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Governance for Earth system tipping points – A research agenda

Manjana Milkoreit [a,*], Emily Boyd [b], Sara M. Constantino [c], Vera Helene Hausner [d], Dag O. Hessen [e], Andreas Kääb [f], Duncan McLaren [g], Christina Nadeau [e], Karen O'Brien [a], Frans-Jan Parmentier [f], Ronny Rotbarth [h], Rolf Rødven [i], Désirée Treichler [f], Elana Wilson-Rowe [j], Yulia Yamineva [k]

[a] Department of Sociology and Human Geography, University of Oslo, Moltke Moes Vei 31, 0831 Oslo, Norway
[b] Lund University Center for Sustainability Studies, (LUCSUS) Lund University, Lund, Sweden
[c] School of Public Policy and Urban Affairs, Northeastern University, Boston, USA
[d] Department of Arctic and Marine Biology, UiT the Arctic University of Norway, Tromsø, Norway
[e] Centre for Biogeochemistry in the Anthropocene, Department of Biosciences, University of Oslo, Oslo, Norway
[f] Centre for Biogeochemistry in the Anthropocene, Department of Geosciences, University of Oslo, Oslo, Norway
[g] School of Law, University of California Los Angeles, Los Angeles, USA
[h] Environmental Sciences Group, Wageningen University, Wageningen, the Netherlands
[i] Arctic Monitoring and Assessment Program (AMAP) Secretariat, Tromsø, Norway
[j] Department of International Environment and Development Studies, Norwegian University of the Life Sciences (NMBU), Norway
[k] Law School, University of Eastern Finland, Joensuu, Finland

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ABSTRACT

Tipping points in the Earth system could be passed within the Paris Agreement's temperature goal range (1.5°C–2°C). Tipping processes are a feature of complex Earth system dynamics that present major governance challenges not addressed by existing global governance institutions. The common governance toolkit is a poor match for dealing with tipping processes, especially non-linear change, and radical intertemporality. To support the development of effective responses to anticipated, rapid state changes in the Earth system, there is an urgent need for new interdisciplinary research programs focused specifically on tipping-point governance. We distinguish two domains of action in a multi-phase framework - prevention and impact governance - and identify key research areas and questions that need to be addressed. These include developing governance principles, identifying actors and institutions that should be involved or need to be created, and determining the appropriate temporal and spatial scales for governance efforts.

1. Introduction

There is growing scientific evidence that Earth system tipping processes – rapid, non-linear, self-perpetuating, and often irreversible shifts in major components of the Earth system – are no longer distant threats but might be triggered within the range of the global temperature goal set by the Paris Agreement: 1.5°C–2°C (Armstrong McKay et al., 2022; Lenton et al., 2019; Naughten et al., 2023). The tipping elements most at risk within this 'Paris temperature range' include the Greenland Ice Sheet, the West Antarctic Ice Sheet, and warm water coral reefs. Beyond 2°C, additional tipping points can be expected. Scholarship in the natural sciences has identified more than 25 potential tipping elements in the cryosphere, oceans, atmosphere, and biosphere (Armstrong McKay and Loriani, 2023), but policy making, the social sciences and humanities are lagging in terms of conceptualising and dealing with the implications of tipping points for society (Milkoreit, 2023). There are even doubts whether the existing global governance institutions or the current global order are capable of addressing this kind of challenge (Biermann, 2021; Kotzé, 2022; Young, 2023).

Earth system tipping points (ESTPs)[1] can be found in major components of the Earth system (tipping elements) that undergo rapid shifts between two or more stable states driven by self-reinforcing feedback dynamics (Lenton et al., 2008). A tipping point is a threshold after which the change process becomes self-perpetuating until a new, qualitatively

* Corresponding author.
E-mail address: manjana.milkoreit@sosgeo.uio.no (M. Milkoreit).

[1] Throughout the article, we abbreviate the term Earth system tipping point(s) with ESTP.

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different state is reached (e.g., a rainforest turns into a grassland; an ice sheet melts to an ice-free state). Earth system tipping processes are diverse regarding their drivers (see Table 1.7.1 in Armstrong McKay and Loriani, 2023) and impacts (see Table 3.3.1 in Constantino et al., 2023), their geographic scope, and their temporal characteristics. They would have significant negative impacts on societies, ranging from infrastructure to food production (Kornhuber et al., 2023) and health (Deivanayagam et al., 2023). Certain tipping processes, such as abrupt permafrost thaw, could weaken or even reverse the current land carbon sink, functioning as a positive feedback to climate change by contributing to emissions of greenhouse gases. Many tipping processes are irreversible on human timescales. Further, tipping elements in the Earth system are connected and interact on a global scale (Kriegler et al., 2009), creating the potential for tipping cascades, i.e., chain reactions where one tipping process triggers another (Klose et al., 2021; Wunderling et al., 2021).

Major scientific uncertainties remain, including the question which Earth system components are tipping elements, the threshold conditions, i.e., the specific values of drivers (e.g., level of atmospheric temperature) that constitute a tipping point, and when tipping points will be reached. For example, there is growing evidence for tipping potential in the North Atlantic Meridional Overturning Circulation (AMOC) (Caesar et al., 2021; Hofmann and Rahmstorf, 2009; van Westen et al., 2024), but significant scientific controversy remains regarding the conditions and timing of a potential future collapse of the ocean circulation system, and to what extent signs of slowing down can be observed today (e.g., Boers, 2021; Caesar et al., 2018; Chen and Tung, 2024; Rahmstorf et al., 2015).

Environmental governance has developed a set of approaches that aim to deal with problems where knowledge is incomplete, and the science is uncertain (Wynne, 1992; Mehta et al., 2001; Dewulf and Biesbroek, 2018). But so far, existing institutions for global environmental governance do not address the specific risks presented by Earth system tipping points, including the novel vulnerabilities created by specific tipping processes and the implications of systemic reorganisations (state shifts) as opposed to gradual changes. Today's dominant toolkit of political, policy, and technocratic decision-making is poorly suited to this task because its fundamental logics are linear, based in trend extrapolation, reactive rather than anticipatory, and insensitive to multiple time horizons. The existing landscape of governance, including the regime complex for climate change, and the basic ordering principles it is built upon, appears inadequate when it comes to global-scale, human driven changes in the Earth's major systems (Biermann, 2021; Young, 2023).

The governance challenges related to ESTPs have been subject to growing scholarly debates about Earth system governance. Along with the Anthropocene (Stoermer and Crutzen, 2000) planetary boundaries (Rockström et al., 2009), and resilience (Folke, 2006), the concept of climate tipping points has anchored and motivated governance research with a complex Earth-system ontology. However, this scholarship has remained largely conceptual and has generally not distinguished the specific challenges related to non-linear state shifts from other features of complex Earth systems. This lack of focus and practically-relevant insights is becoming more problematic with the rapidly growing attention to tipping points in political and policy discourse, especially related to climate change.

Climate tipping points were first mentioned in formal debates and decisions at the 27th Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) (UNFCCC, 2022). In 2023, tipping point-language appeared in the COP28 decision on the first Global Stocktake (UNFCCC, 2023), indicating that global policy makers require more information about tipping processes and what can be done about them. These developments indicate a quickly growing need for knowledge co-production at the science-policy interface to support governance efforts and decision-making regarding Earth system tipping points, within and beyond existing climate governance institutions (Milkoreit et al., 2023).

Building on the growing, yet still marginal, scholarship on Earth system governance, we argue that significantly expanded interdisciplinary and solutions-oriented research programs in the social sciences, humanities, and natural sciences are urgently needed to support governance to address Earth system tipping points. The development of these research programs should be informed by the specific characteristics of Earth system tipping processes that demand a reconsideration of existing approaches to climate and environmental governance. Focusing on tipping processes enables a shift from abstract and conceptual discussions of complex systems more generally to more concrete and action-oriented insights. An important component of this work is the differentiation of distinct phases of tipping processes, with different system dynamics, possible governance objectives and tasks in each phase. Below, we provide a framework based on three phases of tipping processes and begin to elaborate the differences between governance before and after the tipping point.

