Biological Conservation 313 (2026) 111622

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon

Perspective

Gaps in tipping points research across freshwater, marine, and terrestrial ecosystems

Meagan Harper[a,b,*], Charlotte Carrier-Belleau[c], Trina Rytwinski[a,b], Brian Helmuth[d,e], Irena F. Creed[f], John P. Smol[g], Joseph R. Bennett[a,b,h], Dalal E.L. Hanna[a,b], Leonardo A. Saravia[i], Juan Rocha[j,k], Aubrey Foulk[d], Sam Dupont[l,m], Courtney Robichaud[a], Ana Hernández Martínez de la Riva[a], Angeli Sahdra[n], Steven J. Cooke[a,b,h]

[a] Department of Biology, Carleton University, 1125 Colonel By Drive, Ottawa, ON K1S 5B6, Canada
[b] Canadian Centre for Evidence-Informed Conservation, Carleton University, 1125 Colonel By Drive, Ottawa, ON K1S 5B6, Canada
[c] Department of Biology, Université Laval, 1045, av. de la Médecine, Québec, G1V 0A6, Canada
[d] Coastal Sustainability Institute and Department of Marine and Environmental Sciences, Northeastern University Marine Science Center, 430 Nahant Road, Nahant, MA 01908, USA
[e] School of Public Policy and Urban Affairs, Northeastern University, Boston, MA, 02115, USA
[f] Department of Physical and Environmental Sciences, University of Toronto, Toronto, ON M1C 1A4, Canada
[g] Paleoecological Environmental Assessment and Research Lab, Department of Biology, Queen's University, Kingston, ON K7L 3N6, Canada
[h] Institute for Environmental and Interdisciplinary Science, Carleton University, 1125 Colonel By Drive, Ottawa, ON K1S 5B6, Canada
[i] Centro Austral de Investigaciones Científicas (CADIC-CONICET), Bernardo Houssay 200, 9410, Ushuaia, Argentina
[j] Beijer Institute of Ecological Economics, The Royal Swedish Academy of Sciences, Stockholm, Sweden
[k] Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden
[l] Department of Biological and Environmental Sciences, University of Gothenburg, 566 Kristineberg, 45178 Fiskebäckskil, Sweden
[m] IAEA Marine Environment Laboratories, Radioecology Laboratory, 4 Quai Antoine 1er, 98000, Monaco
[n] Department of Biology, University of Ottawa, 30 Marie-Curie, Ottawa, ON, K1N 6N5, Canada

ARTICLE INFO

Keywords:
Horizon scan
Regime shift
Resilience
Environmental management
Policy
Knowledge gaps

ABSTRACT

The concept of tipping points is increasingly being addressed in both fundamental and applied environmental contexts, and is particularly salient in the context of anthropogenic threats, including climate change. Most research on tipping points has been conducted through the lens of a single realm (i.e., freshwater, marine, or terrestrial). Yet, there is both the need and opportunity to learn and share across ecosystems, and to engage in coordinated and comparative research. We aimed to identify priority questions that are germane to freshwater, marine and terrestrial realms, and that, if answered, would improve our ability to understand what tipping points are, why they occur, where they occur, and what to do about them. To help enable such efforts, we assembled a team with diverse expertise to identify key research questions, supplemented by an outreach call distributed via various electronic outlets (e.g., email, websites, social media). The responses were then thematized, evaluated, aggregated or disaggregated, and prioritized. Through workshops, and using a modified Delphi approach, we developed a final list of 18 priority research questions. Key themes that emerged included questions of societal relevance (i.e., why questions), drivers, ecological processes, and sensitivity (i.e., what questions), scale and connectivity (i.e., where questions), and tools, techniques, and resources for implementation (i.e., how questions). These questions frame a research agenda intended to help guide future fundamental and applied research related to tipping points in freshwater, marine, and terrestrial ecosystems.

1. Introduction

The concept of tipping points, adapted by systems ecology from dynamical systems theory, refers to the critical threshold at which a small change in external conditions can trigger a sudden shift in a system to an alternative stable state, driven by nonlinear feedbacks and often

---

[*] Corresponding author at: Department of Biology, Carleton University, 1125 Colonel By Drive, Ottawa, ON K1S 5B6, Canada.
E-mail address: meaganharper@cmail.carleton.ca (M. Harper).

https://doi.org/10.1016/j.biocon.2025.111622
Received 12 July 2025; Received in revised form 4 November 2025; Accepted 9 November 2025

difficult to reverse (Scheffer et al., 2001; Milkoreit et al., 2018). In keeping with recent reviews of tipping points in ecological systems, we consider tipping points as points or zones of rapid change in a nonlinear relationship between ecosystem condition and driver intensity (potentially influenced by positive feedback mechanisms) that lead to different states, which could be irreversible (Carrier-Belleau et al., 2022; Milkoreit et al., 2018; Selkoe et al., 2015). Ecological and environmental transitions that are observed with human-induced tipping points are often detrimental to ecosystem function, structure, and the services that ecosystems provide (Mooney et al., 2009). Ecological tipping points can occur as a result of natural phenomena (e.g., geophysical disasters; Lenton, 2013) but, given the manifold human impacts (Vitousek et al., 1997) causing persistent and emerging drivers of ecosystem change (e.g., Reid et al., 2019; Tilman et al., 2017), there is growing awareness of the potential for ecological tipping points at scales ranging from a single waterbody or patch of land to the planet (Lenton and Williams, 2013). In general, there is strong interest among environmental regulators and ecosystem stewards to identify what leads to tipping points and to know when a tipping point is likely to be exceeded such that ecosystems can be managed to avoid them (Foley et al., 2015; Kelly et al., 2014; Selkoe et al., 2015). Moreover, there is interest in knowing the types of interventions needed to reverse tipping points (if possible), once they have occurred (Foley et al., 2015).

Supported by theoretical, empirical, and modeling work, a substantial body of research on tipping points and regime shifts has been undertaken in laboratory conditions (e.g., Dai et al., 2012), mesocosms (e.g., Zhu and Zhang, 2020), and in the field (e.g., Haberstroh et al., 2022). Further, several syntheses on the topic have been conducted, bringing together relevant evidence to understand general spatial and temporal patterns in tipping points (e.g., Hernández Martínez de la Riva et al., 2023; Litzow and Hunsicker, 2016; Reynolds and Aldridge, 2021). However, not unlike other topics in ecology and environmental science, much of the research (and thinking) has been siloed by realm (i.e., freshwater, marine, or terrestrial). Most empirical papers focus on a single ecological realm and rely little on research from others. Similarly, most syntheses also tend to focus on a single realm (e.g., freshwater systems (Carrier-Belleau et al., 2022); marine systems (Monaco and Helmuth, 2011); and terrestrial systems (Brook et al., 2013; Nobre and Borma, 2009)). This narrower focus can provide important insight into the unique attributes of tipping points in different systems. However, it leads to a less holistic understanding of tipping points than would be otherwise possible and can result in research duplication. Synergies among research findings and potential management solutions may be missed.

Tipping points are a multi-faceted social-ecological problem and taking a system-based approach may provide important insights into how tipping points work and how to manage them (Harper et al., 2024). Thinking and planning across systems can have the added benefit of more efficient management actions (Adams et al., 2014; Tulloch et al., 2021). For example, when comparisons of ecological concepts are made across marine and terrestrial systems, apparent differences frequently disappear (Webb, 2012). Similar to advances that may be yielded from comparisons between geographic regions, such as lessons learned in Arctic and Antarctic environments (e.g., Bennett et al., 2015), we submit that there are opportunities for learning and sharing across realms to better understand tipping points as a general phenomenon and to identify coordinated strategies to avoid them (Dudney and Suding, 2020; Moore, 2018). There are also opportunities to adopt research methods that are similar across realms to enable more direct comparative work.

To date there have been no attempts to generate a research agenda specific to tipping points in ecological systems (but see Dobner and Finkeldey (2022) for an example related to natural resources and political systems). Even less work has been done to consider tipping points at a cross-system level. To that end, we present a multi-realm horizon scan focused on generating a research agenda for tipping points. Horizon scans serve to generate research agendas that can catalyze effort by the research community (ideally with new funding support), leading to a novel and cohesive understanding (Dietz et al., 2021; Sutherland et al., 2011; Sutherland and Woodroof, 2009). In this horizon scan, we aimed to identify priority questions that are germane to all ecosystems and that, if answered, would improve our ability to understand what tipping points are, why they occur, where they occur, and what to do about them. Our goal was to identify priority questions in tipping points research that need to be answered across, and within freshwater, marine and terrestrial realms to support improved policy and management of these complex ecological events. Although questions may need to be refined for study within different ecosystems (and some answers may not be immediately generalizable across realms) we use this perspective to identify consistent research gaps and generate a research agenda to guide future fundamental and applied research related to tipping points across ecosystems.

2. Methods

To obtain questions and thematize responses, we invited a multinational, interdisciplinary team of experts with experience in tipping points research across freshwater, marine and terrestrial systems, as well as social-ecological systems, conservation, and environmental management. Working group members were selected based on their expertise related to these topics, their disciplinary experience, and career stages. We aimed to balance representation of different latitudes and ecosystems. Members have experience working in ecosystems from the arctic to the tropics and a wide variety of ecosystems (e.g., terrestrial and tropical forests, boreal and temperate lakes and rivers, coastal and open marine systems). Working group members also had expertise in a wide variety of research areas, from landscape ecology, to hydrology, and environmental policy, among others. The group of thirteen experts were from four Canadian institutions (Carleton University, Queen's University, Université Laval, and University of Toronto), three Swedish institutions (Royal Swedish Academy of Sciences, Stockholm University, and University of Gothenburg), one American institution (Northeastern University), and one Argentinian institution (Centro Austral de Investigaciones Científicas). Three early-career researchers from Carleton University and University of Ottawa also took part in the two-day online workshop (Nov–Dec 2022). Our methods are consistent with other horizon scans in conservation and ecology, including those conducted following best practices recommended by Sutherland et al. (2011).

Prior to the workshop, members were asked to provide questions on tipping points knowledge gaps that they felt needed to be addressed. Additional questions were requested through an online callout to the wider research community, with the aim of supplementing the question list. Requests for questions were distributed to other experts (both academic and government experts), via targeted emails, as well as through organizational websites (e.g., the Collaboration for Environmental Evidence), and social media (e.g., Twitter) in November 2022. A non-probabilistic snowball or chain referral approach to sampling was used and no limit on outreach was applied. Therefore, quantifying the full extent of the reach of the callout is not possible (i.e., it is not known what number of individuals or nations received the request but did not participate). See Appendix A for additional details on the supplementary call-for-questions.

An initial list of 85 questions (Appendix B) consisting of questions from working group members and the wider community was reviewed by MH and SJC to remove unclear questions or those that were not applicable. The submissions were edited for clarity and split to isolate individual questions if multiple questions were included in a single submission. Selected questions were those that were broad enough to allow for the development of further, more specific questions, but narrow enough to be reasonably answerable within a research project. A total of 17 questions were considered overly specific (i.e., taxonomic or geographic in nature) or too broad (i.e., are habitats at risk of disappearing) and were removed from further consideration. An additional 22 questions were combined into 8 when multiple submissions asked the same or similar questions.

A resulting list of 54 questions was considered during the workshop. Using a modified Delphi approach, this list was evaluated by all members during the first day of the workshop to further group, split and remove questions, re-word questions for clarity, and assess the likelihood of the question leading to the advancement of fundamental or applied research on tipping points. All working group members had an opportunity to advocate for questions removed from previous iterations of the list, or to advocate for the addition of new questions. The final list of 18 questions was created through an iterative process and edited by all authors, and these were then sorted into four themes developed by a subset of the members (due to unanticipated changes to participant availability) on the second day of the workshop. All authors reviewed and approved the assignment of questions to themes and the order of themes.

