Global Tipping Points

Report 2023

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Section coordinating authors David I. Armstrong McKay; Sina Loriani; Jesse F. Abrams; Steven J. Lade; Jonathan F. Donges; Manjana Milkoreit; Tom Powell; Steven R. Smith; Caroline Zimm; Joshua E. Buxton and Emma Bailey, have shown immense determination and drive in producing, editing and co-ordinating each section. For this we are eternally grateful.

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Thank you all.

The Global Tipping Points Team

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Foreword

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

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

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

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

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

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

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

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

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

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

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

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

What the experts say

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

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

Christiana Figueres, Co-host of the podcast Outrage and Optimism and former Executive Secretary, UN Convention on Climate Change:

"The Global Tipping Points Report sets out the choice we have in front of us right now. Business as usual will trigger Earth system tipping points that will be negative for all of us, with the consequences falling hardest, first, on the most vulnerable.

"Business as transformational, including fast, fair action to phase out fossil fuels can trigger positive tipping points across societies that would save millions of lives, billions of people from hardship, trillions of dollars in climate-related damage, and begin regenerating the natural world upon which we all depend."

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

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

What the experts say

Ani Dasgupta, President and CEO, World Resources Institute:

We are at a pivotal moment in the history of our planet. If climate change and nature loss continue at current rates, we could reach negative tipping points that result in increasingly dangerous and irreversible impacts unlike anything we have ever faced before.

"And yet, we have solutions that can build towards the scale we need. If we take advantage of positive tipping points in areas like renewable energy, food, and electric vehicles, we can create a cascade of change to transform our communities and economies. A greener, healthier and fairer world is possible, and the Global Tipping Points Report sets out the urgent actions we need to take now to make it happen, starting with a fossil fuel phase out, land-use transformation and better governance. This is our critical moment to act and tip the world towards a positive future."

Professor Johan Rockström, the Director of the Potsdam Institute for Climate Impact Research:

The world is no longer in the realm of incremental and linear change. Instead, we need to trigger exponential change across sectors and geographies by phasing out fossil fuels while taking advantage of positive social and economic tipping points. The incentives, solutions or levers of change need to shift so fundamentally that social feedback decisively moves societies onto a new sustainable trajectory. The Global Tipping Points report provides a comprehensive guide, the first of its kind, to the threats and opportunities that lie ahead."

Kelly Levin, Chief of Science, Data and Systems Change for the Bezos Earth Fund:

Climate change is the defining issue of our time; it is essential that we advance the science on global tipping points to address the threats and opportunities ahead. The path we choose now will determine the future of humanity, and this extraordinary report sets out the Earth system tipping points we need to prevent, the governance we need to urgently implement, and critically the positive tipping points we need to trigger to transform our society and world.

"Solving the climate and nature crises will require major transitions across most multiple sectors – from shifting diets to restoring forests to phasing out the internal combustion engine. "Given the required scale of action, we must target the most beneficial positive tipping points so that change takes off in a way that is unstoppable.

"At Bezos Earth Fund, we are dedicated to identifying and triggering positive tipping points in this decisive decade. The Global Tipping Points Report paves the way."

Introduction

Timothy M. Lenton, David I. Armstrong McKay, Jesse F. Abrams, Steven J. Lade, Steven R. Smith, Manjana Milkoreit, Sina Loriani, Emma Bailey, Tom Powell, Jonathan F. Donges, Caroline Zimm

Why we need to talk about tipping points

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

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

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

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

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

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

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

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

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

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

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

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

Who this report is for

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

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

The authors and origins of this report

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

Aims of this report

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

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

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

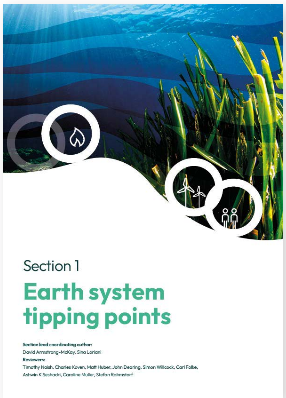
Scope

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

Style and structure

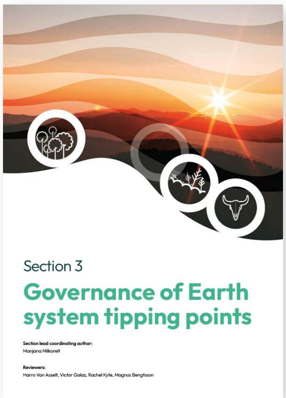
The report tackles diverse subject matter and complex concepts, and marshalls myriad data. It is drawn from an extensive and growing body of academic research, but is written for a non-academic audience. Hence we have worked hard to ensure it is comprehensible.