We outline the core dimensions of such a research agenda grounded in a review of existing scholarship and an analysis of the specific problem structure of Earth system tipping processes. The following section (2) develops a framework for Earth system tipping point governance. The remaining sections elaborate on this framework, each addressing one of four fundamental dimensions of governance: (3) principles and logics, (4) goals and tasks, (5) scales and diversity, and (6) actors and institutions. We conclude each of these four sections with a box that offers a set of research questions that can guide future work.

2. A framework for tipping point governance

"Governance refers to rules, regulations, norms and institutions that structure and guide collective behaviour and actions" (Milkoreit, 2023, p. 8). Our view of governance covers multiple scales of rulemaking from the global to the local, and involves diverse kinds of actors, including (national and sub-national) governments and their intergovernmental initiatives, corporations, industry associations and private governance initiatives, civil society organisations and social movements, as well as transnational networks.

Over the last fifteen years, scholarship on environmental governance has performed a major shift towards Earth system governance (also governance in the Anthropocene) (Biermann et al., 2009; Pattberg and Zelli, 2016; Young, 2017; Burch et al., 2019). The emerging paradigm has been grounded in the growing understanding of humanity's large-scale impacts on planet Earth and the nature of Earth systems and societies as tightly coupled, complex-adaptive systems (Duit and Galaz, 2008; Loorbach, 2010; Galaz, 2017), which are characterised by deep uncertainty, the potential for surprise, and limited predictability and control. This ontological shift required a reconceptualization of basic governance logics, emphasising system dynamics across multiple scales (Galaz et al., 2016), connectivity and globally networked risks (Homer-Dixon et al., 2015; Lawrence et al., 2024), including the potential for instability at the global scale.

Scholarship within this Earth system governance paradigm (Biermann, 2021) recognizes that the characteristics of complex systems have to become the foundations of governance (Loorbach, 2010), i.e., that they present a major problem of 'institutional fit' (Young, 2002; Folke et al., 2007; Galaz et al., 2008). Core tenets of governance that follow include multi-scale governance, polycentricity and (cross-scale) interaction management, the need for flexible objectives that can adjust according to changing system dynamics, increased long-term thinking and anticipatory governance to address unusual temporalities (Boyd et al., 2015; Muiderman et al., 2020), adaptive governance and diversity in response capacity to deal with surprises and adjust to rapidly shifting circumstances (Duit and Galaz, 2008; Galaz et al., 2016; Walker et al., 2023). Further, reflexivity and (social) learning, i.e., "the capacity of an agent, structure or process to change in the light of reflection on its performance" (Pickering, 2019, p. 1145), become increasingly important for adaptive governance (Dryzek, 2016) and can be fostered with participatory, multi-stakeholder governance processes.

In response to the idea of the Anthropocene and the planetary boundaries concept, scholarship within this Earth system governance paradigm has developed a consistent set of global governance reform proposals.: (1) new norms and principles (e.g., biosphere stewardship), (2) institutional change (e.g., a framework convention on planetary boundaries), (3) a focus on institutional interaction management, and (4) ways to foster reflexivity, especially with more effective and more frequent science-policy interactions (e.g., a recurring planetary boundary assessment) (Galaz, 2017; Kim and Kotzé, 2021).

However, so far this scholarship has had very limited practical impacts (Kim and Kotze, 2021; Biermann, 2021), which has been attributed to a lack of democratic legitimacy of Earth system science (Pickering and Persson, 2020), path-dependency (Dryzek, 2014), and even the international system's inability to deal with complex Earth system change (Young, 2021; 2023). The recent proposal of 'planetary commons' governance (Rockström et al., 2024) takes the latter challenge head-on. The authors make the case for expanding the concept of global commons to cover components of the Earth system that are currently distributed across multiple nations, i.e., subject to sovereignty, but key for human life support systems, including a number of Earth system tipping elements. The planetary commons approach challenges core principles of the current global order, especially territorially delimited sovereignty.

Here, we build on the existing framework of global complex-adaptive systems governance and apply it to the specific phenomenon of ESTPs. Tipping points are an integral part of the scholarship summarised above as one feature of complex systems (Young, 2012; Galaz et al., 2016; Milkoreit, 2015; 2019). However, the literature so far rarely treats tipping processes as the core issue and object of governance, i.e., exploring the specific risks they present and how these risks can and should be addressed. Applying the various dimensions of the Earth system governance paradigm specifically to the phenomenon of ESTPs, we discuss a set of governance principles and logics that are associated with a complex-systems ontology (3), the objectives and tasks of tipping point governance and their change over time (4), the importance of attending to multiple temporal and spatial scales when addressing Earth system tipping (5), and the implications, including the potential need for new, actors and institutions (6). The focus on ESTPs rather than complex systems dynamics more generally, enables and requires the development of a concrete, policy-relevant and action-oriented set of insights that moves beyond the predominantly conceptual discussions to date and can inform and support future decision-making in this domain.

Further, we integrate multiple components of our proposal for tipping point governance research in a framework that distinguishes three discrete phases of a tipping process: (1) the approach of a tipping point ('pre-tipping'), (2) reorganisation after having passed a tipping point ('reorganisation'), and (3) stabilisation of a new system state. Each phase has different characteristics, which require distinct governance approaches, e.g., pursuing different objectives and involving different actors. Fig. 1 visualises this multi-phase framework, indicating the

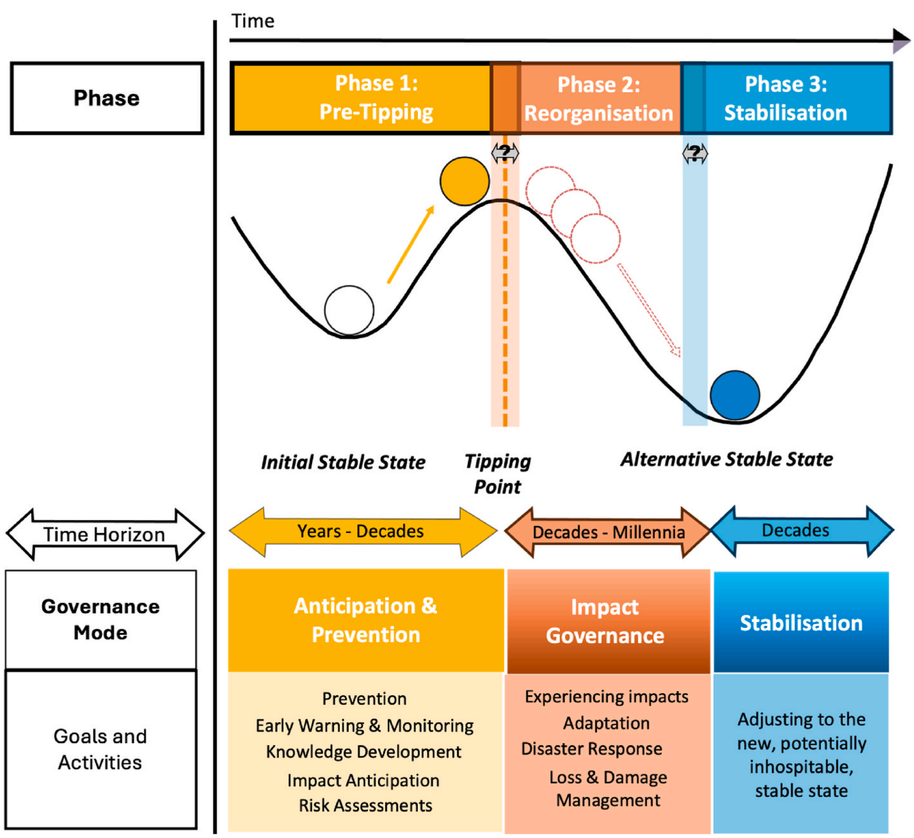

Fig. 1. Multi-phase framework for Earth System Tipping Point Governance
Fig. 1 is adapted from Fig 3.1.2 in Milkoreit et al., (2023). It provides a simplified illustration of how a tipping process unfolds over time, using a common bowl-and-cup diagram. It distinguishes three phases: (1) pre-tipping (the system is approaching the tipping point), (2) reorganisation (the system has passed the tipping point and transitions towards a new stable state), and (3) stabilisation (the system reaches a new stable but potentially inhospitable state for humans). The framework integrates governance objectives, principles and logics, and time scales. The objectives and activities of governance would differ significantly in each phase matching the characteristics of the Earth system change process. For example, in phase 1, the main objective would be prevention while impact governance would be the main goal in phase 2. Governance efforts might also be able to affect the shape of the curves, i.e., to deepen the bowl or increase the height of the peak. Different principles dominate across the three phases. For example, phase 1 is predominantly anticipatory and precautious while phase 2 is adaptive. The framework indicates estimates of how long each phase might last for different tipping processes (time horizon).

