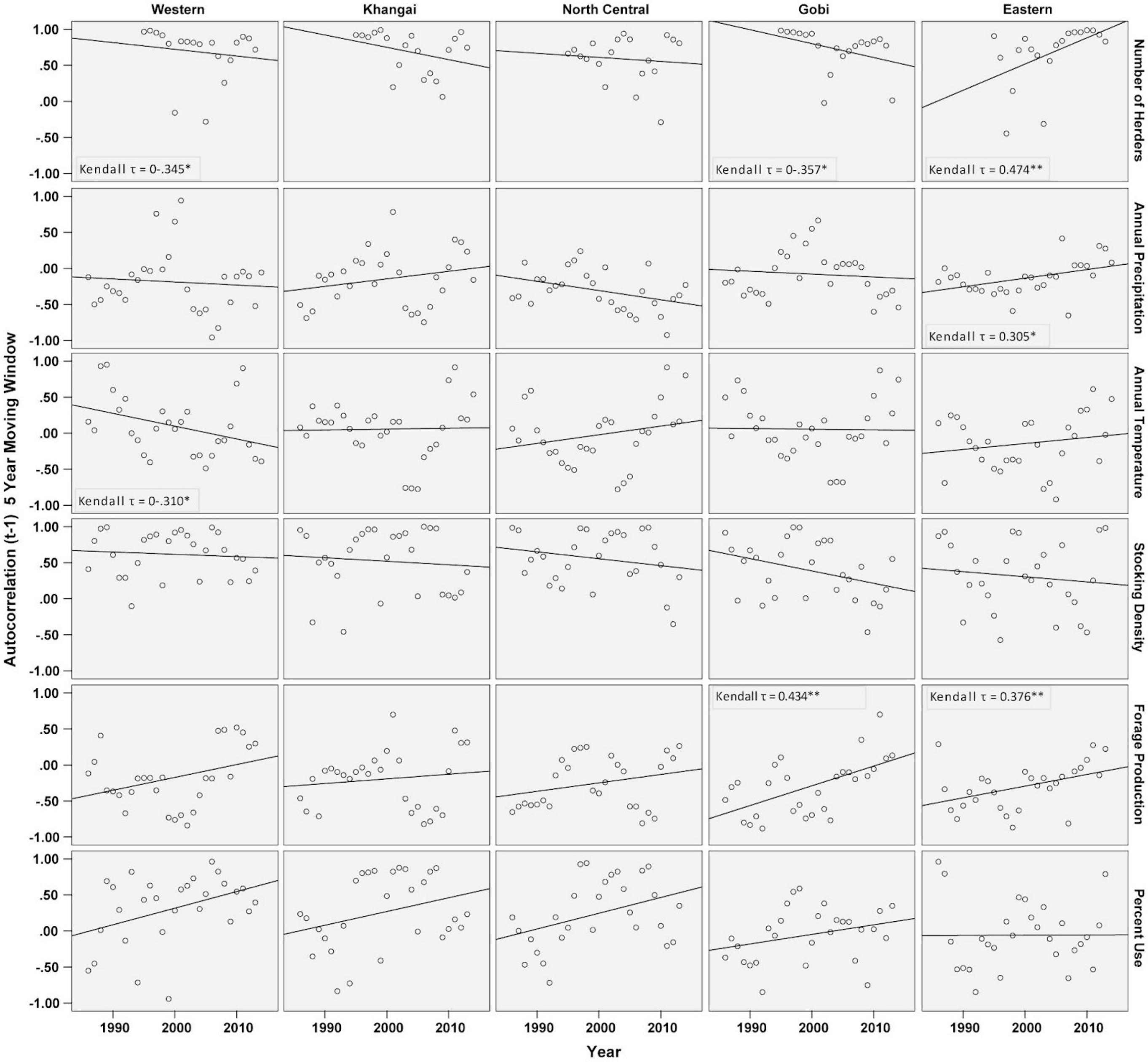

Figure 2.5.5: Trends in five-year moving window autocorrelation. Where original values indicated a significant trend, data were detrended before analysis. Strength of correlations is indicated by Kendall's Tau where significant. * indicates $p < 0.05$, ** indicates $p < 0.001$. Reproduced from (Fernandez-Gimenez 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.

References: Chapter 2.1

Centeno, M. A., Nag, M., Patterson, T. S., Shaver, A., & Windawi, A. J. (2015). The Emergence of Global Systemic Risk. Annual Review of Sociology, 41(1), 65–85. https://doi.org/10.1146/annurev-soc-073014-112317

Juhola, S., Filatova, T., Hochrainer-Stigler, S., Mechler, R., Scheffran, J., & Schweizer, P.-J. (2022). Social tipping points and adaptation limits in the context of systemic risk: Concepts, models and governance. Frontiers in Climate, 4, 1009234. https://doi.org/10.3389/fclim.2022.1009234.

Kemp, L., Xu, C., Depledge, J., Ebi, K. L., Gibbins, G., Kohler, T. A., Rockström, J., Scheffer, M., Schellnhuber, H. J., Steffen, W., & Lenton, T. M. (2022). Climate Endgame: Exploring catastrophic climate change scenarios. Proceedings of the National Academy of Sciences, 119(34), e2108146119. https://doi.org/10.1073/pnas.2108146119

Sillmann, J., Christensen, I., Hochrainer-Stigler, S., Huang-Lachmann, J., Juhola, S., Kornhuber, K., Mahecha, M., Mechler, R., Reichstein, M., Ruane, A.C., Schweizer, P.-J. and Williams, S. (2022). ISC-UNDRR-RISK KAN Briefing note on systemic risk. International Science Council. Paris, France https://doi.org/10.24948/2022.01

References: Chapter 2.2

Alahmad, B., Khraishah, H., Althalji, K., Borchert, W., Al-Mulla, F., & Koutrakis, P. (2023). Connections Between Air Pollution, Climate Change, and Cardiovascular Health. The Canadian Journal of Cardiology, 39(9), 1182–1190. https://doi.org/10.1016/j.cjca.2023.03.025

Alfieri, L., Bisselink, B., Dottori, F., Naumann, G., De Roo, A., Salamon, P., Wyser, K., & Feyen, L. (2017). Global projections of river flood risk in a warmer world. Earth's Future, 5(2), 171–182. https://doi.org/10.1002/2016EF000485

Alves De Oliveira, B. F., Bottino, M. J., Nobre, P., & Nobre, C. A. (2021). Deforestation and climate change are projected to increase heat stress risk in the Brazilian Amazon. Communications Earth & Environment, 2(1), 207. https://doi.org/10.1038/s43247-021-00275-8

Armstrong McKay, D. I., Staal, A., Abrams, J. F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S. E., Rockström, J., & Lenton, T. M. (2022). Exceeding 1.5°C global warming could trigger multiple climate tipping points. Science, 377(6611), eabn7950. https://doi.org/10.1126/science.abn7950

Bailey, R. T., Barnes, K., & Wallace, C. D. (2016). Predicting Future Groundwater Resources of Coral Atoll Islands. Hydrological Processes, 30(13), 2092–2105. https://doi.org/10.1002/hyp.10781

Banks-Leite, C., Pardini, R., Tambosi, L. R., Pearse, W. D., Bueno, A. A., Bruscagin, R. T., Condez, T. H., Dixo, M., Igari, A. T., Martensen, A. C., & Metzger, J. P. (2014). Using ecological thresholds to evaluate the costs and benefits of set-asides in a biodiversity hotspot. Science, 345(6200), 1041–1045. https://doi.org/10.1126/science.1255768.

Barbour, E. J., Adnan, M. S. G., Borgomeo, E., Paprocki, K., Khan, M. S. A., Salehin, M., & Hall, J. W. (2022). The unequal distribution of water risks and adaptation benefits in coastal Bangladesh. Nature Sustainability, 5(4), 294–302. https://doi.org/10.1038/s41893-021-00846-9

Barlow, J., Lennox, G. D., Ferreira, J., Berenguer, E., Lees, A. C., Nally, R. M., Thomson, J. R., Ferraz, S. F. D. B., Louzada, J., Oliveira, V. H. F., Parry, L., Ribeiro De Castro Solar, R., Vieira, I. C. G., Aragão, L. E. O. C., Begotti, R. A., Braga, R. F., Cardoso, T. M., De Oliveira, R. C., Souza Jr, C. M., … Gardner, T. A. (2016). Anthropogenic disturbance in tropical forests can double biodiversity loss from deforestation. Nature, 535(7610), 144–147. https://doi.org/10.1038/nature18326

Barnes, E. A., & Screen, J. A. (2015). The impact of Arctic warming on the midlatitude jet-stream: Can it? Has it? Will it? WIREs Climate Change, 6(3), 277–286. https://doi.org/10.1002/wcc.337.

Beermann, S., Dobler, G., Faber, M., Frank, C., Habedank, B., Hagedorn, P., Kampen, H., Kuhn, C., Nygren, T., Schmidt-Chanasit, J., Schmolz, E., Stark, K., Ulrich, R. G., Weiss, S., & Wilking, H. (2023). Impact of climate change on vector- and rodent-borne infectious diseases. Journal of Health Monitoring, 8(Suppl 3), 33–61. https://doi.org/10.25646/11401.

Bellomo, K., Angeloni, M., Corti, S., & von Hardenberg, J. (2021). Future climate change shaped by inter-model differences in Atlantic meridional overturning circulation response. Nature Communications, 12(1), 3659. https://doi.org/10.1038/s41467-021-24015-w.

Benton, T., Fairweather, D., Graves, A., Harris, J., Jones, A., Lenton, T., Norman, R., O'Riordan, T., Pope, E., & Tiffin, R. (2017). Environmental tipping points and food system dynamics: Main report. http://dspace.stir.ac.uk/handle/1893/24796.

Benton, T. G. (2020). Running AMOC in the farming economy. Nature Food, 1(1), 22–23. https://doi.org/10.1038/s43016-019-0017-x.

Betts, R. A. (1999). Self-beneficial effects of vegetation on climate in an ocean-atmosphere general circulation model. Geophysical Research Letters, 26(10), 1457–1460. https://doi.org/10.1029/1999GL900283.

Betts, R., Sanderson, M., & Woodward, S. (2008). Effects of large-scale Amazon forest degradation on climate and air quality through fluxes of carbon dioxide, water, energy, mineral dust and isoprene. Philosophical Transactions of the Royal Society B: Biological Sciences, 363(1498), 1873–1880. https://doi.org/10.1098/rstb.2007.0027

Bezner Kerr, R., T. Hasegawa, R. Lasco, I. Bhatt, D. Deryng, A. Farrell, H. Gurney-Smith, H. Ju, S. Lluch-Cota, F. Meza, G. Nelson, H. Neufeldt, and P. Thornton, (2022). Food, Fibre, and Other Ecosystem Products. In: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 713-906, https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_Chapter05.pdf.

Boers, N., Marwan, N., Barbosa, H. M. J., & Kurths, J. (2017). A deforestation-induced tipping point for the South American monsoon system. Scientific Reports, 7(1), 41489. https://doi.org/10.1038/srep41489.

Brayshaw, D. J., Woollings, T., & Vellinga, M. (2009). Tropical and Extratropical Responses of the North Atlantic Atmospheric Circulation to a Sustained Weakening of the MOC. Journal of Climate, 22(11), 3146–3155. https://doi.org/10.1175/2008JCLI2594.1.

Buckley, M. W., & Marshall, J. (2016). Observations, inferences, and mechanisms of the Atlantic Meridional Overturning Circulation: A review. Reviews of Geophysics, 54(1), 5–63. https://doi.org/10.1002/2015RG000493.

Calder, P. C. (2021). Nutrition and immunity: lessons for COVID-19. European Journal of Clinical Nutrition, 75(9), 1309–1318. https://doi.org/10.1038/s41430-021-00949-8

Caminade, C., McIntyre, K. M., & Jones, A. E. (2019). Impact of recent and future climate change on vector-borne diseases. Annals of the New York Academy of Sciences, 1436(1), 157–173. https://doi.org/10.1111/nyas.13950.

Caretta, M.A., A. Mukherji, M. Arfanuzzaman, R.A. Betts, A. Gelfan, Y. Hirabayashi, T.K. Lissner, J. Liu, E. Lopez Gunn, R. Morgan, S. Mwanga, and S. Supratid (Ed.). (2023). Water. In Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (pp. 551–712). Cambridge University Press. https://doi.org/10.1017/9781009325844.006.

Cascio, W. E. (2018). Wildland fire smoke and human health. Science of The Total Environment, 624, 586–595. https://doi.org/10.1016/j.scitotenv.2017.12.086.

Castellanos, E., M.F. Lemos, L. Astigarraga, N. Chacón, N. Cuvi, C. Huggel, L. Miranda, M. Moncassim Vale, J.P. Ometto, P.L. Peri, J.C. Postigo, L. Ramajo, L. Roco, and M. Rusticucci. (2023). Central and South America. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (1st ed.). Cambridge University Press. https://doi.org/10.1017/9781009325844.

Chadburn, S. E., Burke, E. J., Cox, P. M., Friedlingstein, P., Hugelius, G., & Westermann, S. (2017). An observation-based constraint on permafrost loss as a function of global warming. Nature Climate Change, 7(5), 340–344. https://doi.org/10.1038/nclimate3262.

Challinor, Andy, & Benton, Tim G. (2021). Technical Report Chapter 7: International Dimensions. https://www.ukclimaterisk.org/wp-content/uploads/2021/06/CCRA3-Chapter-7-FINAL.pdf

Chang, P., Zhang, R., Hazeleger, W., Wen, C., Wan, X., Ji, L., Haarsma, R. J., Breugem, W.-P., & Seidel, H. (2008). Oceanic link between abrupt changes in the North Atlantic Ocean and the African monsoon. Nature Geoscience, 1(7), 444–448. https://doi.org/10.1038/ngeo218.

Charlson, F., Ali, S., Benmarhnia, T., Pearl, M., Massazza, A., Augustinavicius, J., & Scott, J. G. (2021). Climate Change and Mental Health: A Scoping Review. International Journal of Environmental Research and Public Health, 18(9), 4486. https://doi.org/10.3390/ijerph18094486.

Chemison, A., Ramstein, G., Tompkins, A. M., Defrance, D., Camus, G., Charra, M., & Caminade, C. (2021). Impact of an accelerated melting of Greenland on malaria distribution over Africa. Nature Communications, 12(1), 3971. https://doi.org/10.1038/s41467-021-24134-4.

Chen, G., Guo, Y., Yue, X., Tong, S., Gasparrini, A., Bell, M. L., Armstrong, B., Schwartz, J., Jaakkola, J. J. K., Zanobetti, A., Lavigne, E., Nascimento Saldiva, P. H., Kan, H., Royé, D., Milojevic, A., Overcenco, A., Urban, A., Schneider, A., Entezari, A., … Li, S. (2021). Mortality risk attributable to wildfire-related PM2.5 pollution: a global time series study in 749 locations. The Lancet Planetary Health, 5(9), e579–e587. https://doi.org/10.1016/S2542-5196(21)00200-X.

Chen, J., & Mueller, V. (2018). Coastal climate change, soil salinity and human migration in Bangladesh. Nature Climate Change, 8(11), 981–985. https://doi.org/10.1038/s41558-018-0313-8.

Cissé, G., R. McLeman, H. Adams, P. Aldunce, K. Bowen, D. Campbell-Lendrum, S. Clayton, K.L. Ebi, J. Hess, C. Huang, Q. Liu, G. McGregor, J. Semenza, and M.C. Tirado, (2022). Health, Wellbeing, and the Changing Structure of Communities. In: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1041-1170, https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_Chapter07.pdf

Cohn, A. S., Bhattarai, N., Campolo, J., Crompton, O., Dralle, D., Duncan, J., & Thompson, S. (2019). Forest loss in Brazil increases maximum temperatures within 50 km. Environmental Research Letters, 14(8), 084047. https://doi.org/10.1088/1748-9326/ab31fb.

Cooley, S., D. Schoeman, L. Bopp, P. Boyd, S. Donner, D.Y. Ghebrehiwet, S.-I. Ito, W. Kiessling, P. Martinetto, E. Ojea, M.-F. Racault, B. Rost, and M. Skern-Mauritzen, (2022). Ocean and Coastal Ecosystems and their Services. In: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 379-550, https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_FinalDraft_Chapter03.pdf

Covert, H. H., Abdoel Wahid, F., Wenzel, S. E., & Lichtveld, M. Y. (2023). Climate change impacts on respiratory health: exposure, vulnerability, and risk. Physiological Reviews, 103(4), 2507–2522. https://doi.org/10.1152/physrev.00043.2022.

d'Amour, C. B., Wenz, L., Kalkuhl, M., Steckel, J. C., & Creutzig, F. (2016). Teleconnected food supply shocks. Environmental Research Letters, 11(3), 035007. https://doi.org/10.1088/1748-9326/11/3/035007.

Defrance, D., Ramstein, G., Charbit, S., Vrac, M., Famien, A. M., Sultan, B., Swingedouw, D., Dumas, C., Gemenne, F., Alvarez-Solas, J., & Vanderlinden, J.-P. (2017). Consequences of rapid ice sheet melting on the Sahelian population vulnerability. Proceedings of the National Academy of Sciences, 114(25), 6533–6538. https://doi.org/10.1073/pnas.1619358114.

Deutloff, J. E., Held, H., & Lenton, T. M. (2023). The risky middle of the road – probabilities of triggering climate tipping points and how they increase due to tipping points within the Earth's carbon cycle [Preprint]. Climate change/Biosphere/atmosphere interactions/Idealized models. https://doi.org/10.5194/egusphere-2023-1469.

Dos Santos, S., Adams, E. A., Neville, G., Wada, Y., De Sherbinin, A., Mullin Bernhardt, E., & Adamo, S. B. (2017). Urban growth and water access in sub-Saharan Africa: Progress, challenges, and emerging research directions. Science of The Total Environment, 607–608, 497–508. https://doi.org/10.1016/j.scitotenv.2017.06.157.

Dutton, A., Carlson, A. E., Long, A. J., Milne, G. A., Clark, P. U., DeConto, R., Horton, B. P., Rahmstorf, S., & Raymo, M. E. (2015). Sea-level rise due to polar ice-sheet mass loss during past warm periods. Science, 349(6244), aaa4019. https://doi.org/10.1126/science.aaa4019.

