Environmental Reviews

Perspective

A multi-realm perspective on applying potential tipping points to environmental decision-making

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

[a]Department of Biology, Carleton University, 1125 Colonel By Drive, Ottawa, ON K1S 5B6, Canada; [b]Canadian Centre for Evidence-Based Conservation, Carleton University, 1125 Colonel By Drive, Ottawa, ON K1S 5B6, Canada; [c]Department of Physical and Environmental Sciences, University of Toronto Scarborough, 1265 Military Trail, Toronto, ON M1C 1A4, Canada; [d]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]Paleoecological Environmental Assessment and Research Lab, Department of Biology, Queen's University, 99 University Ave, Kingston, ON K7L 3N6, Canada; [g]Institute for Environmental and Interdisciplinary Science, Carleton University, 1125 Colonel By Drive, Ottawa, ON K1S 5B6, Canada; [h]Centro Austral de Investigaciones Científicas (CADIC-CONICET), Ushuaia, 9410, Argentina; [i]Beijer Institute of Ecological Economics, The Royal Swedish Academy of Sciences, Stockholm, Sweden; [j]Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden; [k]Department of Biology, Université Laval, 1045, av. de la Médecine, Québec, G1V 0A6, Canada; [l]Marine Macroevolution Unit, Okinawa Institute of Science and Technology (OIST), 1919-1 Tancha, Onna-son, Kunigami-gun, Okinawa, Japan 904-0495; [m]Department of Biology, University of Ottawa, 30 Marie-Curie, Ottawa, ON K1N 6N5, Canada

Corresponding author: **Meagan Harper** (email: meaganharper@cmail.carleton.ca)

Abstract

Ecosystems experiencing pressures are at risk of rapidly transitioning ("tipping") from one state to another. Identifying and managing these so-called tipping points continue to be a challenge in marine, freshwater, and terrestrial ecosystems, particularly when multiple potentially interacting drivers are present. Knowledge of tipping points, the mechanisms that cause them, and their implications for management practices are evolving, but often in isolation within specific ecological realms. Here, we summarize current knowledge of tipping points in marine, freshwater, and terrestrial realms and provide a multi-realm perspective of the challenges and opportunities for applying this knowledge to ecosystem management. We brought together conservation practitioners and global experts in marine, freshwater, and terrestrial tipping points and identified seven challenges that environmental policymakers and managers contend with including (1) predictability, (2) spatiotemporal scales, (3) interactions, (4) reversibility, (5) socio-ecological context, (6) complexity and heterogeneity, and (7) selecting appropriate action. We highlight opportunities for cross-scalar and cross-realm knowledge production and provide recommendations for enabling the management of tipping points. Although knowledge of tipping points is imperfect, we stress the need to continue working toward incorporating tipping points perspectives in environmental management across all realms.

Key words: drivers, thresholds, ecological change, transitions

Introduction

Human impacts on ecosystems, such as accelerating climate change (IPCC 2021) and increasing intensity of resource use (Vitousek et al. 1997), are leading to dramatic alterations of ecosystem structure and function in marine, freshwater, and terrestrial systems. These impacts can include complete ecological transitions from one state to another entirely different state, that is, "regime shifts", which may be precipitated by crossing a "tipping point". For example, coral reefs can rapidly transition from a stony coral state to an algal state due to exposure to elevated temperatures and (or) nitrogen levels (Lapointe et al. 2019) over a period of days to weeks, or from loss of grazing species due to diseases or overharvesting (Holbrook et al. 2016). Furthermore, transitions can also occur among forest, savanna, and treeless states due to changes in forest-rain feedback precipitated by deforestation, climate change, or fire (Hirota et al. 2011), and lake conditions can change from clear to turbid due to increasing phosphorus (Bayley et al. 2007). These regime shifts (Scheffer et al. 2001) are now well documented, and there is an expanding interest in how these regime shifts manifest in coupled ecological and social systems (Biggs et al. 2018).

Tipping points occur when changes in driver intensities or durations trigger an ecosystem to transition between two or more potential alternative states. Changes in drivers may be gradual or abrupt, leading to switches from one state to another when the tipping point is transgressed (Scheffer and Carpenter 2003; Hughes et al. 2013*b*; van Nes et al. 2016). These nonlinear responses are reinforced by positive feedback mechanisms (e.g., increasing nutrients in shallow lakes leads to turbidity and causes decreasing vegetation, which leads to additional turbidity; Sheffer and van Nes, 2007) and lead to changes in state that are often irreversible (Hughes et al. 2013*a*; Milkoreit et al. 2018; Carrier-Belleau et al. 2022). Changes in state can have lasting consequences for species (e.g., local extirpation or extinction of species), ecosystem functions (e.g., primary production), and ultimately, ecosystem services (e.g., the collapse of fisheries with knock-on effects on humans who depend upon fisheries).

Tipping points occur at a range of spatial and temporal scales. They have the potential to be large, long-term planetary transitions due to mass extinction and niche refilling (e.g., Sallan and Coates 2010) or as small as a lake undergoing rapid transitions from native- to invasive-dominated assemblages over a few years (e.g., Hansen et al. 2013). The capacity of an ecosystem to resist or be resilient to change determines the risk of a transition from its current, often-desirable, state to a different, and potentially less desirable, state. While transitions themselves can be dramatic, predicting if a tipping point will occur is difficult (Scheffer et al. 2009). The diverse and complex pathways that trigger tipping points, the potential for ecological surprises (Filbee-Dexter et al. 2017), and the high costs of staving off change (i.e., slowing the rate of change in ecosystem states or attempting to return the system to its original state) make managing them complex (Kelly et al. 2014). This complexity, and a lack of empirical data, has resulted in arguments that because clearly defined thresholds are often difficult to quantify, the concept of tipping points is not an effective management framework (Hillebrand et al. 2020). Here, we argue that despite inherent complexities and uncertainties, tipping point theory can and should serve a useful role in management and conservation.

Despite their predictive challenges, the questions of if, when, and how the effects of drivers lead to tipping points continues to be identified as important knowledge gaps for ecological management in marine (Parsons et al. 2014; Mason et al. 2017; Friedman et al. 2020), freshwater (Pérez-Jvostov et al. 2020; Dey et al. 2021), and terrestrial (Ammer et al. 2018; Allsopp et al. 2019) contexts. Enabling managers to incorporate concepts surrounding tipping points into their operational plans is prudent and thus of value for management strategies. Formal incorporation of this perspective into management decisions will enable better decisions when faced with potentially catastrophic environmental changes, influencing monitoring strategies, management actions, and decision-making in ecosystem management.

Efforts, such as the Ocean Tipping Points Project (http://oceantippingpoints.org/), have made important strides in addressing knowledge gaps surrounding tipping points. However, these efforts could benefit from integrating multi-realm considerations. Evidence suggests that tipping points may have occurred in all realms and have fundamental concepts that are consistent. This is due to the commonality in drivers and due to drivers such as climate change or changes in water cycling crossing the boundaries of realms. Such an integrative approach can lead to management actions that are multipurpose (Tulloch et al. 2021), allowing for co-benefits from individual management actions (Adams et al. 2014). Considering multiple realms can have the added benefit of more easily identifying general patterns and mechanisms (Webb 2012) and decreasing research duplication across fields (Menge et al. 2009). If tipping points occur in multiple connected systems, a system's tipping may drive a second tipping point in a different system, thus facilitating tipping point cascades or domino effects (Rocha et al. 2018). Considering multiple realms ensures that tipping points research and management could facilitate the identification of more effective management actions and better predictions. Further, we argue that efforts could benefit from exploring causes of positive feedback loops that can potentially lead to tipping points from molecular to organismal to ecosystem scales because tipping points can occur in systems across all levels of ecosystem organization.

Here, we use a multi-realm perspective to identify challenges and opportunities for applying a tipping points perspective to ecosystem management. We do so through a lens that spans multiple levels of biological organization from the physiological sensitivity of individuals within populations of a species (Monaco and Helmuth 2011; Gunderson et al. 2016; Kroeker et al. 2017) to entire ecosystems (Selkoe et al. 2015; Holbrook et al. 2016). We explore opportunities for working and learning across realms and provide recommendations to enable incorporating tipping points into future management.

Tipping points concepts

There are many definitions of tipping points (see Box 1). Here, we use the one developed from recent reviews on tipping points in ecological systems (Milkoreit et al. 2018; Carrier-Belleau et al. 2022) (see Table 1 for definitions of tipping point terms used throughout this article). Tipping points are 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 (Selkoe et al. 2015; Milkoreit et al. 2018; Carrier-Belleau et al. 2022). Continuing pressure of the driver (including small, cumulative changes), significantly large transient fluctuations in state, or abrupt pulses from driver(s) can all be sufficient to push an ecosystem across a tipping point. Once the tipping point is passed, internal processes of the system maintain the new regime through reinforcing feedback (van Nes et al. 2016). The ecosystem is then considered to have entered a new state (e.g., a new valley of attraction; Fig. 1) (Beisner et al. 2003).