We framed the 18 priority questions under four general research themes: 1) Societal relevance; 2) Drivers, ecological processes, and sensitivity; 3) Scale and connectivity; and 4) Tools, techniques, and resources for implementation. These themes represent the why, what, where, and how of fundamental and applied research on tipping points. The questions within each theme are presented in no particular order, as priorities are necessarily dependent on the context, ecological realm, geographical region, and socio-economic and political realities on the ground. Themes do not have the same number of questions; however, this does not imply weight or preference for specific themes.

3. Research themes and questions

3.1. Societal relevance (Why?)

Tipping points have garnered much attention given that they are key concepts to help understand the impacts on ecosystem services that directly or indirectly affect humans. These impacts span food and water security, economies and livelihoods, and culture and leisure, among others (Nuttall, 2012). There is interest in ensuring that regulatory and management actions (see Kelly et al., 2014) can be applied in a meaningful way to identify thresholds and attempt to prevent the crossing of tipping points or to reverse systems that have tipped over. Here, we focus on questions that explore why tipping points matter to society and why their effective regulation or management is essential to minimize societal impacts (Table 1).

In what ways can crossing ecological tipping points affect human well-being and socio-economic systems? There are numerous well-documented examples of tipping points in ecosystems, resulting in significant negative consequences for humanity (Table 1). For example, the collapse of Canada's Newfoundland cod fishery in the early 1990s had profound effects, displacing around 35,000 fishers and fish-plant workers, reducing annual revenue from cod landings by over $200 million, and triggering widespread economic and social consequences in the region (Biggs et al., 2009; Finlayson and McCay, 1998). However, large-scale environmental changes projected for the coming decades could lead to abrupt shifts in ecosystem conditions and services, and the consequences are currently unknown (Flores et al., 2024). For example, substantial portions of the Amazon rainforest are predicted to face mass mortality events due to climate change and land-use disturbances (Cano et al., 2022; Parry et al., 2022). Such events could cause irreversible biodiversity loss along with severe socio-economic and cultural repercussions (Bromham et al., 2022; Cámara-Leret et al., 2019; Science Panel for the Amazon, 2021). The Amazon, home to over 40 million people, including 2.2 million Indigenous individuals, would see its Indigenous peoples and local communities disproportionately affected (Science Panel for the Amazon, 2021). Forest loss threatens their livelihoods, cultural practices, and knowledge systems, yet the full extent of these impacts remains uncertain (Bromham et al., 2022; Cámara-Leret et al., 2019).

Table 1
Specific context and examples for the questions in the theme *Societal relevance (Why?)*

Societal relevance (Why?)	
In what ways can crossing ecological tipping points affect human well-being and socio-economic systems?	Future ecological and global tipping points may potentially lead to new, less hospitable climate states, widespread deforestation and sea level rise (Lenton, 2020). Already, tipping points have led to collapses of pasture lands (e.g., Tibetan Plateau; Li et al., 2021) and fisheries (e.g., Baltic cod; Möllmann et al., 2021) and the livelihoods they support.
What changes in management systems are required to incorporate tipping points thinking effectively?	Many management decision frameworks are reactive, rather than proactive, and are not supportive of rapid decision making (Foley et al., 2015). Whether these current systems can support avoidance and management of tipping points or whether new systems should be implemented has yet to be determined.
How do the concepts of reversibility or irreversibility of tipping point shifts affect societal decision-making and priorities?	In many systems, reversibility (i.e., the ability to maintain and restore the functional performance of a system; Verbruggen, 2013) after a tipping point is uncertain. Irreversibility may result after any tipping point, and understanding the relative likelihood of reversibility may influence future societal decisions, such as adaptation or avoidance (i.e., responding to coastal flooding; van Ginkel et al. (2020)).
In what ways do tipping points influence the perception and tolerance of risk in ecosystem management?	The consequences of tipping points can be potentially catastrophic, and managers and policy makers are often faced with value-laden decisions and trade-offs (Wong, 2021). Improved understanding of tipping points may lead to better management but has the potential to increase risk taking under some conditions (Diekert et al., 2022).

What changes in management systems are required to incorporate tipping points thinking effectively? Tipping points are ubiquitous across a wide range of ecosystems, making their management a crucial focus at the science-policy interface in addressing challenges affecting ecosystem services such as climate change, fishery collapses, vegetation shifts, and invasive species (Carpenter and Brock, 2006; Lenton et al., 2008). However, managers and policy-makers must navigate political, economic, and budgetary constraints, often making difficult decisions to maximize overall benefits. There is an urgent need to systematically and effectively integrate tipping point management into socio-economic and ecological systems to ensure sustainable outcomes (Table 1).

How do the concepts of reversibility or irreversibility of tipping point shifts affect societal decision-making and priorities? Managers often alter ecosystem properties to prevent catastrophic shifts, often without knowing whether these shifts are reversible or irreversible (Hughes et al., 2013). Understanding the degree to which ecosystem changes can be reversed after crossing tipping points (Table 1), along with the level and cost of interventions required, is essential for effective decision-making. This knowledge helps frame discussions on the relative importance, costs, and complexities of predicting and preventing tipping events versus managing systems after they have tipped. Processes to integrate the concepts of reversibility and irreversibility, and the uncertainty surrounding whether reversibility is possible, into ecosystem tipping point management is urgently needed to enhance resilience and ensure sustainable outcomes.

In what ways do tipping points influence the perception and tolerance of risk in ecosystem management? Managers and stakeholders must consistently navigate risk when managing complex ecosystems, leading to the development of various risk assessment frameworks and concepts, such as planetary boundaries (Rockström et al., 2009), to define safe thresholds for anthropogenic drivers. These efforts aim to prevent long-term damage to planetary systems and the societies that rely on them. However, limited attention has been given to how the occurrence of tipping points influences our capacity to assess and tolerate risk in ecosystem management (Table 1), despite their potential to cause abrupt and irreversible changes.

Table 2
Specific context and examples for the questions in the theme *Drivers, ecological processes, and sensitivity (What?)*

Drivers, ecological processes and sensitivity (What?)	
How can we best identify the key drivers of tipping points and develop a mechanistic understanding of their underlying processes?	Although many drivers may lead to tipping points, it remains unclear if there are individual drivers that are the key impacts leading to changes. Multiple sources of information at different scales, and multiple viewpoints may lend clues, but effectively integrating these sources into a mechanistic understanding, in many cases, remains elusive (but see Männer et al., 2022).
At which levels of biological organization can early warning indicators of tipping points be most effectively detected, and what biological responses/indicators provide the earliest signals of their approach?	Drivers differentially impact the involved mechanisms and pathways of action in biological components (Galic et al., 2018). We often collect data at the individual or community level, but tend to manage higher levels of biological organization (Forbes et al., 2017). We thus need to identify at which levels of biological organization it is more likely for us to avoid the over or underestimation of the occurrence of tipping points.
How can we address the combined effects of multiple drivers on tipping points?	Combined effects of multiple drivers add additional complexity to tipping points research. Exploring the links between responses and along environmental gradients, and utilizing techniques novel to tipping points research (e.g., Ban et al., 2022), could further our understanding and identify levers for management (Carrier-Belleau et al., 2022).
What is the role of biodiversity and community structure/function in avoiding tipping points?	Biodiversity and redundancy in community functions can lead to more stable systems with less risk of collapse (e.g., the portfolio concept; Schindler et al., 2015). Mass extinctions (an extreme type of ecological tipping point) have been preceded by loss of key ecosystem components (Dick, 2021), indicating that bolstering biodiversity, community function/structure, and resiliency (Hirota et al., 2011) may be important in avoiding tipping points.
What is the modulating role of evolution for tipping points?	Evolution and associated processes have the potential to influence how species and ecosystems experience tipping points by altering the probability of tipping points being reached, delaying or leading to earlier tipping points, and could influence recovery post-tipping (Dakos et al., 2019). Laboratory tests of cyanobacteria have shown that adaptation can alter the predicted outcomes of systems experiencing tipping points (Faassen et al., 2015), indicating that improved understanding of evolution's role in systems approaching tipping points is warranted.

3.2. *Drivers, ecological processes, and sensitivity (What?)*

Social-ecological systems and tipping points are complex (see Table 2) and are influenced by various and potentially interacting drivers and processes (Moore, 2018). Moreover, the relative sensitivity of a given ecosystem to a specific driver may differ from others, or vary over time, based on inherent ecological and evolutionary processes (Dakos et al., 2019).

How can we best identify the key drivers of tipping points and develop a mechanistic understanding of their underlying processes? Biological systems are exposed to a multifaceted suite of threats, encompassing both global stressors and local pressures, each shaping habitats and ecosystems differently through distinct biological and ecological pathways. However, identifying the key drivers and underlying mechanisms that lead to tipping points in specific systems remains a major challenge, limiting the development of effective mitigation strategies and informed policy decisions. While early-warning signals and statistical approaches have been employed to detect tipping points, we still lack a comprehensive mechanistic understanding—spanning physiological, individual, and ecological processes—of why, when, and how these tipping points occur (Stelzer et al., 2021). Developing a mechanistic understanding of how drivers affect organisms, populations, and ecosystems is repeatedly emphasized as crucial for advancing our knowledge and enabling comparisons across multiple ecosystem components and habitats (Table 2). Such a mechanistic understanding of the processes driving tipping points can substantially enhance monitoring and management efforts, enabling early detection of critical transitions and more effective intervention at the scale of entire ecosystems (van de Pol et al., 2017; Wingfield et al., 2017).

At which levels of biological organization can early warning indicators of tipping points be most effectively detected, and what biological responses/indicators provide the earliest signals of their approach? Significant advancements in detecting tipping points have been achieved through the development of early warning indicators, such as critical slowing down. This phenomenon is characterized by increased temporal correlation and variance, which together act as signals of reduced resilience to perturbation (Dakos et al., 2012a, 2012b; Scheffer et al., 2009). These indicators have been applied to various systems, including yeast and zooplankton populations nearing extinction (Dai et al., 2012; Drake and Griffen, 2010), collapsing phytoplankton monocultures (Veraart et al., 2012), eutrophication transitions (Wang et al., 2012), trophic cascades in lakes (Carpenter et al., 2011), and soil ecosystem functioning (Muscolo et al., 2015). However, the use of these indicators varies widely across systems, scales, and levels of biological organization (Table 2). Currently, there is a lack of standardized approaches to selecting indicators, understanding biological responses, and identifying the most effective levels of biological organization for early warning signals. It also remains unclear whether generalized indicators exist across realms, ecosystems or levels of biological organization. These knowledge gaps hinder meaningful comparisons across habitats and ecosystems.

How can we address the combined effects of multiple drivers on tipping points? A recent comprehensive synthesis of 36 meta-analyses examining ecosystem responses to environmental drivers challenges the universal applicability of tipping points (Hillebrand et al., 2020). This critique highlights a key limitation: most studies focus on single drivers, despite growing evidence that interactions between multiple drivers can trigger abrupt changes (Benedetti-Cecchi et al., 2015; Dudney and Suding, 2020). These combined drivers often produce nonlinear effects and interact in complex and often unexpected ways. Experimental studies have demonstrated that tipping points may only be crossed along environmental gradients when multiple stressors are present (Carrier-Belleau et al., 2023a). Furthermore, stressor interactions have been shown to vary along environmental gradients, with tipping points potentially occurring earlier under multiple-stressor scenarios (Carrier-Belleau et al., 2023b). However, significant knowledge gaps remain regarding the role of stressor interactions in driving regime shifts and there remain differences in the amount of knowledge and data available on different drivers across systems. Integrating the concepts of multiple stressor interactions and tipping points is essential for developing a holistic understanding of ecosystem sensitivity to environmental stressors, ultimately aiding efforts to preserve ecosystem services and functions (Table 2).