Dvorak, A. C., Solo-Gabriele, H. M., Galletti, A., Benzecry, B., Malone, H., Boguszewski, V., & Bird, J. (2018). Possible impacts of sea level rise on disease transmission and potential adaptation strategies, a review. Journal of Environmental Management, 217, 951–968. https://doi.org/10.1016/j.jenvman.2018.03.102

Ebi, K. L., Vanos, J., Baldwin, J. W., Bell, J. E., Hondula, D. M., Errett, N. A., Hayes, K., Reid, C. E., Saha, S., Spector, J., & Berry, P. (2021). Extreme Weather and Climate Change: Population Health and Health System Implications. Annual Review of Public Health, 42(1), 293–315. https://doi.org/10.1146/annurev-publhealth-012420-105026

Esquivel-Muelbert, A., Galbraith, D., Dexter, K. G., Baker, T. R., Lewis, S. L., Meir, P., Rowland, L., Costa, A. C. L. D., Nepstad, D., & Phillips, O. L. (2017). Biogeographic distributions of neotropical trees reflect their directly measured drought tolerances. Scientific Reports, 7(1), 8334. https://doi.org/10.1038/s41598-017-08105-8

Flores, B. M., & Holmgren, M. (2021). White-Sand Savannas Expand at the Core of the Amazon After Forest Wildfires. Ecosystems, 24(7), 1624–1637. https://doi.org/10.1007/s10021-021-00607-x

Flores, B. M., Staal, A., Jakovac, C. C., Hirota, M., Holmgren, M., & Oliveira, R. S. (2020). Soil erosion as a resilience drain in disturbed tropical forests. Plant and Soil, 450(1), 11–25. https://doi.org/10.1007/s11104-019-04097-8

Fox-Kemper, B., H.T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S.S. Drijfhout, T.L. Edwards, N.R. Golledge, M. Hemer, R.E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I.S. Nurhati, L. Ruiz, J.-B. Sallée, A.B.A. Slangen, and Y. Yu. (2023). 2021: Ocean, Cryosphere and Sea Level Change. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (1st ed.). Cambridge University Press. https://doi.org/10.1017/9781009157896

Garcia-Tigreros, F., Leonte, M., Ruppel, C. D., Ruiz-Angulo, A., Joung, D. J., Young, B., & Kessler, J. D. (2021). Estimating the Impact of Seep Methane Oxidation on Ocean pH and Dissolved Inorganic Radiocarbon Along the U.S. Mid-Atlantic Bight. Journal of Geophysical Research: Biogeosciences, 126(1), e2019JG005621. https://doi.org/10.1029/2019JG005621

Garry, S., & Checchi, F. (2020). Armed conflict and public health: into the 21st century. Journal of Public Health, 42(3), e287–e298. https://doi.org/10.1093/pubmed/fdz095

Gasser, T., Kechiar, M., Ciais, P., Burke, E. J., Kleinen, T., Zhu, D., Huang, Y., Ekici, A., & Obersteiner, M. (2018). Path-dependent reductions in CO2 emission budgets caused by permafrost carbon release. Nature Geoscience, 11(11), 830–835. https://doi.org/10.1038/s41561-018-0227-0

Gaupp, F. (2020). Extreme Events in a Globalized Food System. One Earth, 2(6), 518–521. https://doi.org/10.1016/j.oneear.2020.06.001

Gomes, V. H. F., Vieira, I. C. G., Salomão, R. P., & Ter Steege, H. (2019). Amazonian tree species threatened by deforestation and climate change. Nature Climate Change, 9(7), 547–553. https://doi.org/10.1038/s41558-019-0500-2

Gosling, S. N., & Arnell, N. W. (2016). A global assessment of the impact of climate change on water scarcity. Climatic Change, 134(3), 371–385. https://doi.org/10.1007/s10584-013-0853-x

Haarsma, R. J., Selten, F. M., & Drijfhout, S. S. (2015). Decelerating Atlantic meridional overturning circulation main cause of future west European summer atmospheric circulation changes. Environmental Research Letters, 10(9), 094007. https://doi.org/10.1088/1748-9326/10/9/094007

Hanlon, H., Palmer, M., & Betts, R. (2021). Effect of Potential Climate Tipping Points on UK Impacts. MetOffice Hadley Centre, UK https://www.ukclimaterisk.org/wp-content/uploads/2021/06/Effect-of-Potential-Climate-Tipping-Points-on-UK-Impacts.pdf

Hauer, M. E. (2017). Migration induced by sea-level rise could reshape the US population landscape. Nature Climate Change, 7(5), 321–325. https://doi.org/10.1038/nclimate3271

Hauer, M. E., Fussell, E., Mueller, V., Burkett, M., Call, M., Abel, K., McLeman, R., & Wrathall, D. (2019). Sea-level rise and human migration. Nature Reviews Earth & Environment, 1(1), 28–39. https://doi.org/10.1038/s43017-019-0002-9

Heinze, C., Blenckner, T., Martins, H., Rusiecka, D., Döscher, R., Gehlen, M., Gruber, N., Holland, E., Hov, Ø., Joos, F., Matthews, J. B. R., Rødven, R., & Wilson, S. (2021). The quiet crossing of ocean tipping points. Proceedings of the National Academy of Sciences, 118(9), e2008478118. https://doi.org/10.1073/pnas.2008478118

Higgins, S. I., Conradi, T., & Muhoko, E. (2023). Shifts in vegetation activity of terrestrial ecosystems attributable to climate trends. Nature Geoscience, 16(2), 147–153. https://doi.org/10.1038/s41561-022-01114-x

Hirota, M., Flores, B. M., Betts, R., Borma, L. S., Esquivel-Muelbert, A., Jakovac, C., Lapola, D. M., Montoya, E., Oliveira, R. S., & Sakschewski, B. (2021). Chapter 24: Resilience of the Amazon forest to global changes: Assessing the risk of tipping points. In C. Nobre, A. Encalada, E. Anderson, F. H. Roca Alcazar, M. Bustamante, C. Mena, M. Peña-Claros, G. Poveda, J. P. Rodriguez, S. Saleska, S. E. Trumbore, A. Val, L. Villa Nova, R. Abramovay, A. Alencar, A. C. Rodriguez Alzza, D. Armenteras, P. Artaxo, S. Athayde, … G. Zapata-Ríos (Eds.), Amazon Assessment Report 2021 (1st ed.). UN Sustainable Development Solutions Network (SDSN). https://doi.org/10.55161/QPYS9758

Hjort, J., Karjalainen, O., Aalto, J., Westermann, S., Romanovsky, V. E., Nelson, F. E., Etzelmüller, B., & Luoto, M. (2018). Degrading permafrost puts Arctic infrastructure at risk by mid-century. Nature Communications, 9(1), 5147. https://doi.org/10.1038/s41467-018-07557-4

Hjort, J., Streletskiy, D., Doré, G., Wu, Q., Bjella, K., & Luoto, M. (2022). Impacts of permafrost degradation on infrastructure. Nature Reviews Earth & Environment, 3(1), 24–38. https://doi.org/10.1038/s43017-021-00247-8

Hu, A., Meehl, G. A., Han, W., & Yin, J. (2009). Transient response of the MOC and climate to potential melting of the Greenland Ice Sheet in the 21st century. Geophysical Research Letters, 36(10), L10707. https://doi.org/10.1029/2009GL037998

Hugelius, G., Loisel, J., Chadburn, S., Jackson, R. B., Jones, M., MacDonald, G., Marushchak, M., Olefeldt, D., Packalen, M., Siewert, M. B., Treat, C., Turetsky, M., Voigt, C., & Yu, Z. (2020). Large stocks of peatland carbon and nitrogen are vulnerable to permafrost thaw. Proceedings of the National Academy of Sciences, 117(34), 20438–20446. https://doi.org/10.1073/pnas.1916387117

IPCC, (2019). IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 755 pp. https://doi.org/10.1017/9781009157964.

Jackson, L. C., Kahana, R., Graham, T., Ringer, M. A., Woollings, T., Mecking, J. V., & Wood, R. A. (2015). Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM. Climate Dynamics, 45(11–12), 3299–3316. https://doi.org/10.1007/s00382-015-2540-2

Jacob, D., Goettel, H., Jungclaus, J., Muskulus, M., Podzun, R., & Marotzke, J. (2005). Slowdown of the thermohaline circulation causes enhanced maritime climate influence and snow cover over Europe. Geophysical Research Letters, 32(21), L21711. https://doi.org/10.1029/2005GL023286

Khan, A. E., Ireson, A., Kovats, S., Mojumder, S. K., Khusru, A., Rahman, A., & Vineis, P. (2011). Drinking Water Salinity and Maternal Health in Coastal Bangladesh: Implications of Climate Change. Environmental Health Perspectives, 119(9), 1328–1332. https://doi.org/10.1289/ehp.1002804

Khanom, T. (2016). Effect of salinity on food security in the context of interior coast of Bangladesh. Ocean & Coastal Management, 130, 205–212. https://doi.org/10.1016/j.ocecoaman.2016.06.013

Kienert, H., & Rahmstorf, S. (2012). On the relation between Meridional Overturning Circulation and sea-level gradients in the Atlantic. Earth System Dynamics, 3(2), 109–120. https://doi.org/10.5194/esd-3-109-2012

Knapp, C. N., & Trainor, S. F. (2015). Alaskan stakeholder-defined research needs in the context of climate change. Polar Geography, 38(1), 42–69. https://doi.org/10.1080/1088937X.2014.999844

Kornhuber, K., Lesk, C., Schleussner, C. F., Jägermeyr, J., Pfleiderer, P., & Horton, R. M. (2023). Risks of synchronized low yields are underestimated in climate and crop model projections. Nature Communications, 14(1), 3528. https://doi.org/10.1038/s41467-023-38906-7

Kulp, S. A., & Strauss, B. H. (2019). New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. Nature Communications, 10(1), 4844. https://doi.org/10.1038/s41467-019-12808-z

Kummu, M., De Moel, H., Salvucci, G., Viviroli, D., Ward, P. J., & Varis, O. (2016). Over the hills and further away from coast: global geospatial patterns of human and environment over the 20th–21st centuries. Environmental Research Letters, 11(3), 034010. https://doi.org/10.1088/1748-9326/11/3/034010

Kwiatkowski, L., Naar, J., Bopp, L., Aumont, O., Defrance, D., & Couespel, D. (2019). Decline in Atlantic Primary Production Accelerated by Greenland Ice Sheet Melt. Geophysical Research Letters, 46(20), 11347–11357. https://doi.org/10.1029/2019GL085267

Lane, K., Charles-Guzman, K., Wheeler, K., Abid, Z., Graber, N., & Matte, T. (2013). Health Effects of Coastal Storms and Flooding in Urban Areas: A Review and Vulnerability Assessment. Journal of Environmental and Public Health, 2013, 1–13. https://doi.org/10.1155/2013/913064

Langer, M., Von Deimling, T. S., Westermann, S., Rolph, R., Rutte, R., Antonova, S., Rachold, V., Schultz, M., Oehme, A., & Grosse, G. (2023). Thawing permafrost poses environmental threat to thousands of sites with legacy industrial contamination. Nature Communications, 14(1), 1721. https://doi.org/10.1038/s41467-023-37276-4

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

Lapola, D. M., Pinho P., Quesada, C.A., Strassburg, B. B. N., Rammig, A., Kruijt, B., Brown, F., Jean P. Ometto, H. B., Premebida, A., Marengo, J.A., Vergara, W., Nobre, C.A. (2018) Limiting the high impacts of Amazon forest dieback with no-regrets science and policy action. Proceedings of the National Academy of Sciences, 115(46), 11671-11679.

Laurance, S. G. W., Stouffer, P. C., & Laurance, W. F. (2004). Effects of Road Clearings on Movement Patterns of Understory Rainforest Birds in Central Amazonia. Conservation Biology, 18(4), 1099–1109. https://doi.org/10.1111/j.1523-1739.2004.00268.x

Laurian, A., Drijfhout, S. S., Hazeleger, W., & Van Den Hurk, B. (2010). Response of the Western European climate to a collapse of the thermohaline circulation. Climate Dynamics, 34(5), 689–697. https://doi.org/10.1007/s00382-008-0513-4

Lemieux, A., Colby, G. A., Poulain, A. J., & Aris-Brosou, S. (2022). Viral spillover risk increases with climate change in High Arctic lake sediments. Proceedings of the Royal Society B: Biological Sciences, 289(1985), 20221073. https://doi.org/10.1098/rspb.2022.1073

Levermann, A., Griesel, A., Hofmann, M., Montoya, M., & Rahmstorf, S. (2005). Dynamic sea level changes following changes in the thermohaline circulation. Climate Dynamics, 24(4), 347–354. https://doi.org/10.1007/s00382-004-0505-y

Link, P. M., & Tol, R. S. J. (2009). Economic impacts on key Barents Sea fisheries arising from changes in the strength of the Atlantic thermohaline circulation. Global Environmental Change, 19(4), 422–433. https://doi.org/10.1016/j.gloenvcha.2009.07.007

Little, C. M., Hu, A., Hughes, C. W., McCarthy, G. D., Piecuch, C. G., Ponte, R. M., & Thomas, M. D. (2019). The Relationship Between U.S. East Coast Sea Level and the Atlantic Meridional Overturning Circulation: A Review. Journal of Geophysical Research: Oceans, 124(9), 6435–6458. https://doi.org/10.1029/2019JC015152

Liu, T., Chen, D., Yang, L., Meng, J., Wang, Z., Ludescher, J., Fan, J., Yang, S., Chen, D., Kurths, J., Chen, X., Havlin, S., & Schellnhuber, H. J. (2023). Teleconnections among tipping elements in the Earth system. Nature Climate Change, 13(1), 67–74. https://doi.org/10.1038/s41558-022-01558-4

Lorbacher, K., Dengg, J., Böning, C. W., & Biastoch, A. (2010). Regional Patterns of Sea Level Change Related to Interannual Variability and Multidecadal Trends in the Atlantic Meridional Overturning Circulation*. Journal of Climate, 23(15), 4243–4254. https://doi.org/10.1175/2010JCLI3341.1

Loring, P. A., & Gerlach, S. C. (2009). Food, culture, and human health in Alaska: an integrative health approach to food security. Environmental Science & Policy, 12(4), 466–478. https://doi.org/10.1016/j.envsci.2008.10.006

Magnan, A. K., Oppenheimer, M., Garschagen, M., Buchanan, M. K., Duvat, V. K. E., Forbes, D. L., Ford, J. D., Lambert, E., Petzold, J., Renaud, F. G., Sebesvari, Z., Van De Wal, R. S. W., Hinkel, J., & Pörtner, H.-O. (2022). Sea level rise risks and societal adaptation benefits in low-lying coastal areas. Scientific Reports, 12(1), 10677. https://doi.org/10.1038/s41598-022-14303-w

Marzin, C., Kallel, N., Kageyama, M., Duplessy, J.-C., & Braconnot, P. (2013). Glacial fluctuations of the Indian monsoon and their relationship with North Atlantic climate: new data and modelling experiments. Climate of the Past, 9(5), 2135–2151. https://doi.org/10.5194/cp-9-2135-2013

Maslakov, A., Sotnikova, K., Gribovskii, G., & Evlanov, D. (2022). Thermal Simulation of Ice Cellars as a Basis for Food Security and Energy Sustainability of Isolated Indigenous Communities in the Arctic. Energies, 15(3), 972. https://doi.org/10.3390/en15030972

Math, S. B., Nirmala, M. C., Moirangthem, S., & Kumar, N. C. (2015). Disaster Management: Mental Health Perspective. Indian Journal of Psychological Medicine, 37(3), 261–271. https://doi.org/10.4103/0253-7176.162915

Mazhar, S., Pellegrini, E., Contin, M., Bravo, C., & De Nobili, M. (2022). Impacts of salinization caused by sea level rise on the biological processes of coastal soils - A review. Frontiers in Environmental Science, 10. https://www.frontiersin.org/articles/10.3389/fenvs.2022.909415

McGuire, A. D., Lawrence, D. M., Koven, C., Clein, J. S., Burke, E., Chen, G., Jafarov, E., MacDougall, A. H., Marchenko, S., Nicolsky, D., Peng, S., Rinke, A., Ciais, P., Gouttevin, I., Hayes, D. J., Ji, D., Krinner, G., Moore, J. C., Romanovsky, V., … Zhuang, Q. (2018). Dependence of the evolution of carbon dynamics in the northern permafrost region on the trajectory of climate change. Proceedings of the National Academy of Sciences, 115(15), 3882–3887. https://doi.org/10.1073/pnas.1719903115

McLeman, R. A. (2011). Settlement abandonment in the context of global environmental change. Global Environmental Change, 21, S108–S120. https://doi.org/10.1016/j.gloenvcha.2011.08.004

Miner, K. R., D'Andrilli, J., Mackelprang, R., Edwards, A., Malaska, M. J., Waldrop, M. P., & Miller, C. E. (2021). Emergent biogeochemical risks from Arctic permafrost degradation. Nature Climate Change, 11(10), 809–819. https://doi.org/10.1038/s41558-021-01162-y

Morlighem, M., Williams, C. N., Rignot, E., An, L., Arndt, J. E., Bamber, J. L., Catania, G., Chauché, N., Dowdeswell, J. A., Dorschel, B., Fenty, I., Hogan, K., Howat, I., Hubbard, A., Jakobsson, M., Jordan, T. M., Kjeldsen, K. K., Millan, R., Mayer, L., … Zinglersen, K. B. (2017). BedMachine v3: Complete Bed Topography and Ocean Bathymetry Mapping of Greenland From Multibeam Echo Sounding Combined With Mass Conservation. Geophysical Research Letters, 44(21). https://doi.org/10.1002/2017GL074954

Myers-Smith, I. H., Kerby, J. T., Phoenix, G. K., Bjerke, J. W., Epstein, H. E., Assmann, J. J., John, C., Andreu-Hayles, L., Angers-Blondin, S., Beck, P. S. A., Berner, L. T., Bhatt, U. S., Bjorkman, A. D., Blok, D., Bryn, A., Christiansen, C. T., Cornelissen, J. H. C., Cunliffe, A. M., Elmendorf, S. C., … Wipf, S. (2020). Complexity revealed in the greening of the Arctic. Nature Climate Change, 10(2), 106–117. https://doi.org/10.1038/s41558-019-0688-1

Natali, S. M., Holdren, J. P., Rogers, B. M., Treharne, R., Duffy, P. B., Pomerance, R., & MacDonald, E. (2021). Permafrost carbon feedbacks threaten global climate goals. Proceedings of the National Academy of Sciences, 118(21), e2100163118. https://doi.org/10.1073/pnas.2100163118

Neumann, B., Vafeidis, A. T., Zimmermann, J., & Nicholls, R. J. (2015). Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding - A Global Assessment. PLOS ONE, 10(3), e0118571. https://doi.org/10.1371/journal.pone.0118571

Nichols, G., Lake, I., & Heaviside, C. (2018). Climate Change and Water-Related Infectious Diseases. Atmosphere, 9(10), 385. https://doi.org/10.3390/atmos9100385

Nitzbon, J., Schneider Von Deimling, T., Aliyeva, M., Chadburn, S., Grosse, G., Laboor, S., Lee, H., Lohmann, G., Steinert, N., Stuenzi, S., Werner, M., Westermann, S., & Langer, M. (2023). No respite from permafrost-thaw impacts in absence of a global tipping point [Preprint]. Biogeochemistry. https://doi.org/10.31223/X55X08