The relationships between drivers and biological responses are almost always nonlinear in nature but may appear linear or even uncorrelated over much of their range. As a result, changes in drivers, such as temperature or nutrients, can initially have an apparently minor impact until some threshold value or inflection point is reached (Scheffer et al. 2001). In some cases, tipping points are the result of multiple drivers, which can create additional complexities through their interactions (Folt et al. 1999). For example, while increases in tem-

Box 1. A call for consistent terminology in tipping points research

While the concept of tipping points has been present in the literature since the 1950s and in common usage in ecosystem sciences since the 2000s (van Nes et al. 2016), the terminology surrounding tipping points is often confusing, with multiple terms being used interchangeably. Similar to the findings of Orr et al. (2020) on multiple-stressor literature, recent syntheses on ecological tipping points (e.g., Carrier-Belleau et al. 2022) have highlighted the variability in terminology both within and across realms (i.e., regime shift used more frequently in aquatic than terrestrial systems) and through time (e.g., the term “tipping point” is a relative new-comer to the topic) (Carrier-Belleau et al. 2022). Consistent terminology can greatly enhance cross-realm collaboration (Bonar and Hubert 2002). In the context of tipping points, consistent terminology can enable easier application of tipping point concepts in ecosystem management, especially where marine, freshwater, terrestrial, and social realms collide. As such, we amplify previous calls for consistent terminology and recommend definitions be used, as suggested by Carrier-Belleau et al. (2022) and Milkoreit et al. (2018). At a minimum, individuals considering tipping point phenomena for management should consider (1) the tipping point itself, (2) regime shifts, (3) alternative stable states, and (4) hysteresis (Table 1).

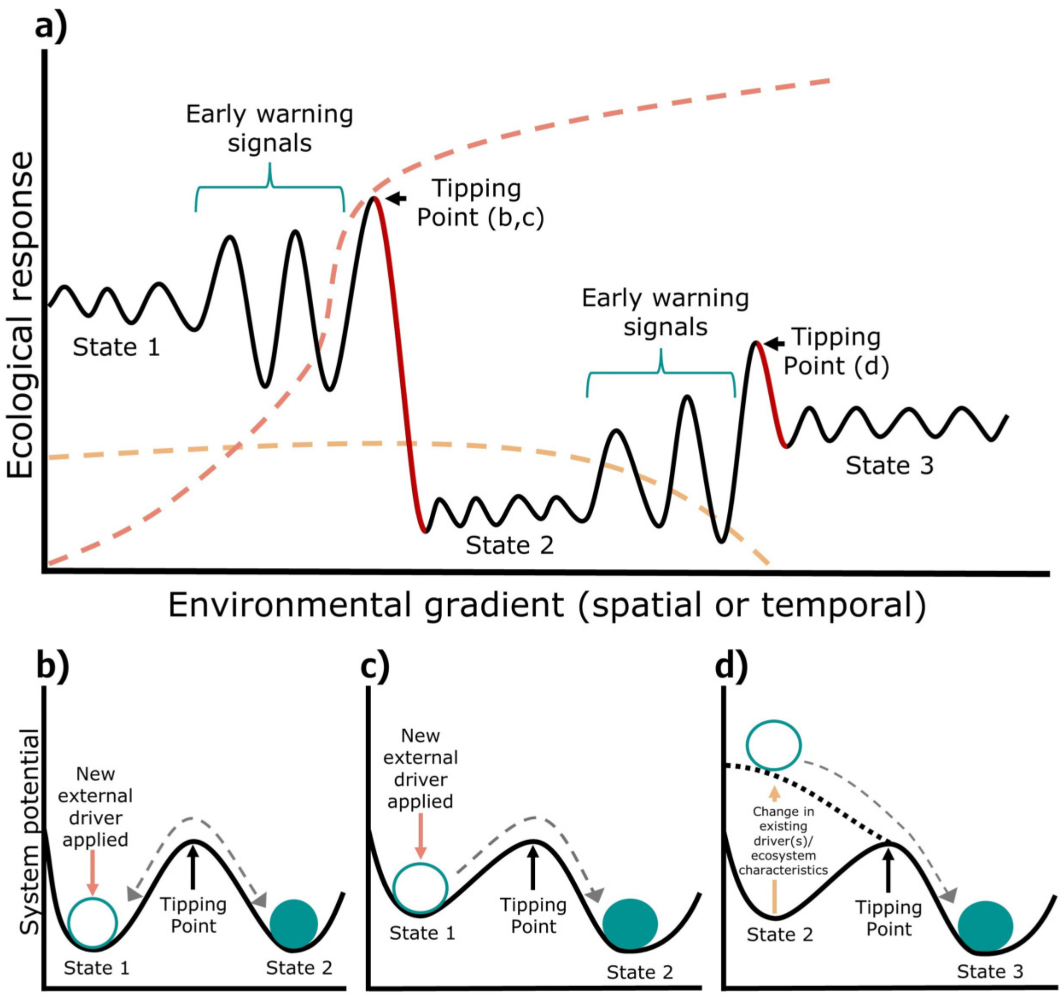
Table 1. Definitions of terms with relevance to tipping points used throughout the article.

Term	Definition	Synonyms	Source
Driver	Environmental parameters (natural or anthropogenic) that exceed the natural range of variation within a system, resulting in a quantifiable biological response, regardless of its direction	Stressor, factor, pressure	(Hughes et al. 2013*b*; Côté et al. 2016; Carrier-Belleau et al. 2022)
Multi-drivers	The aggregate effect of multiple drivers and their interactions	Multi-stressor	(Orr et al. 2020)
Tipping point	Tipping points are 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	Critical threshold, breakpoint, catastrophic bifurcation	(Selkoe et al. 2015; Milkoreit et al. 2018; Carrier-Belleau et al. 2022)
Regime shift	Transition from one state to a contrasting one. In this context, the “state” is a set of characteristics with its own fluctuations and (or) cycles	Critical transitions, phase transitions	(Scheffer et al. 2009)
Alternative stable state	Contrasting non-transitory states to which a system may converge	Alternative equilibrium, alternative state	(Scheffer and Carpenter 2003)
Hysteresis	A feature of the system that exists if the alternative stable states persist even after the pressure from drivers is relaxed. The trajectory for recovery differs from the path of the original; in some cases, even after the driver relaxes, the ecosystem does not return to the previous state.		(Beisner et al. 2003; Suding and Hobbs 2009; Litzow and Hunsicker 2016)
Resilience	The ability of a system to withstand pressure upon exposure to changes in driver(s) and remain in its current state.	Resistance	(Litzow and Hunsicker 2016)

perature most frequently are the proximate cause of coral bleaching and reef collapse, exposure to elevated levels of nutrients can lower the tolerance of corals to heat and light (Riegl et al. 2015). Drivers can decrease an ecosystem’s resistance to change, and its resilience to bounce back from change, particularly if multiple drivers work in concert (Ling et al. 2009), making it more difficult for the ecosystem to maintain its current state (i.e., its current valley of attraction; Fig. 1).

Tipping points can present in four general stages: (1) an original equilibrium state; (2) an unstable, perturbed state due to increasing pressures and loss of resilience (i.e., regime shift); (3) a tipping point; and (4) an alternative state (Figs. 1*b* and 1*c*). Alternative states can include both changes to the original equilibrium state or switches from one state to another (i.e., alternative equilibrium states). There is the potential for more than one equilibrium state under the range of variation of a driver within a system, such as is the case in kelp forest-urchin barrens (Simenstad et al. 1978; Stewart and Konar 2012). Whether alternative states can be considered “stable” or are dynamic, transient states, and whether all tipping points will lead to an alternative state, remains debatable (see Petraitis and Dudgeon 2004). For our purposes, we assume that some change in state is likely to occur. Whether alternative states are “stable” may be dependent on the time horizons considered; frequent year-to-year regime shifts may be considered “unstable” alternative states (Bayley et al. 2007), whereas more subtle, longer term changes that occur over decades may be considered “stable”. Henceforth, we use “alternative stable states” for consistency but recognize that this term includes some assumption of the time horizon in question. Hysteresis (Fig. 1*d*) is present if, after a perturbation to the ecosystem, alternative stable states persist even after drivers are relaxed because the trajectory for recovery differs from the path of the original change; in some cases, even after the driver relaxes, the ecosystem does not return to the previous state (Beisner et al. 2003; Suding and Hobbs 2009; Litzow and Hunsicker 2016). The amount of

Fig. 1. Tipping point concepts. (*a*) Relationship of a theoretical ecological response variable (solid line) and the drivers impacting it (dashed lines). Periods of stability (stable states; 1-3) contrast with periods of transitions (regime shifts; red line), culminating in a tipping point and change to an alternative state. Regime shifts can be differentiated by their cause and reversibility. In (*b*) (reversible), (*c*), and (*d*) (irreversible), the basins represent stable states, and the balls represent current states. Open balls indicate stable states, while filled balls indicate alternative stable states. A regime shift is caused by "shifts in variables" (*b* and *c*), where the addition of new external drivers (e.g., fishing) pushes the ecosystem across a fixed threshold into a new basin of attraction. A regime shift is also caused by "shifts in parameters" (*d*), where changes in existing external drivers (e.g., carrying capacity) alter the basin of attraction itself, moving the ecosystem from one stable state to another without having to overcome a fixed threshold (cf. Beisner et al. 2003; Scheffer and Carpenter 2003; Horan et al. 2011).



hysteresis present in the system is dependent on the difference between the tipping points of degradation and recovery (Filbee-Dexter and Scheibling 2014) and is an important component to consider when evaluating or applying concepts of tipping points.