What is the role of biodiversity and community structure/function in avoiding tipping points? The role of biodiversity in enhancing resilience, buffering against disturbances, and promoting stability has been widely studied across various ecosystems. Key mechanisms include functional redundancy, where certain species compensate for the loss of others, thereby maintaining crucial ecosystem functions (Loreau and de Mazancourt, 2013). Biodiverse communities are more likely to harbor species or genotypes capable of tolerating environmental stressors, providing an insurance effect against disturbances (Yachi and Loreau, 1999). Furthermore, biodiversity fosters complementary interactions among species, which reduce variability in ecosystem processes and enhance resistance to stress (Tilman et al., 2006). Despite these insights, there remains a limited integration of findings from ecosystems to identify universal versus system-specific mechanisms by which biodiversity prevents tipping points. Differences in dispersal, community turnover, and the propagation of stressors between these systems complicate direct comparisons. Exploring the mechanistic links between biodiversity, community structure, and ecosystem complexity is crucial for improving predictions of tipping point dynamics (Table 2). This understanding is particularly important in ecosystems with inherently lower biodiversity or limited functional redundancy, where the risk of tipping points may be amplified.

What is the modulating role of evolution for tipping points? Populations exposed to environmental stressors may evolve traits that enhance their tolerance to environmental changes, potentially reducing the likelihood of abrupt transitions. For instance, rapid evolution in phytoplankton populations has been shown to increase resilience to shifting temperature regimes (Collins and Bell, 2004), while evolutionary changes in phenology can buffer populations against climate variability in terrestrial habitats (Franks et al., 2007). Evolution influences ecosystem stability by altering species interactions and ecosystem processes; for example, eco-evolutionary feedbacks in aquatic systems have been found to stabilize community dynamics (Fussmann et al., 2007). Furthermore, populations on the verge of extinction may adapt quickly enough to recover, a phenomenon known as evolutionary rescue (Bell and Gonzalez, 2009; Gonzalez and Bell, 2013). Despite these benefits, evolution is not always a safeguard against tipping points. Maladaptive traits or evolutionary trade-offs can emerge, potentially increasing the risk of abrupt system changes (Lynch and Lande, 1993; Urban et al., 2014). Current models and frameworks of tipping points often exclude evolutionary processes, resulting in an incomplete understanding of system dynamics (Table 2). Crucial knowledge gaps include, for example, the variability of evolutionary rates across ecosystems, the role of evolutionary trade-offs and maladaptation in driving tipping points, the capacity of genetic and phenotypic plasticity to buffer against tipping points, the evolutionary response to novel anthropogenic stressors, and the temporal and spatial scales at which evolutionary processes interact with ecological dynamics. Incorporating evolutionary mechanisms into predictive frameworks will enable more accurate projections of ecosystem responses to environmental change and provide a holistic understanding of resilience and tipping point dynamics.

3.3. Scale and connectivity (Where?)

Ecosystems are inherently interconnected making it possible for regime shifts to cascade to adjacent ecosystems (Galaz et al., 2016; Stafford et al., 2010). In some cases, tipping points occur in discrete, almost isolated, ecosystems. In other cases, tipping points occur along more continuous or connected systems, such as watersheds or mosaics of patches on terrestrial or coastal landscapes (Helmuth et al., 2006) that interact with each other. Determining the scale at which drivers act is crucial to develop fit-for-purpose management at relevant scales (Lenton, 2013). Understanding where tipping points may be crossed, the distribution of the drivers and their impacts, and the extent to which crossing tipping points may impact adjacent systems will inform effective management strategies (Table 3).

How do spatial and temporal variations in drivers and feedbacks affect ecosystem resilience and susceptibility to tipping points? Drivers exhibit highly complex spatial and temporal regimes, influencing organisms and ecosystems in both terrestrial and aquatic environments. Spatial heterogeneity in environmental drivers can shape resilience and susceptibility to tipping points by creating localized areas of varying vulnerability. For instance, regions within an ecosystem that are less affected by stressors, known as spatial refugia, can serve as reservoirs for species or functions, thereby enhancing overall ecosystem resilience (Keppel et al., 2012). Temporal dynamics, such as seasonality, interannual variability, and long-term trends, further modulate ecosystem resilience by altering the strength and timing of feedbacks. For example, pulse disturbances (i.e., sudden, short-term stressors) can push ecosystems toward tipping points, particularly when combined with chronic stressors (Scheffer et al., 2009). Despite significant observational and experimental advances in disentangling the effects of stressor regimes on ecosystem resilience, crucial knowledge gaps remain regarding spatial and temporal variations in drivers and their influence on tipping points (Table 3). For instance, our understanding of how interactions between local (fine-scale) and regional (broad-scale) drivers affect resilience and feedbacks is limited (Dakos et al., 2019). Similarly, processes at one spatial and temporal scale interacting with processes at another scale (i.e. cross-scale interactions) remain underexplored (Peters et al., 2007). Finally, delays in ecological feedbacks, such as nutrient cycling, and their implications for tipping points are poorly quantified (Dakos et al., 2015). Incorporating spatial and temporal variability, along with diverse stressor regimes, into tipping point research will ultimately ground this area of study in natural dynamics, enhancing predictive accuracy and ecosystem management strategies.

How do teleconnections influence the onset or mediation of tipping points

Table 3

Specific context and examples for the questions in the theme *Scale and connectivity (Where?)*

Scale and connectivity (Where?)	
How do spatial and temporal variations in drivers and feedbacks affect ecosystem resilience and susceptibility to tipping points?	Interactions between large-scale processes and smaller-scale modifiers result in complex outcomes in ecological systems (Torossian et al., 2016). Appropriately matching the scales at which relevant biological impacts and drivers are measured to the scope of the research or management objective informed by subsequent analysis will be vital to assessing tipping point vulnerabilities.
How do teleconnections influence the onset or mediation of tipping points in connected ecosystems?	Tipping points in one part of the globe can have consequences in teleconnected systems (e.g., Amazon Rainforest and Tibetan Plateau; Liu et al., 2023). Cascading effects can even be present between ecological and social systems if teleconnections are present (Franzke et al., 2022). Understanding the role of connections requires further study.
How are socio-economic, socio-cultural, and ecological tipping points interconnected, and what are the implications?	Inherent nonlinearities in how changes in physical drivers impact ecosystems, and how those subsequently drive ecosystem services and socio-economic systems, mean that tipping points may not occur at the same time at these different levels (van Ginkel et al., 2020).

in connected ecosystems? Teleconnections refer to long-distance interactions between spatially distinct ecosystems or regions, often driven by climatic, hydrological, or ecological processes (Heffernan et al., 2014; Liu et al., 2023). These connections can propagate disturbances across ecosystems, amplifying stressors in one region and pushing another toward a tipping point (Table 3). For example, recent research analyzing 30 types of regime shifts spanning physical climate and ecological systems, from the collapse of the West Antarctic ice sheet to a transition from rainforest to savanna, highlighted that exceeding tipping points in one system can increase the risk of crossing them in others (Rocha et al., 2018). These links were found for 45 % of possible interactions, underscoring the interconnectedness of global tipping points (Rocha et al., 2018). For instance, the rapid melting of the Greenland ice sheet beyond a certain threshold could slow the Atlantic Meridional Overturning Circulation, which could destabilize the West African monsoon, triggering drought in Africa's Sahel region (Caesar et al., 2018). Such changes could also dry the Amazon, disrupt the East Asian monsoon, and cause heat to accumulate in the Southern Ocean, further accelerating Antarctic ice loss (Lenton et al., 2019). Addressing knowledge gaps related to how teleconnections influence tipping points is crucial. For example, our understanding of how feedback loops between connected ecosystems amplify or dampen tipping point dynamics, particularly in systems with nonlinear interactions, remains limited (Hastings et al., 2018). Furthermore, the interactions between local ecosystem dynamics and global teleconnections are poorly understood—for example, how do local thresholds aggregate to influence global system stability? Finally, research is needed to explore why some ecosystems respond to teleconnected drivers with significant delays, while others exhibit synchronous transitions (Lenton et al., 2019). Current models and frameworks in tipping point research fail to capture the spatiotemporal complexity of teleconnections. Incorporating these dynamics is crucial for making accurate predictions.

How are socio-economic, socio-cultural, and ecological tipping points interconnected, and what are the implications? Socio-economic, socio-cultural, and ecological tipping points are deeply interconnected through complex feedback mechanisms. Changes in one domain often propagate and amplify changes in others, creating cascading effects that destabilize entire systems. For example, economic activities such as deforestation degrade ecosystems, pushing them toward ecological tipping points, such as a rainforest transitioning to savanna. In turn, ecological collapse can trigger economic downturns and resource scarcity, exacerbating socio-economic instability (Folke et al., 2004). Similarly, cultural practices and values significantly influence resource use and conservation strategies; shifts in cultural attitudes toward environmental stewardship can either mitigate or accelerate ecological tipping points. Conversely, ecological crises can reshape cultural practices, such as through migration or the erosion of traditional knowledge systems (Adger et al., 2013). Despite these evident interdependencies, our understanding of the feedback loops between socio-economic, socio-cultural, and ecological tipping points remains limited (Table 3). Current models often address these domains in isolation, lacking an integrated framework to account for their interactions. Addressing these knowledge gaps is essential for developing holistic policies that prevent cascading tipping points and foster resilience across systems.

3.4. *Tools, techniques, and resources for implementation (How?)*

Implementation of tipping points thinking into management has yet to be fully realized despite an urgent need to do so (Foley et al., 2015). Several examples exist (e.g., Selkoe et al., 2015), yet there are few attempts to formally evaluate or compare different approaches for integrating tipping points concepts into management (Pace et al., 2015). Priority research questions underpin opportunities for improving implementation (Table 4), but there are additional efforts needed (e.g., resourcing, institutional changes) that are themselves non-research questions.

Table 4
Specific context and examples for the questions in the theme *Tools, techniques, and resources for implementation (How?)*

Tools, techniques, and resources for implementation (How?)	
How can tipping points research be translated into actionable decision-making tools?	Integrating tipping points knowledge in management decisions is challenging but has the potential to lead to improved outcomes (Johnson and Ray, 2021). Efforts to operationalize tipping points in climate policy and management have begun at the supranational level (Van Ginkel et al., 2018), but it remains unclear how tipping points can be integrated at other levels of management.
How and what existing and emerging tools are most effective for detecting early warning signals of tipping points?	Predicting tipping points is difficult, often requiring long-term, high frequency data and modeling. Combining existing tools and developing new ones (e.g., new biomonitoring methods; Mendoza-Penagos et al., 2021) to aid in the early detection of warning signals is necessary.
How can resource allocation strategies be prioritized to address future tipping points effectively?	A key aspect of this question will be how to balance resources between understanding the nature of tipping points and responding to them quickly enough that they can be prevented or possibly reversed. Gathering information takes time and financial resources, and it is important to account for these when weighing management options (McDonald-Madden et al., 2010).
Which ecosystem attributes influence the generalizability of tipping point outcomes across similar systems?	Although there is high variation across ecosystems in terms of biota, function and services, it may be possible to generalize some aspects of ecosystems and tipping points (e.g., loss of resilience before tipping; Dai et al., 2012). Understanding what aspects of an ecosystem can be generalized to others (e.g., Keith et al., 2022) remains uncertain in tipping points science.
What are the key uncertainties that affect tipping point detection and management?	Tipping points are heterogeneous, occur at a variety of scales and are influenced by many interacting forces. Uncertainties exist at all levels of tipping points, from likelihood to outcomes, to effective interventions. Additional complexities, such as management goals, social, economic and cultural expectations and jurisdictional concerns, may all influence our ability to identify and act on tipping points (Johnson and Ray, 2021; Rodriguez Lopez et al., 2019).
What strategies are effective for integrating diverse knowledge systems in tipping points research and management?	Tipping points research has not fully realized the potential for integrated knowledge production and use made possible by co-creation and co-production across knowledge sources and knowledge systems. Examples of successful transdisciplinary and transboundary participation exist (e.g., Rodriguez Lopez et al., 2019), but efforts to ensure successful knowledge exchange and mobilization are needed (Nguyen et al., 2017).