Science Panel for the Amazon (2021). Executive Summary of the Amazon Assessment Report 2021. C. Nobre, A. Encalada, E. Anderson, F.H. Roca Alcazar, M. Bustamante, C. Mena, M. Peña-Claros, G. Poveda, J.P. Rodriguez, S. Saleska, S. Trumbore, A.L. Val, L. Villa Nova, R. Abramovay, A. Alencar, A.C.R. Alzza, D. Armenteras, P. Artaxo, S. Athayde, H.T. Barretto Filho, J. Barlow, E. Berenguer, F. Bortolotto, F.A. Costa, M.H. Costa, N. Cuvi, P.M. Fearnside, J. Ferreira, B.M. Flores, S. Frieri, L.V. Gatti, J.M. Guayasamin, S. Hecht, M. Hirota, C. Hoorn, C. Josse, D.M. Lapola, C. Larrea, D.M. Larrea-Alcazar, Z. Lehm Ardaya, Y. Malhi, J.A. Marengo, M.R. Moraes, P. Moutinho, M.R. Murmis, E.G. Neves, B. Paez, L. Painter, A. Ramos, M.C. Rosero-Peña, M. Schmink, P. Sist, H. ter Steege, P. Val, H. van der Voort, M. Varese, Zapata-Ríos (eds.) United Nations Sustainable Development Solutions Network, New York, USA. https://www.theamazonwewant.org/spa_publication/amazon-assessment-report-2021/

Nova, N., Athni, T. S., Childs, M. L., Mandle, L., & Mordecai, E. A. (2022). Global Change and Emerging Infectious Diseases. Annual Review of Resource Economics, 14(1), 333–354. https://doi.org/10.1146/annurev-resource-111820-024214

Oliveira, B. F. A. D., Jacobson, L. D. S. V., Perez, L. P., Silveira, I. H. D., Junger, W. L., & Hacon, S. D. S. (2020). Impacts of heat stress conditions on mortality from respiratory and cardiovascular diseases in Brazil. Sustentabilidade Em Debate, 11(3), 297–330. https://doi.org/10.18472/SustDeb.v11n3.2020.33970

O'Neill, B. C., Oppenheimer, M., Warren, R., Hallegatte, S., Kopp, R. E., Pörtner, H. O., Scholes, R., Birkmann, J., Foden, W., Licker, R., Mach, K. J., Marbaix, P., Mastrandrea, M. D., Price, J., Takahashi, K., Van Ypersele, J.-P., & Yohe, G. (2017). IPCC reasons for concern regarding climate change risks. Nature Climate Change, 7(1), 28–37. https://doi.org/10.1038/nclimate3179

Oppenheimer, M., B.C. Glavovic , J. Hinkel, R. van de Wal, A.K. Magnan, A. Abd-Elgawad, R. Cai, M. Cifuentes-Jara, R.M. DeConto, T. Ghosh, J. Hay, F. Isla, B. Marzeion, B. Meyssignac, and Z. Sebesvari. (2019). 2019: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. https://www.ipcc.ch/site/assets/uploads/sites/3/2019/11/08_SROCC_Ch04_FINAL.pdf

Palinkas, L. A., & Wong, M. (2020). Global climate change and mental health. Current Opinion in Psychology, 32, 12–16. https://doi.org/10.1016/j.copsyc.2019.06.023

Pan, L., Powell, E. M., Latychev, K., Mitrovica, J. X., Creveling, J. R., Gomez, N., Hoggard, M. J., & Clark, P. U. (2021). Rapid postglacial rebound amplifies global sea level rise following West Antarctic Ice Sheet collapse. Science Advances, 7(18), eabf7787. https://doi.org/10.1126/sciadv.abf7787

Parsons, L. A., Yin, J., Overpeck, J. T., Stouffer, R. J., & Malyshev, S. (2014). Influence of the Atlantic Meridional Overturning Circulation on the monsoon rainfall and carbon balance of the American tropics. Geophysical Research Letters, 41(1), 146–151. https://doi.org/10.1002/2013GL058454

Pawlak, K., & Kołodziejczak, M. (2020). The Role of Agriculture in Ensuring Food Security in Developing Countries: Considerations in the Context of the Problem of Sustainable Food Production. Sustainability, 12(13), 5488. https://doi.org/10.3390/su12135488

Pinho, P. F., Marengo, J. A., & Smith, M. S. (2015). Complex socio-ecological dynamics driven by extreme events in the Amazon. Regional Environmental Change, 15(4), 643–655. https://doi.org/10.1007/s10113-014-0659-z

Ramasamy, R., & Surendran, S. N. (2011). Possible impact of rising sea levels on vector-borne infectious diseases. BMC Infectious Diseases, 11(1), 18. https://doi.org/10.1186/1471-2334-11-18

Rantanen, M., Karpechko, A. Yu., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., Vihma, T., & Laaksonen, A. (2022). The Arctic has warmed nearly four times faster than the globe since 1979. Communications Earth & Environment, 3(1), 168. https://doi.org/10.1038/s43247-022-00498-3

Ritchie, P. D. L., Smith, G. S., Davis, K. J., Fezzi, C., Halleck-Vega, S., Harper, A. B., Boulton, C. A., Binner, A. R., Day, B. H., Gallego-Sala, A. V., Mecking, J. V., Sitch, S. A., Lenton, T. M., & Bateman, I. J. (2020). Shifts in national land use and food production in Great Britain after a climate tipping point. Nature Food, 1(1), 76–83. https://doi.org/10.1038/s43016-019-0011-3

Rockström, J., Gupta, J., Qin, D., Lade, S. J., Abrams, J. F., Andersen, L. S., Armstrong McKay, D. I., Bai, X., Bala, G., Bunn, S. E., Ciobanu, D., DeClerck, F., Ebi, K., Gifford, L., Gordon, C., Hasan, S., Kanie, N., Lenton, T. M., Loriani, S., Zhang, X. (2023). Safe and just Earth system boundaries. Nature, 619(7968), 102–111. https://doi.org/10.1038/s41586-023-06083-8

Ruv Lemes, M., Sampaio, G., Fisch, G., Alves, L. M., Maksic, J., Guatura, M., & Shimizu, M. (2023). Impacts of atmospheric CO_2 increase and Amazon deforestation on the regional climate: A water budget modelling study. International Journal of Climatology, 43(3), 1497–1513. https://doi.org/10.1002/joc.7929

Salas, R. N., & Jha, A. K. (2019). Climate change threatens the achievement of effective universal healthcare. BMJ, l5302. https://doi.org/10.1136/bmj.l5302

Sandeep, N., Swapna, P., Krishnan, R., Farneti, R., Prajeesh, A. G., Ayantika, D. C., & Manmeet, S. (2020). South Asian monsoon response to weakening of Atlantic meridional overturning circulation in a warming climate. Climate Dynamics, 54(7–8), 3507–3524. https://doi.org/10.1007/s00382-020-05180-y

Schaefer, K., Elshorbany, Y., Jafarov, E., Schuster, P. F., Striegl, R. G., Wickland, K. P., & Sunderland, E. M. (2020). Potential impacts of mercury released from thawing permafrost. Nature Communications, 11(1), 4650. https://doi.org/10.1038/s41467-020-18398-5

Schellnhuber, Hans Joachim, and Maria A. Martin. (2014). Climate-system tipping points and extreme weather events. Pontifical Academy of Sciences and Pontifical Academy of Social Sciences: Sustainable Humanity, Sustainable Nature: Our Responsibility. https://www.pas.va/content/dam/casinapioiv/pas/pdf-volumi/extra-series/es_41/es41-schellnhuber.pdf

Schmittner, A. (2005). Decline of the marine ecosystem caused by a reduction in the Atlantic overturning circulation. Nature, 434(7033), 628–633. https://doi.org/10.1038/nature03476

Schuur, E. A. G., Abbott, B. W., Commane, R., Ernakovich, J., Euskirchen, E., Hugelius, G., Grosse, G., Jones, M., Koven, C., Leshyk, V., Lawrence, D., Loranty, M. M., Mauritz, M., Olefeldt, D., Natali, S., Rodenhizer, H., Salmon, V., Schädel, C., Strauss, J., … Turetsky, M. (2022). Permafrost and Climate Change: Carbon Cycle Feedbacks From the Warming Arctic. Annual Review of Environment and Resources, 47(1), 343–371. https://doi.org/10.1146/annurev-environ-012220-011847

Schuur, E. A. G., & Mack, M. C. (2018). Ecological Response to Permafrost Thaw and Consequences for Local and Global Ecosystem Services. Annual Review of Ecology, Evolution, and Systematics, 49(1), 279–301. https://doi.org/10.1146/annurev-ecolsys-121415-032349

Schuur, E. A. G., McGuire, A. D., Schädel, C., Grosse, G., Harden, J. W., Hayes, D. J., Hugelius, G., Koven, C. D., Kuhry, P., Lawrence, D. M., Natali, S. M., Olefeldt, D., Romanovsky, V. E., Schaefer, K., Turetsky, M. R., Treat, C. C., & Vonk, J. E. (2015). Climate change and the permafrost carbon feedback. Nature, 520(7546), 171–179. https://doi.org/10.1038/nature14338

Siegert, M., Alley, R. B., Rignot, E., Englander, J., & Corell, R. (2020). Twenty-first century sea-level rise could exceed IPCC projections for strong-warming futures. One Earth, 3(6), 691–703. https://doi.org/10.1016/j.oneear.2020.11.002

Simpson, D. M., Weissbecker, I., & Sephton, S. E. (2011). Extreme Weather-Related Events: Implications for Mental Health and Well-Being. In I. Weissbecker (Ed.), Climate Change and Human Well-Being (pp. 57–78). Springer New York. https://doi.org/10.1007/978-1-4419-9742-5_4

Siriwardhana, C., & Stewart, R. (2013). Forced migration and mental health: prolonged internal displacement, return migration and resilience. International Health, 5(1), 19–23. https://doi.org/10.1093/inthealth/ihs014

Sorensen, C., & Hess, J. (2022). Treatment and Prevention of Heat-Related Illness. The New England Journal of Medicine, 387(15), 1404–1413. https://doi.org/10.1056/NEJMcp2210623

Spector, J. T., Masuda, Y. J., Wolff, N. H., Calkins, M., & Seixas, N. (2019). Heat Exposure and Occupational Injuries: Review of the Literature and Implications. Current Environmental Health Reports, 6(4), 286–296. https://doi.org/10.1007/s40572-019-00250-8

Stickler, C. M., Coe, M. T., Costa, M. H., Nepstad, D. C., McGrath, D. G., Dias, L. C. P., Rodrigues, H. O., & Soares-Filho, B. S. (2013). Dependence of hydropower energy generation on forests in the Amazon Basin at local and regional scales. Proceedings of the National Academy of Sciences, 110(23), 9601–9606. https://doi.org/10.1073/pnas.1215331110

Stouffer, R. J., Yin, J., Gregory, J. M., Dixon, K. W., Spelman, M. J., Hurlin, W., Weaver, A. J., Eby, M., Flato, G. M., Hasumi, H., Hu, A., Jungclaus, J. H., Kamenkovich, I. V., Levermann, A., Montoya, M., Murakami, S., Nawrath, S., Oka, A., Peltier, W. R., … Weber, S. L. (2006). Investigating the Causes of the Response of the Thermohaline Circulation to Past and Future Climate Changes. Journal of Climate, 19(8), 1365–1387. https://doi.org/10.1175/JCLI3689.1

Suhrcke, M., Stuckler, D., Suk, J. E., Desai, M., Senek, M., McKee, M., Tsolova, S., Basu, S., Abubakar, I., Hunter, P., Rechel, B., & Semenza, J. C. (2011). The Impact of Economic Crises on Communicable Disease Transmission and Control: A Systematic Review of the Evidence. PLOS ONE, 6(6), e20724. https://doi.org/10.1371/journal.pone.0020724

Tauhid Ur Rahman, M., Rasheduzzaman, Md., Habib, M. A., Ahmed, A., Tareq, S. M., & Muniruzzaman, S. M. (2017). Assessment of fresh water security in coastal Bangladesh: An insight from salinity, community perception and adaptation. Ocean & Coastal Management, 137, 68–81. https://doi.org/10.1016/j.ocecoaman.2016.12.005

The IMBIE team. (2018). Mass balance of the Antarctic Ice Sheet from 1992 to 2017. Nature, 558(7709), 219–222. https://doi.org/10.1038/s41586-018-0179-y

Turner, M. G., Baker, W. L., Peterson, C. J., & Peet, R. K. (1998). Factors Influencing Succession: Lessons from Large, Infrequent Natural Disturbances. Ecosystems, 1(6), 511–523. https://doi.org/10.1007/s100219900047

Vellinga, M., & Wood, R. A. (2008). Impacts of thermohaline circulation shutdown in the twenty-first century. Climatic Change, 91(1), 43–63. https://doi.org/10.1007/s10584-006-9146-y

Vidas, D., Freestone, D., & McAdam, J. (2015). International Law And Sea Level Rise: The New ILA Committee. ILSA Journal of International & Comparative Law, 21(2), 157–167. https://nsuworks.nova.edu/ilsajournal/vol21/iss2/9

Vincent, W. F., Lemay, M., & Allard, M. (2017). Arctic permafrost landscapes in transition: towards an integrated Earth system approach. Arctic Science, 3(2), 39–64. https://doi.org/10.1139/as-2016-0027

Wang, H., Zuo, Z., Qiao, L., Zhang, K., Sun, C., Xiao, D., Lin, Z., Bu, L., & Zhang, R. (2022). Frequency of the winter temperature extremes over Siberia dominated by the Atlantic Meridional Overturning Circulation. Npj Climate and Atmospheric Science, 5(1), 84. https://doi.org/10.1038/s41612-022-00307-w

Wang, S., Foster, A., Lenz, E. A., Kessler, J. D., Stroeve, J. C., Anderson, L. O., Turetsky, M., Betts, R., Zou, S., Liu, W., Boos, W. R., & Hausfather, Z. (2023). Mechanisms and Impacts of Earth System Tipping Elements. Reviews of Geophysics, 61(1), e2021RG000757. https://doi.org/10.1029/2021RG000757

Ward Jones, M. K., Schwoerer, T., Gannon, G. M., Jones, B. M., Kanevskiy, M. Z., Sutton, I., St. Pierre, B., St. Pierre, C., Russell, J., & Russell, D. (2022). Climate-driven expansion of northern agriculture must consider permafrost. Nature Climate Change, 12(8), 699–703. https://doi.org/10.1038/s41558-022-01436-z

World Health Organisation (2011). Sanitation and hygiene. https://iris.who.int/handle/10665/370541

Zemp, D. C., Schleussner, C.-F., Barbosa, H. M. J., Hirota, M., Montade, V., Sampaio, G., Staal, A., Wang-Erlandsson, L., & Rammig, A. (2017). Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks. Nature Communications, 8(1), 14681. https://doi.org/10.1038/ncomms14681

Zhang, R., & Delworth, T. L. (2005). Simulated Tropical Response to a Substantial Weakening of the Atlantic Thermohaline Circulation. Journal of Climate, 18(12), 1853–1860. https://doi.org/10.1175/JCLI3460.1

References: Chapter 2.3

Abou-Chadi, T., & Krause, W. (2020). The Causal Effect of Radical Right Success on Mainstream Parties' Policy Positions: A Regression Discontinuity Approach. British Journal of Political Science, 50(3), 829–847. https://doi.org/10.1017/S0007123418000029

Agius, C., Rosamond, A. B., & Kinnvall, C. (2020). Populism, Ontological Insecurity and Gendered Nationalism: Masculinity, Climate Denial and Covid-19. Politics, Religion & Ideology, 21(4), 432–450. https://doi.org/10.1080/21567689.2020.1851871

Allen, T. F., Tainter, J. A., & Hoekstra, T. W. (2003). Supply-side sustainability. Columbia University Press.

Aquino, G., Guo, W., & Wilson, A. (2019). Nonlinear Dynamic Models of Conflict via Multiplexed Interaction Networks. https://doi.org/10.48550/ARXIV.1909.12457

Atwoli, L., Muhia, J., & Merali, Z. (2022). Mental health and climate change in Africa. BJPsych International, 19(4), 86–89. https://doi.org/10.1192/bji.2022.14

Avis, W. (2020). War economy in North East Nigeria. Publisher: Institute of Development Studies. 734_War_Economy_in_North_East_Nigeria.pdf (ids.ac.uk)

Babb, N. (2021). Baby won't you please come home": Studying ethnoracial segregation trends in New Orleans pre and Post Hurricane Katrina. Journal of Public and International Affairs. Jpia. Princeton. Edu/News/Baby-Wont-You-Please-Come-Home-Studying-Ethnoracial-Segregation-Trends-New-Orleans-Pre-and-Post.