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



Section 1

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

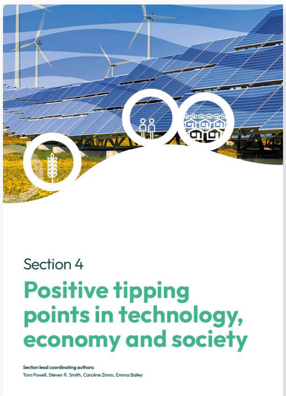


Section 3

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

Section 2

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



Section 4

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

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

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

Key concepts

Authors: Timothy M. Lenton, Jesse F. Abrams, Steven J. Lade, Steven R. Smith, David I. Armstrong McKay, Manjana Milkoreit, Sara M. Constantino, J. David Tàbara, Vasilis Dakos, Juan C. Rocha, Sonia Kéfi, Laura Pereira, Joshua E. Buxton, Chris A. Boulton, Caroline Zimm, Sina Loriani, Emma Bailey, Tom Powell, Sirkku Juhola, Jonathan F. Donges, Reinette (Oonsie) Biggs, Avit Bhowmik, Lukas Fesenfeld, Johan Rockström

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

What is a tipping point?

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

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

Here we define a **tipping point** as occurring when change in part of a system becomes self-perpetuating beyond a threshold, leading to substantial, widespread, frequently abrupt and often irreversible impact (inspired by Armstrong McKay et al., 2022 and Milkoreit et al., 2018). This definition includes the possibilities of non-abrupt and reversible tipping points.

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

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

Sources of tipping point behaviour

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

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

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

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

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

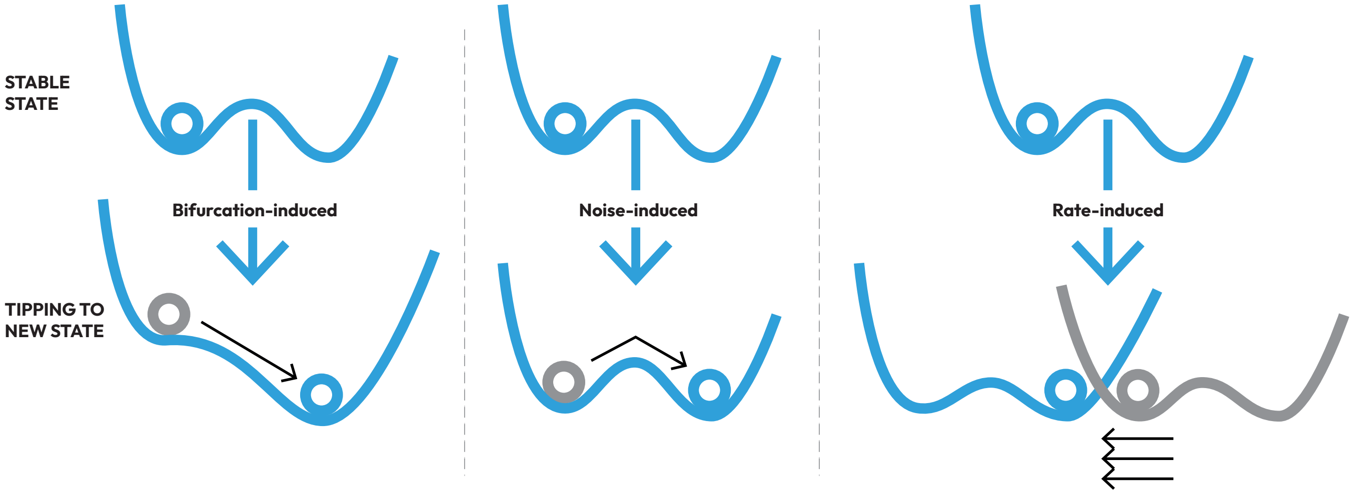


Figure 2: Three types of tipping point. Schematic representations of: (left) bifurcation-induced tipping (Figure 1); (middle) noise-induced tipping, and; (right) rate-induced tipping.