How can tipping points research be translated into actionable decision-making tools? Translating tipping points research into actionable decision-making tools requires identifying, quantifying, and effectively communicating ecological thresholds. This endeavor necessitates interdisciplinary training and approaches, and collaboration among scientists, policymakers, and stakeholders. Key strategies have already been explored in various habitats, including the use of early warning indicators (Dakos et al., 2012a), modeling future ecosystem responses under different management scenarios (Scheffer et al., 2009), and integrating research findings into governance frameworks like the EU Water Framework Directive or IPCC reports. However, no comprehensive framework or monitoring program currently exists to systematically incorporate tipping points into ecosystem management (Table 4). Furthermore, existing tools often fail to account for ecological surprises (e.g., shifts outside of existing expectations due to rare events; Filbee-Dexter et al., 2017) or complexities such as connectivity between ecosystems, multiple levels of biological organization, and interactions among multiple stressors.

How and what existing and emerging tools are most effective for detecting early warning signals of tipping points? The detection of early warning signals is essential for anticipating tipping points and mitigating their effects. However, there is little success in identifying generalizable early warning signals to forecast tipping points in environmental data, and theories of early warning from critical slowing down and flickering have rarely been demonstrated empirically. Current tools include statistical and data-driven tools, such as critical slowing down (Scheffer et al., 2009), variance-based methods (Dakos et al., 2012b), and spectral analysis (Boettiger and Hastings, 2012). More recent tools also include modeling and predictive tools. Such tools include Bayesian approaches (Karssenberg and Bierkens, 2012) and machine learning (Bury et al., 2021; Liu et al., 2024; O'Brien et al., 2023). Finally, technological and observational tools, such as remote sensing, environmental DNA, and automated sensors are also becoming more common in tipping-point related research (Lenton et al., 2008). The development and integration of existing and emerging tools are currently underway (Table 4), as bridging the gap between limited empirical data at the correct spatial and temporal resolution, models and effective decision-making to maintain the biodiversity, ecosystem functions, and provision of services has been identified as a priority (Carpenter et al., 2009; Gladstone-Gallagher et al., 2019; Knight et al., 2008).

How can resource allocation strategies be prioritized to address future tipping points effectively? Conservation planning has developed an array of tools, frameworks, and strategies to identify conservation priorities with the aim of allocating resources effectively. Monitoring early warning signals helps guide proactive interventions by detecting indicators of ecosystem instability (Scheffer et al., 2009). Ecosystem-based management is another approach, emphasizing holistic ecosystem management by prioritizing biodiversity hotspots or ecosystems that provide critical services, such as coastal protection or carbon sequestration (Folke et al., 2004). Using nature-based solutions, such as ecosystem protection or restoration, is yet another approach used to allocate resources to protective or restorative practices that enhance ecosystem resilience (Seddon et al., 2021). Additionally, adaptive governance and decision-making frameworks advocate for participatory governance models, integrating local knowledge and stakeholder input to increase flexibility and responsiveness in conservation efforts (Ostrom, 2009). Despite these advancements, significant challenges persist in the efficient allocation of conservation resources (Table 4). As highlighted in this paper, crucial knowledge gaps remain regarding drivers, connectivity, and the levels of biological organization that must be actively incorporated into management frameworks. To address these knowledge gaps, it is essential to modernize and adapt existing frameworks while developing new management tools. These advancements will enable the prioritization of conservation and management actions, ensuring resources are allocated as efficiently as possible to achieve the greatest ecological and societal outcomes.

Which ecosystem attributes influence the generalizability of tipping point outcomes across similar systems? Rather than attempting to identify the outcome of every possible stressor and impact—a task that is unfeasible—focusing on identifying general patterns in ecosystems, stressors, and responses that can reliably predict the occurrence of tipping points represents a more practical and impactful goal. As it remains uncertain how consistent tipping point responses are across ecosystems and realms, identifying and providing generalities could offer valuable insight to conservation scientists and managers (Côté et al., 2016). Informing managers and decision-makers about the likelihood of tipping points in their specific systems, the stressors that generate these thresholds, and whether they can be mitigated through management, could significantly enhance decision-making. Meta-analyses and systematic reviews provide promising tools to achieve this objective. Although a few studies have explored these stressor-impact relationships for specific stressors or organisms (e.g., Bednaršek et al., 2019; Fussmann et al., 2014; Mufungizi et al., 2023), the diversity of potential covariates remains vast. The effects of stressors and the occurrence of tipping points may vary widely across ecosystems, latitude, taxa, trophic groups, life-history traits, ontogenetic stages, and response metrics. This variability underscores the challenge of identifying broad generalities and highlights the need for comprehensive synthesis across drivers and ecosystems (Table 4). Achieving generalizations will require robust data banks and monitoring programs designed to ensure data quality, with standardized formats that facilitate efficient searches and the extraction of tailored data subsets for meta-analyses (Kraberg et al., 2011).

What are the key uncertainties that affect tipping point detection and management? Uncertainty is an inherent challenge in management decision-making, particularly when addressing poorly understood phenomena such as tipping points (Table 4). Understanding these uncertainties—spanning temporal and spatial components, the extent and thresholds of tipping points, and the underlying feedback mechanisms—is crucial for developing adaptive management frameworks tailored to tipping points. A more comprehensive understanding of these uncertainties can improve risk tolerance assessments and guide the establishment of precautionary buffers and management actions. This approach ensures that management targets remain within the safe operating space, reducing the likelihood of crossing ecological thresholds (Selkoe et al., 2015).

What strategies are effective for integrating diverse knowledge systems in tipping points research and management? Western science represents only one form of knowledge, highlighting the importance of including diverse knowledge sources (e.g., policymakers, practitioners) and knowledge systems (e.g., Indigenous and non-Indigenous knowledge, including traditional and local ecological knowledge) to gain a holistic understanding of ecosystem tipping points. For instance, Idrobo et al. (2024) present a community-based case study incorporating the knowledge of the Eeyou (James Bay Cree) from Eeyou Istchee (Eastern James Bay, Québec) to examine the transformation of their traditional fall goose hunting system. This transformation, driven by social and environmental changes across marine and terrestrial ecosystems, exemplifies the value of Indigenous knowledge in interpreting the multifaceted impacts of environmental change and tipping points. Such work underscores the essential role of Indigenous knowledge in providing crucial insights into the complex dynamics of social-ecological systems. Identifying innovative approaches to include diverse knowledge sources and systems where possible and available should be a priority for assessing and effectively communicating tipping points and their impacts across ecosystems (Table 4).

4. Discussion

We generated a multiple realm research agenda for ecological tipping points to improve understanding of fundamental biological processes and to inform management. By thinking across realms when prioritizing the questions in this agenda, our hope is they will stimulate opportunities to learn and share across realms. Nonetheless, the questions can be tailored by individual researchers to best meet specific research objectives related to a given realm and their relevant contexts. Engaging with relevant stakeholders and rights holders is essential for ensuring that such research is co-produced and thus has the greatest potential to be embraced by diverse actors and decision makers (Djenontin and Meadow, 2018; Norström et al., 2020).

Historically, a great deal of research focuses on either the ecological or social dimensions of systems, but for most questions related to tipping points, there would be benefits to approaching them through a more inclusive and interdisciplinary lens that integrates social and ecological considerations (Hicks et al., 2010). Furthermore, beyond the published literature there is a large body of relevant knowledge held by different individuals. For example, practitioners who work on tipping points daily will have lived experiences that are informative for understanding how, in practice, tipping points function. Similarly, Indigenous knowledge holders have valuable knowledge that should be bridged with Western science (e.g., using two-eyed seeing frameworks; Reid et al., 2019). Given the complexity of tipping points, and the inherent value in co-developing solutions with a diversity of perspectives and lived experiences, this field can clearly benefit from the inclusion of multiple sources and systems of knowledge. Relatedly, as work to understand tipping points across realms continues, there will be an increased need for practitioners and researchers who can approach the problem from a systems perspective. Current training opportunities frequently do not provide sufficient exposure to these complex topics. Developing new training opportunities to build this expertise is needed both at the post-secondary and professional level (Cooke et al., 2021; Nguyen et al., 2012).

While we used well-established methods (e.g., those developed by Sutherland et al., 2011), we did not receive questions from all geographic regions. Our callout was distributed only in English, influencing the level of international engagement that we obtained. We also did not receive the same volume of responses across the multiple realms, as the number of contributors with terrestrial expertise was lower than expected. Nonetheless, we were able to collect over 80 questions from a relatively diverse range of geographies and contributors. We acknowledge that future efforts should attempt to engage an even broader suite of participants both in terms of geographies (especially the global south) as well as expertise (e.g., more practitioners and decision makers).

To conclude, if efforts are made to address the questions outlined here, we will be in a much stronger position to forecast, prevent, and manage tipping points and associated regime shifts in different systems and across various spatial and temporal scales. We encourage funding agencies to consider what they can do to support research on the questions outlined here. We recognize that horizon scans use our best collective perspective to inform the research agenda that is needed at a given time, and that this research agenda must be revisited in due course to evaluate progress and to integrate new perspectives. As we expand the evidence base on tipping points in diverse ecosystems and socio-economic and socio-cultural contexts from around the globe, we will be in a better position to generate evidence-informed and evidence-based approaches to managing ecosystems and human activities.

CRediT authorship contribution statement

Meagan Harper: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Charlotte Carrier-Belleau:** Writing – review & editing, Writing – original draft, Formal analysis. **Trina Rytwinski:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Brian Helmuth:** Writing – review & editing, Formal analysis. **Irena F. Creed:** Writing – review & editing, Formal analysis. **John P. Smol:** Writing – review & editing, Formal analysis. **Joseph R. Bennett:** Writing – review & editing, Formal analysis. **Dalal E.L. Hanna:** Writing – review & editing, Formal analysis. **Leonardo A. Saravia:** Writing – review & editing, Formal analysis. **Juan Rocha:** Writing – review & editing, Formal analysis. **Aubrey Foulk:** Writing – review & editing, Formal analysis. **Sam Dupont:** Writing – review & editing, Formal analysis. **Courtney Robichaud:** Writing – review & editing, Formal analysis. **Ana Hernández Martínez de la Riva:** Writing – review & editing, Formal analysis. **Angeli Sahdra:** Writing – review & editing, Formal analysis. **Steven J. Cooke:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Ethics approval

None required.

Declaration of Generative AI and AI-assisted technologies in the writing process

No generative AI or AI assisted technologies were used in the preparation of this work.

Funding

This project was supported by a financial contribution from Fisheries and Oceans Canada (grant No. 302509). Additional support was provided by Carleton University and the Natural Sciences and Engineering Research Council of Canada.

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.

Acknowledgements

This paper was inspired by the outcomes of a series of collaborative workshops held in 2022, bringing together global experts in marine, freshwater, and terrestrial tipping points, environmental stressors, and ecosystem management. The authors would like to thank the participants of the workshops for providing perspectives during the workshops that helped influence this work. We also thank the marine, freshwater and terrestrial research community for their involvement in this project. The IAEA is grateful to the Government of the Principality of Monaco for the support provided to its Marine Environment Laboratories. This is a product of the Canadian Centre for Evidence-Informed Conservation.

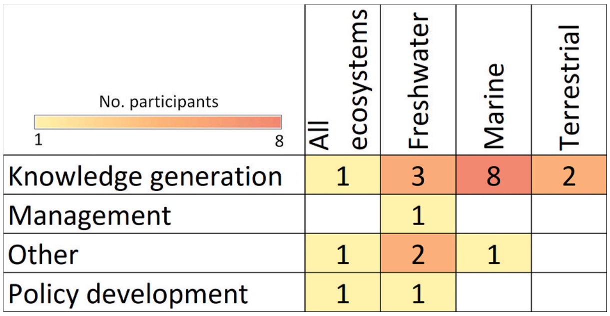
Appendix A

A short (1 month; October 31 and November 27, 2022) call-for-questions was distributed by workshop participants and authors through their professional networks (via targeted email), organizational websites (e.g., the Canadian Centre for Evidence-Informed Conservation) and social media (*X*, formerly Twitter). This call-for-questions was meant to supplement workshop participant questions and was done using a non-probabilistic ‘snowball’ or ‘chain-referral’ approach and no limit on outreach was applied. Therefore, quantifying the full extent of the callout reach was not possible (i.e., it is not known what number of individuals or nations received the request but did not participate).