governance objectives and tasks in each phase, dominant principles or logics of governance, and the uncertain timescales of each phase. This framework and Fig. 1 focus on a single tipping process and do not account for the potential of tipping cascades, i.e., the possibility that one tipping process increases the likelihood of passing another. We attempt to capture this aspect of linked ESTPs in Figure S1 in the supplementary materials.

Based on current scientific understanding, all identified Earth system tipping elements are in the pre-tipping phase, although there is uncertainty whether some have already passed a tipping point (i.e., have entered phase 2). In this pre-tipping phase, governance should be anticipatory and focus on preventing the passing of the most proximate tipping points. Other tasks in this phase include knowledge development (i.e., better understanding the drivers, threshold values, and prevention options), systemic risk and vulnerability assessments, development of early warning systems, and a reconsideration of existing impact governance approaches (e.g. efforts to increase preparedness, adaptation, and resilience, or to compensate for loss and damage) in light of tipping points. Further, raising preparedness for potential impacts, transformative adaptation efforts, and resilience building are most effective in phase 1 and continue in phase 2. In the reorganisation phase of a tipping process, the governance mode shifts to adaptive and responsive. Well-functioning institutions are needed to address impacts with adaptation measures, loss and damage, migration governance, and disaster response. Once the tipping element stabilises, governance should foster sustainability, with norms and institutions that can rely on increased stability in the post-tipping state (e.g., securing coastal livelihoods independent of coral reefs and fishing).

3. Governance principles and logics

This section explores the logics and principles for ESTP governance, considering both the core tenets of complex-adaptive systems governance and seven specific characteristics of Earth system tipping processes described above. Each logic or principle relates to one or more tipping-point features, addressing the challenge of 'fit' between the problem at hand and the governance approach. Some principles dominate in particular tipping point phases (see Fig. 1), e.g., anticipation, precaution and prevention in the pre-tipping phase. Table 1 summarises these tipping point characteristics, the governance principles, and their relationships.

3.1. Global and multi-scale governance

Earth system tipping processes are global environmental phenomena in the sense that both their causes and impacts are distributed across multiple countries, requiring at least to some extent international cooperation and global governance. General principles of global environmental governance and international environmental law apply, including (among others) the no transboundary environmental harm principle, preventive action, precaution, transparency and accountability, and international cooperation. Because the drivers and impacts of tipping processes are distributed unevenly among countries, key among these principles is the pursuit of equity and justice.

Table 1
Key characteristics of climate tipping points and corresponding governance logics (full-page/two-column).

Characteristics of Earth System Tipping Processes	LINK	Governance Logics and Principles
(1) Large Geographic Scale: Earth system tipping elements cover multiple countries and have global and regional drivers and impacts.		Global governance Multi-scale governance
(2) Alternative Stable States: A tipping element can exist in two or more fundamentally different conditions. When moving from one set of stable conditions to another (transition), the system undergoes a fundamental restructuring – a qualitative or identity change.		Prevention as main objective Precaution as main principle
(3) Tipping Point: Once changes in the tipping element transgress a certain threshold (tipping point), the transition to an alternative stable state begins and can no longer be stopped. The system is now committed to the transition. The tipping point presents a boundary between the system's different stable states.		Anticipatory governance
(4) Non-linearity and Positive Feedback: Beyond the tipping point, the change process accelerates due to the dominance of positive (self-amplifying) feedback dynamics, which serve as main drivers of the transition to a new table state. There is an increase in the system's rate of change. The system's response is disproportionate to the forcing (the small change that moved the system over the tipping point).		Adaptive governance Diversity in response capacity
(5) Limited Reversibility and Hysteresis: Many tipping processes are irreversible, at least on human timescales, and it is difficult to return the system to its initial conditions.		
(6) Temporal Characteristics: Tipping processes – the time span from passing the tipping point to reaching an alternative stable state - can last multiple years, decades, centuries, or millennia. The point in time when different tipping elements reach their tipping point differs for each element. For most tipping elements, this depends on when the Earth reaches certain levels of global average temperature.		Intertemporal Decision making Future care/intergenerational justice
(7) Cascading Potential: Many Earth system tipping elements are connected to each other in the sense that triggering one tipping process makes it more likely that another tipping element will undergo a tipping process. This creates the possibility of tipping-point cascades that span the entire planet.		Systemic risk governance

At the same time, each tipping element has a specific regional scale, regional drivers, and impacts that vary across scales of social organisation. For example, the dieback of the Amazon rainforest is most directly affected by policies and activities of the countries sharing the Amazon basin. Given this multi-scale problem structure, multi-scale or polycentric governance approaches are most suitable for climate tipping processes (Galaz et al., 2016).

3.2. Prevention and precaution

Tipping processes have a fundamentally different logic of change compared to the common view of global warming, changes in ocean heat content, or sea-level rise as linear and incremental. The difference is two-fold: one dimension concerns the character and scope of change and is discussed here. The other the speed or temporal character or change, addressed below in subsection 3.4.

Shifts between alternative stable states of a system (e.g., rainforest vs. grassland, ice sheet vs. ice free) imply fundamental, structural reorganisations of entire systems compared to incremental changes in a particular variable. This type of change at large scales implies that in many cases, the very foundations of social-ecological organisation and stability could be irrevocably lost at local, national, and maybe even higher levels. This could include the loss of cultural identities and ways of life, the collapse of industries and interruption of international trade, social instability, mass migration and conflict (Constantino et al., 2023). For example, the dieback of the Amazon Rainforest would (among other things) destroy the current way of life of Indigenous Peoples in the Amazon Basin, change the hydrological conditions of the region to an extent that would create water scarcity, increase heat stress, challenge the viability of the current power generation systems, the agricultural use of cleared land and correspondingly economic and political conditions in Brazil and other countries (Lapola et al., 2018). This could result in migration flows, interruptions of trade relations and tensions between South American states despite previous strong cooperative relations. Given the severity, proximity and long-lasting nature of these threats, scholars have associated climate tipping points with the concept of catastrophic risk (Kemp et al., 2022; Pereira and Viola, 2018) and economic shocks (Kopp et al., 2016). It is possible that tipping processes, especially when they are poorly understood, could overwhelm or weaken governance capacities of governments and other institutions, reducing collective capacities to address this and other global challenges throughout this century, including sustainability transitions efforts (Laybourn et al., 2023).

The prospect of these grave consequences coupled with significant uncertainties has two important consequences for tipping-point governance. First, it elevates the prevention of climate tipping point as a central objective of governance. Second, it strengthens the relevance of the precautionary principle (Kriebel et al., 2001; Read and O'Riordan, 2017; Stirling, 2007).