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

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

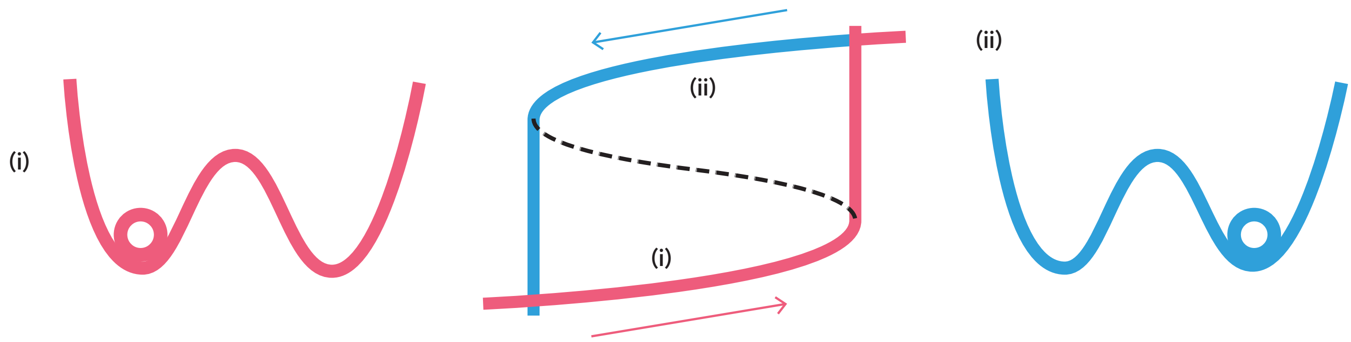


Figure 3: A simple representation of hysteresis. A system starts in one of two alternative stable states (red) at position (i). Forcing the system in one direction (red arrow from left to right) causes it to pass a tipping point into the other stable state (blue). Then when the forcing is reversed (blue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

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

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

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

Focal types of system and tipping point

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

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

The **Earth system** is the complex system at the surface of the planet Earth, comprising the atmosphere, hydrosphere (including oceans and freshwaters), cryosphere (including ice sheets), biosphere (living organisms) and lithosphere (land, soils, sediments and parts of the Earth's crust) (Lenton, 2016). The **climate system** is the parts of the Earth system that govern the **climate** at the surface of the Earth. Referring to the climate system rather than the Earth system tends to involve a shift in emphasis towards shorter timescales and those subsystems most affecting climate (e.g. the atmosphere and oceans).

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

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

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

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

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

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

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

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

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

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

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

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

Related concepts

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

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

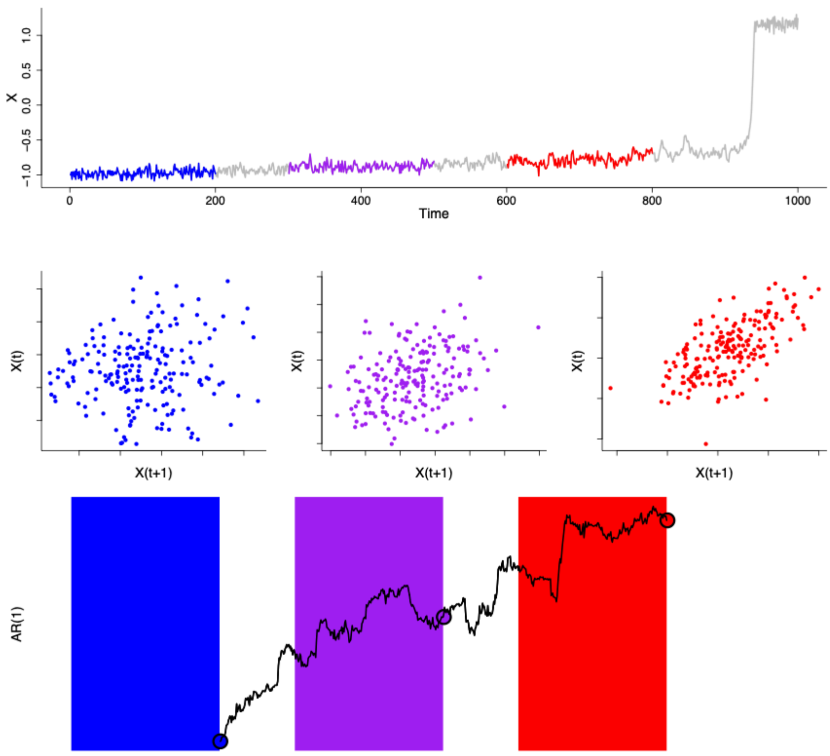


Figure 4 : Early indicators before a tipping point. (Top row) The time-series of the state of a system ('X') that is being slowly forced towards a tipping point (blue, purple, red), exhibits slowing recovery from fluctuations. (Middle row) This 'critical slowing down' can be seen as an increase in correlation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

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

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

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

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

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

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

What is *not* a tipping point?

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

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

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

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

Approach

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

Systemic risk

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

Handling uncertainty

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

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

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

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

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

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

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

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

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

Our normative position

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

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

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

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

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

Governance

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

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

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

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

A particular risk is the creation of green sacrifice zones. These are ecologies, places and populations that will be severely affected by the sourcing, transportation, installation and operation of solutions for powering low-carbon transitions, as well as end-of-life treatment of related material waste (Zografos and Robbins, 2020). More broadly, we seek to avoid (and counter) climate colonialism, defined as *"the deepening or expanding of domination of less powerful countries and peoples through initiatives that intensify foreign exploitation of poorer nations' resources or undermine the sovereignty of native and Indigenous communities in the course of responding to the climate crisis"* (Zografos and Robbins, 2020: p543).

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

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