Those that did respond were asked to provide questions on tipping points to help identify knowledge gaps on the topic, as well as provide information on their country of operation, primary role (i.e., knowledge generation, policy development, social engagement, management, teaching, other), and what domain they worked in most often (i.e., marine, terrestrial, freshwater, or all equally). Participants could opt out of the questionnaire at any time and were not required to provide personal information. To maximize the number of questions submitted, there was no limit to the number of questions contributed, or the number of times individuals could participate.

A.1. Questionnaire participant demographics

A total of 29 participants submitted questions through our online questionnaire or through emails. Those who provided personal information were mainly from North America (57%) and Europe (24%), with the remaining submissions from Asia-Pacific (14%) and Central and South America (5%). No questions were submitted by individuals operating in Africa. Only Canada (10 participants), USA and Australia (two participants each) were represented by more than one participant. More questions were submitted by knowledge generators (14 participants; 58%) than those working in policy development (two; 8%) or ecosystem management (one; 4%). A total of five participants (30%) self-identified as 'other' or did not provide information (Fig. A.1). Most submitted questions were from participants working in marine or freshwater environments, with fewer working in all ecosystems equally or in terrestrial systems (Fig. A.1).



	All ecosystems	Freshwater	Marine	Terrestrial
Knowledge generation	1	3	8	2
Management		1		
Other	1	2	1	
Policy development	1	1		

Fig. A.1. Number of participants whose primary roles included knowledge generation, policy development, management or other, and work in marine, freshwater, terrestrial ecosystems, or all ecosystems equally. An additional three participants did not provide personal information

Appendix B

Original questions as submitted by participants.

1. How can we avoid tipping points when there is uncertainty about their location in parameter space?
2. How generalizable are (observed) tipping points across systems and contexts?
3. How does/should the presence of tipping points alter risk tolerance in ecosystem management decisions?
4. Are the changes we observe in ecosystems tipping points?
5. What is the threshold of riparian zone alteration/degradation that may be permissible to still allow freshwater fish (e.g., salmonids) to carry out their life processes in a way that won't harm the population as a whole?
6. How can cumulative effects be considered at the catchment scale for decision making with regards to land use (forestry intensity, mining, culverts, etc.)?
7. How do different management systems (provincial, federal, indigenous) with various mandates come to a consensus regarding land use at the catchment scale?
8. How do we know if we've reached the tipping point?
9. How do we go beyond organizational silos and make data available to all parties so that effective/informed decision making can occur?
10. How can we measure cumulative effects and tipping points?
11. What are the best practices to measure cumulative effects and tipping points?
12. Are there clear methodologies for measuring cumulative effects and tipping points? Bioindicators?
13. What are bioindicators of measuring cumulative effects and tipping points?
14. How do we add the cumulative effects of climate change to the existing impacts on ecosystems?
15. How can we model or determine where the tipping point is?
16. How do we determine the tipping points for different species - then how do we add/combine them for management actions?
17. How can we derive tipping points for (or along) longitudinal systems such as rivers?
18. How do we get tipping points to assist managers?
19. Lets model populations to determine tipping points, then work our way back to achieve acceptable management outcomes?
20. How can researchers best communicate tipping points to the general public and policymakers?
21. What are the multiple pressures and underlying environmental sensitivities that together result in blooms of (a) filamentous algae and (b) phytoplankton in Atlantic, northern European rivers?
22. How can ecological responses to the multiple pressures resulting in algal blooms best be measured and converted to evidence-based environmental standards for river management?
23. Warming aquatic environments also result in lower oxygen saturation. These factors plus BOD creates lethal tipping points. Do we know enough about those interactions to take effective steps in management to prevent mass mortalities?
24. As oceans warm, species distributions trend poleward however, most marine resource management assumes geographic stasis. Can marine fisheries management develop dynamic strategies based on thermogeography rather than static geography?
25. Are all tipping points bad?
26. What are the characteristics of a bad tipping point outcome?
27. In what cases would we "prefer" the new alternative stable state as opposed to the old one?
28. How should we allocate our resources to be as efficient as possible in preventing or mitigating negative impacts of tipping points?
29. How can we address tipping points occurring in large areas?

30. It might be important to create a platform for collaboration amongst multiple countries, would agencies like the United Nations be interested in something like this?
31. How can we ensure that the knowledge that we gather about tipping points is passed over to the next generations?
32. How can we make sure that all the voices involved in tipping points events are heard?
33. Can tipping points be irreversible?
34. Would it be better to forget about that already lost ecosystem and focus on another one that hasn't reached that critical level?
35. Marine heat waves can cause spawning failure. Will this lead to the loss of populations?
36. Local populations could vanish quickly. Nearly all of the species in our study are not commercially important so most are not followed closely if at all. Populations of these species could vanish without anyone noticing. For example, if feather duster worms vanished here in central Oregon who would notice?
37. The regime shift of intertidal community in the context of climate change and human activity?
38. The changes of benthic community with offshore mariculture?
39. Are tipping points consistent enough in space and time (mid-term) to be useful in the management of natural systems?
40. How can the compounded effects of multiple biotic and abiotic drivers be taken into account to make tipping points a useful management tool?
41. How can tipping points be altered by multiple interacting stressors?
42. How can we use results generated through laboratory or *in situ* experiments to guide management actions?
43. How can a tipping point in one realm affect the reach of another tipping point in another realm?
44. What ecosystem measurements can reliably predict an imminent tipping point?
45. Can we identify which aspects of an ecosystem will make it possible to reverse a tipping point?
46. Are there indicators of a system approaching a tipping point?
47. Could tipping points in a given ecosystem trigger tipping points in other systems?
48. Are there key species in ecosystems that contribute to resilience and where their loss can trigger tipping points?
49. Do observable spatial tipping points provide reliable and usable information on temporal climate change driven tipping points?
50. What is the definition of and how to identify tipping points in a heterogeneous landscape?
51. Are peatlands/wetlands in the boreal plain at risk of disappearing in a warming climate and by what mechanism?
52. If tipping points exist in the wetland-forest mosaic of the boreal plains, what do the alternative states look like?
53. Can we use spatial analogue landscapes to define the alternative landscapes?
54. What are relevant thresholds for different marine organisms of pO2, temperature?
55. How (strategy, methodology) can we resolve the impacts of multiple environmental drivers?
56. What are the rules defining local sensitivity to local and global environmental changes?
57. What is the modulating role of evolution for tipping points in a multiple stressor world?
58. What is the best strategy to define a priority list of stressors (e.g. for management) in a given location?
59. How do you know if you are approaching a tipping point in any system? Are there any predictive factors?
60. Can empirical examples of tipping points be compiled and published as a review/summary?
61. Can compiled empirical examples of tipping points in reviews and summaries be used to set thresholds for decisions?
62. Are there any examples of habitat thresholds in freshwater? (for fish or invertebrates or others?)
63. What is the range of natural variation in ecosystem indicators?
64. What method can be standardized to identify tipping points?
65. In the absence of empirical data, what methods can be used to determine tipping points?
66. Given imperfect knowledge, how do we consistently and accurately incorporate tipping points into management of aquatic resources?
67. Without knowing how all factors may interact, what are the risks of making management decisions based on solely the elements/relationships we understand?
68. Are there simpler (less quantitative) ways of incorporating or integrating effects to support faster management decisions?
69. What are the risks of taking simpler (less quantitative) ways of incorporating or integrating effects to support faster management decisions?
70. What is the minimum information required to derive an estimate for a tipping point threshold?
71. If based on very limited sample data, how robust would the estimate be for a tipping point threshold?
72. What are the minimum factors that need to be measured (e.g., response variable, driver/gradient) to derive an estimate for a tipping point threshold?
73. Do you need to observe a system "tipping" to quantify the minimum factors to derive a threshold?
74. Can modeling be based on limited sampled data to derive an estimate for a tipping point threshold?
75. Are there some ecological interactions that are more suitable for deriving a tipping point?
76. Is it best to have scientists working to identify tipping points that they think are relevant or have management groups identify the specific stressors/drivers of interest?
77. How universal (i.e., consistent across similar ecosystems) are tipping points?
78. Buffer effect of trophic complexity in building resilience?
79. Temporal scaling of bottlenecks in complex ecological networks?
80. Probabilistic framework for early warning signals (EWS)?
81. Do tipping points really exist or are they a consequence of sensitivity analysis of rolling windows?
82. The role of teleconnections in building up resilience?
83. Given that there is often uncertainty around when a tipping point has been reached, how do we balance resources between learning (i.e., monitoring) and acting around tipping points?
84. At what point does sea ice loss (due to climate change) lead to irreparable harm to pagophilic species?
85. Many caribou herds are in decline. How low can numbers get before populations are unable to recover due to Allee effects, etc.?

Data availability

Data will be made available on request.

References

Adams, V.M., Álvarez-Romero, J.G., Carwardine, J., Cattarino, L., Hermoso, V., Kennard, M.J., Linke, S., Pressey, R.L., Stoeckl, N., 2014. Planning across freshwater and terrestrial realms: cobenefits and tradeoffs between conservation actions: cross-realm systematic planning. Conserv. Lett. 7, 425–440. https://doi.org/10.1111/conl.12080.

Adger, W.N., Barnett, J., Brown, K., Marshall, N., O'Brien, K., 2013. Cultural dimensions of climate change impacts and adaptation. Nat. Clim. Change 3, 112–117. https://doi.org/10.1038/nclimate1666.

Ban, Z., Hu, X., Li, J., 2022. Tipping points of marine phytoplankton to multiple environmental stressors. Nat. Clim. Change 12, 1045–1051. https://doi.org/10.1038/s41558-022-01489-0.

Bednaršek, N., Feely, R.A., Howes, E.L., Hunt, B.P.V., Kessouri, F., León, P., Lischka, S., Maas, A.E., McLaughlin, K., Nezlin, N.P., Sutula, M., Weisberg, S.B., 2019. Systematic review and meta-analysis toward synthesis of thresholds of ocean acidification impacts on calcifying pteropods and interactions with warming. Front. Mar. Sci. 6. https://doi.org/10.3389/fmars.2019.00227.

Bell, G., Gonzalez, A., 2009. Evolutionary rescue can prevent extinction following environmental change. Ecol. Lett. 12, 942–948. https://doi.org/10.1111/j.1461-0248.2009.01350.x.

Benedetti-Cecchi, L., Tamburello, L., Maggi, E., Bulleri, F., 2015. Experimental perturbations modify the performance of early warning indicators of regime shift. Curr. Biol. 25, 1867–1872. https://doi.org/10.1016/j.cub.2015.05.035.

Bennett, J.R., Shaw, J.D., Terauds, A., Smol, J.P., Aerts, R., Bergstrom, D.M., Blais, J.M., Cheung, W.W., Chown, S.L., Lea, M.-A., Nielsen, U.N., Pauly, D., Reimer, K.J., Riddle, M.J., Snape, I., Stark, J.S., Tulloch, V.J., Possingham, H.P., 2015. Polar lessons learned: long-term management based on shared threats in Arctic and Antarctic environments. Front. Ecol. Environ. 13, 316–324. https://doi.org/10.1890/140315.

Biggs, R., Carpenter, S.R., Brock, W.A., 2009. Turning back from the brink: detecting an impending regime shift in time to avert it. PNAS 106, 826–831. https://doi.org/10.1073/pnas.0811729106.

Boettiger, C., Hastings, A., 2012. Quantifying limits to detection of early warning for critical transitions. J. R. Soc. Interface 9, 2527–2539. https://doi.org/10.1098/rsif.2012.0125.

Bromham, L., Dinnage, R., Skirgård, H., Ritchie, A., Cardillo, M., Meakins, F., Greenhill, S., Hua, X., 2022. Global predictors of language endangerment and the future of linguistic diversity. Nat. Ecol. Evol. 6, 163–173. https://doi.org/10.1038/s41559-021-01604-y.

Brook, B.W., Ellis, E.C., Perring, M.P., Mackay, A.W., Blomqvist, L., 2013. Does the terrestrial biosphere have planetary tipping points? Trends Ecol. Evol. 28, 396–401. https://doi.org/10.1016/j.tree.2013.01.016.