Bacani, B. (2016). New financing approaches, instruments and opportunities that address the risks of loss and damage. 2016 Forum of the UNFCCC Standing Committee on Finance 5-6 September 2016, Manila,. https://www.google.com/url?q=https://unfccc.int/files/adaptation/application/pdf/unep_fi_-_butch_bacani_(sep_2016,_manila)_(final)_(1).pdf&sa=D&source=docs&ust=1698348316931772&usg=AOvVaw3wXfYmA8eXP3pZHxCMgWos

Baele, S., Brace, L., & Ging, D. (2023a). A Diachronic Cross-Platforms Analysis of Violent Extremist Language in the Incel Online Ecosystem. Terrorism and Political Violence, 1–24. https://doi.org/10.1080/09546553.2022.2161373

Baele, S., Brace, L., & Ging, D. (2023b). A Diachronic Cross-Platforms Analysis of Violent Extremist Language in the Incel Online Ecosystem. Terrorism and Political Violence, 1–24. https://doi.org/10.1080/09546553.2022.2161373

Banda, K. K., & Cluverius, J. (2018). Elite polarization, party extremity, and affective polarization. Electoral Studies, 56, 90–101. https://doi.org/10.1016/j.electstud.2018.09.009

Barfuss, W., Donges, J. F., Vasconcelos, V. V., Kurths, J., & Levin, S. A. (2020). Caring for the future can turn tragedy into comedy for long-term collective action under risk of collapse. Proceedings of the National Academy of Sciences, 117(23), 12915–12922. https://doi.org/10.1073/pnas.1916545117

Battiston, S., Mandel, A., Monasterolo, I., Schütze, F., & Visentin, G. (2017a). A climate stress-test of the financial system. Nature Climate Change, 7(4), 283–288. https://doi.org/10.1038/nclimate3255

Battiston, S., Mandel, A., Monasterolo, I., Schütze, F., & Visentin, G. (2017b). A climate stress-test of the financial system. Nature Climate Change, 7(4), 283–288. https://doi.org/10.1038/nclimate3255

Belgioioso, M., Costalli, S., & Gleditsch, K. S. (2021). Better the Devil You Know? How Fringe Terrorism Can Induce an Advantage for Moderate Nonviolent Campaigns. Terrorism and Political Violence, 33(3), 596–615. https://doi.org/10.1080/09546553.2018.1559836

Boas, I., Farbotko, C., Adams, H., Sterly, H., Bush, S., Van Der Geest, K., Wiegel, H., Ashraf, H., Baldwin, A., Bettini, G., Blondin, S., De Bruijn, M., Durand-Delacre, D., Fröhlich, C., Gioli, G., Guaita, L., Hut, E., Jarawura, F. X., Lamers, M., … Hulme, M. (2019). Climate migration myths. Nature Climate Change, 9(12), 901–903. https://doi.org/10.1038/s41558-019-0633-3

Bomberg, E. (2021). The environmental legacy of President Trump. Policy Studies, 42(5–6), 628–645. https://doi.org/10.1080/01442872.2021.1922660

Brown, A. R. (2022). Environmental anomie and the disruption of physical norms during disaster. Current Sociology, 001139212211293. https://doi.org/10.1177/00113921221129316

Bruun, J. T., Allen, J. I., & Smyth, T. J. (2017a). Heartbeat of the S outhern O scillation explains ENSO climatic resonances. Journal of Geophysical Research: Oceans, 122(8), 6746–6772. https://doi.org/10.1002/2017JC012892

Buhaug, H., Nordkvelle, J., Bernauer, T., Böhmelt, T., Brzoska, M., Busby, J. W., Ciccone, A., Fjelde, H., Gartzke, E., Gleditsch, N. P., Goldstone, J. A., Hegre, H., Holtermann, H., Koubi, V., Link, J. S. A., Link, P. M., Lujala, P., O-Loughlin, J., Raleigh, C., … Von Uexkull, N. (2014). One effect to rule them all? A comment on climate and conflict. Climatic Change, 127(3–4), 391–397. https://doi.org/10.1007/s10584-014-1266-1

Buhaug, H., & Von Uexkull, N. (2021). Vicious Circles: Violence, Vulnerability, and Climate Change. Annual Review of Environment and Resources, 46(1), 545–568. https://doi.org/10.1146/annurev-environ-012220-014708

Burden, B. C., Fletcher, J. M., Herd, P., Jones, B. M., & Moynihan, D. P. (2017). How Different Forms of Health Matter to Political Participation. The Journal of Politics, 79(1), 166–178. https://doi.org/10.1086/687536

Burke, M., Hsiang, S. M., & Miguel, E. (2015). Global non-linear effect of temperature on economic production. Nature, 527(7577), 235–239. https://doi.org/10.1038/nature15725

Burns, J., Collin, P., & Blanchard, M. (2008). Preventing youth disengagement and promoting engagement. https://doi.org/10.4225/50/557E201418C49

Burns, J. K. (2015). Poverty, inequality and a political economy of mental health. Epidemiology and Psychiatric Sciences, 24(2), 107–113. https://doi.org/10.1017/S2045796015000086

Bursztyn, L., Egorov, G., & Fiorin, S. (2020). From Extreme to Mainstream: The Erosion of Social Norms. American Economic Review, 110(11), 3522–3548. https://doi.org/10.1257/aer.20171175

Busching, R., & Krahé, B. (2018). The Contagious Effect of Deviant Behavior in Adolescence: A Longitudinal Multilevel Study. Social Psychological and Personality Science, 9(7), 815–824. https://doi.org/10.1177/1948550617725151

Caldecott, B., Clark, A., Koskelo, K., Mulholland, E., & Hickey, C. (2021). Stranded Assets: Environmental Drivers, Societal Challenges, and Supervisory Responses. Annual Review of Environment and Resources, 46(1), 417–447. https://doi.org/10.1146/annurev-environ-012220-101430

Capisani, S. (2021). Livability and a Framework for Climate Mobilities Justice. Philosophy and Public Issues - Filosofia E Questioni Pubbliche 11 (1):217-262

Carbó Valverde, S., Chinazzi, M., Fagiolo, G., Lux, T., Martín Oliver, A., Montagna, M., & Rodríguez Fernández, F. (2015). Banking integration and financial crisis: some recent developments, chapter 4 Systemic Risk, Contagion, and Financial Networks: A Survey (I. Arribas & E. Tortosa-Ausina, Eds.; 1.a ed). Fundación BBVA.

Carleton, T. A. (2017). Crop-damaging temperatures increase suicide rates in India. Proceedings of the National Academy of Sciences, 114(33), 8746–8751. https://doi.org/10.1073/pnas.1701354114

Carleton, T. A., & Hsiang, S. M. (2016). Social and economic impacts of climate. Science, 353(6304), aad9837. https://doi.org/10.1126/science.aad9837

Carvajal, L., & Pereira, I. (2010). Evidence on the link between migration, climate shocks, and adaptive capacity. In Risk, Shocks, and Human Development: On the Brink (pp. 257–283). Springer.

Chadefaux, T. (2015) The Triggers of War: Disentangling the Spark from the Powder Keg (April 28, 2015). Available at SSRN: https://ssrn.com/abstract=2409005 or http://dx.doi.org/10.2139/ssrn.2409005

Chinazzi, M. & Fagiolo, G. In Banking Integration and Financial Crisis: Some Recent Developments

eds Fernández, I. A. & Tortosa, E.) Ch. 4 (Fundacion BBVA 2015). Banking Integration and Financial Crisis: Some Recent Developments (fbbva.es)Clayton, S., Manning, C., Krygsman, K., & Speiser, M. (2017). Mental health and our changing climate: Impacts, implications, and guidance. Washington, DC: American Psychological Association and EcoAmerica. https://www.preventionweb.net/publication/mental-health-and-our-changing-climate-impacts-implications-and-guidance

Clement, V., Rigaud, K. K., de Sherbinin, A., Jones, B., Adamo, S., Schewe, J., Sadiq, N., & Shabahat, E. (2021). Groundswell part 2. Publisher: World Bank, Washington, DC Groundswell Part 2: Acting on Internal Climate Migration (worldbank.org)

Cohen-Cole, E., & Fletcher, J. M. (2008). Detecting implausible social network effects in acne, height, and headaches: longitudinal analysis. BMJ, 337(dec04 2), a2533–a2533. https://doi.org/10.1136/bmj.a2533

Cole, J. C., Gillis, A., Linden, S. V. D., Cohen, M., & Vandenbergh, M. (2023). Social Psychological Perspectives on Political Polarization: Insights and Implications for Climate Change [Preprint]. PsyArXiv. https://doi.org/10.31234/osf.io/xz6wk

Constantino, S. M., Sparkman, G., Kraft-Todd, G. T., Bicchieri, C., Centola, D., Shell-Duncan, B., Vogt, S., & Weber, E. U. (2022). Scaling Up Change: A Critical Review and Practical Guide to Harnessing Social Norms for Climate Action. Psychological Science in the Public Interest, 23(2), 50–97. https://doi.org/10.1177/15291006221105279

Crawford, N. C. (2019). Pentagon fuel use, climate change, and the costs of war. Watson Institute, Brown University.

Crona, B., Folke, C., & Galaz, V. (2021). The Anthropocene reality of financial risk. One Earth, 4(5), 618–628.Publisher: Elsevier

Curcio, D., Gianfrancesco, I., & Vioto, D. (2023). Climate change and financial systemic risk: Evidence from US banks and insurers. Journal of Financial Stability, 66, 101132. https://doi.org/10.1016/j.jfs.2023.101132

Dafermos, Y., Nikolaidi, M., & Galanis, G. (2018). Climate Change, Financial Stability and Monetary Policy. Ecological Economics, 152, 219–234. https://doi.org/10.1016/j.ecolecon.2018.05.011

Daggett, C. (2018). Petro-masculinity: Fossil Fuels and Authoritarian Desire. Millennium: Journal of International Studies, 47(1), 25–44. https://doi.org/10.1177/0305829818775817

Daoudy, M. (2021). Rethinking the Climate–Conflict Nexus: A Human–Environmental–Climate Security Approach. Global Environmental Politics, 1–22. https://doi.org/10.1162/glep_a_00609

Daoudy, M., Sowers, J., & Weinthal, E. (2022). What is climate security? Framing risks around water, food, and migration in the Middle East and North Africa. WIREs Water, 9(3), e1582. https://doi.org/10.1002/wat2.1582

Darian-Smith, E. (2023). Entangled Futures: Big Oil, Political Will, and the Global Environmental Movement. Perspectives on Global Development and Technology, 21(5–6), 403–425. https://doi.org/10.1163/15691497-12341640

de Klerk, L., Shmurak, A., Gassan-Zade, O., Shlapak, M., Tomliak, K., & Korthuis, A. (2022). Climate Damage Caused by Russia's war in Ukraine. Initiative on GHG accounting of war. https://climatefocus.com/wp-content/uploads/2022/11/ClimateDamageinUkraine.pdf

De La Sablonnière, R., & Taylor, D. M. (2020). A social change framework for addressing collective action: introducing collective inertia. Current Opinion in Psychology, 35, 65–70. https://doi.org/10.1016/j.copsyc.2020.03.006

Diffenbaugh, N. S., & Burke, M. (2019). Global warming has increased global economic inequality. Proceedings of the National Academy of Sciences, 116(20), 9808–9813. https://doi.org/10.1073/pnas.1816020116

Döring, S., & Hall, J. (2023). Drought exposure decreases altruism with salient group identities as key moderator. Nature Climate Change, 13(8), 856–861. https://doi.org/10.1038/s41558-023-01732-2

Duffy, M. E., Twenge, J. M., & Joiner, T. E. (2019). Trends in Mood and Anxiety Symptoms and Suicide-Related Outcomes Among U.S. Undergraduates, 2007–2018: Evidence From Two National Surveys. Journal of Adolescent Health, 65(5), 590–598. https://doi.org/10.1016/j.jadohealth.2019.04.033

Dunlap, R. E., McCright, A. M., & Yarosh, J. H. (2016). The Political Divide on Climate Change: Partisan Polarization Widens in the U.S. Environment: Science and Policy for Sustainable Development, 58(5), 4–23. https://doi.org/10.1080/00139157.2016.1208995

European Central Bank (ECB). (2021). Financial Stability review, Climate-related risks to financial stability, pp.100-114, May 2021. Frankfurt am Mai. Financial Stability Review, May 2021 (europa.eu)

Ehret, S., Constantino, S. M., Weber, E. U., Efferson, C., & Vogt, S. (2022). Group identities can undermine social tipping after intervention. Nature Human Behaviour, 6(12), 1669–1679. https://doi.org/10.1038/s41562-022-01440-5

Ekberg, K., Forchtner, B., Hultman, M., & Jylhä, K. M. (2022). Climate obstruction: How denial, delay and inaction are heating the planet. Routledge, London

European Systemic Risk Board (ESRB). (2020). Positively green: Measuring climate change risks to financial stability, European Systemic Risk Board, European System of Financial Supervision,. Positively green: measuring climate change risks to financial stability (europa.eu)

Fairbrother, M. (2017). Environmental attitudes and the politics of distrust. Sociology Compass, 11(5), e12482. https://doi.org/10.1111/soc4.12482

Fehr, E., Fischbacher, U., & Gächter, S. (2002). Strong reciprocity, human cooperation, and the enforcement of social norms. Human Nature, 13(1), 1–25. https://doi.org/10.1007/s12110-002-1012-7

Feinberg, M., Willer, R., & Kovacheff, C. (2020). The activist's dilemma: Extreme protest actions reduce popular support for social movements. Journal of Personality and Social Psychology, 119(5), 1086–1111. https://doi.org/10.1037/pspi0000230

Ferrara, E. (2017). Contagion dynamics of extremist propaganda in social networks. Information Sciences, 418–419, 1–12. https://doi.org/10.1016/j.ins.2017.07.030

Ferreira, M. A. M., Leite, Y. L. R., Junior, C. C., & Vicente, C. R. (2023). Impact of climate change on public health in Brazil. Public Health Challenges, 2(1), e62. https://doi.org/10.1002/puh2.62

Flores, A., Cole, J. C., Dickert, S., Eom, K., Jiga-Boy, G. M., Kogut, T., Loria, R., Mayorga, M., Pedersen, E. J., Pereira, B., Rubaltelli, E., Sherman, D. K., Slovic, P., Västfjäll, D., & Van Boven, L. (2022). Politicians polarize and experts depolarize public support for COVID-19 management policies across countries. Proceedings of the National Academy of Sciences, 119(3), e2117543119. https://doi.org/10.1073/pnas.2117543119

Folke, C., Carpenter, S. R., Walker, B., Scheffer, M., Chapin, T., & Rockström, J. (2010). Resilience Thinking: Integrating Resilience, Adaptability and Transformability. Ecology and Society, 15(4), art20. https://doi.org/10.5751/ES-03610-150420

Frank, S., Gusti, M., Havlík, P., Lauri, P., DiFulvio, F., Forsell, N., Hasegawa, T., Krisztin, T., Palazzo, A., & Valin, H. (2021). Land-based climate change mitigation potentials within the agenda for sustainable development. Environmental Research Letters, 16(2), 024006. https://doi.org/10.1088/1748-9326/abc58a

Freedom House. (2022). Freedom in the World 2022. The Global Expansion of Authoritarian Rule. Washington D.C. https://freedomhouse.org/sites/default/files/2022-02/FIW_2022_PDF_Booklet_Digital_Final_Web.pdf

Fritsche, I., Cohrs, J. C., Kessler, T., & Bauer, J. (2012). Global warming is breeding social conflict: The subtle impact of climate change threat on authoritarian tendencies. Journal of Environmental Psychology, 32(1), 1–10. https://doi.org/10.1016/j.jenvp.2011.10.002

Financial Stability Board (FSB). (2020). The Implications of Climate Change for Financial Stability, Financial Stability Board, November 2020. The implications of climate change for financial stability - Financial Stability Board (fsb.org)

FSB and NGFS. (2022). Climate Scenario Analysis by Jurisdictions — Initial findings and lessons. https://www.fsb.org/wp-content/uploads/P151122.pdf

Fussell, E., Curtis, K. J., & DeWaard, J. (2014). Recovery migration to the City of New Orleans after Hurricane Katrina: a migration systems approach. Population and Environment, 35(3), 305–322. https://doi.org/10.1007/s11111-014-0204-5

Fussell, E., Sastry, N., & VanLandingham, M. (2010). Race, socioeconomic status, and return migration to New Orleans after Hurricane Katrina. Population and Environment, 31(1–3), 20–42. https://doi.org/10.1007/s11111-009-0092-2

Gadarian, S. K. (2010). The Politics of Threat: How Terrorism News Shapes Foreign Policy Attitudes. The Journal of Politics, 72(2), 469–483. https://doi.org/10.1017/S0022381609990910

Gai, P., & Kapadia, S. (2010). Contagion in financial networks. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 466(2120), 2401–2423. https://doi.org/10.1098/rspa.2009.0410

Galaz García, C., Bagstad, K. J., Brun, J., Chaplin-Kramer, R., Dhu, T., Murray, N. J., Nolan, C. J., Ricketts, T. H., Sosik, H. M., Sousa, D., Willard, G., & Halpern, B. S. (2023). The future of ecosystem assessments is automation, collaboration, and artificial intelligence. Environmental Research Letters, 18(1), 011003. https://doi.org/10.1088/1748-9326/acab19

Galaz, V., Crona, B., Dauriach, A., Scholtens, B., & Steffen, W. (2018). Finance and the Earth system – Exploring the links between financial actors and non-linear changes in the climate system. Global Environmental Change, 53, 296–302. https://doi.org/10.1016/j.gloenvcha.2018.09.008

Ge, Q., Hao, M., Ding, F., Jiang, D., Scheffran, J., Helman, D., & Ide, T. (2022a). Modelling armed conflict risk under climate change with machine learning and time-series data. Nature Communications, 13(1), 2839. https://doi.org/10.1038/s41467-022-30356-x

Go, M. H. (2018). The tale of a two-tiered city: Community civic structure and spatial inequality in post-Katrina New Orleans. Journal of Urban Affairs, 40(8), 1093–1114. https://doi.org/10.1080/07352166.2018.1490151

Goldberg, R. F., & Vandenberg, L. N. (2019). Distract, delay, disrupt: examples of manufactured doubt from five industries. Reviews on Environmental Health, 34(4), 349–363. https://doi.org/10.1515/reveh-2019-0004

Green, J., Druckman, J. N., Baum, M. A., Lazer, D., Ognyanova, K., & Perlis, R. H. (2023). Depressive symptoms and conspiracy beliefs. Applied Cognitive Psychology, 37(2), 332–359. https://doi.org/10.1002/acp.4011

Guo, W., Gleditsch, K., & Wilson, A. (2018). Retool AI to forecast and limit wars. Nature, 562(7727), 331–333. https://doi.org/10.1038/d41586-018-07026-4

Guo, W., Sun, S., & Wilson, A. (2023). Exploring Potential Causal Models for Climate-Society-Conflict Interaction: Proceedings of the 8th International Conference on Complexity, Future Information Systems and Risk, 69–76. https://doi.org/10.5220/0011968400003485

Haidt, J. Twenge, J. Rausch, Z.. (2010). Adolescent mood disorders since 2010. Adolescent Mood Disorders since 2010: A Collaborative Review. Retrieved 25 October 2023, from https://docs.google.com/document/d/1diMvsMeRphUH7E6D1d_J7R6WbDdgnzFHDHPx9HXzR5o/edit?usp=embed_facebook

Hamideh, S., Sen, P., & Fischer, E. (2022). Wildfire impacts on education and healthcare: Paradise, California, after the Camp Fire. Natural Hazards, 111(1), 353–387. https://doi.org/10.1007/s11069-021-05057-1

Haraldson, H. (2004). Introduction to system thinking and causal loop diagrams. https://www.researchgate.net/profile/Hoerdur-Haraldsson/publication/258261003_Introduction_to_system_thinking_and_causal_loop_diagrams/links/5bcceed6458515f7d9d01e81/Introduction-to-system-thinking-and-causal-loop-diagrams.pdf

Harris, D. (2022). How the war in Ukraine derails future climate negotiations: Can we put ourselves back on track for COP27? Oxford Policy. https://www.opml.co.uk/blog/how-war-ukraine-derails-future-climate-negotiations-back-track-cop2

Hauer, M. E., Fussell, E., Mueller, V., Burkett, M., Call, M., Abel, K., McLeman, R., & Wrathall, D. (2019). Sea-level rise and human migration. Nature Reviews Earth & Environment, 1(1), 28–39. https://doi.org/10.1038/s43017-019-0002-9

Hetherington, M. J., & Weiler, J. D. (2009). Authoritarianism and polarization in American politics. Cambridge University Press.