The objective of prevention requires expanding best possible efforts to avoid the passing of tipping points in Earth systems. This implies anticipatory action before the consequences of a tipping process can be observed and used to foster support for collective action. Scientific knowledge about ‘when’ a tipping point can be expected is subject to uncertainty and, will in many cases not be available or certain until years or even decades after the fact. Instead, there is an uncertainty range of possible values (e.g., 1.5°C–3.5°C of warming). Under these conditions - uncertainty and the prospect of severe, negative, and irreversible impacts - the precautionary principle is an important guide to decision-making. The precautionary principle implies that preventive mitigation efforts must not be delayed because of this uncertainty or with the argument that the tipping point might be at 3.5°C (Boswell, 2017). On the contrary, one should work with the more pessimistic assumption that tipping can occur at 1.5°C. However, interpretations of the precautionary principle vary, and its implementation in governance of tipping processes is not straightforward. Some versions of precaution support undemocratic and securitised pre-emptive responses to perceived threats (de Goede and Randalls, 2009) which would likely undermine effective cooperative governance of tipping processes.

Beyond applying precaution, common decision-making frameworks in policy making, financial investment and strategic corporate planning, are not suitable in the context of climate tipping elements. For example, the limitations of cost-benefit-analysis (CBA) and discounting of the future have been discussed for so-called fat-tail events - high-impact but low-likelihood occurrences, especially the perverse effects of future discounting in economic models (Roemer, 2011; Weitzman, 2009, 2011). As Weitzman argued, the application of uncertain discount rates “trivialises even truly enormous distant future impacts” in economic analyses (2011, p. 284).

While these arguments question the application of CBA, discount rates, and other economic frameworks when dealing with catastrophic risks that have a low likelihood of occurring, at least some Earth system tipping points present catastrophic risks that can no longer be considered low likelihood events, because the likelihood of passing a tipping point is, in many cases, closely tied to global average temperature. With the current trajectories of GHG emissions, the question is not *whether* some of these tipping processes (e.g., the dieback of the warm-water coral reefs) will be set in motion, but *when* (Hughes et al., 2017).

3.3. Anticipatory governance

The tipping point is the key feature of tipping processes and has become the dominant label for the larger phenomenon in question. The tipping point represents the boundary between the relative stability of the system in its present state and the turbulent transition to an alternative stable state. The tipping point also represents a moment of commitment - once it is reached, positive feedback dynamics become dominant and set in motion a self-perpetuating process of (accelerating) change that can no longer be arrested. The system is now committed to future changes and reorganisation.

Given these characteristics, the tipping point has important implications for governance related to Earth system tipping processes. It separates possibility domains and different phases of governance with distinct logics (see Fig. 1). Before the tipping point is reached (pre-tipping phase), prevention, system stabilisation, and harm avoidance are possible. After the tipping point has been transgressed (reorganisation phase), these objectives are no longer attainable, and governance efforts must focus on preparing for, minimising, and responding to various impacts. This is different from continuous warming, where limiting future change is always possible and meaningful.

The existence of tipping points demands a greater future-orientation of governance, including the ability to be proactive rather than reactive (e.g., to avoid crossing thresholds before experiencing impacts), the development of anticipatory knowledge (e.g., regarding the drivers of tipping processes, the linkages between tipping elements), and monitoring and early warning capabilities. Anticipatory governance is “governing (or steering) in the present to engage with, adapt to or shape uncertain futures” (Boyd et al., 2015; Muiderman et al., 2020). Anticipatory governance employs a variety of foresight and scenario building approaches to understand and identify potential future system trajectories, to assess how different risks could play out, and to minimise risks across multiple possible futures. Such disciplined engagement with possible futures differs fundamentally from trend- or history-based projections, linear modelling and planning exercises that underpin most decision making today. Anticipatory governance requires distinct capacities and tools that governance actors and institutions need to develop and acquire, such as future and systems thinking (Neuvonen et al., 2014; Flood et al., 2018; van Beek et al., 2022).

The development of monitoring and early warning capacities is an important dimension of anticipatory governance, providing governance actors the information they need for agile, proactive decision-making. Monitoring of Earth system elements involves continuous scientific observation to detect patterns and changes, especially signs that the system might be on a trajectory towards a potential tipping point, or part of a tipping-point cascade. Earth system tipping points can in theory be preceded by particular system behaviours, such as changing levels of system variability (Dakos et al., 2023). Scientific insights would then be linked to an early-warning system (EWS) - a process of assessment and decision-making at the interface of science and policy.

3.4. Adaptive governance

Transitions between two stable states are driven by positive - self-amplifying - feedback dynamics. Due to this driver of change, the transition process is non-linear. The increasing rate of change presents additional challenges for impacted communities to respond and adapt. The beginning of the transition process can be hard to predict and plan for, with unexpected impacts and surprises along the way. Under these conditions - limited predictability and controllability in complex systems - adaptive approaches to governance are most effective (Berkes, 2017).

The concept of adaptive governance entails continuous monitoring of changes and early warning signals for the different tipping elements, flexibility (e.g., regarding the objectives and tools of governance) to adjust to changes in the system based on learning and reflexivity (Pickering, 2019; Dryzek, 2016), and, more generally, an openness and ability to adapt strategies, plans, and rules based on new scientific findings (Duit and Galaz, 2008).

Adaptive governance also includes measures to enhance resilience by increasing the diversity in response capacity of socio-ecological systems (Galaz et al., 2016). The logic of response diversity corresponds to the fact that changes in complex systems can be unanticipated and rapid. Being well prepared for such unexpected challenges requires having a broad set of tools and response options available. Walker et al. make the case for increasing response diversity for a larger set of global challenges: “As we enter an era of unprecedented turbulence at the planetary level, we argue that ample responses to this new reality — that is, response diversity — can no longer be taken for granted and must be actively designed and managed” (Walker et al., 2023, p. 621). While increasing response diversity contrasts with standard logics of efficiency and cost-effectiveness in policymaking by building in redundancies and diversity, it is aligned with best practices for decision-making under conditions of uncertainty and irreversibility.

3.5. Limited reversibility

Irreversibility remains a contested characteristic of Earth system tipping processes and is not required to establish a tipping point. For some tipping elements, such as ocean currents or ice sheets, a return from a future alternative stable state to the current conditions is possible, but only under circumstances that will not be reached for centuries or millennia. Hence, for the practical purposes of collective decision and policy making today, these tipping processes can be considered de-facto irreversible. The time horizon of a return to initial conditions renders that prospect irrelevant for humanity today.

This de-facto irreversibility strengthens the logic for several governance principles already discussed, e.g., it elevates the imperative of prevention as a governance goal and precaution as a guiding principle for decision making. Anticipatory governance gains more weight, i.e., the need to actively engage in decision making with a broad range of possible futures with the aim to foster pathways that avoid undesirable outcomes. If one or multiple tipping processes take place, no future human generation will experience the planet the way past and current generations have done and do today, and future generations will have limited or no power to return the planet to its pre-tipping conditions. These implications of tipping for the relations between generations amplify the need for more deliberate intertemporal decision-making frameworks that can account for large-scale, irreversible reorganisations of major components of the Earth system.

3.6. Intertemporal decision making

The characteristics of tipping points lend new weight to the argument for expanding current conceptions of justice to include future generations and future non-human life on Earth. Tipping processes can unfold over very different time periods, ranging from a decade to multiple millennia. Given that some tipping points can be triggered – and only avoided – with decisions in the near-term (years to decades), but their effects will manifest for hundreds or even thousands of years, it is imperative that decision makers today grapple with and adjust their notions of responsibility for the future. Political office holders, industry leaders, and other governance actors shape the conditions of human wellbeing not only contemporaneously, or for several years or decades into the future, but now have impacts on the conditions of life on planet Earth for millennia to come. This profound intertemporal expansion of the causal effects of today’s decisions and actions is even more important when considering that tipping processes involve the reorganisation of Earth systems at large scales, removing the past and current environmental and climatic conditions for social-ecological organisation, stability, and resilience, and that some of these reorganisations can take centuries or millennia, with the potential for returning to current conditions beyond human imagination.