Need for integration of tipping points concepts in ecosystem management

Integration of tipping points in ecosystem management is challenging because it assumes that tipping points are to some degree predictable and that management applied judiciously, either before (preventing) or after (restoring) the tipping point, can influence the outcome of the event. Successful integration of tipping points into strategic planning and management actions can enable better decision-making (Hastings et al. 2018). Management strategies that explicitly avoid potential tipping points have been found to be more effective than those that do not (Kelly et al. 2015). Although tipping points are recognized in many management scenarios (e.g., maximum safe yield in fisheries harvests; Blöcker et al. 2023), there is still a need to operationalize tipping points explicitly in legislation, policies, and guidelines that inform ecosystem management, in a similar manner to the way risk is currently embedded in this guidance (e.g., the IUCN Red Lists Keith 2015). Doing so would enable avoidance of surprises (Selkoe et al. 2015) and assist managers in defining safe operating spaces to avoid catastrophic changes (Rockström et

Box 2. Examples of managing tipping points

Terrestrial example—grassland degradation of the Tibetan Plateau

The regime experienced in the Tibetan pastoral landscape is an example of the importance of scale when considering management activities. Li et al. (2021) found that shifts from a functioning alpine meadow state to a degraded black-soil, grassless state have occurred due to the combined effects of changes in pastoral land use (privatization and fencing), increased land-use intensity (extended grazing by more yak and sheep in smaller pastures), and increased number of pika. Early warning signals of the regime shift to the black-soil, grassless state appeared first in only a few pastures. Responses to these early warning signals were haphazard and at the scale of the individual pasture. However, the drivers leading to black-soil formation occurred at the scale of the landscape, and it took almost 15 years after the first early signals for landscape-scale management to be considered. shift

Marine—overexploitation of the Baltic cod fishery

A classical example of how tipping points can impact highly connected socio-ecological systems is the Atlantic cod socio-ecological complex, where overfishing (the driver) led to the collapse of the Baltic cod population. This in turn led to the collapse of the fishery and the community that it supported (Möllmann et al. 2021). The combined effect of the warming of the Western Baltic Sea and overfishing of the cod fishery led to a dramatic decline in catches and significant changes in cod stock dynamics. The biomass of adult cod decreased to such a point that it impaired reproductive success, which led to an unproductive state. The necessary changes to allowable catch to facilitate biological recovery endangered the socio-ecological system and therefore overfishing continued until it reached a stable unproductive state. It is unlikely that ecological recovery efforts to move this system into a more productive state will be successful; therefore, other measures to mitigate the social impacts of this tipping point will be required.

Freshwater—eutrophication management at Cootes Paradise

While some tipping points are undesirable, facilitating tipping points to push a degraded system to a more desirable form can be a viable management goal. Kim et al. (2021) demonstrated how eutrophication management in Cootes Paradise Marsh in Ontario (Canada) could help tip the system from an undesirable turbid phytoplankton-dominated state to a desirable clear macrophyte-dominated state. Using a eutrophication model, the authors showed that a drastic decrease in phosphorus concentration could lead to a tipping point on its own and that this tipping point could be accelerated if a healthy macrophyte community was established. These management actions would support management objectives to increase the extent of native macrophytes in the marsh.

al. 2009; Johnson and Ray 2021). If tipping points are not considered, ineffective actions may be implemented, resulting in poor management outcomes. If tipping points are assumed as a potential threat, and managers focus on reducing drivers of ecosystem change, improved management outcomes are likely to occur. Monitoring for tipping points may come at a high cost, but it is important to stress that restoring a system that has crossed a tipping point is significantly more costly than monitoring. Early action to ensure resistance and resilience is likely more practical, affordable, and effective than inaction (Kelly et al. 2014) or action after the fact (Selkoe et al. 2015).

Institutional robustness in determining how and when to act in the face of potential tipping points is another important component of integrating tipping points into ecosystem management. Responses to potential negative outcomes (either ecological, social, economic, cultural) will vary with context and are dependent on the components of the system. Crossing tipping points can also occur rapidly, making fast responses necessary. Tipping points become especially important for institutions that can influence fewer drivers within a system and have less management flexibility (Horan et al. 2011). There are many cases of systems experiencing tipping points being successfully, or unsuccessfully, managed. We provide some realm-specific examples in Box 2.

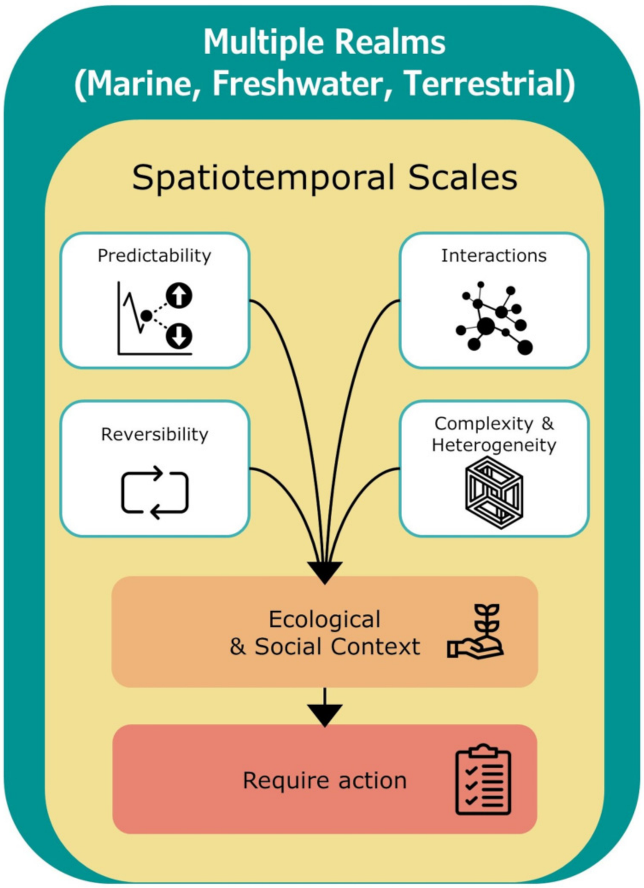
Overcoming challenges in integrating tipping point concepts into ecosystem management

Many challenges face policymakers and managers working to integrate tipping points into current management objectives. We identify seven challenges (Fig. 2) that will likely be encountered by all policymakers and managers, regardless of realm. Most challenges are context-dependent, and we do not report them in any particular order. There may be instances for which a given challenge is irrelevant. For each, we identify ways for policymakers and managers to address these challenges.

Tipping points are difficult to predict

Tipping points can be identified once they have happened by considering sudden changes in time-series data or sharp boundaries between contrasting states in space, among others, although it is important to consider other possible causes before determining that a tipping point is present (Scheffer and Carpenter 2003). It is difficult to accurately predict an approaching tipping point, particularly when caused by stochastic events. Because tipping points occur when a threshold is crossed, detecting the approach to the threshold requires an understanding of the normal variation within

Fig. 2. Challenges to consider when managing tipping points from a multi-realm perspective. After identifying relevant spatiotemporal scales, policymakers and managers must consider whether tipping points can be predicted and whether they are reversible, as well as the interactions between realms, drivers, and tipping points themselves, and the complexity and heterogeneity of tipping points and the systems within which they occur. Effective policy and management will require the integration of ecological and social perspectives when taking action to avoid and (or) decrease the negative consequences of future tipping points among marine, freshwater, and terrestrial realms.



the system, the system's underlying mechanisms and processes, as well as other system-specific knowledge. Prediction can be especially tricky under the novel suites of environmental conditions often created by climate change (Mahony et al. 2017). However, the construction and investigation of observational, historical, and fossil datasets, as well as long-term ecological experiments, may reveal early warning indicators in environmentally similar ecosystems under similar pressures and involving functionally similar species.

Several types of potential early warning indicators could help fine-tune monitoring and enable managers to identify (and ideally avoid) perturbations resulting in tipping points. These include (1) loss of resilience; (2) critical slowing down (increased variance and autocorrelation, as has been seen prior to abrupt climate shifts (Dakos et al. 2019) or in time series once climate oscillations and trends have been removed (Mengistu et al. 2013*a*, 2013*b*); (3) increased skewness and flickering of variables; (4) slower recovery from perturbation; and (5) increased change and variation in spatial organization. Many other warning indicators also exist (see: Scheffer and Carpenter 2003; Dakos et al. 2008; Pace et al. 2017; Saravia et al. 2018; Rietkerk et al. 2021), although not all early warning signals may be useful to identify an approaching tipping point consistently in all situations (Gsell et al. 2016).

A recent synthesis of experimentally identified early warning signals found that no early warning signal was 100% reliable at identifying regime shifts (whether linked to a tipping point or not) (Stelzer et al. 2021). Additionally, not all abrupt changes will have early warning signals (Boettiger and Hastings 2012; Dutta et al. 2018), and the presence of early warning indicators does not mean a tipping point must occur. The use of time-series data often runs the risk of false positives (Boettiger and Hastings 2012). Other limitations can include signal-to-noise ratios (Perretti and Munch 2012), and our ability to select relevant, measurable variables in real systems (Burthe et al. 2016) may make identifying early warning signals difficult. It is therefore important to consider multiple forms of evidence and multiple early warning signals together because some signals may actually be indicators of resilience (e.g., complex spatial systems avoid tipping points with multi-stability; Rietkerk et al. 2021).