Bury, T.M., Sujith, R.I., Pavithran, I., Scheffer, M., Lenton, T.M., Anand, M., Bauch, C.T., 2021. Deep learning for early warning signals of tipping points. PNAS 118, e2106140118. https://doi.org/10.1073/pnas.2106140118.

Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G., Saba, V., 2018. Observed fingerprint of a weakening Atlantic Ocean overturning circulation. Nature 556, 191–196. https://doi.org/10.1038/s41586-018-0006-5.

Cámara-Leret, R., Fortuna, M.A., Bascompte, J., 2019. Indigenous knowledge networks in the face of global change. PNAS 116, 9913–9918. https://doi.org/10.1073/pnas.1821843116.

Cano, I.M., Shevliakova, E., Malyshev, S., John, J.G., Yu, Y., Smith, B., Pacala, S.W., 2022. Abrupt loss and uncertain recovery from fires of Amazon forests under low climate mitigation scenarios. PNAS 119, e2203200119. https://doi.org/10.1073/pnas.2203200119.

Carpenter, S.R., Brock, W.A., 2006. Rising variance: a leading indicator of ecological transition. Ecol. Lett. 9, 311–318. https://doi.org/10.1111/j.1461-0248.2005.00877.x.

Carpenter, S.R., Mooney, H.A., Agard, J., Capistrano, D., DeFries, R.S., Díaz, S., Dietz, T., Duraiappah, A.K., Oteng-Yeboah, A., Pereira, H.M., Perrings, C., Reid, W.V., Sarukhan, J., Scholes, R.J., Whyte, A., 2009. Science for managing ecosystem services: beyond the millennium ecosystem assessment. PNAS 106, 1305–1312. https://doi.org/10.1073/pnas.0808772106.

Carpenter, S.R., Cole, J.J., Pace, M.L., Batt, R., Brock, W.A., Cline, T., Coloso, J., Hodgson, J.R., Kitchell, J.F., Seekell, D.A., Smith, L., Weidel, B., 2011. Early warnings of regime shifts: a whole-ecosystem experiment. Science 332, 1079–1082. https://doi.org/10.1126/science.1203672.

Carrier-Belleau, C., Pascal, L., Nozais, C., Archambault, P., 2022. Tipping points and multiple drivers in changing aquatic ecosystems: a review of experimental studies. Limnol. Oceanogr. 67, S312–S330. https://doi.org/10.1002/lno.11978.

Carrier-Belleau, C., Pascal, L., Tiegs, S.D., Nozais, C., Archambault, P., 2023a. From organismal physiology to ecological processes: effects of nutrient enrichment and salinity variation in a freshwater ecosystem. Limnol. Oceanogr. 68, S115–S130. https://doi.org/10.1002/lno.12269.

Carrier-Belleau, C., Pascal, L., Tiegs, S.D., Nozais, C., Archambault, P., 2023b. Tipping point arises earlier under a multiple-stressor scenario. Sci. Rep. 13, 16780. https://doi.org/10.1038/s41598-023-44012-x.

Collins, S., Bell, G., 2004. Phenotypic consequences of 1,000 generations of selection at elevated CO2 in a green alga. Nature 431, 566–569. https://doi.org/10.1038/nature02945.

Cooke, J., Araya, Y., Bacon, K.L., Bagniewska, J.M., Batty, L.C., Bishop, T.R., Burns, M., Charalambous, M., Daversa, D.R., Dougherty, L.R., Dyson, M., Fisher, A.M., Forman, D., Garcia, C., Harney, E., Hesselberg, T., John, E.A., Knell, R.J., Maseyk, K., Mauchline, A.L., Peacock, J., Pernetta, A.P., Pritchard, J., Sutherland, W.J., Thomas, R.L., Tigar, B., Wheeler, P., White, R.L., Worsfold, N.T., Lewis, Z., 2021. Teaching and learning in ecology: a horizon scan of emerging challenges and solutions. Oikos 130, 15–28. https://doi.org/10.1111/oik.07847.

Côté, I.M., Darling, E.S., Brown, C.J., 2016. Interactions among ecosystem stressors and their importance in conservation. Proc. R. Soc. B. 283, 20152592. https://doi.org/10.1098/rspb.2015.2592.

Dai, L., Vorselen, D., Korolev, K.S., Gore, J., 2012. Generic indicators for loss of resilience before a tipping point leading to population collapse. Science 336, 1175–1177. https://doi.org/10.1126/science.1219805.

Dakos, V., Carpenter, S.R., Brock, W.A., Ellison, A.M., Guttal, V., Ives, A.R., Kéfi, S., Livina, V., Seekell, D.A., van Nes, E.H., Scheffer, M., 2012a. Methods for detecting early warnings of critical transitions in time series illustrated using simulated ecological data. PLoS One 7, e41010. https://doi.org/10.1371/journal.pone.0041010.

Dakos, V., van Nes, E.H., D'Odorico, P., Scheffer, M., 2012b. Robustness of variance and autocorrelation as indicators of critical slowing down. Ecology 93, 264–271. https://doi.org/10.1890/11-0889.1.

Dakos, V., Carpenter, S.R., van Nes, E.H., Scheffer, M., 2015. Resilience indicators: prospects and limitations for early warnings of regime shifts. Philos. Trans. R. Soc. Lond. B 370, 20130263. https://doi.org/10.1098/rstb.2013.0263.

Dakos, V., Matthews, B., Hendry, A.P., Levine, J., Loeuille, N., Norberg, J., Nosil, P., Scheffer, M., De Meester, L., 2019. Ecosystem tipping points in an evolving world. Nat. Ecol. Evol. 3, 355–362. https://doi.org/10.1038/s41559-019-0797-2.

Dick, D., 2021. Quantifying Similarity in Paleontological Settings: Accuracy, Complexity, and Macroevolutionary Implications (Doctoral thesis). University of Toronto, Toronto.

Diekert, F., Heyen, D., Nesje, F., Shayegh, S., 2022. Early Warnings about Tipping Points Improve Management but May Encourage Risk Taking. Report for the European Research Council Project NATCOOP.

Dietz, S., Beazley, K.F., Lemieux, C.J., St. Clair, C., Coristine, L., Higgs, E., Smith, R., Pellatt, M., Beaty, C., Cheskey, E., Cooke, S.J., Crawford, L., Davis, R., Forbes, G., Gadallah, F. (ZuZu), Kendall, P., Mandrak, N., Moola, F., Parker, S., Quayle, J., Ray, J.C., Richardson, K., Smith, K., Snider, J., Smol, J.P., Sutherland, W.J., Vallillee, A., White, L., Woodley, A., 2021. Emerging issues for protected and conserved areas in Canada. FACETS 6, 1892–1921. https://doi.org/10.1139/facets-2021-0072.

Djenontin, I.N.S., Meadow, A.M., 2018. The art of co-production of knowledge in environmental sciences and management: lessons from international practice. Environ. Manag. 61, 885–903. https://doi.org/10.1007/s00267-018-1028-3.

Dobner, P., Finkeldey, J., 2022. Natural resources and the tipping points of political power—a research agenda. Sustainability 14, 14721. https://doi.org/10.3390/su142214721.

Drake, J.M., Griffen, B.D., 2010. Early warning signals of extinction in deteriorating environments. Nature 467, 456–459. https://doi.org/10.1038/nature09389.

Dudney, J., Suding, K.N., 2020. The elusive search for tipping points. Nat. Ecol. Evol. 4, 1449–1450. https://doi.org/10.1038/s41559-020-1273-8.

Faassen, E.J., Veraart, A.J., Van Nes, E.H., Dakos, V., Lürling, M., Scheffer, M., 2015. Hysteresis in an experimental phytoplankton population. Oikos 124, 1617–1623. https://doi.org/10.1111/oik.02006.

Filbee-Dexter, K., Pittman, J., Haig, H.A., Alexander, S.M., Symons, C.C., Burke, M.J., 2017. Ecological surprise: concept, synthesis, and social dimensions. Ecosphere 8, e02005. https://doi.org/10.1002/ecs2.2005.

Finlayson, A., McCay, B., 1998. Crossing the Threshold Of Ecosystem Resilience: The Commercial Extinction of Northern Cod. In: Berkes, F., Folke, C. (Eds.), Linking Social and Ecological Systems: Managing Practices and Social Mechanisms for Building Resilience. Cambridge University Press, Cambridge, UK, pp. 311–337.

Flores, B.M., Montoya, E., Sakschewski, B., Nascimento, N., Staal, A., Betts, R.A., Levis, C., Lapola, D.M., Esquível-Muelbert, A., Jakovac, C., Nobre, C.A., Oliveira, R. S., Borma, L.S., Nian, D., Boers, N., Hecht, S.B., ter Steege, H., Arieira, J., Lucas, I.L., Berenguer, E., Marengo, J.A., Gatti, L.V., Mattos, C.R.C., Hirota, M., 2024. Critical transitions in the Amazon forest system. Nature 626, 555–564. https://doi.org/10.1038/s41586-023-06970-0.

Foley, M.M., Martone, R.G., Fox, M.D., Kappel, C.V., Mease, L.A., Erickson, A.L., Halpern, B.S., Selkoe, K.A., Taylor, P., Scarborough, C., 2015. Using ecological thresholds to inform resource management: current options and future possibilities. Front. Mar. Sci. 2. https://doi.org/10.3389/fmars.2015.00095.

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., Holling, C. S., 2004. Regime shifts, resilience, and biodiversity in ecosystem management. Annu. Rev. Ecol. Evol. Syst. 35, 557–581. https://doi.org/10.1146/annurev.ecolsys.35.021103.105711.

Forbes, V.E., Salice, C.J., Birnir, B., Bruins, R.J.F., Calow, P., Ducrot, V., Galic, N., Garber, K., Harvey, B.C., Jager, H., Kanarek, A., Pastorok, R., Railsback, S.F., Rebarber, R., Thorbek, P., 2017. A framework for predicting impacts on ecosystem services from (sub)organismal responses to chemicals. Environ. Toxicol. Chem. 36, 845–859. https://doi.org/10.1002/etc.3720.

Franks, S.J., Sim, S., Weis, A.E., 2007. Rapid evolution of flowering time by an annual plant in response to a climate fluctuation. PNAS 104, 1278–1282. https://doi.org/10.1073/pnas.0608379104.

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

Fussmann, G.F., Loreau, M., Abrams, P.A., 2007. Eco-evolutionary dynamics of communities and ecosystems. Funct. Ecol. 21, 465–477. https://doi.org/10.1111/j.1365-2435.2007.01275.x.

Fussmann, K.E., Schwarzmüller, F., Brose, U., Jousset, A., Rall, B.C., 2014. Ecological stability in response to warming. Nat. Clim. Chang. 4, 206–210. https://doi.org/10.1038/nclimate2134.

Galaz, V., Österblom, H., Bodin, Ö., Crona, B., 2016. Global networks and global change-induced tipping points. Int. Environ. Agreements 16, 189–221. https://doi.org/10.1007/s10784-014-9253-6.

Galic, N., Sullivan, L.L., Grimm, V., Forbes, V.E., 2018. When things don't add up: quantifying impacts of multiple stressors from individual metabolism to ecosystem processing. Ecol. Lett. 21, 568–577. https://doi.org/10.1111/ele.12923.

van Ginkel, K.C.H., Botzen, W.J.W., Haasnoot, M., Bachner, G., Steininger, K.W., Hinkel, J., Watkiss, P., Boere, E., Jeuken, A., de Murieta, E.S., Bosello, F., 2020. Climate change induced socio-economic tipping points: review and stakeholder consultation for policy relevant research. Environ. Res. Lett. 15, 023001. https://doi.org/10.1088/1748-9326/ab6395.

Gladstone-Gallagher, R.V., Pilditch, C.A., Stephenson, F., Thrush, S.F., 2019. Linking traits across ecological scales determines functional resilience. Trends Ecol. Evol. 34, 1080–1091. https://doi.org/10.1016/j.tree.2019.07.010.