Existing utilitarian concepts of justice, including international climate justice (Jamieson, 2001; Moellendorf, 2015; Okereke and Coventry, 2016) or fairness (Rajamani et al., 2021), are unable to effectively balance long and near-term justice: either ignoring or actively devaluing the long-term through discounting, or overweighting it. An increasingly robust discourse about intergenerational justice and ways to strengthen the democratic representation of the interests of future generations is developing (Barry, 1997; Gardiner, 2011; Meyer, 2017; Skillington, 2019), but so far with limited impacts on political processes and decision frameworks. Novel concepts such as Earth system justice (Gupta et al., 2023) might be particularly useful guideposts for tipping point governance but need to be operationalised. In asserting the equal importance of inter- and intra-generational equity, the Earth system justice framework promotes equality and inclusion today as a means to minimise harms from inherited inequality in the future; and asserts the right of all future people to enjoy no less well-being than today’s. Beyond principles for the relationships between generations, conceptions of justice also need to encompass future non-human life on Earth. Earth system tipping processes provide causal linkages between decisions taken by individuals and communities today and the conditions for all life on the planet for millennia to come.

3.7. Systemic risk governance

A number of ESTP characteristics present fundamental challenges to conventional risk governance, including non-linearity, long time horizons, and severe impacts. What is more, linkages between many Earth system tipping elements create the potential for tipping-point cascades (Kriegler et al., 2009; Wunderling et al., 2021). A cascade refers to a process where the initiation of one tipping process contributes to pushing another tipping element over the threshold, which in turn increases the chances of further tipping events (Klose et al., 2021). Cascading potential is still poorly understood, but presents significant compounding risks, i.e., the possibility for risk propagation across scales and systems (Homer-Dixon et al., 2015).

Considering these complex-systems characteristics, major questions remain regarding whether and how networked global risks can be governed (Galaz et al., 2017). A number of emerging concepts, such as global systemic risk (Centeno et al., 2015; Schweizer and Renn, 2019), systemic risk governance (Helbing, 2013; Juhola et al., 2022), polycrisis (Lawrence et al., 2024), and integrated catastrophe assessment (Kemp et al., 2022) are developing a set of principles and approaches to respond to this challenge. These approaches consider a broader range of risks, including those related to the human responses to problems, such as mitigation measures or increasing authoritarianism, and a broader range of risk outcomes. They also assess multiple possible interactions and trade-offs between different kinds of risks (Juhola et al., 2022; Liu et al., 2015; Simpson et al., 2021), and the possibility of compound, cross-scale and cascading risks in networked systems.

Table 1 lists seven distinct characteristics of tipping processes that are frequently discussed in the scientific literature (Milkoreit et al., 2018). The arrows indicate relationships ('fit') between these characteristics and relevant governance principles or decision-making logics in the sense that these principles are the best available match for the nature of the problem. Some characteristics relate to several principles.

Box 1 provides a set of key questions that can guide future research regarding the principles and logics of Earth system tipping point governance.

4. Governance objectives and tasks

The principles and logics discussed above highlight that the prevention of Earth system tipping processes should be at the heart of governance efforts. The primacy of prevention as a governance goal is based on the severity of potential impacts linked to large-scale state shifts in Earth systems (i.e., threats to human and ecological well-being), the limited prospects for reversing these changes over relevant time horizons, the potential for tipping cascades (exponential harm amplification), and the presence of major uncertainties regarding the conditions for and consequences of tipping events. While prevention should be the focus of climate tipping governance research and efforts, it should not crowd out work on the governance of climate tipping impacts, which could minimise the harm if prevention efforts fail. Indeed, measures to address these two goals may also have synergies. We discuss both goals and synergistic approaches below.

Importantly, the pursuit of these governance objectives has to be understood in the context of the multi-phase framework for tipping governance (Fig. 1). Prevention and synergistic approaches are only effective in the pre-tipping phase. Impact governance should start in phase 1 (e.g., anticipatory adaptation planning) and becomes the dominant objective in the turbulent reorganisation phase, when the state shift has been set in motion.

4.1. Prevention of earth system tipping

Most climate tipping processes have multiple drivers that operate at different spatial and temporal scales. Effective prevention approaches need to distinguish and address all these drivers in a coordinated cross-scale approach.

Global temperature increase is a key driver for many tipping processes, rendering global-scale greenhouse gas emissions reductions central to tipping-point prevention. The threat of passing ESTPs already at current levels of global average warming raises questions concerning the adequacy and interpretation of the global temperature goal established by the Paris Agreement. More stringent temperature goals, while unlikely to be achieved without overshoot, are better suited to averting tipping points associated with several tipping elements in the Earth system, especially those at risk under 2°C of global warming. Considering tipping points increases the salience and importance of adhering to the existing global goals and could galvanise the international community.

Recent studies that consider climate tipping points in the calculation of the social cost of carbon estimate that it must be increased by two-to nearly eightfold to account for the externalities associated with carbon emissions (Cai et al., 2016). These calculations indicate a need to dramatically strengthen mitigation policies relative to estimates under climate change in the absence of tipping dynamics (Lontzek et al., 2015). Short-lived climate pollutants (SLCPs), such as methane, provide short-term leverage over global and regional temperature change and should receive increased attention.

There is also a need to consider which mitigation pathways are best suited to minimise the risk of transgressing different tipping points (Pouille et al., 2023). Delayed action makes temperature overshoot scenarios more likely, where global temperatures increase beyond the 1.5°C threshold before decreasing again later this century or beyond 2100, for example due to future carbon removal efforts. Such temporary temperature overshoot scenarios present possible pathways to still meet the requirements of the Paris Agreement but increase the risk of crossing critical thresholds (Wunderling et al., 2023). Depending on the peak overshoot temperature and the length of the overshoot phase, tipping processes could be triggered and would not be reversed even if temperatures are eventually reduced to 1.5°C. Minimising temperature rises and the duration of any exceedances of key temperature levels suggests also mobilising carbon removal techniques to a maximum just and sustainable level (Nawaz et al., 2024). This requires attention and dedicated governance (Low et al., 2024). However, to realise useful benefits from carbon removal it must only be deployed as a supplement to accelerated emissions reduction (Ho, 2023).

Most tipping element have multiple drivers, and atmospheric warming is not the primary driver for all. Other drivers often operate at regional, national, and local scales, and interact with global warming processes. For example, regional and national deforestation processes are important drivers for Amazon dieback, while local pollution adds pressure on coral reefs in addition to global scale factors like ocean heat or sea-level rise. Hence, each tipping element needs to be considered on its own terms, requiring prevention efforts at the scales that match their specific profile of drivers.

In sum, effective prevention strategies need to consider several factors, including the existence of multiple drivers and the scales at which different drivers operate (e.g., global temperature and regional deforestation or pollution), the estimated threshold values of each driver (e.g., 1.5°C for the West Antarctic Ice Sheet or 3.0°C for the East Antarctic Subglacial Basins), potential interactions between drivers (e.g., atmospheric temperature and deforestation for the Amazon Rainforest; ocean temperature, ocean acidity, and pollution for coral reefs), and uncertainties related to each of these elements.

BOX 1
Key research questions regarding principles and logics

(1) Which governance logics and principles should guide the development of new norms, processes and policies regarding Earth system tipping points?
(2) What kinds of decision-making frameworks and processes are needed to address the radical intertemporality of tipping-point governance?
(3) What are the implications of tipping processes for Earth system justice, and how can Earth system justice be implemented in practice?
(4) What types of governance capacities and skills are needed to deal with Earth system tipping points, and how can they be fostered?
(5) How could adaptive governance contribute to identifying, monitoring, preventing, and reducing the risks of the cascading impacts of tipping points?