Hetherington, M., & Suhay, E. (2011). Authoritarianism, Threat, and Americans' Support for the War on Terror: AUTHORITARIANISM, THREAT, AND THE WAR ON TERROR. American Journal of Political Science, 55(3), 546–560. https://doi.org/10.1111/j.1540-5907.2011.00514.x

Hickman, C., Marks, E., Pihkala, P., Clayton, S., Lewandowski, R. E., Mayall, E. E., Wray, B., Mellor, C., & Van Susteren, L. (2021). Climate anxiety in children and young people and their beliefs about government responses to climate change: a global survey. The Lancet Planetary Health, 5(12), e863–e873. https://doi.org/10.1016/S2542-5196(21)00278-3

Hoffarth, M. R., & Hodson, G. (2016). Green on the outside, red on the inside: Perceived environmentalist threat as a factor explaining political polarization of climate change. Journal of Environmental Psychology, 45, 40–49. https://doi.org/10.1016/j.jenvp.2015.11.002

Homer-Dixon, T. (1999). Environment, scarcity, and violence. Princeton University Press.

Horton, R. M., De Sherbinin, A., Wrathall, D., & Oppenheimer, M. (2021). Assessing human habitability and migration. Science, 372(6548), 1279–1283. https://doi.org/10.1126/science.abi8603

Holling, C. S., Gunderson, L. H., & Ludwig, D. (2002). In quest of a theory of adaptive change. In C. S. Holling & L. H. Gunderson (Eds.), Panarchy: Understanding Transformations in Human and Natural Systems (pp. 3–24). Island Press.

Hsiang, S., Kopp, R., Jina, A., Rising, J., Delgado, M., Mohan, S., Rasmussen, D. J., Muir-Wood, R., Wilson, P., Oppenheimer, M., Larsen, K., & Houser, T. (2017). Estimating economic damage from climate change in the United States. Science, 356(6345), 1362–1369. https://doi.org/10.1126/science.aal4369

Hsiang, S. M., & Meng, K. C. (2014). Reconciling disagreement over climate–conflict results in Africa. Proceedings of the National Academy of Sciences, 111(6), 2100–2103. https://doi.org/10.1073/pnas.1316006111

Huddy, L., & Feldman, S. (2011). Americans respond politically to 9/11: Understanding the impact of the terrorist attacks and their aftermath. American Psychologist, 66(6), 455–467. https://doi.org/10.1037/a0024894

Hulme, M., Biermann, F., & Boas, I. (2008). Climate refugees: cause for a new agreement? Environment, 50(6), 50, 50-54, https://doi.org/10.3200/ENVT.50.6.50-54

Ide, T., Johnson, M. F., Barnett, J., Krampe, F., Le Billon, P., Maertens, L., Von Uexkull, N., & Vélez-Torres, I. (2023). The Future of Environmental Peace and Conflict Research. Environmental Politics, 32(6), 1077–1103. https://doi.org/10.1080/09644016.2022.2156174

International Monitory fund (IMF). (2020). Global Financial Stability Report: Markets in the Time of COVID-19, International Monetary Fund, Chapter 5: Climate Change: Physical Risk and Equity Prices. https://www.imf.org/en/Publications/GFSR/Issues/2020/04/14/global-financial-stability-report-april-2020#Chapter5

Intergovernmental Panel On Climate Change (IPCC). (2022). Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (1st ed.). Cambridge University Press. https://doi.org/10.1017/9781009325844

Institute for Democracy and Electoral Assistance (IDEA). (2022). The Global State of Democracy 2022 Forging Social Contracts in a Time of Discontent. https://www.idea.int/democracytracker/sites/default/files/2022-11/the-global-state-of-democracy-2022.pdf

Jackson, J. C., Van Egmond, M., Choi, V. K., Ember, C. R., Halberstadt, J., Balanovic, J., Basker, I. N., Boehnke, K., Buki, N., Fischer, R., Fulop, M., Fulmer, A., Homan, A. C., Van Kleef, G. A., Kreemers, L., Schei, V., Szabo, E., Ward, C., & Gelfand, M. J. (2019). Ecological and cultural factors underlying the global distribution of prejudice. PLOS ONE, 14(9), e0221953. https://doi.org/10.1371/journal.pone.0221953

Jermacane, D., Waite, T. D., Beck, C. R., Bone, A., Amlôt, R., Reacher, M., Kovats, S., Armstrong, B., Leonardi, G., James Rubin, G., & Oliver, I. (2018). The English National Cohort Study of Flooding and Health: the change in the prevalence of psychological morbidity at year two. BMC Public Health, 18(1), 330. https://doi.org/10.1186/s12889-018-5236-9

Johnson, C. A., & Krishnamurthy, K. (2010). Dealing with displacement: Can "social protection" facilitate long-term adaptation to climate change? Global Environmental Change, 20(4), 648–655. https://doi.org/10.1016/j.gloenvcha.2010.06.002

Judge, M., Kashima, Y., Steg, L., & Dietz, T. (2023). Environmental Decision-Making in Times of Polarization. Annual Review of Environment and Resources, 48(1), annurev-environ-112321-115339. https://doi.org/10.1146/annurev-environ-112321-115339

Jylhä, K. M., & Hellmer, K. (2020). Right-Wing Populism and Climate Change Denial: The Roles of Exclusionary and Anti-Egalitarian Preferences, Conservative Ideology, and Antiestablishment Attitudes. Analyses of Social Issues and Public Policy, 20(1), 315–335. https://doi.org/10.1111/asap.12203

Kakinuma, K., Puma, M. J., Hirabayashi, Y., Tanoue, M., Baptista, E. A., & Kanae, S. (2020). Flood-induced population displacements in the world. Environmental Research Letters, 15(12), 124029. https://doi.org/10.1088/1748-9326/abc586

Kedward, K., Ryan-Collins, J., & Chenet, H. (2023). Biodiversity loss and climate change interactions: financial stability implications for central banks and financial supervisors. Climate Policy, 23(6), 763–781. https://doi.org/10.1080/14693062.2022.2107475

Keen, S. (2021). The appallingly bad neoclassical economics of climate change. Globalizations, 18(7), 1149–1177. https://doi.org/10.1080/14747731.2020.1807856

Kelley, C. P., Mohtadi, S., Cane, M. A., Seager, R., & Kushnir, Y. (2015). Climate change in the Fertile Crescent and implications of the recent Syrian drought. Proceedings of the National Academy of Sciences, 112(11), 3241–3246. https://doi.org/10.1073/pnas.1421533112

Kemp, L., Xu, C., Depledge, J., Ebi, K. L., Gibbins, G., Kohler, T. A., Rockström, J., Scheffer, M., Schellnhuber, H. J., Steffen, W., & Lenton, T. M. (2022). Climate Endgame: Exploring catastrophic climate change scenarios. Proceedings of the National Academy of Sciences, 119(34), e2108146119. https://doi.org/10.1073/pnas.2108146119

Kester, J., & Sovacool, B. K. (2017). Torn between war and peace: Critiquing the use of war to mobilize peaceful climate action. Energy Policy, 104, 50–55. https://doi.org/10.1016/j.enpol.2017.01.026

Kimmel, M. S. (2018). Healing from hate: How young men get into-and out of-violent extremism. University of California Press

Kintisch, E. (2016). The lost norse. Science, 354(6313), 696–701. https://doi.org/10.1126/science.354.6313.69Kiyotaki, N., & Moore, J. (2002). Balance-Sheet Contagion. American Economic Review, 92(2), 46–50. https://doi.org/10.1257/000282802320188989

Kolmes, S. A. (2008). The Social Feedback Loop. Environment: Science and Policy for Sustainable Development, 50(2), 57–58. https://doi.org/10.3200/ENVT.50.2.57-58

Koubi, V. (2019a). Climate Change and Conflict. Annual Review of Political Science, 22(1), 343–360. https://doi.org/10.1146/annurev-polisci-050317-070830

Kousser, T., & Tranter, B. (2018). The influence of political leaders on climate change attitudes. Global Environmental Change, 50, 100–109. https://doi.org/10.1016/j.gloenvcha.2018.03.005

Krishnamurthy, P. K. (2012). Disaster-induced migration: Assessing the impact of extreme weather events on livelihoods. Environmental Hazards, 11(2), 96–111. https://doi.org/10.1080/17477891.2011.609879

Lamperti, F., Bosetti, V., Roventini, A., & Tavoni, M. (2019a). The public costs of climate-induced financial instability. Nature Climate Change, 9(11), 829–833. https://doi.org/10.1038/s41558-019-0607-5

Lawrence, J., Blackett, P., & Cradock-Henry, N. A. (2020). Cascading climate change impacts and implications. Climate Risk Management, 29, 100234. https://doi.org/10.1016/j.crm.2020.100234

Lenton, T. M. (2011). Early warning of climate tipping points. Nature Climate Change, 1(4), 201–209. https://doi.org/10.1038/nclimate1143

Lenton, T. M., Xu, C., Abrams, J. F., Ghadiali, A., Loriani, S., Sakschewski, B., Zimm, C., Ebi, K. L., Dunn, R. R., Svenning, J.-C., & Scheffer, M. (2023). Quantifying the human cost of global warming. Nature Sustainability, 6(10), 1237–1247. https://doi.org/10.1038/s41893-023-01132-6

Lettinga, N., Jacquet, P. O., André, J.-B., Baumand, N., & Chevallier, C. (2020). Environmental adversity is associated with lower investment in collective actions. PLOS ONE, 15(7), e0236715. https://doi.org/10.1371/journal.pone.0236715

Mach, K. J., Kraan, C. M., Adger, W. N., Buhaug, H., Burke, M., Fearon, J. D., Field, C. B., Hendrix, C. S., Maystadt, J.-F., O'Loughlin, J., Roessler, P., Scheffran, J., Schultz, K. A., & Von Uexkull, N. (2019). Climate as a risk factor for armed conflict. Nature, 571(7764), 193–197. https://doi.org/10.1038/s41586-019-1300-6

Macy, M. W., Ma, M., Tabin, D. R., Gao, J., & Szymanski, B. K. (2021). Polarization and tipping points. Proceedings of the National Academy of Sciences, 118(50), e2102144118. https://doi.org/10.1073/pnas.2102144118

Magrin, G. (2016). The disappearance of Lake Chad: history of a myth. Journal of Political Ecology, 23(1). https://doi.org/10.2458/v23i1.20191

Malm, A. (2021). How to blow up a pipeline. Verso Books.

Mann, M. E. (2021). The new climate war: The fight to take back our planet. PublicAffairs.

Marcucci, G., Mazzuto, G., Bevilacqua, M., Ciarapica, F. E., & Urciuoli, L. (2022). Conceptual model for breaking ripple effect and cycles within supply chain resilience. Supply Chain Forum: An International Journal, 23(3), 252–271. https://doi.org/10.1080/16258312.2022.2031275

Martinich, J., & Crimmins, A. (2019). Climate damages and adaptation potential across diverse sectors of the United States. Nature Climate Change, 9(5), 397–404. https://doi.org/10.1038/s41558-019-0444-6

Mäs, M., & Opp, K.-D. (2016). When is ignorance bliss? Disclosing true information and cascades of norm violation in networks. Social Networks, 47, 116–129. https://doi.org/10.1016/j.socnet.2016.05.004

McLeman, R. (2018). Thresholds in climate migration. Population and Environment, 39(4), 319–338. https://doi.org/10.1007/s11111-017-0290-2

Mercure, J.-F., Pollitt, H., Viñuales, J. E., Edwards, N. R., Holden, P. B., Chewpreecha, U., Salas, P., Sognnaes, I., Lam, A., & Knobloch, F. (2018). Macroeconomic impact of stranded fossil fuel assets. Nature Climate Change, 8(7), 588–593. https://doi.org/10.1038/s41558-018-0182-1

Miller, D. S. (2016). Public trust in the aftermath of natural and na-technological disasters: Hurricane Katrina and the Fukushima Daiichi nuclear incident. International Journal of Sociology and Social Policy, 36(5/6), 410–431. https://doi.org/10.1108/IJSSP-02-2015-0030

Mueller, V., Gray, C., & Kosec, K. (2014). Heat stress increases long-term human migration in rural Pakistan. Nature Climate Change, 4(3), 182–185. https://doi.org/10.1038/nclimate2103

Muñoz, J., & Anduiza, E. (2019). 'If a fight starts, watch the crowd': The effect of violence on popular support for social movements. Journal of Peace Research, 56(4), 485–498. https://doi.org/10.1177/0022343318820575

Neumann, B., Vafeidis, A. T., Zimmermann, J., & Nicholls, R. J. (2015). Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding - A Global Assessment. PLOS ONE, 10(3), e0118571. https://doi.org/10.1371/journal.pone.0118571

Organisation for Economic Co-Operation and Development (OECD). (2021). Global pension statistics. https://www.oecd.org/pensions/globalpensionstatistics.htm

Oginni, S. O., Opoku, M. P., & Alupo, B. A. (2020). Terrorism in the Lake Chad Region: Integration of Refugees and Internally Displaced Persons. Journal of Borderlands Studies, 35(5), 725–741. https://doi.org/10.1080/08865655.2018.1457975

Ojeda, C. (2015). Depression and Political Participation*. Social Science Quarterly, 96(5), 1226–1243. https://doi.org/10.1111/ssqu.12173

Okpara, U. T., Stringer, L. C., & Dougill, A. J. (2017). Using a novel climate–water conflict vulnerability index to capture double exposures in Lake Chad. Regional Environmental Change, 17(2), 351–366. https://doi.org/10.1007/s10113-016-1003-6

Okpara, U. T., Stringer, L. C., Dougill, A. J., & Bila, M. D. (2015). Conflicts about water in Lake Chad: Are environmental, vulnerability and security issues linked? Progress in Development Studies, 15(4), 308–325. https://doi.org/10.1177/1464993415592738

Parodi, K. B., Holt, M. K., Green, J. G., Porche, M. V., Koenig, B., & Xuan, Z. (2022). Time trends and disparities in anxiety among adolescents, 2012–2018. Social Psychiatry and Psychiatric Epidemiology, 57(1), 127–137. https://doi.org/10.1007/s00127-021-02122-9

Paz, L. V., Viola, T. W., Milanesi, B. B., Sulzbach, J. H., Mestriner, R. G., Wieck, A., & Xavier, L. L. (2022). Contagious depression: Automatic mimicry and the mirror neuron system - A review. Neuroscience & Biobehavioral Reviews, 134, 104509. https://doi.org/10.1016/j.neubiorev.2021.12.032

Piff, P. K., Stancato, D. M., Côté, S., Mendoza-Denton, R., & Keltner, D. (2012). Higher social class predicts increased unethical behavior. Proceedings of the National Academy of Sciences, 109(11), 4086–4091. https://doi.org/10.1073/pnas.1118373109

Polk, M. (2011). Institutional Capacity-building in Urban Planning and Policy-making for Sustainable Development: Success or Failure? Planning Practice and Research, 26(2), 185–206. https://doi.org/10.1080/02697459.2011.560461

IPCC, 2022: Summary for Policymakers [H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem (eds.)]. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3–33, doi:10.1017/9781009325844.001

Rafaty, R. (2018). Perceptions of Corruption, Political Distrust, and the Weakening of Climate Policy. Global Environmental Politics, 18(3), 106–129. https://doi.org/10.1162/glep_a_00471

Rantanen, M., Karpechko, A. Yu., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., Vihma, T., & Laaksonen, A. (2022). The Arctic has warmed nearly four times faster than the globe since 1979. Communications Earth & Environment, 3(1), 168. https://doi.org/10.1038/s43247-022-00498-3

Rockström, J., Gupta, J., Qin, D., Lade, S. J., Abrams, J. F., Andersen, L. S., Armstrong McKay, D. I., Bai, X., Bala, G., Bunn, S. E., Ciobanu, D., DeClerck, F., Ebi, K., Gifford, L., Gordon, C., Hasan, S., Kanie, N., Lenton, T. M., Loriani, S., … Zhang, X. (2023). Safe and just Earth system boundaries. Nature, 619(7968), 102–111. https://doi.org/10.1038/s41586-023-06083-8

Ross, A. R., Modi, M., Paresky, P., Jussim, L., Harrell, B., Goldenberg, A., Goldenberg, P., Finkelstein, D., Farmer, J., & Holden, K. (2021). A contagion of institutional distrust: Viral disinformation of the COVID vaccine and the road to reconciliation. Rutgers Miller Center for Community Protection and Resilience. Rutges NCRI_Anti-Vaccination_v5.pdf (rutgers.edu)

Roukny, T., Bersini, H., Pirotte, H., Caldarelli, G., & Battiston, S. (2013). Default Cascades in Complex Networks: Topology and Systemic Risk. Scientific Reports, 3(1), 2759. https://doi.org/10.1038/srep02759

Russo, S., Mirisola, A., Dallago, F., & Roccato, M. (2020). Facing natural disasters through the endorsement of authoritarian attitudes. Journal of Environmental Psychology, 68, 101412. https://doi.org/10.1016/j.jenvp.2020.101412

Sakaguchi, K., Varughese, A., & Auld, G. (2017). Climate Wars? A Systematic Review of Empirical Analyses on the Links between Climate Change and Violent Conflict. International Studies Review, 19(4), 622–645. https://doi.org/10.1093/isr/vix022

Sampaio, A. (2022). Conflict economies and urban systems in the Lake Chad Region. https://globalinitiative.net/wp-content/uploads/2022/11/Lake-Chad.9Nov-web-copy.pdf

Sampaio, G., Nobre, C., Costa, M. H., Satyamurty, P., Soares-Filho, B. S., & Cardoso, M. (2007). Regional climate change over eastern Amazonia caused by pasture and soybean cropland expansion. Geophysical Research Letters, 34(17), L17709. https://doi.org/10.1029/2007GL030612

Scartozzi, C. M. (2021). Reframing Climate-Induced Socio-Environmental Conflicts: A Systematic Review. International Studies Review, 23(3), 696–725. https://doi.org/10.1093/isr/viaa064

Scatà, M., Di Stefano, A., La Corte, A., & Liò, P. (2018). Quantifying the propagation of distress and mental disorders in social networks. Scientific Reports, 8(1), 5005. https://doi.org/10.1038/s41598-018-23260-2

Scheffran, J., Brzoska, M., Kominek, J., Link, P. M., & Schilling, J. (2012). Climate Change and Violent Conflict. Science, 336(6083), 869–871. https://doi.org/10.1126/science.1221339

Schneider, C. R., & Van Der Linden, S. (2023). Social norms as a powerful lever for motivating pro-climate actions. One Earth, 6(4), 346–351. https://doi.org/10.1016/j.oneear.2023.03.014

Selby, J., Dahi, O. S., Fröhlich, C., & Hulme, M. (2017). Climate change and the Syrian civil war revisited. Political Geography, 60, 232–244. https://doi.org/10.1016/j.polgeo.2017.05.007

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

Sharpe, S. (2023a). Five Times Faster: Rethinking the Science, Economics, and Diplomacy of Climate Change (1st ed.). Cambridge University Press. https://doi.org/10.1017/9781009326506