The loss of functional redundancy and key components of ecosystems (e.g., primary producers, trophic levels) prior to mass extinctions (Dick 2021) indicates that bolstering functional redundancy and therefore resiliency (Hirota et al. 2011) could help stave off the negative impacts of tipping points. Long-term, high-frequency data (i.e., higher than the natural frequency of oscillations of the system) are useful for detecting early warning signals of tipping points and also enable the identification of when past tipping points occurred and their potential causes, with lower levels of uncertainty. Unfortunately, obtaining such records is time-consuming and demands resources that are out of reach for most management organizations. The use of remote sensing (with broad coverage but lower resolution) and community science (at high spatial and (or) temporal resolution, such as the "Adopt a plant" program; Garcia et al. 2021) could potentially help in the establishment of robust datasets and decrease the burden of data collection, especially when these approaches are combined. Although early warning indicators prior to a tipping point have been identified experimentally (see examples in Hewitt and Thrush 2019), many are identified post-tipping (Dakos et al. 2008; Gsell et al. 2016). However, these cases can provide useful guidance on the need for effective and flexible long-term monitoring programs (Hewitt and Thrush 2019) to allow for future application of improving knowledge of early warning signals.

Most management actions take time and resources to implement, and much of the experimental evidence has shown that early warning signals are present for short durations and have high data requirements (e.g., Carpenter et al. 2011). However, post hoc assessments of marine empirical studies have noted that markedly less data are required to identify tipping points, than theory might suggest (Hewitt and Thrush 2019). It is important to acknowledge that the process of monitoring and analyzing data may delay implementation, leading to missed opportunities to influence the system prior to the tipping point occurring. Because of this, using a combination of monitoring and modeling approaches that assess multiple sources of data will better enable the recognition of approaching tipping points and the implementation of appropriate management (see Box 2). Experimental lake studies have found that preset thresholds of impacts, paired with consideration of early warning indicators, may allow managers to implement actions early enough to modify drivers of approaching tipping points (Pace et al. 2017). Therefore, assuming that tipping points are likely to occur is an important first precautionary step (Selkoe et al. 2015).

Tipping points are shaped by multiple spatial and temporal scales

One of the most difficult aspects of integrating tipping points into strategic planning and management activities is determining the scale at which to make decisions. Drivers may operate at multiple scales, as will sensitivity to those drivers. Understanding variability in how different species (i.e., populations) within an ecosystem respond to various drivers could improve predictions of tipping points (Harley et al. 2017) and provide earlier opportunities for intervention. Similarly, tipping points can occur at a variety of scales, ranging from the sub-population scale (e.g., colony level failure of social bees; Bryden et al. 2013) to the planetary scale. In their study of climate networks, Liu et al. (2023) found teleconnections between the Amazon Rainforest and the Tibetan Plateau. Because of these connections, tipping in one part of the globe has consequences when teleconnections cause cascades.

Two things can help mitigate tipping points across spatial scales: first, spatial self-organization can help ecosystems evade tipping points across a landscape when alternative states occur in space at the same time (Rietkerk et al. 2021); second, meta-communities can facilitate rescue effects (Thompson et al. 2020) through dispersion into and out of impacted areas heading to, or experiencing, a regime shift. If the spatial scale being considered is too small, evasion becomes impossible. Conversely, if the spatial scale being considered is too large (e.g., due to spatial or temporal averaging which masks important levels of heterogeneity), important opportunities for solutions such as refugia may be missed (Salois et al. 2022). An additional complication arises when homogenous restoration activities occur, which may decrease the landscapes' ability to self-organize and avoid tipping points.

Although regime shifts can occur at any spatial scale, making it essential to monitor at a variety of scales in spatially structured systems, the speed at which they occur can vary. This is an additional reason why prediction is so complex. Regime shifts seen in paleo-records can range anywhere from 1 to 1000 years (Smol et al. 2005; Brovkin et al. 2021) or even 100 000 several million years at a global and mass extinction scale (Sallan and Coates 2010; Sallan et al. 2011). Our ability to determine the duration of a regime shift and if a tipping point has truly occurred is, however, necessarily dependent on the temporal resolution of these paleorecords. Global tipping points are likely the cumulative result of localized turnover and regime shifts occurring on shorter or even sudden time scales, and some studies have shown that previous regime shifts often occur within what could be considered "management relevant" time scales, such as the Black Sea flooding (9.5–9.0 thousand years ago) that resulted in the complete loss of land ecosystems and transition to saltwater ecosystems in less than 40 years (Yanchilina et al. 2017). The time horizon that should be considered by managers is therefore linked to the size of the area under consideration (i.e., managers operating at smaller scales should be prepared for faster changes to occur). Time horizons determine when and how fast managers must respond to early warning signals and after tipping points have occurred.

Management planning has the challenge of determining under what spatial and temporal scales to operate (see Box 2). In some cases, scales will be beyond a management entity's capacity, but connecting temporal and spatial scales will allow for more complete management plans, especially if the scale is large enough to consider the entirety of a driver's influence (i.e., the entire invasion front of an invasive plant), or interconnections among different realms. Supporting metacommunities through ecosystem management can facilitate rescue effects at local scales and potentially decrease the likelihood of future tipping points. While planners often work at regional scales, planning beyond regional scales, employing similar frameworks and ensuring effective knowledge exchange among management entities are essential, especially in the case of multi-scalar governance scenarios. Considering multiple realms has been shown to lead to increased benefits and decreased costs (Tulloch et al. 2021). Considering multiple spatiotemporal scales is expected to have similar effects.

Tipping points are influenced by multiple interactions

Tipping points drivers are diverse (and increasing in diversity and number; Reid et al. 2019) and often beyond the scope of most local environmental managers' reach (i.e., climate drivers). Interacting drivers can influence the probability of tipping points in different ways. If drivers' effects are additive (sum of driver effects) or synergistic (combined impact effects greater than the expected sum of drivers; Folt et al. 1999; Piggott et al. 2015), the system can be pushed closer to the tipping point than would otherwise be expected (Côté et al. 2016). In many cases, drivers interact to not only decrease the integrity of the system but make it more susceptible to change. In their study of Tasmanian coastal waters, Ling et al. (2009) found that the impacts of climate-driven sea urchin expansion were exacerbated by overfishing of large spiny lobsters (a main predator of sea urchins); these combined impacts led to increased likelihood of overgrazing of kelp beds and conversion to urchin barrens. In this case, controlling climate-driven change is beyond the manager's influence, but intervening to decrease overfishing could decrease the risk of a tipping point event. This example also highlights the need to consider interactions within species networks as these may contribute to the emergence of alternative states (Kéfi et al. 2022) or management opportunities.

Whether interacting drivers will always push systems into detrimental states more quickly is not clear, as interactions can also be antagonistic in their physical and ecological effects on key species (Kroeker et al. 2017), or a single driver may be dominant, even though multiple drivers are present (Côté et al. 2016). If the cumulative effects of interacting drivers are not considered, it is likely that the risk of a tipping point event may be under- or overestimated (Carrier-Belleau et al. 2022).

An additional complication may arise if one tipping point has the potential to trigger other tipping points (i.e., domino effects, knock-on effects, or tipping point cascades). A shift in one system's drivers and a subsequent regime shift may produce additional changes in driver impacts in another system, leading to changes beyond the original tipping point event (Klose et al. 2020). This means that managers should not consider drivers or systems in isolation (e.g., if a tipping point in a coral reef is likely, considering potentially connected tipping points in mangrove systems may be necessary). Drivers may act as connectors among potential tipping points (Rocha et al. 2018), particularly larger drivers such as climate change, and make it essential for managers to consider overlapping drivers across multiple systems.

Considering tipping points within and across various governance levels will allow planners and managers to work together more effectively, developing holistic plans and taking effective actions to reduce the risk of tipping points and tipping point cascades. Similar to the way portfolio management suggests considering protecting networks and their connections (Schindler et al. 2015), predicting multiple drivers and connections leading to cascading tipping points could help alleviate the need for predicting individual drivers' influence on single tipping points. If managers assume that, when a tipping point in one location has already occurred, changes in drivers and a tipping point in a connected system will follow, they can react faster to impending events. Managing the consequences of these events across multiple interactions using multi-realm perspectives and collaborations becomes essential.

Tipping points may, or may not, be reversible

When considering management actions in anticipation of, or response to, tipping points, it is important to determine if reversibility is possible. In some cases, no amount of intervention is likely capable of returning an altered system to its original state. Changes to the system are so all-encompassing that components of the original system no longer exist (e.g., complete collapse and loss of glaciers; Rosier et al. 2021). If this result is likely, it is especially important to avoid or delay the tipping point, rather than allowing the tipping point to occur. This may be possible through building redundancy to improve the resilience of an ecosystem and is one way to facilitate successful intervention to maintain the original state. Determining safe operating space and appropriate management thresholds (Rockström et al. 2009; Kelly et al. 2014; Foley et al. 2015) that are flexible in the face of changing conditions is therefore essential.

A system that has exceeded a tipping point may be influenced to return to its original state, even if the path along which this occurs is different (Beisner et al. 2003). For example, facilitating the return of an annual fire regime in shrub-invaded lands helped push the system back toward its original state, a tall grass prairie (Collins et al. 2021). By influencing the drivers, or by adaptively managing new system components, managers may be able to push systems from new (presumably undesirable) states to the original (desirable) state. Although complete reversibility to the original state may not always be the goal, deliberately tipping systems from an undesirable to a new, more desirable, state could allow managers to influence the overall outcomes post-tip (Lenton 2020).