The increased threats and dire consequences associated with ESTPs could also be seen as justification for risky or experimental governance responses (Laakso et al., 2017) or for measures that mitigate the risks of ESTPs but compromise equity, justice, or other priorities in the process. For example, several geoengineering approaches have been put forward as ways to help prevent or delay various climate tipping points (Gupta et al., 2020; Moore et al., 2021). Some proposed forms of geoengineering, especially solar geoengineering - large-scale, intentional interventions in the Earth's radiative balance designed to counter the effects of climate change - are highly contested (Biermann et al., 2022). While they at first glance seem to offer potential for substantial and rapid effects on global atmospheric temperature, their technical, political, and social viability is largely unknown (McLaren and Corry, 2021). Serious concerns related to these approaches include the potential for regional climate disruption, rapid temperature rebounds should solar geoengineering activities be abruptly halted for any reason, political disagreement undermining international cooperation or even leading to conflict, and the likelihood of solar geoengineering promises justifying delay in the phasing out of fossil fuels. A robust governance framework is required to ensure that such proposals are properly assessed with full evaluation of material, social and political risks (McLaren, 2023) and that premature deployment is avoided. At present, geoengineering does not offer reliable approaches to prevent tipping processes, and even where they might help, they are typically evaluated as less effective than emissions reductions with equivalent effects on temperatures.

4.2. *Governing the impacts of earth system tipping*

A second set of objectives concerns the avoidance and minimization of harm related to tipping processes in case preventive efforts are not successful. What could be labelled impact governance covers a broad range of issues, including adaptation, migration, disaster risk reduction and response, and conflict prevention (Constantino et al., 2023). So far, the challenges associated with tipping point impact governance have hardly been considered in Earth system governance scholarship.

Impact governance for ESTPs will have to differ from existing climate impact governance, especially adaptation and loss and damage, in several ways. These differences include the magnitude of change (e.g., centimetres or metres of sea-level rise), the speed of change (esp., increases in the rate of change), the distribution of impacts across space and time, including the emergence of newly vulnerable groups, and the potential for novel impact types (Constantino et al., 2023). It will also be important to consider that tipping processes might - at least temporarily - reverse current trends of climate change in particular regions. For example, if the North Atlantic Subpolar Gyre shuts down, Northern Europe could experience regional cooling rather than warming for several decades (Swingedouw et al., 2021), rendering current adaptation strategies ineffective.

Given the nature of tipping processes, loss and damage (Mechler et al., 2019) will play a much larger role in ESTP impact governance than it does in today's governance framework for climate change. Tipping processes involve the fundamental reorganisation of large systems that currently provide the foundations for human well-being, social organisation, and stability. These reorganisations are not just environmental change processes, but would transform all human experiences, interactions with, and uses of the biome, making current social-ecological relations impossible. Tipping processes threaten to generate a large and diverse set of de-facto permanent losses that are currently understudied and likely require careful, anticipatory planning and coordination of responses across scales and actors.

Further, tipping processes have broad implications for both human and sovereign state security, including the potential to exacerbate conflict. The governance of questions of climate security is already contested and complex (Dalby, 2016; Hardt et al., 2023). Climate change is rarely more than a contributing factor in conflict, and focusing on climate drivers can detract from political and justice concerns (Daoust and Selby, 2023). There are also strong arguments for avoiding conventional military securitization of climate issues, despite the key role of militaries in activities such as disaster relief (Crawford, 2022). But the potential for rapid state-changes due to tipping dynamics can be expected to further exacerbate drivers of conflict.

An important and unique aspect of impact governance for ESTPs concerns the need to contain potential tipping-point cascades. Cascade governance is a specific dimension of systemic risk governance (Schweizer and Renn, 2019). It focuses on the insight that connections between different components (here, tipping elements) of a larger system (here, the Earth system) can act as transmitters and pathways of risk. Based on a growing understanding of the coupling and interactions between ESTPs, the objective of preventing or halting an ongoing cascading process could be pursued with efforts to untie linkages in the Earth system or to weaken well-understood feedback dynamics (Riekhof et al., 2022).

4.3. *Synergistic approaches*

Impact governance could be synergistic with strategies for prevention. It is increasingly accepted that rapid decarbonization and the successful replacement of fossil energy dependence requires radical economic, political, and behavioural transformations (Moore et al., 2021; Morrison et al., 2022). Existing regimes construct economic and environmental vulnerability as societal, economic, and geo-political structures drive resource extractivism, create precarious labour reserves, and increase inequality (Ghosh, 2022; Gupta et al., 2023; Whyte, 2020). Sustainability transformations that seek to reconstruct political and economic regimes to support equity in mitigation and adaptation offer the potential to simultaneously reduce pressures on tipping systems and contribute to resilience to impacts (Bennett et al., 2019; O'Brien, 2018; Patterson et al., 2017; Scoones et al., 2020). For example, supporting increasing access to community-owned renewable power energy development in communities without electricity access could increase adaptive capacity, reduce vulnerability, enhance justice, and contribute to mitigation at the same time.

5. Governance scales and diversity of tipping elements

ESTPs are diverse in many dimensions, including the conditions of tipping, the geography of tipping elements, and impacts (what, when, where) of tipping processes. Here, we focus on two of these dimensions that are particularly relevant for the design of governance structures and decision making: their spatial and temporal scales.

5.1. *Multiple spatial scales*

The Earth system tipping elements we are concerned with here have a large geographic scale, typically covering or affecting multiple countries (e.g., the Amazon Rainforest, boreal forests) or continents (e.g., the AMOC). Armstrong-McKay et al. (2022) distinguish global and regional impact tipping elements. Global ('core') tipping elements contribute to the overall operation of the Earth system, and tipping would have effects beyond the geographic boundaries of the tipping element (e.g., additional global warming from CO_2 and methane released from permafrost thaw). These features require a global-scale governance approach.

Regional ('impact') tipping elements have primarily regional-scale impacts, i.e., importance for people and communities across multiple countries or have value as a unique feature of the Earth system. Even regional tipping elements like coral reef dieback and fisheries collapse could have global-scale implications, e.g., through migration flows, or disruptions to international trade and supply chains. The regional (i.e., multi-country or continental) scale of tipping elements demands an increasing focus on and possibly the creation of governance institutions at this particular spatial scale (see also Rockström et al., 2024). Existing institutions at the scale of specific tipping elements include the Arctic

BOX 2
Key Research Questions regarding goals and tasks

(1) What should be the objectives of governance related to Earth system tipping processes?
(2) How should governance goals differ across Earth system tipping elements and across different scales of governance?
(3) How should different objectives be prioritised, balanced, and sequenced?
(4) To what extent do current global governance objectives in the domains of climate change adaptation, international migration, disaster preparedness and response, and international security need to be revised to account for Earth system tipping processes?
(5) How should geoengineering research be governed to maximise learning about its potential, limitations, and risks without creating harmful expectations or deterring other climate responses?

Council and the Amazon Cooperation Treaty Organisation but are generally rare.

Further, there are also distinct national and local-scale impacts of tipping processes, e.g., the collapse of specific national economic sectors or industries or the abandonment of local settlements, that matter for the design of governance, e.g., the design of inclusive decision-making processes.

The diversity of spatial scales associated with Earth system tipping elements requires a multi-scale governance structure that can attend to scale-specific issues and cross-scale interactions. Challenging questions concern the allocation and sharing of responsibilities across scales (distribution of labour), effective coordination and information flows, and the management of resources and capacities to balance effectiveness and redundancy. Existing regional bodies, particularly those anchored in a logic of ecosystems and ecosystem management (Arctic, Amazon), have unique histories and different logics about and varied levels of capacity in interfacing with both global and national institutions (Paes, 2022; Wilson Rowe, 2021). Thus, the ability of existing regional institutions to mediate between national/local and global governance levels cannot be taken for granted.

5.2. Multiple temporal scales

Tipping processes exhibit complex temporal characteristics, e.g., they differ regarding the expected time of passing the tipping point, the duration of the change process, and the timing of their impacts. Some tipping systems are at risk of being triggered even at current warming levels, and the chance of passing another five tipping points could increase significantly within the coming decades. Other tipping processes, such as the East Antarctic Ice Sheet, have much higher threshold temperatures and will not be triggered for decades or even centuries. The duration of a tipping process (system reorganisation following the tipping point) can be as short as a decade (e.g., North Atlantic Subpolar Gyre) and as long as multiple millennia (e.g., Greenland Ice Sheet). Fig. 2 illustrates this temporal diversity with a simplified depiction of the temporal unfolding of three tipping elements.