Sillmann, J. Soppel,S. Russo, S (2019) Climate Extremes and Their Implications for Impact and Risk Assessment. Elsevier ent

Simpson, B., Willer, R., & Feinberg, M. eds. (2022). Radical flanks of social movements can increase support for moderate factions. PNAS Nexus, 1(3), pgac110. https://doi.org/10.1093/pnasnexus/pgac110

Skinner, E. B., Glidden, C. K., MacDonald, A. J., & Mordecai, E. A. (2023). Human footprint is associated with shifts in the assemblages of major vector-borne diseases. Nature Sustainability, 6(6), 652–661. https://doi.org/10.1038/s41893-023-01080-1

Smith, D. N., & Hanley, E. (2018). The Anger Games: Who Voted for Donald Trump in the 2016 Election, and Why? Critical Sociology, 44(2), 195–212. https://doi.org/10.1177/0896920517740615

Snow, D. A., Soule, S. A., Kriesi, H., & McCammon, H. J. (Eds.). (2018). The Wiley Blackwell Companion to Social Movements (1st ed.). Wiley. https://doi.org/10.1002/9781119168577

Solow, A. R. (2013). A call for peace on climate and conflict. Nature, 497(7448), 179–180. https://doi.org/10.1038/497179a

Sovacool, B. K., & Dunlap, A. (2022). Anarchy, war, or revolt? Radical perspectives for climate protection, insurgency and civil disobedience in a low-carbon era. Energy Research & Social Science, 86, 102416. https://doi.org/10.1016/j.erss.2021.102416

Spaiser, V., Dunn, K., Milner, P., & Moore, J. (2022). The Effects of Communicating Climate Change Threat: Mobilization or Polarization? [Preprint]. PsyArXiv. https://doi.org/10.31234/osf.io/gftvc

Spaiser, V., Juhola, S., Constantino, S. M., Guo, W., Watson, T., Sillmann, J., Craparo, A., Basel, A., Bruun, J. T., Krishnamurthy, K., Scheffran, J., Pinho, P., Okpara, U. T., Donges, J. F., Bhowmik, A., Yasseri, T., Safra De Campos, R., Cumming, G. S., Chenet, H., … Abrams, J. F. (2023). Negative Social Tipping Dynamics Resulting from and Reinforcing Earth System Destabilisation [Preprint]. Climate change/Human/Earth system interactions/Other methods. https://doi.org/10.5194/egusphere-2023-1475

Stal M (2009): Case study report on Mozambique for the environmental change and forced migration scenarios project. In: EACH-FOR Environmental Change and Forced Migration Scenarios. D.3.4. Synthesis Report. p.40-41. https://rosamartinez.org/wp-content/uploads/2015/11/Migraciones-y-Cambio-Climatico_EACHFOR.pdf

Staal, A., Flores, B. M., Aguiar, A. P. D., Bosmans, J. H. C., Fetzer, I., & Tuinenburg, O. A. (2020). Feedback between drought and deforestation in the Amazon. Environmental Research Letters, 15(4), 044024. https://doi.org/10.1088/1748-9326/ab738e

Stanley, S. K., & Wilson, M. S. (2019). Meta-analysing the association between social dominance orientation, authoritarianism, and attitudes on the environment and climate change. Journal of Environmental Psychology, 61, 46–56. https://doi.org/10.1016/j.jenvp.2018.12.002

Stanley, S. K., Wilson, M. S., & Milfont, T. L. (2017). Exploring short-term longitudinal effects of right-wing authoritarianism and social dominance orientation on environmentalism. Personality and Individual Differences, 108, 174–177. https://doi.org/10.1016/j.paid.2016.11.059

Stechemesser, A., Levermann, A., & Wenz, L. (2022). Temperature impacts on hate speech online: evidence from 4 billion geolocated tweets from the USA. The Lancet Planetary Health, 6(9), e714–e725. https://doi.org/10.1016/S2542-5196(22)00173-5

Stewart, A. J., McCarty, N., & Bryson, J. J. (2020). Polarization under rising inequality and economic decline. Science Advances, 6(50), eabd4201. https://doi.org/10.1126/sciadv.abd4201

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

Sultana, F. (2022a). The unbearable heaviness of climate coloniality. Political Geography, 99, 102638. https://doi.org/10.1016/j.polgeo.2022.102638

Sun, S. C., Jin, B., Wei, Z., & Guo, W. (2022). Revealing the Excitation Causality between Climate and Political Violence via a Neural Forward-Intensity Poisson Process. Proceedings of the Thirty-First International Joint Conference on Artificial Intelligence, 5171–5177. https://doi.org/10.24963/ijcai.2022/718

Tafere, M. (2018). Forced displacements and the environment: Its place in national and international climate agenda. Journal of Environmental Management, 224, 191–201. https://doi.org/10.1016/j.jenvman.2018.07.063

Taylor, B. (2019). Alt-right ecology. 2019). The Far Right and the Environment: Politics, Discourse and Communication, 275–292. In Forchtner, B (2019) The Far Right and the Environment. Politics, Discourse and communication, Routledge, London

Teymoori, A., Bastian, B., & Jetten, J. (2017). Towards a Psychological Analysis of Anomie. Political Psychology, 38(6), 1009–1023. https://doi.org/10.1111/pops.12377

Thalheimer, L., & Oh, W. S. (2023). An inventory tool to assess displacement data in the context of weather and climate-related events. Climate Risk Management, 40, 100509. https://doi.org/10.1016/j.crm.2023.100509

Thøgersen, J. (2008). Social norms and cooperation in real-life social dilemmas. Journal of Economic Psychology, 29(4), 458–472. https://doi.org/10.1016/j.joep.2007.12.004

Thomas, A., Theokritoff, E., Lesnikowski, A., Reckien, D., Jagannathan, K., Cremades, R., Campbell, D., Joe, E. T., Sitati, A., Singh, C., Segnon, A. C., Pentz, B., Musah-Surugu, J. I., Mullin, C. A., Mach, K. J., Gichuki, L., Galappaththi, E., Chalastani, V. I., Ajibade, I., … Global Adaptation Mapping Initiative Team. (2021). Global evidence of constraints and limits to human adaptation. Regional Environmental Change, 21(3), 85. https://doi.org/10.1007/s10113-021-01808-9

Tompkins, E. (2015). A Quantitative Reevaluation of Radical Flank Effects within Nonviolent Campaigns. In P. G. Coy (Ed.), Research in Social Movements, Conflicts and Change (Vol. 38, pp. 103–135). Emerald Group Publishing Limited. https://doi.org/10.1108/S0163-786X20150000038004

Townshend, I., Awosoga, O., Kulig, J., & Fan, H. (2015). Social cohesion and resilience across communities that have experienced a disaster. Natural Hazards, 76(2), 913–938. https://doi.org/10.1007/s11069-014-1526-4

Trust, S., Sanjay, J., Lendon, T. & Oliver, J. (2023). The Emperor's New Climate Scenarios. Limitations and assumptions of commonly used climate-change scenarios in financial services. Report. Institute and Faculty of Actuaries & University of Exeter. https://actuaries.org.uk/media/qeydewmk/the-emperor-s-new-climate-scenarios.pdf

Uenal, F., Sidanius, J., Roozenbeek, J., & Van Der Linden, S. (2021). Climate change threats increase modern racism as a function of social dominance orientation and ingroup identification. Journal of Experimental Social Psychology, 97, 104228. https://doi.org/10.1016/j.jesp.2021.104228

Van Nes, E. H., Arani, B. M. S., Staal, A., Van Der Bolt, B., Flores, B. M., Bathiany, S., & Scheffer, M. (2016). What Do You Mean, 'Tipping Point'? Trends in Ecology & Evolution, 31(12), 902–904. https://doi.org/10.1016/j.tree.2016.09.011

Vihma, A., Reischl, G., & Nonbo Andersen, A. (2021). A Climate Backlash: Comparing Populist Parties' Climate Policies in Denmark, Finland, and Sweden. The Journal of Environment & Development, 30(3), 219–239. https://doi.org/10.1177/10704965211027748

Vivekananda, J., Wall, M., Sylvestre, F., and Nagarajan, C. (2019). horing Up Stability – Addressing Climate and Fragility Risks in the Lake Chad Region. Berlin: Adelphi. https://www.google.com/url?q=https://adelphi.de/en/publications/shoring-up-stability&sa=D&source=docs&ust=1698348316923168&usg=AOvVaw3HUPpoe4oabFr-g3NzFhNZ

Walker, B., Crépin, A.-S., Nyström, M., Anderies, J. M., Andersson, E., Elmqvist, T., Queiroz, C., Barrett, S., Bennett, E., Cardenas, J. C., Carpenter, S. R., Chapin, F. S., De Zeeuw, A., Fischer, J., Folke, C., Levin, S., Nyborg, K., Polasky, S., Segerson, K., … Vincent, J. R. (2023). Response diversity as a sustainability strategy. Nature Sustainability, 6(6), 621–629. https://doi.org/10.1038/s41893-022-01048-7

Watson, T., Lenton, T., & De Campos, R. S. (2023). The climate change, conflict and migration nexus: A holistic view. Climate Resilience and Sustainability, 2(2), e250. https://doi.org/10.1002/cli2.50

Weber, L., & Peek, L. (Eds.). (2012). Displaced: Life in the Katrina Diaspora. University of Texas Press. https://doi.org/10.7560/735774

Winkler, H. (2019). The effect of income inequality on political polarization: Evidence from European regions, 2002–2014. Economics & Politics, 31(2), 137–162. https://doi.org/10.1111/ecpo.12129

Youngblood, M. (2020). Extremist ideology as a complex contagion: the spread of far-right radicalization in the United States between 2005 and 2017. Humanities and Social Sciences Communications, 7(1), 49. https://doi.org/10.1057/s41599-020-00546-3

References: Chapter 2.4

Aragão, L. E. O. C., Anderson, L. O., Fonseca, M. G., Rosan, T. M., Vedovato, L. B., Wagner, F. H., Silva, C. V. J., Silva Junior, C. H. L., Arai, E., Aguiar, A. P., Barlow, J., Berenguer, E., Deeter, M. N., Domingues, L. G., Gatti, L., Gloor, M., Malhi, Y., Marengo, J. A., Miller, J. B., … Saatchi, S. (2018). 21st Century drought-related fires counteract the decline of Amazon deforestation carbon emissions. Nature Communications, 9(1), 536. https://doi.org/10.1038/s41467-017-02771-y

Armstrong McKay, D. I., Staal, A., Abrams, J. F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S. E., Rockström, J., & Lenton, T. M. (2022). Exceeding 1.5°C global warming could trigger multiple climate tipping points. Science, 377(6611), eabn7950. https://doi.org/10.1126/science.abn7950

Barrett, S., & Dannenberg, A. (2014). Sensitivity of collective action to uncertainty about climate tipping points. Nature Climate Change, 4(1), 36–39. https://doi.org/10.1038/nclimate2059

Bartelet, H. A., Barnes, M. L., & Cumming, G. S. (2023a). Microeconomic adaptation to severe climate disturbances on Australian coral reefs. Ambio, 52(2), 285–299. https://doi.org/10.1007/s13280-022-01798-w

Bartelet, H. A., Barnes, M. L., & Cumming, G. S. (2023b). Microeconomic adaptation to severe climate disturbances on Australian coral reefs. Ambio, 52(2), 285–299. https://doi.org/10.1007/s13280-022-01798-w

Bellwood, D. R., Pratchett, M. S., Morrison, T. H., Gurney, G. G., Hughes, T. P., Álvarez-Romero, J. G., Day, J. C., Grantham, R., Grech, A., Hoey, A. S., Jones, G. P., Pandolfi, J. M., Tebbett, S. B., Techera, E., Weeks, R., & Cumming, G. S. (2019). Coral reef conservation in the Anthropocene: Confronting spatial mismatches and prioritizing functions. Biological Conservation, 236, 604–615. https://doi.org/10.1016/j.biocon.2019.05.056

Bentley, R. A., Maddison, E. J., Ranner, P. H., Bissell, J., Caiado, C. C. S., Bhatanacharoen, P., Clark, T., Botha, M., Akinbami, F., Hollow, M., Michie, R., Huntley, B., Curtis, S. E., & Garnett, P. (2014). Social tipping points and Earth systems dynamics. Frontiers in Environmental Science, 2. https://doi.org/10.3389/fenvs.2014.00035

Blei, D. M. (2012). Probabilistic topic models. Communications of the ACM, 55(4), 77–84. https://doi.org/10.1145/2133806.2133826

Bose, K. S., & Sarma, R. H. (1975). Delineation of the intimate details of the backbone conformation of pyridine nucleotide coenzymes in aqueous solution. Biochemical and Biophysical Research Communications, 66(4), 1173–1179. https://doi.org/10.1016/0006-291x(75)90482-9

Boulton, C. A., Lenton, T. M., & Boers, N. (2022). Pronounced loss of Amazon rainforest resilience since the early 2000s. Nature Climate Change, 12(3), 271–278. https://doi.org/10.1038/s41558-022-01287-8

Brovkin, V., Brook, E., Williams, J. W., Bathiany, S., Lenton, T. M., Barton, M., DeConto, R. M., Donges, J. F., Ganopolski, A., McManus, J., Praetorius, S., De Vernal, A., Abe-Ouchi, A., Cheng, H., Claussen, M., Crucifix, M., Gallopín, G., Iglesias, V., Kaufman, D. S., … Yu, Z. (2021a). Past abrupt changes, tipping points and cascading impacts in the Earth system. Nature Geoscience, 14(8), 550–558. https://doi.org/10.1038/s41561-021-00790-5

Brovkin, V., Brook, E., Williams, J. W., Bathiany, S., Lenton, T. M., Barton, M., DeConto, R. M., Donges, J. F., Ganopolski, A., McManus, J., Praetorius, S., De Vernal, A., Abe-Ouchi, A., Cheng, H., Claussen, M., Crucifix, M., Gallopín, G., Iglesias, V., Kaufman, D. S., … Yu, Z. (2021b). Past abrupt changes, tipping points and cascading impacts in the Earth system. Nature Geoscience, 14(8), 550–558. https://doi.org/10.1038/s41561-021-00790-5

Cannon, S. E., Aram, E., Beiateuea, T., Kiareti, A., Peter, M., & Donner, S. D. (2021). Coral reefs in the Gilbert Islands of Kiribati: Resistance, resilience, and recovery after more than a decade of multiple stressors. PLOS ONE, 16(8), e0255304. https://doi.org/10.1371/journal.pone.0255304

Carpenter, S., Brock, W., & Hanson, P. (1999). Ecological and Social Dynamics in Simple Models of Ecosystem Management. Conservation Ecology, 3(2). https://doi.org/10.5751/ES-00122-030204

Carter, R., Choularton, R., Ferdinand, T., Ding, H., Ginoya, N., & Preethan, P. (2021). Food Systems at Risk: Transformative Adaptation for Long-Term Food Security. https://www.wri.org/research/food-systems-risk

Cattaneo, C., & Peri, G. (2016). The migration response to increasing temperatures. Journal of Development Economics, 122, 127–146. https://doi.org/10.1016/j.jdeveco.2016.05.00

Cooper, T. F., Gilmour, J. P., & Fabricius, K. E. (2009). Bioindicators of changes in water quality on coral reefs: review and recommendations for monitoring programmes. Coral Reefs, 28(3), 589–606. https://doi.org/10.1007/s00338-009-0512-x

Costanza, R., De Groot, R., Sutton, P., Van Der Ploeg, S., Anderson, S. J., Kubiszewski, I., Farber, S., & Turner, R. K. (2014). Changes in the global value of ecosystem services. Global Environmental Change, 26, 152–158. https://doi.org/10.1016/j.gloenvcha.2014.04.002

Crona, B. I., Basurto, X., Squires, D., Gelcich, S., Daw, T. M., Khan, A., Havice, E., Chomo, V., Troell, M., Buchary, E. A., & Allison, E. H. (2016). Towards a typology of interactions between small-scale fisheries and global seafood trade. Marine Policy, 65, 1–10. https://doi.org/10.1016/j.marpol.2015.11.016

Cumming, G. S., Adamska, M., Barnes, M. L., Barnett, J., Bellwood, D. R., Cinner, J. E., Cohen, P. J., Donelson, J. M., Fabricius, K., Grafton, R. Q., Grech, A., Gurney, G. G., Hoegh-Guldberg, O., Hoey, A. S., Hoogenboom, M. O., Lau, J., Lovelock, C. E., Lowe, R., Miller, D. J., … Wilson, S. K. (2023). Research priorities for the sustainability of coral-rich western Pacific seascapes. Regional Environmental Change, 23(2), 66. https://doi.org/10.1007/s10113-023-02051-0

Cumming, G. S., Southworth, J., Rondon, X. J., & Marsik, M. (2012). Spatial complexity in fragmenting Amazonian rainforests: Do feedbacks from edge effects push forests towards an ecological threshold? Ecological Complexity, 11, 67–74. https://doi.org/10.1016/j.ecocom.2012.03.002

Darling, E. S., McClanahan, T. R., & Côté, I. M. (2013). Life histories predict coral community disassembly under multiple stressors. Global Change Biology, 19(6), 1930–1940. https://doi.org/10.1111/gcb.12191

Deloitte Access Economics. (2013). Economic Contribution of the Great Barrier Reef. https://www.dcceew.gov.au/sites/default/files/documents/gbr-economic-contribution.pdf

Demirsu, I., & Cihangir-Tetik, D. (2019). Constructing the Partnership with Turkey on the Refugee Crisis: EU Perceptions and Expectations. Journal of Balkan and Near Eastern Studies, 21(6), 625–642. https://doi.org/10.1080/19448953.2018.1506291

Dun, O. (2009). Linkages between flooding, migration and resettlement: Viet Nam case study report for EACH-FOR Projectstudy report for EACH-FOR Projec. University of WollongongUniver. https://environmentalmigration.iom.int/sites/g/files/tmzbdl1411/files/documents/Linkages%20between%20flooding%20migration%20and%20resettlement_%20Viet%20Nam%20c.pdf

Dun, O., & Gemenne, F. (2008). Defining 'environmental migration' | Forced Migration Review. Forced Migration Review. https://www.fmreview.org/climatechange/dun-gemenne

Eddy, T. D., Lam, V. W. Y., Reygondeau, G., Cisneros-Montemayor, A. M., Greer, K., Palomares, M. L. D., Bruno, J. F., Ota, Y., & Cheung, W. W. L. (2021). Global decline in capacity of coral reefs to provide ecosystem services. One Earth, 4(9), 1278–1285. https://doi.org/10.1016/j.oneear.2021.08.016

Filatova, T., Polhill, J. G., & Van Ewijk, S. (2016). Regime shifts in coupled socio-environmental systems: Review of modelling challenges and approaches. Environmental Modelling & Software, 75, 333–347. https://doi.org/10.1016/j.envsoft.2015.04.003