Tipping points need both ecological and social contexts

The social and ecological dimensions of ecosystems cannot be disentangled when considering tipping points and regime shifts. These dimensions are not isolated from one another; therefore, transdisciplinary approaches must be adopted during both planning and management. For example, when an ecosystem that supports a fishery is impacted by resource use, failing to include the social aspects of fisheries communities in management can impact the long-term responses of the system to harvesting (Yletyinen et al. 2018; Box 2).

Conflicting priorities and preferences among stakeholders to the consequences of tipping points can create additional complications. Ensuring that different perspectives are evenly represented and considered by decision-making bodies can be challenging. Some actors may benefit from a regime shift resulting in stakeholder reluctance to support restoration to the original state. For example, a collapse of the cod fishery in the Gulf of Maine was followed by a transition to a lucrative lobster fishery (Steneck et al. 2011), and the invasion of blue crabs into the Mediterranean has led to a new fishery in Tunisia alongside efforts to remove the non-native species in Italy and elsewhere (Marchessaux et al. 2023). Those who see the most benefit after a tipping point will thus likely have the least motivation for change (Selkoe et al. 2015). In other cases, stakeholder support for changes back to an original state is more robust because those changes have little impact on stakeholders but have large ecological benefits. For instance, changing from car-based transport to bus-based transport in Mount Zion National Park resulted in positive impacts on cougar numbers with little associated impact on park visitors (Ripple and Beschta 2006).

Societal values almost always dictate what can and cannot be successfully acted upon, and decision-making is dependent on societal values requiring inclusive co-development of solutions with diverse stakeholders. Without taking this into account, managers may be faced with a near-impossible task. Knowing that risk tolerance and acceptance are necessary components of decision-making, managers should work to integrate not only economic risk aversion/tolerance, but also cultural risk aversion/tolerance (see examples in

Biggs et al. 2018). Local managers are uniquely positioned to capture this context and the relational value of the results of intervention to manage past or anticipated tipping points.

Management decisions can be made based only on ecological context, but management decisions integrating tipping points perspectives will necessitate some consideration of social and or economic context. Some management objectives currently incorporate these (i.e., Lester et al. 2021), but doing so will require transdisciplinary teams and diverse voices, which in turn mandates fostering of trusted relationships in advance of crises. Considering different societal values (Ford et al. 2021) and actively integrating different knowledge bases will lead to management outcomes that are better supported by communities and are effective across social and ecological boundaries. This will also enable the inclusion of historically underrepresented voices and viewpoints (Yletyinen et al. 2019).

Tipping points are complex and heterogeneous

Due to the complexity of predicting, identifying, and managing tipping points before they occur, they are often considered "ecological surprises" (Filbee-Dexter et al. 2017). Surprises may arise from differences in manager expectations and the actual results of management interventions. For example, if hysteresis is present in a system, more effort to decrease drivers may be necessary to return the system to the original state than was required to cause the switch (Foley et al. 2015).

Ecological systems are complex, but most models do not reflect this complexity. Simple models consider only a subset of the components of an ecosystem that may influence, or be influenced by, a tipping point. They are insufficient to truly understand if, and when, a tipping point will occur and what the end result will be (Kéfi et al. 2022). More complex models may only be part of the solution to understanding tipping points, as they run the risk of misidentifying an ecosystems likelihood of tipping if they are parameterized incorrectly and therefore should be integrated with other approaches, such as experimentation, to accurately understand tipping points (Kéfi et al. 2022). Quantifying uncertainty is exceptionally difficult, especially since tipping points are quite heterogeneous. As the complexity of the scales and dynamics of a system increases, the risk associated with incorrectly identifying thresholds for management within systems also increases. If further complicated by social, economic, and cultural considerations and the management entities' organizational complexity, different goals add to this uncertainty (Johnson and Ray 2021).

When systems have multiple potential alternative stable states, quantifying the risk of each outcome can help during management decision-making. Assuming that only a single outcome is possible can lead to management that does not function as expected, especially if potential feedback loops are not parameterized. Christiansen et al. (2014) determined that when marine protected areas were established to decrease fishing pressures on sea turtles, an unexpected consequence was increased the herbivory of seagrass, leading to potential ecosystem collapse. By controlling for one potential tipping point, but not considering how drivers will change, the foundation for another tipping point was developed. The complexity of the interactions within an ecosystem requires consideration of complexity and uncertainty at many scales.

Tipping points require action

Determining when it is necessary to gather more information before acting is a difficult problem in environmental sciences in general (McDonald-Madden et al. 2010; Bennett et al. 2018). This difficulty may be exacerbated in systems that are subject to tipping points because the consequences of acting too late are potentially catastrophic. It is likely that some tipping points are more readily acted upon than others. It may be difficult for managers to act upon unpredictable tipping points, particularly if acting comes with a significant cost, and there are more predictable options for limited resources. There may also be considerable lags between recognizing a tipping point and acting upon it, and resource limitations mean that managers are typically unable to act on every potential threat to an ecosystem. They must choose what is within their capacity and where to direct limited resources.

Whether to focus on drivers or the consequences of tipping points may depend on the types of management interventions that can be used and what the ultimate management goals are. By focusing on drivers, managers have the opportunity to capture additional early warning signals (e.g., Pace et al. 2017). Drivers are often easier to identify on short time scales than the consequences of a tipping point, and by considering potential drivers, managers can intervene in a timely manner. There are risks if managers focus on one driver over other, more impactful drivers, but focusing on consequences is almost always the more costly option. Incorporating tipping points in cost-benefit analysis can result in more effective processes being recommended for implementation (Cai et al. 2015). Combining different management goals (i.e., avoiding regime shifts and working on ecosystem restoration) could also lead to synergies in management activities.

Careful, evidence-based decision-making is essential, and information should be collected on social, scientific, and management aspects of decisions. Using this information in adaptive management enables us to learn and improve management choices as new information comes to light. By utilizing adaptive management as tipping points are approached (assuming it is possible to predict them) or to decrease overall driver effects in the system, better results are likely possible. In addition to collecting sufficiently high-frequency and long-term data prior to acting, it will be essential to monitor interventions to see if they work as intended and to avoid negative, unintended consequences. Additionally, there is a need to improve information sharing across realms (Menge et al. 2009; Orr et al. 2020) to improve progress in tipping point management.

While working toward general principles that apply to all tipping points is a worthwhile goal in the long run, focusing on this and delaying the application of current knowledge may contribute to future tipping points. Through their re-

Table 2. Recommendations for moving forward with tipping points in ecosystem policy and management.

Recommendation	Why?	How?
Learn across multiple realms	• Enables faster uptake of new knowledge/techniques • Enables potential to understand the generalizability of tipping point knowledge • Builds on existing knowledge	• Attend multi- or inter-realm conferences • Publish in generalist journals (not specifically marine, freshwater, and terrestrial) • Read literature outside one's core realm • Participate in interdisciplinary student mentoring
Seek opportunities for cross-realm action	• Enhances interconnectedness of realms • Enables potential to control future tipping points in connected systems • Creates potential to access to new sources of funding	• Develop cross-realm research/management teams • Consider multi-realm funding opportunities
Coordinate to decrease duplication of effort across realms and scales	• Decreases research repetition • Saves limited funding resources • Enables cost-/benefit-sharing	• Develop multi-realm research projects • Collaborate with agencies at different organizational levels • Conduct cross-realm evidence syntheses • Embrace accessible information sharing • Facilitate inter-realm knowledge sharing through plain language summaries
Act on tipping points holistically	• Acknowledges that drivers do not operate in isolation • Acknowledges that drivers can extend across realms	• Engage in integrated approaches to management • Ensure realm-specific management agencies collaborate when developing holistic management goals/strategies
Build transdisciplinary teams to ensure social and economic contexts are integrated in decision-making	• Enhances cross-realm knowledge exchanges • Enables socio-ecological connections to be embedded explicitly • Creates multiple viewpoints/knowledge bases • Recognizes different stakeholder and rightsholder needs	• Foster collaboration among ecological and social sciences • Develop funding sources for transdisciplinary teams • Incorporate different knowledge bases within projects

view of 51 case studies, Kelly et al. (2014) determined that the best ways to successfully avoid or respond to tipping points were (1) continuous ecosystem monitoring, (2) considering known or expected thresholds in management decisions, and (3) managing drivers at appropriate scales. However, there are cases where one or more of these components may not be possible or efficient. In those cases, avoiding tipping points is likely to produce the best results in the absence of complete information, since our ability to predict tipping points using early warning indicators remains limited. Because of the high uncertainty, especially if paired with high likelihood of irreversibility, a precautionary approach is necessary. Precautionary approaches can be costly (Scheffer et al. 2009), necessitating high-frequency and high-quality data and strong regulator control (Selkoe et al. 2015). However, because crossing tipping points is likely to result in higher costs overall, working to avoid tipping points and acting for the highest ecological benefit prior to tipping occurring is likely the best option available to managers. Effectively communicating these trade-offs to decision-makers will make a cautious approach to future tipping points more palatable.

Moving forward to effectively manage tipping points

The narrative around tipping points is often one of despair and loss, which can hinder managers from effectively managing tipping points. While these types of narratives can be counterproductive, inspiring narratives can produce improved outcomes (Bennett et al. 2016). Gaining public buy-in and social license is yet another complexity that could potentially constrain managers' ability to tackle tipping points in ecological systems using a tipping points perspective. Highlighting bright spots and success stories in tipping points management may be one way to bolster public buy-in and social license when managing these complex interactions (Cvitanovic and Hobday 2018). Improved sharing of management outcomes is one way to start changing public perception surrounding tipping points. That being noted, continuing to share examples of instances where systems have experienced tipping points along with associated consequences to society can also help to foster support. Finding the balance between hope and despair is always challenging (Kidd et al. 2019; Park et al. 2020) and would be a worthy area of research for tipping points.