The combination of a proximate tipping point (e.g., a threshold temperature of 1.5°C) and a very long reorganisation phase (millennia) creates particular challenges for governance. In these cases, there is very limited time for prevention efforts, and change dynamics would continuously create impacts over unimaginable time horizons. In such situations, decision makers may face limited incentives to act because of the uncertain distribution of impacts over time and space. Examples of such hard cases include the Greenland Ice Sheet and the West Antarctic Ice Sheet.

Overlaying both spatial and temporal scales with the framework of tipping in three phases, key questions arise concerning the division of governance tasks across actors and institutions at multiple spatial scales and across time.

6. Actors and institutions

The existing landscape of global environmental governance institutions, including the United Nations (UN) system, provides the context for considering where and by whom ESTPs could and should be addressed. At the global scale, institutions within the UN system, including treaty-based organisations, specialised agencies (e.g., UN Environment Programme, UN Development Program), are obvious

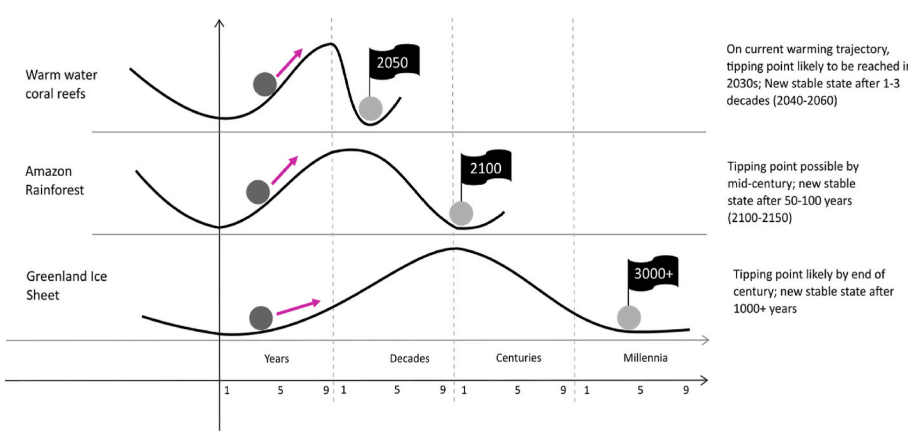

Fig. 2. Diverse Temporalities of Earth System Tipping Processes
Fig. 2 is adapted from Fig 3.1.1in Milkoreit et al., (2023) and illustrates the diversity of Earth system tipping processes regarding their temporal characteristics, using three examples. It shows all three systems in their pre-tipping phase (dark grey). Each tipping process can reach the tipping point (peak of the curve) at a different time in the future, e.g., in the 2030s for the warm water coral reefs or around 2050 for the Amazon Rainforest. The reorganisation time, i.e., the time period from passing a tipping point to reaching a new stable state, is different for each tipping process. For example, the warm water coral reefs could complete this transition within a couple of decades while the Greenland Ice Sheet would melt over several thousand years. Assumptions about global temperature changes in the course of the century are based on Climate Action Tracker 2023, i.e., 1.5°C in the 2030s, 2.7°C by 2100.

BOX 3
Key research questions regarding scale

(1) At what scales should tipping point governance take place? How does this vary across the different tipping elements?
(2) How should responsibilities and tasks be distributed across scales?
(3) How can multi-actor and cross-scale interactions be coordinated?
(4) What kinds of decision-making frameworks are best suited to address the temporal characteristics of tipping processes, especially the causal links between near-term decisions and their impacts in the distant future (hyper-intertemporality)?
(5) What are the implications for justice between groups and generations arising from these diverse scales of drivers and impacts? How can those most affected be represented in governance processes?

candidates for assuming responsibility. Other relevant bodies and institutions include the EU, OECD, ASEAN, and the Global Compact for Safe, Orderly and Regular Migration (GCM). But given the multiple differences between the principles we have outlined above and the dominant mode of governance in these existing institutions, it is questionable to what extent settings like the UNFCCC would be able to address tipping risks effectively. There is also a concern that ESTPs could undermine the effectiveness and functionality of international governance processes, e.g., by raising geopolitical tensions and nationalistic tendencies or overwhelming countries' capacity to engage in global governance (Laybourne et al., 2023).

Nevertheless, existing institutions are the most likely initial venues for ESTP governance, and offer possibilities for multi-scale governance, e.g., addressing Arctic tipping processes across the UNFCCC, CBD, IMO, Arctic Council, the Council of Nordic Ministers, and national governments. While their effectiveness in addressing tipping risks might be limited, and major questions exist regarding the management of institutional interactions, they offer - to some extent - legitimate, accountable, and participatory settings for decision making.

Some regional institutions match the geographic extent of specific tipping elements and could assume corresponding governance responsibilities at this scale. For example, the Arctic Council, including the Arctic Monitoring and Assessment Program (AMAP), is technically well-positioned to assess and consolidate knowledge on tipping elements in the Arctic region, including the Greenland Ice Sheet and permafrost thaw, as long as data is already available and open access. On the other hand, tipping points would affect Arctic states to varying degrees and in economically and militarily significant ways, activating national security interests that may work against the consensus-based and non-security issue orientation of the Council. Furthermore, issues of higher security or economic relevance have been among the more challenging areas for circumpolar cooperation, even on the level of data sharing (for example, oil and gas assessments). Similarly, the Amazon Cooperation Treaty Organisation (ACTO) could become a key actor for addressing the risks of Amazon dieback. While frequently criticised for its seeming inability to implement lasting changes or new policy directions, the ACTO is a favoured political vehicle for the Amazon states and constitutes an important network of actors that mediate between global and regional policies (de Oliveira Paes, 2022).

In both cases, the status and mandate of these institutions would have to be transformed to turn platforms for primarily lowest-common denominator, consensus-based, best-practice style political coordination into governance bodies with regulatory powers and corresponding resources. It is unclear whether there is political will for such an expansion and corresponding need to expand capacities and resources. However, the possibility of regionally significant tipping point governance being tackled primarily at a global, rather than regional level, may enhance willingness to strengthen governance in bodies scaled to potential tipping points, despite countervailing national interests and a lack of full state-level consensus.

Security institutions such as NATO will also need to take account of tipping point concerns and impacts.

Importantly, for various other tipping elements, governance institutions and capacity at the scale of tipping elements is missing or weak. For example, corresponding governance bodies consisting of geographically affected countries are needed to manage the boreal forest biome, the tropical coral reefs, or major ocean currents. For example, a forum to address adaptation and loss and damage related to the dieback of warm water coral reefs through mutual learning and coordination would provide a helpful platform for several affected countries who do not necessarily share a border. Relevant countries should consider whether new initiatives at this scale are needed to address the specific governance challenges related to tipping processes. In all cases, there will be questions of inclusion (who is at the table) and justice, e.g., with a view to the cascading potential of tipping elements. Stakeholders might want to have a voice not based on the geographic scope of the tipping element in question (e.g., the Greenland Ice Sheet), but based on the possibility of being impacted by its global (e.g., sea-level rise) or cascading effects (e.g., Amazon Rainforest dieback).

Other regional bodies, like the EU, ASEAN, or the African Union, have a less direct geographical correspondence with specific tipping elements, but could assume important roles nevertheless regarding tipping elements that affect some of their member states, or regarding the causal contributions of their members to the increase of tipping risks.

Indeed, in addition to governance bodies or treaties that operate at the scale of the tipping element, there might be others that focus on the drivers of different tipping processes. As discussed in the previous section, global and regional arenas to reduce emissions of short-lived climate pollutants - methane, black carbon, and hydrofluorocarbons - are also important (IPCC, 2023). These include a diverse range of transnational initiatives and institutions, and international treaties, such as the Climate and Clean Air Coalition, the Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone, the Montreal Protocol on Substances that Deplete the Ozone Layer, and the Global Methane Pledge (Yamineva et al., 2023).