Franzke, C. L. E., Ciullo, A., Gilmore, E. A., Matias, D. M., Nagabhatla, N., Orlov, A., Paterson, S. K., Scheffran, J., & Sillmann, J. (2022). Perspectives on tipping points in integrated models of the natural and human Earth system: cascading effects and telecoupling. Environmental Research Letters, 17(1), 015004. https://doi.org/10.1088/1748-9326/ac42fd

Giulioni, G., Di Giuseppe, E., Toscano, P., Miglietta, F., & Pasqui, M. (2019). A Novel Computational Model of the Wheat Global Market with an Application to the 2010 Russian Federation Case. Journal of Artificial Societies and Social Simulation, 22(3), 4. DOI: 10.18564/jasss.4063. https://www.jasss.org/22/3/4.html

Gleick, P. H. (2014). Water, Drought, Climate Change, and Conflict in Syria. Weather, Climate, and Society, 6(3), 331–340. https://www.jstor.org/stable/24907379

Gleick, P. H. (2017). Climate, water, and conflict: Commentary on Selby et al. 2017. Political Geography, 60, 248–250. https://doi.org/10.1016/j.polgeo.2017.06.009

Grantham, R., Álvarez-Romero, J. G., Mills, D. J., Rojas, C., & Cumming, G. S. (2021). Spatiotemporal determinants of seasonal gleaning. People and Nature, 3(2), 376–390. https://doi.org/10.1002/pan3.10179

Grootendorst, M. (2022). BERTopic: Neural topic modeling with a class-based TF-IDF procedure. https://doi.org/10.48550/ARXIV.2203.05794

Groundstroem, F., & Juhola, S. (2021). Using systems thinking and causal loop diagrams to identify cascading climate change impacts on bioenergy supply systems. Mitigation and Adaptation Strategies for Global Change, 26(7), 29. https://doi.org/10.1007/s11027-021-09967-0

Haldane, A. G., & May, R. M. (2011). Systemic risk in banking ecosystems. Nature, 469(7330), 351–355. https://doi.org/10.1038/nature09659

Helbing, D. (2013). Globally networked risks and how to respond. Nature, 497(7447), 51–59. https://doi.org/10.1038/nature12047

Hemley, R., & Kohler, B. E. (1977). Electronic structure of polyenes related to the visual chromophore. A simple model for the observed band shapes. Biophysical Journal, 20(3), 377–382. https://doi.org/10.1016/S0006-3495(77)85556-2

Hoegh-Guldberg, O., Pendleton, L., & Kaup, A. (2019). People and the changing nature of coral reefs. Regional Studies in Marine Science, 30, 100699. https://doi.org/10.1016/j.rsma.2019.100699

Hughes, T. P., Kerry, J. T., Álvarez-Noriega, M., Álvarez-Romero, J. G., Anderson, K. D., Baird, A. H., Babcock, R. C., Beger, M., Bellwood, D. R., Berkelmans, R., Bridge, T. C., Butler, I. R., Byrne, M., Cantin, N. E., Comeau, S., Connolly, S. R., Cumming, G. S., Dalton, S. J., Diaz-Pulido, G., … Wilson, S. K. (2017). Global warming and recurrent mass bleaching of corals. Nature, 543(7645), 373–377. https://doi.org/10.1038/nature21707

Ide, T., Johnson, M. F., Barnett, J., Krampe, F., Le Billon, P., Maertens, L., Von Uexkull, N., & Vélez-Torres, I. (2023). The Future of Environmental Peace and Conflict Research. Environmental Politics, 32(6), 1077–1103. https://doi.org/10.1080/09644016.2022.2156174

Inam, A., Adamowski, J., Halbe, J., & Prasher, S. (2015). Using causal loop diagrams for the initialization of stakeholder engagement in soil salinity management in agricultural watersheds in developing countries: A case study in the Rechna Doab watershed, Pakistan. Journal of Environmental Management, 152, 251–267. https://doi.org/10.1016/j.jenvman.2015.01.052

International Organisation for migration (IOM). (2023). About Migration. Retrieved 24 September 2023, from https://www.iom.int/about-migration

IOM. (2023). Environmental Migration. https://environmentalmigration.iom.int/environmental-migration

Johnstone, S., & Mazo, J. (2011). Global Warming and the Arab Spring. Survival, 53(2), 11–17. https://doi.org/10.1080/00396338.2011.571006

Juhola, S., Filatova, T., Hochrainer-Stigler, S., Mechler, R., Scheffran, J., & Schweizer, P.-J. (2022a). Social tipping points and adaptation limits in the context of systemic risk: Concepts, models and governance. Frontiers in Climate, 4, 1009234. https://doi.org/10.3389/fclim.2022.1009234

Kaizu, T., & Margolius, H. S. (1975). Studies on rat renal cortical cell kallikrein. I. Separation and measurement. Biochimica Et Biophysica Acta, 411(2), 305–315. https://doi.org/10.1016/0304-4165(75)90310-4

Kapsar, K., Hovis, C., Bicudo Da Silva, R., Buchholtz, E., Carlson, A., Dou, Y., Du, Y., Furumo, P., Li, Y., Torres, A., Yang, D., Wan, H., Zaehringer, J., & Liu, J. (2019). Telecoupling Research: The First Five Years. Sustainability, 11(4), 1033. https://doi.org/10.3390/su11041033

Kath, J., Craparo, A., Fong, Y., Byrareddy, V., Davis, A. P., King, R., Nguyen-Huy, T., van Asten, P. J. A., Marcussen, T., Mushtaq, S., Stone, R., & Power, S. (2022). Vapour pressure deficit determines critical thresholds for global coffee production under climate change. Nature Food, 3(10), 871–880. https://doi.org/10.1038/s43016-022-00614-8

Kelley, C., Mohtadi, S., Cane, M., Seager, R., & Kushnir, Y. (2017). Commentary on the Syria case: Climate as a contributing factor. Political Geography, 60, 245–247. https://doi.org/10.1016/j.polgeo.2017.06.013

Klose, A. K., Wunderling, N., Winkelmann, R., & Donges, J. F. (2021a). What do we mean, 'tipping cascade'? Environmental Research Letters, 16(12), 125011. https://doi.org/10.1088/1748-9326/ac3955

Klose, A. K., Wunderling, N., Winkelmann, R., & Donges, J. F. (2021b). What do we mean, 'tipping cascade'? Environmental Research Letters, 16(12), 125011. https://doi.org/10.1088/1748-9326/ac3955

Kominek, J., & Jurgen, S. (2011). Cascading Processes and Path Dependency in Social Networks: Working Paper CLISEC-12. University of Hamburg Research Group Climate Change and Security. https://core.ac.uk/download/pdf/210681427.pdf

Kuehn, C., Martens, E. A., & Romero, D. M. (2014). Critical transitions in social network activity. Journal of Complex Networks, 2(2), 141–152. https://doi.org/10.1093/comnet/cnt022

Lam, V. W. Y., Allison, E. H., Bell, J. D., Blythe, J., Cheung, W. W. L., Frölicher, T. L., Gasalla, M. A., & Sumaila, U. R. (2020). Climate change, tropical fisheries and prospects for sustainable development. Nature Reviews Earth & Environment, 1(9), 440–454. https://doi.org/10.1038/s43017-020-0071-9

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

Lawrence, J., Blackett, P., & Cradock-Henry, N. A. (2020). Cascading climate change impacts and implications. Climate Risk Management, 29, 100234. https://doi.org/10.1016/j.crm.2020.100234

Lenton, T. M., & Ciscar, J.-C. (2013). Integrating tipping points into climate impact assessments. Climatic Change, 117(3), 585–597. https://doi.org/10.1007/s10584-012-0572-8

Lenton, T. M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W., & Schellnhuber, H. J. (2019). Climate tipping points — too risky to bet against. Nature, 575(7784), 592–595. https://doi.org/10.1038/d41586-019-03595-0

Liu, T., Chen, D., Yang, L., Meng, J., Wang, Z., Ludescher, J., Fan, J., Yang, S., Chen, D., Kurths, J., Chen, X., Havlin, S., & Schellnhuber, H. J. (2023). Teleconnections among tipping elements in the Earth system. Nature Climate Change, 13(1), 67–74. https://doi.org/10.1038/s41558-022-01558

Lovejoy, T. E., & Nobre, C. (2018). Amazon Tipping Point. Science Advances, 4(2), eaat2340. https://doi.org/10.1126/sciadv.aat2340

Mackie, E., Jesse.F., A., Boland, E., Gilbert, A., Guo, W., Lenton, T., & Shuckburgh, E. (2020). Climate aware and resilient national security: Challenges for the 21st Century. Alan Turing Institute. Alan Turing Institute. https://www.turing.ac.uk/news/publications/climate-aware-and-resilient-national-security-challenges-21st-century

Magel, J. M. T., Dimoff, S. A., & Baum, J. K. (2020). Direct and indirect effects of climate change-amplified pulse heat stress events on coral reef fish communities. Ecological Applications, 30(6), e02124. https://doi.org/10.1002/eap.2124

Magrin, G., & Montclos, M. (2018). Crisis and development : the lake Chad region and Boko Haram- fdi:010086274- Horizon. Horizon Pleins Textes. https://www.documentation.ird.fr/hor/fdi:010086274

Makar, A. B., McMartin, K. E., Palese, M., & Tephly, T. R. (1975). Formate assay in body fluids: application in methanol poisoning. Biochemical Medicine, 13(2), 117–126. https://doi.org/10.1016/0006-2944(75)90147-7

McLeman, R., Wrathall, D., Gilmore, E., Thornton, P., Adams, H., & Gemenne, F. (2021). Conceptual framing to link climate risk assessments and climate-migration scholarship. Climatic Change, 165(1–2), 24. https://doi.org/10.1007/s10584-021-03056-6

Mellin, C., Hicks, C. C., Fordham, D. A., Golden, C. D., Kjellevold, M., MacNeil, M. A., Maire, E., Mangubhai, S., Mouillot, D., Nash, K. L., Omukoto, J. O., Robinson, J. P. W., Stuart-Smith, R. D., Zamborain-Mason, J., Edgar, G. J., & Graham, N. A. J. (2022). Safeguarding nutrients from coral reefs under climate change. Nature Ecology & Evolution, 6(12), 1808–1817. https://doi.org/10.1038/s41559-022-01878-w

Mitchard, E. T. A. (2018). The tropical forest carbon cycle and climate change. Nature, 559(7715), 527–534. https://doi.org/10.1038/s41586-018-0300-2

Moat, H. S., Curme, C., Avakian, A., Kenett, D. Y., Stanley, H. E., & Preis, T. (2013a). Quantifying Wikipedia Usage Patterns Before Stock Market Moves. Scientific Reports, 3(1), 1801. https://doi.org/10.1038/srep01801

Nagarajan, C., Pohl, B., Rüttinger, L., Sylvestre, F., Vivekananda, J., Wall, M., & Wolfmaier, S. (2018). Climate-fragility profile: lake Chad basin. Berlin: Adelphi, 32.

Nawrotzki, R. J., & Bakhtsiyarava, M. (2017). International Climate Migration: Evidence for the Climate Inhibitor Mechanism and the Agricultural Pathway. Population, Space and Place, 23(4), e2033. https://doi.org/10.1002/psp.2033

Nepstad, D. C., Stickler, C. M., Filho, B. S.-, & Merry, F. (2008). Interactions among Amazon land use, forests and climate: prospects for a near-term forest tipping point. Philosophical Transactions of the Royal Society B: Biological Sciences, 363(1498), 1737–1746. https://doi.org/10.1098/rstb.2007.0036

Neuman, Y., Nave, O., & Dolev, E. (2011). Buzzwords on their way to a tipping-point: A view from the blogosphere. Complexity, 16(4), 58–68. https://doi.org/10.1002/cplx.20347

Nobre, C. A., Sampaio, G., Borma, L. S., Castilla-Rubio, J. C., Silva, J. S., & Cardoso, M. (2016). Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm. Proceedings of the National Academy of Sciences, 113(39), 10759–10768. https://doi.org/10.1073/pnas.1605516113

Otto, I. M., Donges, J. F., Cremades, R., Bhowmik, A., Hewitt, R. J., Lucht, W., Rockström, J., Allerberger, F., McCaffrey, M., Doe, S. S. P., Lenferna, A., Morán, N., Van Vuuren, D. P., & Schellnhuber, H. J. (2020). Social tipping dynamics for stabilizing Earth's climate by 2050. Proceedings of the National Academy of Sciences, 117(5), 2354–2365. https://doi.org/10.1073/pnas.1900577117

Owen, G. (2020). What makes climate change adaptation effective? A systematic review of the literature. Global Environmental Change, 62, 102071. https://doi.org/10.1016/j.gloenvcha.2020.102071

Paes, O. (2022). The Amazon rainforest and the global–regional politics of ecosystem governance. Oxford University Press. https://academic.oup.com/ia/article/98/6/2077/6765180?login=false

Pescaroli, G., & Alexander, D. (2018). Understanding Compound, Interconnected, Interacting, and Cascading Risks: A Holistic Framework. Risk Analysis, 38(11), 2245–2257. https://doi.org/10.1111/risa.13128

Podesta, J. (2019, July 25). The climate crisis, migration, and refugees. Brookings. https://www.brookings.edu/articles/the-climate-crisis-migration-and-refugees/

Renn, O., Lucas, K., Haas, A., & Jaeger, C. (2019). Things are different today: the challenge of global systemic risks. Journal of Risk Research, 22(4), 401–415. https://doi.org/10.1080/13669877.2017.1409252

Reydon, B. P., Fernandes, V. B., & Telles, T. S. (2020). Land governance as a precondition for decreasing deforestation in the Brazilian Amazon. Land Use Policy, 94, 104313. https://doi.org/10.1016/j.landusepol.2019.104313

Reyer, C. P. O., Brouwers, N., Rammig, A., Brook, B. W., Epila, J., Grant, R. F., Holmgren, M., Langerwisch, F., Leuzinger, S., Lucht, W., Medlyn, B., Pfeifer, M., Steinkamp, J., Vanderwel, M. C., Verbeeck, H., & Villela, D. M. (2015). Forest resilience and tipping points at different spatio-temporal scales: approaches and challenges. Journal of Ecology, 103(1), 5–15. https://doi.org/10.1111/1365-2745.12337

Rocha, J. C. (2022). Ecosystems are showing symptoms of resilience loss. Environmental Research Letters, 17(6), 065013. https://doi.org/10.1088/1748-9326/ac73a8

Saavedra, S., Hagerty, K., & Uzzi, B. (2011). Synchronicity, instant messaging, and performance among financial traders. Proceedings of the National Academy of Sciences, 108(13), 5296–5301. https://doi.org/10.1073/pnas.1018462108

Sanches-Pereira, A., & Gómez, M. F. (2015). The dynamics of the Swedish biofuel system toward a vehicle fleet independent of fossil fuels. Journal of Cleaner Production, 96, 452–466. https://doi.org/10.1016/j.jclepro.2014.03.019

Sayan, R. C., Nagabhatla, N., & Ekwuribe, M. (2020). Soft Power, Discourse Coalitions, and the Proposed Interbasin Water Transfer Between Lake Chad and the Congo River. Water Alternatives, 13(3). Soft Power, Discourse Coalitions, and the Proposed Interbasin Water Transfer Between Lake Chad and the Congo River (water-alternatives.org)

Scheffer, M., Bascompte, J., Brock, W. A., Brovkin, V., Carpenter, S. R., Dakos, V., Held, H., van Nes, E. H., Rietkerk, M., & Sugihara, G. (2009). Early-warning signals for critical transitions. Nature, 461(7260), 53–59. https://doi.org/10.1038/nature08227

Scheffer, M., Hosper, S. H., Meijer, M.-L., Moss, B., & Jeppesen, E. (1993). Alternative equilibria in shallow lakes. Trends in Ecology & Evolution, 8(8), 275–279. https://doi.org/10.1016/0169-5347(93)90254-M

Scheffran, J. (2016). From a Climate of Complexity to Sustainable Peace: Viability Transformations and Adaptive Governance in the Anthropocene. In: Brauch, H., Oswald Spring, Ú., Grin, J., Scheffran, J. (eds) Handbook on Sustainability Transition and Sustainable Peace . Hexagon Series on Human and Environmental Security and Peace, vol 10. Springer, Cham. https://doi.org/10.1007/978-3-319-43884-9_1

Scheffran, J., Ide, T., & Schilling, J. (2014). Violent climate or climate of violence? Concepts and relations with focus on Kenya and Sudan. The International Journal of Human Rights, 18(3), 369–390. https://doi.org/10.1080/13642987.2014.914722

Schilling, J., Hertig, E., Tramblay, Y., & Scheffran, J. (2020). Climate change vulnerability, water resources and social implications in North Africa. Regional Environmental Change, 20(1), 15. https://doi.org/10.1007/s10113-020-01597-7

Schindler, D. W., Carpenter, S. R., Chapra, S. C., Hecky, R. E., & Orihel, D. M. (2016). Reducing Phosphorus to Curb Lake Eutrophication is a Success. Environmental Science & Technology, 50(17), 8923–8929. https://doi.org/10.1021/acs.est.6b02204

Schweizer, P.-J., & Renn, O. (2019). Governance of systemic risks for disaster prevention and mitigation. Disaster Prevention and Management: An International Journal, 28(6), 862–874. https://doi.org/10.1108/DPM-09-2019-0282

Selby, J., Dahi, O. S., Fröhlich, C., & Hulme, M. (2017). Climate change and the Syrian civil war revisited. Political Geography, 60, 232–244. https://doi.org/10.1016/j.polgeo.2017.05.007

Seto, K. C., Reenberg, A., Boone, C. G., Fragkias, M., Haase, D., Langanke, T., Marcotullio, P., Munroe, D. K., Olah, B., & Simon, D. (2012). Urban land teleconnections and sustainability. Proceedings of the National Academy of Sciences, 109(20), 7687–7692. https://doi.org/10.1073/pnas.1117622109

Sillmann, J., Christensen, I., Hochrainer-Stigler, S., Huang-Lachmann, J., Juhola, S., Kornhuber, K., Mahecha, M., Mechler, R., Reichstein, M., Ruane, A.C., Schweizer, P.-J. and Williams, S. 2022. ISC-UNDRR-RISK KAN Briefing note on systemic risk, Paris, France, International Science Council, https://doi.org/10.24948/2022.01

Simpson, N. P., Mach, K. J., Constable, A., Hess, J., Hogarth, R., Howden, M., Lawrence, J., Lempert, R. J., Muccione, V., Mackey, B., New, M. G., O'Neill, B., Otto, F., Pörtner, H.-O., Reisinger, A., Roberts, D., Schmidt, D. N., Seneviratne, S., Strongin, S., … Trisos, C. H. (2021). A framework for complex climate change risk assessment. One Earth, 4(4), 489–501. https://doi.org/10.1016/j.oneear.2021.03.005