As we move forward in our understanding of tipping points and our ability to predict them, it is essential that better predictions (based on a variety of techniques such as mechanistic and statistical models, machine learning, and manipulative experiments) help pinpoint early warning signals so that we have sufficient time to act. Analyzing existing datasets in novel ways (e.g., Gutowsky et al. 2019) and using methods that combine disparate datasets (such as evidence syntheses) could help make connections in existing data, further improving our understanding of what to focus on when attempting to predict future tipping points. To further develop our understanding of tipping points management, we recommend the following: (1) learn across multiple realms, (2) seek opportunities for cross-realm action, (3) coordinate to decrease duplication of effort across realms and scales, (4) act on tipping points holistically; and (5) build transdisciplinary teams to ensure social and economic contexts are integrated in decision-making (Table 2).

It is likely that we will be unsuccessful in preventing some tipping points, but this should not be a deterrent in attempting to predict and manage tipping points in the future. Scientists, planners and managers, and practitioners should take these as opportunities for learning and further developing our ability to manage these potentially catastrophic changes moving forward and thereby preventing localized regime shifts from scaling up to become regional or global events. Although our knowledge of tipping points remains imperfect, we must continue working toward incorporating tipping points perspectives in environmental management and conservation in all realms.

Acknowledgements

This paper was inspired by the outcomes of a 2-day collaborative workshop 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 C. Chu, C. Dey, M. Koops, J. Midwood, and K. Smokorowski of Fisheries and Oceans Canada, J. Ray of Wildlife Conservation Society of Canada, and M. Hirota of the Federal University of Santa Catarina, Brazil, for providing their perspectives during the workshop that influenced this work. Their comments and observations greatly improved the quality of this article. This is a product of the Canadian Centre for Evidence-Based Conservation.

Article information

History dates

Received: 8 May 2023
Accepted: 14 September 2023
Accepted manuscript online: 11 October 2023
Version of record online: 27 November 2023

Copyright

Data availability

Article does not report data.

Author information

Author ORCIDs

Meagan Harper https://orcid.org/0000-0002-8462-2039
Trina Rytwinski https://orcid.org/0000-0001-6764-7309
Irena F. Creed https://orcid.org/0000-0001-8199-1472
Brian Helmuth https://orcid.org/0000-0003-0180-3414
John P. Smol https://orcid.org/0000-0002-2499-6696
Joseph R. Bennett https://orcid.org/0000-0002-3901-9513
Dalal Hanna https://orcid.org/0000-0002-0759-6930
Leonardo A. Saravia https://orcid.org/0000-0002-7911-4398
Juan Rocha https://orcid.org/0000-0003-2322-5459
Charlotte Carrier-Belleau https://orcid.org/0000-0003-0019-3175
Aubrey Foulk https://orcid.org/0009-0005-6369-5465
Ana Hernández Martinez De La Riva https://orcid.org/0009-0000-0249-6474
Courtney Robichaud https://orcid.org/0000-0001-9538-2811
Lauren Sallan https://orcid.org/0000-0002-4441-1456
Steven J. Cooke https://orcid.org/0000-0002-5407-0659

Author contributions

Conceptualization: MH, TR, IFC, BH, JPS, JRB, DH, LAS, JR, CC, AF, AHMDLR, CR, LS, AS, SJC
Funding acquisition: SJC
Project administration: MH, TR, SJC
Visualization: MH
Writing – original draft: MH, TR, SJC
Writing – review & editing: MH, TR, IFC, BH, JPS, JRB, DH, LAS, JR, CC, AF, AHMDLR, CR, LS, AS, SJC

Competing interests

The authors declare there are no competing interests.

Funding statement

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.

References

Adams, V.M., Álvarez-Romero, J.G., Carwardine, J., Cattarino, L., Hermoso, V., Kennard, M.J., et al. 2014. Planning across freshwater and terrestrial realms: co-benefits and tradeoffs between conservation actions: cross-realm systematic planning. Conserv. Lett., **7**(5): 425–440. doi:10.1111/conl.12080.

Allsopp, N., Slingsby, J.A., and Esler, K.J. 2019. Identifying research questions for the conservation of the Cape Floristic Region. S. Afr. J. Sci., **115**(9/10). doi:10.17159/sajs.2019/5889.

Ammer, C., Fichtner, A., Fischer, A., Gossner, M.M., Meyer, P., Seidl, R., et al. 2018. Key ecological research questions for Central European forests. Basic Appl. Ecol., **32**: 3–25. doi:10.1016/j.baae.2018.07.006.

Bayley, S.E., Creed, I.F., Sass, G.Z., and Wong, A.S. 2007. Frequent regime shifts in trophic states in shallow lakes on the Boreal Plain: alternative "unstable" states? Limnol. Oceanogr., **52**(5): 2002–2012. doi:10.4319/lo.2007.52.5.2002.

Beisner, B., Haydon, D., and Cuddington, K. 2003. Alternative stable states in ecology. Front. Ecol. Environ., **1**(7): 376–382. doi:10.1890/1540-9295(2003)001[0376:ASSIE]2.0.CO;2.

Bennett, E.M., Solan, M., Biggs, R., McPhearson, T., Norström, A.V., Olsson, P., et al. 2016. Bright spots: seeds of a good Anthropocene. Front. Ecol. Environ., **14**(8): 441–448. doi:10.1002/fee.1309.

Bennett, J.R., Maxwell, S.L., Martin, A.E., Chadès, I., Fahrig, L., and Gilbert, B. 2018. When to monitor and when to act: value of information theory for multiple management units and limited budgets. J. Appl. Ecol., **55**(5): 2102–2113. doi:10.1111/1365-2664.13132.

Biggs, R., Peterson, G., and Rocha, J. 2018. The Regime Shifts Database: a framework for analyzing regime shifts in social-ecological systems. Ecol. Soc., **23**(3). doi:10.5751/ES-10264-230309.

Blöcker, A.M., Gutte, H.M., Bender, R.L., Otto, S.A., Sguotti, C., and Möllmann, C. 2023. Regime shift dynamics, tipping points and the success of fisheries management. Sci. Rep., **13**(1): 289. doi:10.1038/s41598-022-27104-y. PMID: 36609587.

Boettiger, C., and Hastings, A. 2012. Early warning signals and the prosecutor's fallacy. Proc. R. Soc. B: Biol. Sci., **279**(1748): 4734–4739. Available from https://www.jstor.com/stable/41727528. doi:10.1098/rspb.2012.2085.

Bonar, S.A., and Hubert, W.A. 2002. Standard sampling of Inland fish: benefits, challenges, and a call for action. Fisheries, **27**(3): 10–16. doi:10.1577/1548-8446(2002)027⟨0010:SSOIF⟩2.0.CO;2.

Brovkin, V., Brook, E., Williams, J.W., Bathiany, S., Lenton, T.M., Barton, M., et al. 2021. Past abrupt changes, tipping points and cascading impacts in the Earth system. Nat. Geosci., **14**(8): 550–558. doi:10.1038/s41561-021-00790-5.

Bryden, J., Gill, R.J., Mitton, R.A.A., Raine, N.E., Jansen, V.A.A., and Hodgson, D. 2013. Chronic sublethal stress causes bee colony failure. Ecol. Lett., **16**(12): 1463–1469. doi:10.1111/ele.12188. PMID: 24112478.

Burthe, S.J., Henrys, P.A., Mackay, E.B., Spears, B.M., Campbell, R., Carvalho, L., et al. 2016. Do early warning indicators consistently predict nonlinear change in long-term ecological data? J. Appl. Ecol., **53**(3): 666–676. doi:10.1111/1365-2664.12519.

Cai, Y., Judd, K.L., Lenton, T.M., Lontzek, T.S., and Narita, D. 2015. Environmental tipping points significantly affect the cost−benefit assessment of climate policies. Proc. Natl. Acad. Sci. USA, **112**(15): 4606–4611. Proceedings of the National Academy of Sciences. doi:10.1073/pnas.1503890112.

Carpenter, S.R., Cole, J.J., Pace, M.L., Batt, R., Brock, W.A., Cline, T., et al. 2011. Early warnings of regime shifts: a whole-ecosystem experiment. Science, **332**(6033): 1079–1082. doi:10.1126/science.1203672. PMID: 21527677.

Carrier-Belleau, C., Pascal, L., Nozais, C., and Archambault, P. 2022. Tipping points and multiple drivers in changing aquatic ecosystems: a review of experimental studies. Limnol. Oceanogr., **67**(S1): S312–S330. doi:10.1002/lno.11978.

Christianen, M.J.A., Herman, P.M.J., Bouma, T.J., Lamers, L.P.M., van Katwijk, M.M., van der Heide, T., et al. 2014. Habitat collapse due to overgrazing threatens turtle conservation in marine protected areas. Proc. R. Soc. B: Biol. Sci., **281**(1777): 20132890. doi:10.1098/rspb.2013.2890.