National and sub-national governments (cities and municipalities) play central roles in global climate change and environmental governance (Betsill and Bulkeley, 2021), especially regarding mitigation action. Through their regulations, policies, resource allocation and other measures, they drive energy transitions and other decarbonization processes, they make industrial policies (Hochstetler, 2020; Meckling, 2021), and regulate land use and natural resource extraction (e.g., forestry and logging), they conduct adaptation planning and provide support for local action. This importance of governmental actors for climate action will be mirrored in the governance of Earth system tipping processes.

Not only governments and their international initiatives are actors in global environmental governance. As is increasingly recognized formally in international agreements like the Paris Agreement and associated decisions, non-state actors play important and diverse roles in the global response to climate change and other issues (Bulkeley et al., 2012; Hale, 2016). These roles include implementation actions, knowledge generation, and holding governments accountable. Non-state actors include those in the private sector (Folke et al., 2019), including the financial industry (Galaz et al., 2018), and civil society, who will face new opportunities and challenges in the context of ESTP governance. Who will provide much-needed expertise and knowledge to governments? How can emerging scientific insights about tipping points be used to communicate about climate change and mobilise publics? Which investment and business strategies contribute to tipping-point risks and which investments, business operations, and supply chains are at risk from tipping-point impacts?

7. Conclusion

Non-linear whole-system reorganisations at large scale remain a blind spot in global environmental governance and policy (Pereira and Viola, 2018). Much needed scholarly debates about the political, economic, cultural, and ethical implications of and potential responses to Earth system tipping points are still in their infancy and key questions remain unaddressed.

New inter- and transdisciplinary research programs in the social sciences, humanities, and natural sciences are needed to develop a body of knowledge that can support future governance efforts to address the risks and impacts of tipping processes in the Earth system with action-oriented and context-specific insights. Exploring four clusters of topics - principles and logics, goals and tasks, scales and diversity, actors, and institutions - we have begun to delineate the possible contours of such a future research program in Earth system governance, and identified key questions that could motivate this work.

Among the principles for governing Earth system tipping points, anticipatory governance, intertemporal decision making, and systemic risk governance stand out because they differ markedly from the dominant patterns of global environmental governance today and present significant practical challenges. Moving towards an Earth system governance paradigm that provides effective tools for understanding and governing from within complex-adaptive systems will likely require more than expanding the agendas of or adjusting existing institutions. The needed ontological shifts, governance innovations, and changes in the international order are unlikely to happen swiftly or easily.

The distinction of different phases of tipping point governance, especially between prevention efforts pre-tipping and impact governance post-tipping, will be an important structural feature of both research and governance, like the existing distinction between climate change mitigation on one side and adaptation and loss and damage on the other. However, it will remain difficult to assess which of the three phases a tipping process is in at any given point in time. Developing and continuously updating this kind of knowledge –understanding the state of distinct tipping elements – is in itself a task of and precondition of effective governance. Knowledge-co-production between science and policy will play an important role in this context.

In the pre-tipping phase, there is a strong relationship between tipping-point prevention and climate mitigation, but the story is more complicated than it might seem at first glance. Similarly, existing frameworks for adaptation, disaster preparedness or migration are relevant for impact governance related to ESTPs, but effective governance will require significant adjustments to these existing institutions to account for the specific characteristics of tipping processes. More generally, the question of what and how to govern 'after the tipping point' has so far received almost no attention in the scholarship, opening a large and important knowledge gap while evidence is growing that one or two ESTPs might have been crossed already.

We argue that a diverse set of actors across multiple governance scales will need to be involved in ESTP governance, and that many existing institutions at the global and regional scale should adopt governance responsibilities related to relevant tipping points. However, there are significant doubts regarding the effectiveness of existing institutions when addressing complex Earth system change within the dominant paradigm and with the common toolset of global environmental governance. At the same time, significant gaps exist in the given landscape of governance, especially at the scale of specific tipping elements, such as the warm water corals or major ocean currents.

Finally, we highlight the diversity of tipping processes, which has important implications for governance. Rather than treating all Earth system tipping elements as a single problem with a one-size fits all institutional approach, tipping-point specific strategies might be needed to ensure effective decision making. For each tipping element, this could entail a multi-scale prevention strategy spanning global GHG mitigation and carbon removal and regional efforts to address secondary drivers such as deforestation or pollution. Different groups or constellations of actors would likely be involved in governance efforts related to different ESTPs, depending at least to some extent on the geographical scope of a tipping element and the impacts of the corresponding tipping process.

All these topics need to be unpacked, and at the same time our discussion has not yet touched upon several other, equally important research topics. These include the politics of tipping-point governance, e.g., the political dynamics that emerge following a more complete understanding of the geographical and temporal patterns of tipping point risks and distributional consequences of tipping processes. There is a large set of questions regarding the cognitive, emotional, psychological, and behavioural responses by publics, decision-makers, or specific communities to tipping-point knowledge (e.g., Bellamy, 2023; van Beek et al., 2022; Formanski et al., 2022), including fatalism or urgency, and how these in turn shape public and political responses. , There are also important linkages to an emerging research field on positive social tipping points that could help accelerate responses to climate change (Lenton et al., 2022; Otto et al., 2020; Tàbara et al., 2018). Major knowledge gaps remain regarding the potential for non-linear change in technology, economy, and society, including which social systems might have tipping potential, and which agents might be able to create the necessary enabling conditions in specific contexts.

Finally, the research agenda on governance to address ESTPs will necessarily form part of a larger research program and paradigm shift towards Earth system governance, which raises important questions about its relationship to other concepts like planetary boundaries (Rockström et al., 2009) and governance proposals like planetary commons (Rockström et al., 2014). Given the conceptual overlap between these concepts, e.g., planetary boundaries offering guardrails to prevent tipping points, and some tipping elements being considered global commons, future scholarship needs to address questions about

BOX 4
Key research questions regarding governance actors and institutions

(1) Given current decision-making logics and governance paradigms, to what extent are existing governance institutions capable of addressing ESTPs?
(2) What are suitable governance institutions to address ESTPs, and to what extent are new institutions needed?
(3) How can a voice be ensured for the most vulnerable or marginalised actors in governance addressing ESTPs?
(4) What is the role of non-state actors in this domain, including civil society and industry?
(5) Who should finance governance efforts related to Earth system tipping points?

priorities, synergies, and competition between multiple, emerging governance proposals.

The nature of ESTPs as anticipated, future events and the absence of existing governance institutions that specifically address tipping risks today place some important constraints on the kind of research that can be conducted within the broad agenda we outline. Empirical work will initially have to focus on the treatment of tipping processes in science-policy interactions, tipping point discourses, narratives and frames in media, policy making and politics, communication related to tipping points and its effects on various audiences (e.g., public understanding of science, emotions behaviours, risk perceptions and assessments). At the same time, theoretical and conceptual work is needed to advance understanding regarding the principles, actor interests, policies, and institutional design issues related to tipping point governance.

In conclusion, addressing the governance of Earth system tipping points is not merely an academic exercise but a critical endeavour for ensuring the resilience and sustainability of our planet, demanding urgent and comprehensive research that can inform future global environmental governance.

CRediT authorship contribution statement

Manjana Milkoreit: Writing – review & editing, Writing – original draft, Visualization, Funding acquisition, Conceptualization. **Emily Boyd:** Writing – review & editing. **Sara M. Constantino:** Writing – review & editing. **Vera Helene Hausner:** Writing – review & editing. **Dag O. Hessen:** Writing – review & editing. **Andreas Kääb:** Writing – review & editing. **Duncan McLaren:** Writing – review & editing. **Christina Nadeau:** Writing – review & editing, Visualization. **Karen O'Brien:** Writing – review & editing. **Frans-Jan Parmentier:** Writing – review & editing. **Ronny Rotbarth:** Writing – review & editing. **Rolf Rødven:** Writing – review & editing. **Désirée Treichler:** Writing – review & editing. **Elana Wilson-Rowe:** Writing – review & editing. **Yulia Yamineva:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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Appendix A. Supplementary data

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