Sing Wong, A., Vrontos, S., & Taylor, M. L. (2022). An assessment of people living by coral reefs over space and time. Global Change Biology, 28(23), 7139–7153. https://doi.org/10.1111/gcb.16391

Smith, R. J., & Bryant, R. G. (1975). Metal substitutions incarbonic anhydrase: a halide ion probe study. Biochemical and Biophysical Research Communications, 66(4), 1281–1286. https://doi.org/10.1016/0006-291x(75)90498-2

Sohns, A., Ford, J. D., Adamowski, J., & Robinson, B. E. (2021). Participatory Modeling of Water Vulnerability in Remote Alaskan Households Using Causal Loop Diagrams. Environmental Management, 67(1), 26–42. https://doi.org/10.1007/s00267-020-01387-1

Stal M (2009): Case study report on Mozambique for the environmental change and forced migration scenarios project. In: EACH-FOR Environmental Change and Forced Migration Scenarios. D.3.4. Synthesis Report. p.40-41. https://rosamartinez.org/wp-content/uploads/2015/11/Migraciones-y-Cambio-Climatico_EACHFOR.pdf

Staver, A. C., Archibald, S., & Levin, S. A. (2011). The Global Extent and Determinants of Savanna and Forest as Alternative Biome States. Science, 334(6053), 230–232. https://doi.org/10.1126/science.1210465

Sternberg, T. (2012). Chinese drought, bread and the Arab Spring. Applied Geography, 34, 519–524. https://doi.org/10.1016/j.apgeog.2012.02.004

Strona, G., Beck, P. S. A., Cabeza, M., Fattorini, S., Guilhaumon, F., Micheli, F., Montano, S., Ovaskainen, O., Planes, S., Veech, J. A., & Parravicini, V. (2021). Ecological dependencies make remote reef fish communities most vulnerable to coral loss. Nature Communications, 12(1), 7282. https://doi.org/10.1038/s41467-021-27440-z

Sydney, C., & Desai, B. (2020). Policy Paper: Yemen: the implications of forced immobility. https://www.internal-displacement.org/sites/default/files/publications/documents/202006-yemen-policy-paper.pdf

Tebbett, S. B., Connolly, S. R., & Bellwood, D. R. (2023). Benthic composition changes on coral reefs at global scales. Nature Ecology & Evolution, 7(1), 71–81. https://doi.org/10.1038/s41559-022-01937-2

Thompson, C. A., Matthews, S., Hoey, A. S., & Pratchett, M. S. (2019). Changes in sociality of butterflyfishes linked to population declines and coral loss. Coral Reefs, 38(3), 527–537. https://doi.org/10.1007/s00338-019-01792-x

Van De Leemput, I. A., Hughes, T. P., Van Nes, E. H., & Scheffer, M. (2016). Multiple feedbacks and the prevalence of alternate stable states on coral reefs. Coral Reefs, 35(3), 857–865. https://doi.org/10.1007/s00338-016-1439-7

Vivekananda, J., Wall, M., Sylvestre, F., & Nagarajan, C. (2019). Shoring up Stability: Addressing Climate and Fragility risk in the lake Chad region. adelphi research gemeinnützige GmbH. https://shoring-up-stability.org/wp-content/uploads/2019/06/Shoring-up-Stability.pdf

Wismer, S., Tebbett, S. B., Streit, R. P., & Bellwood, D. R. (2019a). Spatial mismatch in fish and coral loss following 2016 mass coral bleaching. Science of The Total Environment, 650, 1487–1498. https://doi.org/10.1016/j.scitotenv.2018.09.114

Wismer, S., Tebbett, S. B., Streit, R. P., & Bellwood, D. R. (2019b). Young fishes persist despite coral loss on the Great Barrier Reef. Communications Biology, 2(1), 456. https://doi.org/10.1038/s42003-019-0703-0

Wunderling, N., Winkelmann, R., Rockström, J., Loriani, S., Armstrong McKay, D. I., Ritchie, P. D. L., Sakschewski, B., & Donges, J. F. (2023). Global warming overshoots increase risks of climate tipping cascades in a network model. Nature Climate Change, 13(1), 75–82. https://doi.org/10.1038/s41558-022-01545-9

Xu, L., Patterson, D., Levin, S. A., & Wang, J. (2023). Non-equilibrium early-warning signals for critical transitions in ecological systems. Proceedings of the National Academy of Sciences, 120(5), e2218663120. https://doi.org/10.1073/pnas.2218663120

Zemp, D. C., Schleussner, C.-F., Barbosa, H. M. J., Hirota, M., Montade, V., Sampaio, G., Staal, A., Wang-Erlandsson, L., & Rammig, A. (2017). Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks. Nature Communications, 8(1), 14681. https://doi.org/10.1038/ncomms14681

Zieba, F. W., Yengoh, G. T., & Tom, A. (2017). Seasonal Migration and Settlement around Lake Chad: Strategies for Control of Resources in an Increasingly Drying Lake. Resources, 6(3), 41. https://doi.org/10.3390/resources6030041

References: Chapter 2.5

Adrian, B., R. A. ;. Maddison, E. ;. Ranner, P. ;. Bissell, J. ;. Caiado, C. ;. Bhatanacharoen, P. ;. CLARK, Timothy, & Robert; Botha M.; Akinbami F.; Hollow M.; Michie R.; Huntley B.; Curtis S.; and Garnett P. (2014). Social tipping points and Earth systems dynamics. Frontiers in Environmental Science., 2, 1–7. https://ink.library.smu.edu.sg/cgi/viewcontent.cgi?params=/context/lkcsb_research/article/7268/&path_info=fenvs_02_00035.pdf

Bardi, U. (2019). Peak oil, 20 years later: Failed prediction or useful insight? Energy Research & Social Science, 48, 257–261. https://doi.org/10.1016/j.erss.2018.09.022

Bauch, C. T., Sigdel, R., Pharaon, J., & Anand, M. (2016). Early warning signals of regime shifts in coupled human–environment systems. Proceedings of the National Academy of Sciences, 113(51), 14560–14567. https://doi.org/10.1073/pnas.1604978113

Bieg, C., McCann, K. S., & Fryxell, J. M. (2017). The dynamical implications of human behaviour on a social-ecological harvesting model. Theoretical Ecology, 10(3), 341–354. https://doi.org/10.1007/s12080-017-0334-3

CitSci.org. (n.d.). Retrieved 3 November 2023, from https://citsci.org/

Coletto, M., Aiello, L., Lucchese, C., & Silvestri, F. (2021). On the Behaviour of Deviant Communities in Online Social Networks. Proceedings of the International AAAI Conference on Web and Social Media, 10(1), 72–81. https://doi.org/10.1609/icwsm.v10i1.14726

Dakos, V., Carpenter, S. R., Brock, W. A., Ellison, A. M., Guttal, V., Ives, A. R., Kéfi, S., Livina, V., Seekell, D. A., Van Nes, E. H., & Scheffer, M. (2012). Methods for Detecting Early Warnings of Critical Transitions in Time Series Illustrated Using Simulated Ecological Data. PLoS ONE, 7(7), e41010. https://doi.org/10.1371/journal.pone.0041010

Diks, C., Hommes, C., & Wang, J. (2019). Critical slowing down as an early warning signal for financial crises? Empirical Economics, 57(4), 1201–1228. https://doi.org/10.1007/s00181-018-1527-3

Ehret, S., Constantino, S. M., Weber, E. U., Efferson, C., & Vogt, S. (2022). Group identities can undermine social tipping after intervention. Nature Human Behaviour, 6(12), 1669–1679. https://doi.org/10.1038/s41562-022-01440-5

Ehrlich, P. (1978). The Population Bomb. Ballantine Books; Rev. https://en.wikipedia.org/w/index.php?title=The_Population_Bomb&oldid=1180522814

Farahbakhsh, I., Bauch, C. T., & Anand, M. (2022). Modelling coupled human–environment complexity for the future of the biosphere: strengths, gaps and promising directions. Philosophical Transactions of the Royal Society B: Biological Sciences, 377(1857), 20210382. https://doi.org/10.1098/rstb.2021.0382

Feng, K., Wang, T., Liu, S., Yan, C., Kang, W., Chen, X., & Guo, Z. (2021). Path analysis model to identify and analyse the causes of aeolian desertification in Mu Us Sandy Land, China. Ecological Indicators, 124, 107386. https://doi.org/10.1016/j.ecolind.2021.107386

Fernández-Giménez, M. E., Venable, N. H., Angerer, J., Fassnacht, S. R., Reid, R. S., & Khishigbayar, J. (2017). Exploring linked ecological and cultural tipping points in Mongolia. Anthropocene, 17, 46–69. https://doi.org/10.1016/j.ancene.2017.01.003

Funk, C., Davenport, F., Eilerts, G., Nourey, N. and Galu, G.,. (2018). Contrasting Kenyan resilience to drought: 2011 and 2017. [USAID Special Report.]. https://2017-2020.usaid.gov/sites/default/files/documents/1867/Kenya_Report_-_Full_Compliant.PDF

Funk, C., Shukla, S., Thiaw, W. M., Rowland, J., Hoell, A., McNally, A., Husak, G., Novella, N., Budde, M., Peters-Lidard, C., Adoum, A., Galu, G., Korecha, D., Magadzire, T., Rodriguez, M., Robjhon, M., Bekele, E., Arsenault, K., Peterson, P., … Verdin, J. (2019). Recognizing the Famine Early Warning Systems Network: Over 30 Years of Drought Early Warning Science Advances and Partnerships Promoting Global Food Security. Bulletin of the American Meteorological Society, 100(6), 1011–1027. https://doi.org/10.1175/BAMS-D-17-0233.1

Gaikwad, M., Ahirrao, S., Kotecha, K., & Abraham, A. (2022). Multi-Ideology Multi-Class Extremism Classification Using Deep Learning Techniques. IEEE Access, 10, 104829–104843. https://doi.org/10.1109/ACCESS.2022.3205744

Guo, W., Gleditsch, K., & Wilson, A. (2018). Retool AI to forecast and limit wars. Nature, 562(7727), 331–333. https://doi.org/10.1038/d41586-018-07026-4

Guo, W., Sun, S., & Wilson, A. (2023). Exploring Potential Causal Models for Climate-Society-Conflict Interaction. 69–76. https://www.scitepress.org/Link.aspx?doi=10.5220/0011968400003485

Hicks, C. C., Crowder, L. B., Graham, N. A., Kittinger, J. N., & Cornu, E. L. (2016). Social drivers forewarn of marine regime shifts. Frontiers in Ecology and the Environment, 14(5), 252–260. https://doi.org/10.1002/fee.1284

Horan, R. D., Fenichel, E. P., Drury, K. L. S., & Lodge, D. M. (2011). Managing ecological thresholds in coupled environmental–human systems. Proceedings of the National Academy of Sciences, 108(18), 7333–7338. https://doi.org/10.1073/pnas.1005431108

Ibáñez, J., Martínez, J., & Schnabel, S. (2007). Desertification due to overgrazing in a dynamic commercial livestock–grass–soil system. Ecological Modelling, 205(3–4), 277–288. https://doi.org/10.1016/j.ecolmodel.2007.02.024

Innes, C., Anand, M., & Bauch, C. T. (2013). The impact of human-environment interactions on the stability of forest-grassland mosaic ecosystems. Scientific Reports, 3(1), 2689. https://doi.org/10.1038/srep02689

Kim, J., Lee, J., Park, E., & Han, J. (2020). A deep learning model for detecting mental illness from user content on social media. Scientific Reports, 10(1), 11846. https://doi.org/10.1038/s41598-020-68764-y

Korecha, D., & Barnston, A. G. (2007). Predictability of June–September Rainfall in Ethiopia. Monthly Weather Review, 135(2), 628–650. https://doi.org/10.1175/MWR3304.1

Koschate-Reis, M., Dickens, L., Stuart, A., Naserian, E., Russo, A., & Levine, M. (2019). Predicting a Salient Social Identity from Linguistic Style [Preprint]. PsyArXiv. https://doi.org/10.31234/osf.io/zkunh

Krishnamurthy, P. K., Choularton, R. J., & Kareiva, P. (2020). Dealing with uncertainty in famine predictions: How complex events affect food security early warning skill in the Greater Horn of Africa. Global Food Security, 26, 100374. https://doi.org/10.1016/j.gfs.2020.100374

Krishnamurthy R, P. K., Fisher, J. B., Choularton, R. J., & Kareiva, P. M. (2022). Anticipating drought-related food security changes. Nature Sustainability, 5(11), 956–964. https://doi.org/10.1038/s41893-022-00962-0

Krishnamurthy R, P. K., Fisher, J. B., Schimel, D. S., & Kareiva, P. M. (2020). Applying Tipping Point Theory to Remote Sensing Science to Improve Early Warning Drought Signals for Food Security. Earth's Future, 8(3), e2019EF001456. https://doi.org/10.1029/2019EF001456

Kuehn, C., Martens, E. A., & Romero, D. M. (2014). Critical transitions in social network activity. Journal of Complex Networks, 2(2), 141–152. https://doi.org/10.1093/comnet/cnt022

Lade, S. J., Tavoni, A., Levin, S. A., & Schlüter, M. (2013). Regime shifts in a social-ecological system. Theoretical Ecology, 6(3), 359–372. https://doi.org/10.1007/s12080-013-0187-3

Milkoreit, M., Hodbod, J., Baggio, J., Benessaiah, K., Calderón-Contreras, R., Donges, J. F., Mathias, J.-D., Rocha, J. C., Schoon, M., & Werners, S. E. (2018). Defining tipping points for social-ecological systems scholarship—an interdisciplinary literature review. Environmental Research Letters, 13(3), 033005. https://doi.org/10.1088/1748-9326/aaaa75

Richter, A., & Dakos, V. (2015). Profit fluctuations signal eroding resilience of natural resources. Ecological Economics, 117, 12–21. https://doi.org/10.1016/j.ecolecon.2015.05.013

Rød, E. G., Gåsste, T., & Hegre, H. (2023). A review and comparison of conflict early warning systems. International Journal of Forecasting, S0169207023000018. https://doi.org/10.1016/j.ijforecast.2023.01.001

Samitas, A., Kampouris, E., & Kenourgios, D. (2020). Machine learning as an early warning system to predict financial crisis. International Review of Financial Analysis, 71, 101507. https://doi.org/10.1016/j.irfa.2020.10150

Sampson, J., Morstatter, F., Wu, L., & Liu, H. (2016). Leveraging the Implicit Structure within Social Media for Emergent Rumor Detection. Proceedings of the 25th ACM International on Conference on Information and Knowledge Management, 2377–2382. https://doi.org/10.1145/2983323.2983697

Shipman, M. D. (2014). The limitations of social research. Routledge.

Sigdel, R., Anand, M., & Bauch, C. T. (2019). Convergence of socio-ecological dynamics in disparate ecological systems under strong coupling to human social systems. Theoretical Ecology, 12(3), 285–296. https://doi.org/10.1007/s12080-018-0394-z

Spielmann, K. A., Peeples, M. A., Glowacki, D. M., & Dugmore, A. (2016). Early Warning Signals of Social Transformation: A Case Study from the US Southwest. PLOS ONE, 11(10), e0163685. https://doi.org/10.1371/journal.pone.0163685

Swingedouw, D., Ifejika Speranza, C., Bartsch, A., Durand, G., Jamet, C., Beaugrand, G., & Conversi, A. (2020). Early Warning from Space for a Few Key Tipping Points in Physical, Biological, and Social-Ecological Systems. Surveys in Geophysics, 41(6), 1237–1284. https://doi.org/10.1007/s10712-020-09604-6

Thampi, V. A., Bauch, C. T., & Anand, M. (2019). Socio-ecological mechanisms for persistence of native Australian grasses under pressure from nitrogen runoff and invasive species. Ecological Modelling, 413, 108830. https://doi.org/10.1016/j.ecolmodel.2019.108830

Uban, A.-S., Chulvi, B., & Rosso, P. (2021). An emotion and cognitive based analysis of mental health disorders from social media data. Future Generation Computer Systems, 124, 480–494. https://doi.org/10.1016/j.future.2021.05.032

Van De Leemput, I. A., Wichers, M., Cramer, A. O. J., Borsboom, D., Tuerlinckx, F., Kuppens, P., Van Nes, E. H., Viechtbauer, W., Giltay, E. J., Aggen, S. H., Derom, C., Jacobs, N., Kendler, K. S., Van Der Maas, H. L. J., Neale, M. C., Peeters, F., Thiery, E., Zachar, P., & Scheffer, M. (2014). Critical slowing down as early warning for the onset and termination of depression. Proceedings of the National Academy of Sciences, 111(1), 87–92. https://doi.org/10.1073/pnas.1312114110

Verbesselt, J., Umlauf, N., Hirota, M., Holmgren, M., Van Nes, E. H., Herold, M., Zeileis, A., & Scheffer, M. (2016). Remotely sensed resilience of tropical forests. Nature Climate Change, 6(11), 1028–1031. https://doi.org/10.1038/nclimate3108

Wang, Y., Kaplan, N., Newman, G., & Scarpino, R. (2015). CitSci.org: A New Model for Managing, Documenting, and Sharing Citizen Science Data. PLOS Biology, 13(10), e1002280. https://doi.org/10.1371/journal.pbio.1002280

Watson, T., Lenton, T., & De Campos, R. S. (2023). The climate change, conflict and migration nexus: A holistic view. Climate Resilience and Sustainability, 2(2), e250. https://doi.org/10.1002/cli2.50

Wiedermann, M., Smith, E. K., Heitzig, J., & Donges, J. F. (2020). A network-based microfoundation of Granovetter's threshold model for social tipping. Scientific Reports, 10(1), 11202. https://doi.org/10.1038/s41598-020-67102-6

Winkelmann, R., Donges, J. F., Smith, E. K., Milkoreit, M., Eder, C., Heitzig, J., Katsanidou, A., Wiedermann, M., Wunderling, N., & Lenton, T. M. (2022). Social tipping processes towards climate action: A conceptual framework. Ecological Economics, 192, 107242. https://doi.org/10.1016/j.ecolecon.2021.107242

University of Exeter | Global Systems Institute

Funded by:

BEZOS EARTH FUND

Report Partners:

EARTH COMMISSION
GLOBAL COMMONS ALLIANCE

SYSTEMS CHANGE LAB

SYSTEMIQ

Disclaimer:

How to Cite:

J.F. Abrams, S.J. Lade, J.F. Donges, J.E. Buxton (eds), 2023, 'Section 2: Tipping Points Impacts' in [T.M. Lenton, D.I. Armstrong McKay, S. Loriani, J.F. Abrams, S.J. Lade, J.F. Donges, M. Milkoreit, T. Powell, S.R. Smith, C. Zimm, J.E. Buxton, L. Laybourn, A. Ghadiali, J. G. Dyke (eds), 2023, The Global Tipping Points Report 2023. University of Exeter, Exeter, UK.]