Collins, S.L., Nippert, J.B., Blair, J.M., Briggs, J.M., Blackmore, P., and Ratajczak, Z. 2021. Fire frequency, state change and hysteresis in tallgrass prairie. Ecol. Lett., **24**(4): 636–647. doi:10.1111/ele.13676. PMID: 33443318.

Côté, I.M., Darling, E.S., and Brown, C.J. 2016. Interactions among ecosystem stressors and their importance in conservation. Proc. R. Soc. B: Biol. Sci., **283**(1824): 20152592. doi:10.1098/rspb.2015.2592.

Cvitanovic, C., and Hobday, A.J. 2018. Building optimism at the environmental science-policy-practice interface through the study of bright spots. Nat. Commun., **9**(1): 3466. doi:10.1038/s41467-018-05977-w.

Dakos, V., Matthews, B., Hendry, A.P., Levine, J., Loeuille, N., Norberg, J., et al. 2019. Ecosystem tipping points in an evolving world. Nat. Ecol. Evol., **3**(3): 355–362. doi:10.1038/s41559-019-0797-2.

Dakos, V., Scheffer, M., van Nes, E.H., Brovkin, V., Petoukhov, V., and Held, H. 2008. Slowing down as an early warning signal for abrupt climate change. Proc. Natl. Acad. Sci. USA, **105**(38): 14308–14312. doi:10.1073/pnas.0802430105.

Dey, C.J., Rego, A.I., Bradford, M.J., Clarke, K.D., McKercher, K., Mochnacz, N.J., et al. 2021. Research priorities for the management of freshwater fish habitat in Canada. Can. J. Fish. Aquat. Sci., **78**(11): 1744–1754. doi:10.1139/cjfas-2021-0002.

Dick, D. 2021. Quantifying similarity in paleontological settings: accuracy, complexity, and macroevolutionary implications. Doctoral thesis, University of Toronto, Toronto. Available from https://www.proquest.com/openview/153a3a9a8da6a4313ef3f5940e053bb0/1.pdf?pq-origsite=gscholar&cbl=18750&diss=y#page=96.

Dutta, P.S., Sharma, Y., and Abbott, K.C. 2018. Robustness of early warning signals for catastrophic and non-catastrophic transitions. Oikos, **127**(9): 1251–1263. doi:10.1111/oik.05172.

Filbee-Dexter, K., Pittman, J., Haig, H.A., Alexander, S.M., Symons, C.C., and Burke, M.J. 2017. Ecological surprise: concept, synthesis, and social dimensions. Ecosphere, **8**(12): e02005. doi:10.1002/ecs2.2005.

Filbee-Dexter, K., and Scheibling, R.E. 2014. Sea urchin barrens as alternative stable states of collapsed kelp ecosystems. Mar. Ecol. Prog. Ser., **495**: 1–25. doi:10.3354/meps10573.

Foley, M.M., Martone, R.G., Fox, M.D., Kappel, C.V., Mease, L.A., Erickson, A.L., et al. 2015. Using ecological thresholds to inform resource management: current options and future possibilities. Front. Mar. Sci., **2**: 95. doi: 10.3389/fmars.2015.00095.

Folt, C.L., Chen, C.Y., Moore, M.V., and Burnaford, J. 1999. Synergism and antagonism among multiple stressors. Limnol. Oceanogr., **44**(3part2): 864–877. doi:10.4319/lo.1999.44.3_part_2.0864.

Ford, R.M., Rawluk, A., and Williams, K.J.H. 2021. What do you mean by values? Integration of social with biophysical knowledge in the development of a landscape decision support system. Environ. Sci. Policy, **124**: 656–664. doi:10.1016/j.envsci.2021.08.011.

Friedman, W.R., Halpern, B.S., McLeod, E., Beck, M.W., Duarte, C.M., Kappel, C.V., et al. 2020. Research priorities for achieving healthy marine ecosystems and human communities in a changing climate. Front. Mar. Sci., **7**: 5. doi: 10.3389/fmars.2020.00005.

García, M.B., Silva, J.L., Tejero, P., and Pardo, I. 2021. Detecting early-warning signals of concern in plant populations with a Citizen Science network. Are threatened and other priority species for conservation performing worse? J. Appl. Ecol., **58**(7): 1388–1398. doi:10.1111/1365-2664.13890.

Gunderson, A.R., Armstrong, E.J., and Stillman, J.H. 2016. Multiple stressors in a changing world: the need for an improved perspective on physiological responses to the dynamic marine environment. Annu. Rev.Mar Sci., **8**: 357–378. doi:10.1146/annurev-marine-122414-033953.

Gutowsky, L.F.G., Giacomini, H.C., de Kerckhove, D.T., Mackereth, R., McCormick, D., and Chu, C. 2019. Quantifying multiple pressure interactions affecting populations of a recreationally and commercially important freshwater fish. Glob. Change Biol., **25**(3): 1049–1062. doi:10.1111/gcb.14556.

Gsell, A.S., Scharfenberger, U., Özkundakci, D., Walters, A., Hansson, L.A., Janssen, A.B., et al. 2016. Evaluating early-warning indicators of critical transitions in natural aquatic ecosystems. Proc. Natl. Acad. Sci. USA, **113**(50): E8089–E8095. doi:10.1073/pnas.1608242113.

Hansen, G.J.A., Ives, A.R., Vander Zanden, M.J., and Carpenter, S.R. 2013. Are rapid transitions between invasive and native species caused by alternative stable states, and does it matter? Ecology, **94**(10): 2207–2219. doi:10.1890/13-0093.1.

Harley, C.D.G., Connell, S.D., Doubleday, Z.A., Kelaher, B., Russell, B.D., Sarà, G., and Helmuth, B. 2017. Conceptualizing ecosystem tipping points within a physiological framework. Nat. Ecol. Evol., **7**(15): 6035–6045. doi:10.1002/ece3.3164.

Hastings, A., Abbott, K.C., Cuddington, K., Francis, T., Gellner, G., Lai, Y.-C., et al. 2018. Transient phenomena in ecology. Science, **361**(6406): eaat6412. doi:10.1126/science.aat6412.

Hewitt, J.E., and Thrush, S.F.,2019. Monitoring for tipping points in the marine environment. J. Environ. Manage., **234**: 131–137. doi:10.1016/j.jenvman.2018.12.092.

Hillebrand, H., Donohue, I., Harpole, W.S., Hodapp, D., Kucera, M., Lewandowska, A.M., et al. 2020. Thresholds for ecological responses to global change do not emerge from empirical data. Nat. Ecol. Evol., **4**(11): 1502–1509. doi:10.1038/s41559-020-1256-9.

Hirota, M., Holmgren, M., Van Nes, E.H., and Scheffer, M. 2011. Global resilience of tropical forest and savanna to critical transitions. Science, **334**(6053): 232–235. doi:10.1126/science.1210657.

Holbrook, S.J., Schmitt, R.J., Adam, T.C., and Brooks, A.J. 2016. Coral reef resilience, tipping points and the strength of herbivory. Sci. Rep., **6**(1): 35817. doi:10.1038/srep35817.

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

Hughes, T.P., Carpenter, S., Rockström, J., Scheffer, M., and Walker, B. 2013a. Multiscale regime shifts and planetary boundaries. Trends Ecol. Evol., **28**(7): 389–395. doi:10.1016/j.tree.2013.05.019.

Hughes, T.P., Linares, C., Dakos, V., van de Leemput, I.A., and van Nes, E.H. 2013b. Living dangerously on borrowed time during slow, unrecognized regime shifts. Trends Ecol. Evol., **28**(3): 149–155. doi:10.1016/j.tree.2012.08.022.

IPCC. 2021. Climate change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. *Edited by* V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger , et al., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. doi:10.1017/9781009157896.

Johnson, C.J., and Ray, J.C. 2021. The challenge and opportunity of applying ecological thresholds to environmental assessment decision making. Handbook of cumulative impact assessment, pp. 140–157. Edward Elgar Publishing, Gloucester UK and Northampton, Massachusetts USA. doi: 10.4337/9781783474028.00020.

Kéfi, S., Saade, C., Berlow, E.L., Cabral, J.S., and Fronhofer, E.A. 2022. Scaling up our understanding of tipping points. Philos. Trans. R. Soc. Lond., B, Biol. Sci., **377**(1857): 20210386. Royal Society. doi:10.1098/rstb.2021.0386.

Keith, D.A. 2015. Assessing and managing risks to ecosystem biodiversity. Austral Ecol., **40**(4): 337–346. doi:10.1111/aec.12249.

Kelly, R.P., Erickson, A.L., and Mease, L.A. 2014. How not to fall off a cliff, or, using tipping points to improve environmental management. Ecol. Law Q., **41**(4): 843–886. doi:10.15779/Z38FP1H.

Kelly, R.P., Erickson, A.L., Mease, L.A., Battista, W., Kittinger, J.N., and Fujita, R. 2015. Embracing thresholds for better environmental management. Philos. Trans. R. Soc.: B, Biol. Sci., **370**(1659): 20130276. doi:10.1098/rstb.2013.0276.

Kidd, L.R., Bekessy, S.A., and Garrard, G.E. 2019. Neither hope nor fear: empirical evidence should drive biodiversity conservation strategies. Trends Ecol. Evol., **34**(4): 278–282. doi:10.1016/j.tree.2019.01.018.

Kim, D.-K., Yang, C., Parsons, C.T., Bowman, J., Theÿsmeÿer, T., and Arhonditsis, G.B. 2021. Eutrophication management in a Great Lakes wetland: examination of the existence of alternative ecological states. Ecosphere, **12**(2): e03339. doi:10.1002/ecs2.3339.