Gonzalez, A., Bell, G., 2013. Evolutionary rescue and adaptation to abrupt environmental change depends upon the history of stress. Philos. Trans. R. Soc. Lond. B 368, 20120079. https://doi.org/10.1098/rstb.2012.0079.

Haberstroh, S., Werner, C., Grün, M., Kreuzwieser, J., Seifert, T., Schindler, D., Christen, A., 2022. Central European 2018 hot drought shifts scots pine forest to its tipping point. Plant Biol. 24 (7), 1186–1197. https://doi.org/10.1111/plb.13455.

Harper, M., Rytwinski, T., Creed, I.F., Helmuth, B., Smol, J.P., Bennett, J.R., Hanna, D., Saravia, L.A., Rocha, J., Carrier-Belleau, C., Foulk, A., Martinez De La Riva, A.H., Robichaud, C., Sallan, L., Sahdra, A., Cooke, S.J., 2024. A multi-realm perspective on applying potential tipping points to environmental decision-making. Environ. Rev. 32, 131–144. https://doi.org/10.1139/er-2023-0042.

Hastings, A., Abbott, K.C., Cuddington, K., Francis, T., Gellner, G., Lai, Y.-C., Morozov, A., Petrovskii, S., Scranton, K., Zeeman, M.L., 2018. Transient phenomena in ecology. Science 361, eaat6412. https://doi.org/10.1126/science.aat6412.

Heffernan, J.B., Soranno, P.A., Angilletta Jr., M.J., Buckley, L.B., Gruner, D.S., Keitt, T. H., Kellner, J.R., Kominoski, J.S., Rocha, A.V., Xiao, J., Harms, T.K., Goring, S.J., Koenig, L.E., McDowell, W.H., Powell, H., Richardson, A.D., Stow, C.A., Vargas, R., Weathers, K.C., 2014. Macrosystems ecology: understanding ecological patterns and processes at continental scales. Front. Ecol. Environ. 12, 5–14. https://doi.org/10.1890/130017.

Helmuth, B., Broitman, B.R., Blanchette, C.A., Gilman, S., Halpin, P., Harley, C.D.G., O'Donnell, M.J., Hofmann, G.E., Menge, B., Strickland, D., 2006. Mosaic patterns of thermal stress in the rocky intertidal zone: implications for climate change. Ecol. Monogr. 76, 461–479. https://doi.org/10.1890/0012-9615(2006)076[0461:MPOTSI]2.0.CO;2.

Hernández Martínez de la Riva, A., Harper, M., Rytwinski, T., Sahdra, A., Taylor, J.J., Bard, B., Bennett, J.R., Burton, D., Creed, I.F., Haniford, L.S.E., Hanna, D.E., Harmsen, E.J., Robichaud, C.D., Smol, J.P., Thapar, M., Cooke, S.J., 2023. Tipping points in freshwater ecosystems: an evidence map. Front. Freshw. Sci. 1. https://doi.org/10.3389/ffwsc.2023.1264427.

Hicks, C.C., Fitzsimmons, C., Polunin, N.V.C., 2010. Interdisciplinarity in the environmental sciences: barriers and frontiers. Environ. Conserv. 37, 464–477. https://doi.org/10.1017/S0376892910000822.

Hillebrand, H., Donohue, I., Harpole, W.S., Hodapp, D., Kucera, M., Lewandowska, A.M., Merder, J., Montoya, J.M., Freund, J.A., 2020. Thresholds for ecological responses to global change do not emerge from empirical data. Nat. Ecol. Evol. 4, 1502–1509. https://doi.org/10.1038/s41559-020-1256-9.

Hirota, M., Holmgren, M., Van Nes, E.H., Scheffer, M., 2011. Global resilience of tropical forest and savanna to critical transitions. Science 334, 232–235. https://doi.org/10.1126/science.1210657.

Hughes, T.P., Carpenter, S., Rockström, J., Scheffer, M., Walker, B., 2013. Multiscale regime shifts and planetary boundaries. Trends Ecol. Evol. 28, 389–395. https://doi.org/10.1016/j.tree.2013.05.019.

Idrobo, C.J., Leblanc, M.-L., O'Connor, M.I., 2024. The "turning point" for the fall goose hunt in Eeyou Istchee: a social-ecological regime shift from an indigenous knowledge perspective. Hum. Ecol. 52, 617–636. https://doi.org/10.1007/s10745-024-00499-0.

Johnson, C.J., Ray, J.C., 2021. The Challenge and Opportunity of Applying Ecological Thresholds to Environmental Assessment Decision Making. In: Handbook of Cumulative Impact Assessment, pp. 140–157. https://doi.org/10.4337/9781783474028.00020.

Karssenberg, D., Bierkens, M.F.P., 2012. Early-warning signals (potentially) reduce uncertainty in forecasted timing of critical shifts. Ecosphere 3, art15. https://doi.org/10.1890/ES11-00293.1.

Keith, D.A., Ferrer-Paris, J.R., Nicholson, E., Bishop, M.J., Polidoro, B.A., Ramirez-Llodra, E., Tozer, M.G., Nel, J.L., Mac Nally, R., Gregr, E.J., Watermeyer, K.E., Essl, F., Faber-Langendoen, D., Franklin, J., Lehmann, C.E.R., Etter, A., Roux, D.J., Stark, J.S., Rowland, J.A., Brummitt, N.A., Fernandez-Arcaya, U.C., Suthers, I.M., Wiser, S.K., Donohue, I., Jackson, L.J., Pennington, R.T., Iliffe, T.M., Gerovasileiou, V., Giller, P., Robson, B.J., Pettorelli, N., Andrade, A., Lindgaard, A., Tahvanainen, T., Terauds, A., Chadwick, M.A., Murray, N.J., Moat, J., Pliscoff, P., Zager, I., Kingsford, R.T., 2022. A function-based typology for earth's ecosystems. Nature 610, 513–518. https://doi.org/10.1038/s41586-022-05318-4.

Kelly, R.P., Erickson, A.L., Mease, L.A., 2014. How not to fall off a cliff, or, using tipping points to improve environmental management. Ecol. Law Quart. 41, 843–886. https://doi.org/10.15779/Z38FP1H.

Keppel, G., Van Niel, K.P., Wardell-Johnson, G.W., Yates, C.J., Byrne, M., Mucina, L., Schut, A.G.T., Hopper, S.D., Franklin, S.E., 2012. Refugia: identifying and understanding safe havens for biodiversity under climate change. Glob. Ecol. Biogeogr. 21, 393–404. https://doi.org/10.1111/j.1466-8238.2011.00686.x.

Knight, A.T., Cowling, R.M., Rouget, M., Balmford, A., Lombard, A.T., Campbell, B.M., 2008. Knowing but not doing: selecting priority conservation areas and the research–implementation gap. Conserv. Biol. 22, 610–617. https://doi.org/10.1111/j.1523-1739.2008.00914.x.

Kraberg, A.C., Wasmund, N., Vanaverbeke, J., Schiedek, D., Wiltshire, K.H., Mieszkowska, N., 2011. Regime shifts in the marine environment: the scientific basis and political context. Mar. Pollut. Bull. 62, 7–20. https://doi.org/10.1016/j.marpolbul.2010.09.010.

Lenton, T.M., 2013. Environmental tipping points. Annu. Rev. Environ. Resour. 38, 1–29. https://doi.org/10.1146/annurev-environ-102511-084654.

Lenton, T.M., 2020. Tipping positive change. Philos. Trans. R. Soc. Lond. B 375, 20190123. https://doi.org/10.1098/rstb.2019.0123.

Lenton, T.M., Williams, H.T.P., 2013. On the origin of planetary-scale tipping points. Trends Ecol. Evol. 28, 380–382. https://doi.org/10.1016/j.tree.2013.06.001.

Lenton, T.M., Held, H., Kriegler, E., Hall, J.W., Lucht, W., Rahmstorf, S., Schellnhuber, H. J., 2008. Tipping elements in the earth's climate system. PNAS 105, 1786–1793. https://doi.org/10.1073/pnas.0705414105.

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

Li, L., Fassnacht, F.E., Bürgi, M., 2021. Using a landscape ecological perspective to analyze regime shifts in social–ecological systems: a case study on grassland degradation of the Tibetan Plateau. Landsc. Ecol. 36, 2277–2293. https://doi.org/10.1007/s10980-021-01191-0.

Litzow, M.A., Hunsicker, M.E., 2016. Early warning signals, nonlinearity, and signs of hysteresis in real ecosystems. Ecosphere 7, e01614. https://doi.org/10.1002/ecs2.1614.

Liu, A., Cheng, X., Wang, C., Chen, Y., 2024. Evidence of ecosystem tipping point on St. Lawrence Island: widespread lake drainage events after 2018. Geophys. Res. Lett. 51, e2024GL110161. https://doi.org/10.1029/2024GL110161.

Liu, T., Chen, Dean, Yang, L., Meng, J., Wang, Z., Ludescher, J., Fan, J., Yang, S., Chen, Deliang, Kurths, J., Chen, X., Havlin, S., Schellnhuber, H.J., 2023. Teleconnections among tipping elements in the earth system. Nat. Clim. Change 13, 67–74. https://doi.org/10.1038/s41558-022-01558-4.

Loreau, M., de Mazancourt, C., 2013. Biodiversity and ecosystem stability: a synthesis of underlying mechanisms. Ecol. Lett. 16, 106–115. https://doi.org/10.1111/ele.12073.

Lynch, M., Lande, R., 1993. Evolution and Extinction in Response to Environmental Change. In: Kareiva, P.M., Kingsolver, J.G., Huey, R.B. (Eds.), Biotic Interactions and Global Change. Sinauer Associates Incorporated, pp. 234–250.

Männer, F., Schwarz, L.-M., Menestrey-Schwieger, D., Amputu, V., Bilton, M., Brinkmann, K., Dressler, G., Hamunyela, N., Heita, H., Heshmati, S., Liehr, S., Mbidzo, M., Munyebvu-Chambara, F., Nesongano, W., Rauchecker, M., Sandhage-Hofmann, A., Tielbörger, K., Zimmer, K., Linstädter, A., 2022. An Integrated Framework to Study Ecological Tipping Points in Social-Ecological Systems. IGC Proceedings (1989–2023).

McDonald-Madden, E., Baxter, P.W.J., Fuller, R.A., Martin, T.G., Game, E.T., Montambault, J., Possingham, H.P., 2010. Monitoring does not always count. Trends Ecol. Evol. 25, 547–550. https://doi.org/10.1016/j.tree.2010.07.002.

Mendoza-Penagos, C.C., Calvão, L.B., Juen, L., 2021. A new biomonitoring method using taxonomic families as substitutes for the suborders of the Odonata (Insecta) in Amazonian streams. Ecol. Indic. 124, 107388. https://doi.org/10.1016/j.ecolind.2021.107388.

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

Möllmann, C., Cormon, X., Funk, S., Otto, S.A., Schmidt, J.O., Schwermer, H., Sguotti, C., Voss, R., Quaas, M., 2021. Tipping point realized in cod fishery. Sci. Rep. 11, 14259. https://doi.org/10.1038/s41598-021-93843-z.

Monaco, C.J., Helmuth, B., 2011. Tipping points, thresholds and the keystone role of physiology in marine climate change research. Adv. Mar. Biol. 60, 123–160. https://doi.org/10.1016/B978-0-12-385529-9.00003-2.

Mooney, H., Larigauderie, A., Cesario, M., Elmquist, T., Hoegh-Guldberg, O., Lavorel, S., Mace, G.M., Palmer, M., Scholes, R., Yahara, T., 2009. Biodiversity, climate change, and ecosystem services. Curr. Opin. Environ. Sustain. 1, 46–54. https://doi.org/10.1016/j.cosust.2009.07.006.

Moore, J.C., 2018. Predicting tipping points in complex environmental systems. PNAS 115, 635–636. https://doi.org/10.1073/pnas.1721206115.

Mufungizi, A.A., Musakwa, W., Chanza, N., 2023. Shifting ecosystems, past, current, and emerging trends: a bibliometric analysis and systematic review of literature. Ecol. Indic. 156, 111175. https://doi.org/10.1016/j.ecolind.2023.111175.

Muscolo, A., Settineri, G., Attinà, E., 2015. Early warning indicators of changes in soil ecosystem functioning. Ecol. Indic. 48, 542–549. https://doi.org/10.1016/j.ecolind.2014.09.017.

Nguyen, N.C., Graham, D., Ross, H., Maani, K., Bosch, O., 2012. Educating systems thinking for sustainability: experience with a developing country. Syst. Res. 29, 14–29. https://doi.org/10.1002/sres.1097.

Nguyen, V.M., Young, N., Cooke, S.J., 2017. A roadmap for knowledge exchange and mobilization research in conservation and natural resource management. Conserv. Biol. 31, 789–798. https://doi.org/10.1111/cobi.12857.

Nobre, C.A., Borma, L.D.S., 2009. 'Tipping points' for the Amazon forest. Curr. Opin. Environ. Sustain. 1, 28–36. https://doi.org/10.1016/j.cosust.2009.07.003.

Norström, A.V., Cvitanovic, C., Löf, M.F., West, S., Wyborn, C., Balvanera, P., Bednarek, A.T., Bennett, E.M., Biggs, R., de Bremond, A., Campbell, B.M., Canadell, J.G., Carpenter, S.R., Folke, C., Fulton, E.A., Gaffney, O., Gelcich, S., Jouffray, J.-B., Leach, M., Le Tissier, M., Martín-López, B., Louder, E., Loutre, M.-F., Meadow, A.M., Nagendra, H., Payne, D., Peterson, G.D., Reyers, B., Scholes, R., Speranza, C.I., Spierenburg, M., Stafford-Smith, M., Tengö, M., van der Hel, S., van Putten, I., Österblom, H., 2020. Principles for knowledge co-production in sustainability research. Nat. Sustain. 3, 182–190. https://doi.org/10.1038/s41893-019-0448-2.

Nuttall, M., 2012. Tipping points and the human world: living with change and thinking about the future. AMBIO 41, 96–105. https://doi.org/10.1007/s13280-011-0228-3.

O'Brien, D.A., Deb, S., Sidheekh, S., Krishnan, N.C., Sharathi Dutta, P., Clements, C.F., 2023. EWSmethods: an R package to forecast tipping points at the community level using early warning signals, resilience measures, and machine learning models. Ecography 2023, e06674. https://doi.org/10.1111/ecog.06674.

Ostrom, E., 2009. A general framework for analyzing sustainability of social-ecological systems. Science 325, 419–422. https://doi.org/10.1126/science.1172133.

Pace, M.L., Carpenter, S.R., Cole, J.J., 2015. With and without warning: managing ecosystems in a changing world. Front. Ecol. Environ. 13, 460–467. https://doi.org/10.1890/150003.

Parry, I.M., Ritchie, P.D.L., Cox, P.M., 2022. Evidence of localised Amazon rainforest dieback in CMIP6 models. Earth Syst. Dynam. 13, 1667–1675. https://doi.org/10.5194/esd-13-1667-2022.

Peters, D.P.C., Bestelmeyer, B.T., Turner, M.G., 2007. Cross–scale interactions and changing pattern–process relationships: consequences for system dynamics. Ecosystems 10, 790–796. https://doi.org/10.1007/s10021-007-9055-6.

van de Pol, M., Jenouvrier, S., Cornelissen, J.H.C., Visser, M.E., 2017. Behavioural, ecological and evolutionary responses to extreme climatic events: challenges and directions. Phil. Trans. R. Soc. B 372, 20160134. https://doi.org/10.1098/rstb.2016.0134.

Reid, A.J., Carlson, A.K., Creed, I.F., Eliason, E.J., Gell, P.A., Johnson, P.T.J., Kidd, K.A., MacCormack, T.J., Olden, J.D., Ormerod, S.J., Smol, J.P., Taylor, W.W., Tockner, K., Vermaire, J.C., Dudgeon, D., Cooke, S.J., 2019. Emerging threats and persistent conservation challenges for freshwater biodiversity. Biol. Rev. 94, 849–873. https://doi.org/10.1111/brv.12480.

Reynolds, S.A., Aldridge, D.C., 2021. Global impacts of invasive species on the tipping points of shallow lakes. Glob. Change Biol. 27, 6129–6138. https://doi.org/10.1111/gcb.15893.

Rocha, J.C., Peterson, G., Bodin, Ö., Levin, S., 2018. Cascading regime shifts within and across scales. Science 362, 1379–1383. https://doi.org/10.1126/science.aat7850.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J., 2009. Planetary boundaries: exploring the safe operating space for humanity. Ecol. Soc. 14 https://www.jstor.org/stable/26268316.

Rodriguez Lopez, J.M., Tielbörger, K., Claus, C., Fröhlich, C., Gramberger, M., Scheffran, J., 2019. A transdisciplinary approach to identifying transboundary tipping points in a contentious area: experiences from across the Jordan River region. Sustainability 11, 1184. https://doi.org/10.3390/su11041184.

Scheffer, M., Carpenter, S., Foley, J.A., Folke, C., Walker, B., 2001. Catastrophic shifts in ecosystems. Nature 413, 591–596. https://doi.org/10.1038/35098000.

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

Schindler, D.E., Armstrong, J.B., Reed, T.E., 2015. The portfolio concept in ecology and evolution. Front. Ecol. Environ. 13, 257–263. https://doi.org/10.1890/140275.

Science Panel for the Amazon, 2021. Amazon Assessment Report 2021, 1st ed. UN Sustainable Development Solutions Network (SDSN). https://doi.org/10.55161/RWSX6527.

Seddon, N., Smith, A., Smith, P., Key, I., Chausson, A., Girardin, C., House, J., Srivastava, S., Turner, B., 2021. Getting the message right on nature-based solutions to climate change. Glob. Change Biol. 27, 1518–1546. https://doi.org/10.1111/gcb.15513.

Selkoe, K.A., Blenckner, T., Caldwell, M.R., Crowder, L.B., Erickson, A.L., Essington, T.E., Estes, J.A., Fujita, R.M., Halpern, B.S., Hunsicker, M.E., Kappel, C.V., Kelly, R.P., Kittinger, J.N., Levin, P.S., Lynham, J.M., Mach, M.E., Martone, R.G., Mease, L.A., Salomon, A.K., Samhouri, J.F., Scarborough, C., Stier, A.C., White, C., Zedler, J., 2015. Principles for managing marine ecosystems prone to tipping points. Ecosyst. Health Sustain. 1, 1–18. https://doi.org/10.1890/EHS14-0024.1.

Stafford, S.G., Bartels, Dennis M., Begay-Campbell, Sandra, Bubier, Jill L., Crittenden, John C., Cutter, Susan L., Delaney, John R., Jordan, Teresa E., Kay, Alan C., Libecap, Gary D., Moore, John C., Rabalais, Nancy N., Rejeski, David, Sala, Osvaldo E., Shepherd, J. Marshall, Travis, J., 2010. Now is the time for action: transitions and tipping points in complex environmental systems. Environ. Sci. Policy Sustain. Dev. 52, 38–45. https://doi.org/10.1080/00139150903481882.

Stelzer, J.A.A., Mesman, J.P., Adrian, R., Ibelings, B.W., 2021. Early warning signals of regime shifts for aquatic systems: can experiments help to bridge the gap between theory and real-world application? Ecol. Complex. 47, 100944. https://doi.org/10.1016/j.ecocom.2021.100944.

Sutherland, W.J., Woodroof, H.J., 2009. The need for environmental horizon scanning. Trends Ecol. Evol. 24, 523–527. https://doi.org/10.1016/j.tree.2009.04.008.

Sutherland, W.J., Fleishman, E., Mascia, M.B., Pretty, J., Rudd, M.A., 2011. Methods for collaboratively identifying research priorities and emerging issues in science and policy. Methods Ecol. Evol. 2, 238–247. https://doi.org/10.1111/j.2041-210X.2010.00083.x.

Tilman, D., Reich, P.B., Knops, J.M.H., 2006. Biodiversity and ecosystem stability in a decade-long grassland experiment. Nature 441, 629–632. https://doi.org/10.1038/nature04742.

Tilman, D., Clark, M., Williams, D.R., Kimmel, K., Polasky, S., Packer, C., 2017. Future threats to biodiversity and pathways to their prevention. Nature 546, 73–81. https://doi.org/10.1038/nature22900.

Torossian, J.L., Kordas, R.L., Helmuth, B., 2016. Cross-Scale Approaches to Forecasting Biogeographic Responses to Climate Change. In: Dumbrell, A.J., Kordas, Rebecca L., Woodward, G. (Eds.), Advances in Ecological Research, Large-Scale Ecology: Model Systems to Global Perspectives. Academic Press, pp. 371–433. https://doi.org/10.1016/bs.aecr.2016.08.003.

Tulloch, V.J.D., Atkinson, S., Possingham, H.P., Peterson, N., Linke, S., Allan, J.R., Kaiye, A., Keako, M., Sabi, J., Suruman, B., Adams, V.M., 2021. Minimizing cross-realm threats from land-use change: a national-scale conservation framework connecting land, freshwater and marine systems. Biol. Conserv. 254, 108954. https://doi.org/10.1016/j.biocon.2021.108954.

Urban, M.C., Richardson, J.L., Freidenfelds, N.A., 2014. Plasticity and genetic adaptation mediate amphibian and reptile responses to climate change. Evol. Appl. 7, 88–103. https://doi.org/10.1111/eva.12114.

Van Ginkel, K., Jeuken, A., Haasnoot, M., Botzen, W., Tesselaar, M., Hunt, A., Watkiss, P., Cimato, F., Steininger, K., Bachner, G., Troeltzsch, J., Lincke, D., Hinkel, J., Boere, E., Sainz de Murieta, E., Scoccimarro, E., Bosello, F., 2018. D3.1 Operationalizing Socio-Economic and Climate Tipping Points (No. Deliverable of the H2020 COACCH project).

Veraart, A.J., Faassen, E.J., Dakos, V., van Nes, E.H., Lürling, M., Scheffer, M., 2012. Recovery rates reflect distance to a tipping point in a living system. Nature 481, 357–359. https://doi.org/10.1038/nature10723.

Verbruggen, A., 2013. Revocability and reversibility in societal decision-making. Ecol. Econ. 85, 20–27. https://doi.org/10.1016/j.ecolecon.2012.10.011.

Vitousek, P.M., Mooney, H.A., Lubchenco, J., Melillo, J.M., 1997. Human domination of earth's ecosystems. Science 277, 494–499. https://doi.org/10.1126/science.277.5325.494.

Wang, R., Dearing, J.A., Langdon, P.G., Zhang, E., Yang, X., Dakos, V., Scheffer, M., 2012. Flickering gives early warning signals of a critical transition to a eutrophic lake state. Nature 492, 419–422. https://doi.org/10.1038/nature11655.

Webb, T.J., 2012. Marine and terrestrial ecology: unifying concepts, revealing differences. Trends Ecol. Evol. 27, 535–541. https://doi.org/10.1016/j.tree.2012.06.002.

Wingfield, J.C., Pérez, J.H., Krause, J.S., Word, K.R., González-Gómez, P.L., Lisovski, S., Chmura, H.E., 2017. How birds cope physiologically and behaviourally with extreme climatic events. Philos. Trans. R. Soc. Lond. B 372, 20160140. https://doi.org/10.1098/rstb.2016.0140.

Wong, D., 2021. Ecological tipping points: uncertainties and policy approaches. Camb. J. Sci. Policy 2, 1–7. https://doi.org/10.17863/CAM.79291.

Yachi, S., Loreau, M., 1999. Biodiversity and ecosystem productivity in a fluctuating environment: the insurance hypothesis. PNAS 96, 1463–1468. https://doi.org/10.1073/pnas.96.4.1463.

Zhu, M., Zhang, X., 2020. The potential persistence of abundant submerged macrophyte and phytoplankton in a shallow system at very high nutrients loading: results from a mesocosm study. Environ. Sci. Pollut. Res. Int. 27, 29384–29390. https://doi.org/10.1007/s11356-020-09248-4.