Klose, A.K., Karle, V., Winkelmann, R., and Donges, J.F. 2020. Emergence of cascading dynamics in interacting tipping elements of ecology and climate. R. Soc. Open Sci., **7**(6): 200599. doi:10.1098/rsos.200599.

Kroeker, K.J., Kordas, R.L., and Harley, C.D.G. 2017. Embracing interactions in ocean acidification research: confronting multiple stressor scenarios and context dependence. Biol. Lett., **13**(3): 20160802. doi:10.1098/rsbl.2016.0802.

Lapointe, B.E., Brewton, R.A., Herren, L.W., Porter, J.W., and Hu, C. 2019. Nitrogen enrichment, altered stoichiometry, and coral reef decline at Looe Key, Florida Keys, USA: a 3-decade study. Mar Biol., **166**(8): 108. doi:10.1007/s00227-019-3538-9.

Lenton, T.M. 2020. Tipping positive change. Philos. Trans. R. Soc.: B, Biol. Sci., **375**(1794): 20190123. doi:10.1098/rstb.2019.0123.

Lester, N.P., Sandstrom, S., de Kerckhove, D.T., Armstrong, K., Ball, H., Amos, J., et al. 2021. Standardized broad-scale management and monitoring of inland lake recreational fisheries: an overview of the Ontario experience. Fisheries, **46**(3): 107–118. doi:10.1002/fsh.10534.

Li, L., Fassnacht, F.E., and 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. Landscape Ecol., **36**(8): 2277–2293. doi:10.1007/s10980-021-01191-0.

Ling, S.D., Johnson, C.R., Frusher, S.D., and Ridgway, K.R. 2009. Overfishing reduces resilience of kelp beds to climate-driven catastrophic phase shift. Proc. Natl. Acad. Sci. USA, **106**(52): 22341–22345. Proceedings of the National Academy of Sciences. doi:10.1073/pnas.0907529106.

Litzow, M.A., and Hunsicker, M.E. 2016. Early warning signals, nonlinearity, and signs of hysteresis in real ecosystems. Ecosphere, **7**(12): e01614. doi:10.1002/ecs2.1614.

Liu, T., Chen, D., Yang, L., Meng, J., Wang, Z., Ludescher, J., et al. 2023. Teleconnections among tipping elements in the Earth system. Nat. Clim. Chang., **13**(1): 67–74. doi:10.1038/s41558-022-01558-4.

Mahony, C.R., Cannon, A.J., Wang, T., and Aitken, S.N. 2017. A closer look at novel climates: new methods and insights at continental to landscape scales. Glob. Change Biol., **23**(9): 3934–3955. doi:10.1111/gcb.13645.

Marchessaux, G., Mangano, M.C., Bizzarri, S., M'Rabet, C., Principato, E., Lago, N., et al. 2023. Invasive blue crabs and small-scale fisheries in the Mediterranean sea: local ecological knowledge, impacts and future management. Mar. Policy, **148**: 105461. doi:10.1016/j.marpol.2022.105461.

Mason, J.G., Rudd, M.A., and Crowder, L.B. 2017. Ocean research priorities: similarities and differences among scientists, policymakers, and fishermen in the United States. BioScience, **67**(5): 418. doi:10.1093/biosci/biw172.

McDonald-Madden, E., Baxter, P.W.J., Fuller, R.A., Martin, T.G., Game, E.T., Montambault, J., and Possingham, H.P. 2010. Monitoring does not always count. rends Ecol. Evol., **25**(10): 547–550. doi:10.1016/j.tree.2010.07.002.

Menge, B.A., Chan, F., Dudas, S., Eerkes-Medrano, D., Grorud-Colvert, K., Heiman, K., et al. 2009. Terrestrial ecologists ignore aquatic literature: asymmetry in citation breadth in ecological publications and implications for generality and progress in ecology. J. Exp. Mar. Biol. Ecol., **377**(2): 93–100. doi:10.1016/j.jembe.2009.06.024.

Mengistu, S.G., Creed, I.F., Kulperger, R.J., and Quick, C.G. 2013a. Russian nesting dolls effect—using wavelet analysis to reveal non-stationary and nested stationary signals in water yield from catchments on a northern forested landscape. Hydrol. Process., **27**(5): 669–686. doi:10.1002/hyp.9552.

Mengistu, S.G., Quick, C.G., and Creed, I.F. 2013b. Nutrient export from catchments on forested landscapes reveals complex nonstationary and stationary climate signals. Water Resour. Res., **49**(6): 3863–3880. doi:10.1002/wrcr.20302.

Milkoreit, M., Hodbod, J., Baggio, J., Benessaiah, K., Calderón-Contreras, R., Donges, J.F., et al. 2018. Defining tipping points for social-ecological systems scholarship—an interdisciplinary literature review. Environ. Res. Lett., **13**(3): 033005. doi:10.1088/1748-9326/aaaa75.

Möllmann, C., Cormon, X., Funk, S., Otto, S.A., Schmidt, J.O., Schwermer, H., et al. 2021. Tipping point realized in cod fishery. Sci. Rep., **11**(1): 14259. doi:10.1038/s41598-021-93843-z.

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

Orr, J.A., Vinebrooke, R.D., Jackson, M.C., Kroeker, K.J., Kordas, R.L., Mantyka-Pringle, C., et al. 2020. Towards a unified study of multiple stressors: divisions and common goals across research disciplines. Proc. R. Soc. B: Biol. Sci., **287**(1926): 20200421. doi: 10.1098/rspb.2020.0421.

Pace, M.L., Batt, R.D., Buelo, C.D., Carpenter, S.R., Cole, J.J., Kurtzweil, J.T., and Wilkinson, G.M. 2017. Reversal of a cyanobacterial bloom in response to early warnings. Proc. Natl. Acad. Sci. USA, **114**(2): 352–357. Proceedings of the National Academy of Sciences. doi:10.1073/pnas.1612424114.

Park, A., Williams, E., and Zurba, M. 2020. Understanding hope and what it means for the future of conservation. Biol. Conserv., **244**: 108507. doi:10.1016/j.biocon.2020.108507.

Parsons, E.C.M., Favaro, B., Aguirre, A.A., Bauer, A.L., Blight, L.K., Cigliano, J.A., et al. 2014. Seventy-one important questions for the conservation of marine biodiversity. Conserv. Biol., **28**(5): 1206–1214. doi:10.1111/cobi.12303.

Pérez-Jvostov, F., Sutherland, W.J., Barrett, R.D.H., Brown, C.A., Cardille, J.A., Cooke, S.J., et al. 2020. Horizon scan of conservation issues for inland waters in Canada. Can. J. Fish. Aquat. Sci., **77**(5): 869–881. doi:10.1139/cjfas-2019-0105.

Perretti, C.T., and Munch, S.B. 2012. Regime shift indicators fail under noise levels commonly observed in ecological systems. Ecol. Appl., **22**(6): 1772–1779. Available from https://www.jstor.org/stable/41722892. doi:10.1890/11-0161.1.

Petraitis, P.S., and Dudgeon, S.R. 2004. Detection of alternative stable states in marine communities. J. Exp. Mar. Biol. Ecol., **300**(1): 343–371. doi:10.1016/j.jembe.2003.12.026.

Piggott, J.J., Townsend, C.R., and Matthaei, C.D. 2015. Reconceptualizing synergism and antagonism among multiple stressors. Ecol. Evol., **5**(7): 1538–1547. doi:10.1002/ece3.1465.

Reid, A.J., Carlson, A.K., Creed, I.F., Eliason, E.J., Gell, P.A., Johnson, P.T.J., et al. 2019. Emerging threats and persistent conservation challenges for freshwater biodiversity. Biol. Rev., **94**(3): 849–873. doi:10.1111/brv.12480.

Riegl, B., Glynn, P.W., Wieters, E., Purkis, S., d'Angelo, C., and Wiedenmann, J. 2015. Water column productivity and temperature predict coral reef regeneration across the Indo-Pacific. Sci. Rep., **5**(1): 8273. doi:10.1038/srep08273.

Rietkerk, M., Bastiaansen, R., Banerjee, S., van de Koppel, J., Baudena, M., and Doelman, A. 2021. Evasion of tipping in complex systems through spatial pattern formation. Science, **374**(6564): eabj0359. doi:10.1126/science.abj0359.

Ripple, W.J., and Beschta, R.L. 2006. Linking a cougar decline, trophic cascade, and catastrophic regime shift in Zion National Park. Biol. Conserv., **133**(4): 397–408. doi:10.1016/j.biocon.2006.07.002.

Rocha, J.C., Peterson, G., Bodin, Ö., and Levin, S. 2018. Cascading regime shifts within and across scales. Science, **362**(6421): 1379–1383. doi:10.1126/science.aat7850.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F., et al. 2009. A safe operating space for humanity. Nature, **461**(7263): 472–475. doi:10.1038/461472a.

Rosier, S.H.R., Reese, R., Donges, J.F., De Rydt, J., Gudmundsson, G.H., and Winkelmann, R. 2021. The tipping points and early warning indicators for Pine Island Glacier, West Antarctica. The Cryosphere, **15**(3): 1501–1516. doi:10.5194/tc-15-1501-2021.

Sallan, L.C., and Coates, M.I. 2010. End-Devonian extinction and a bottleneck in the early evolution of modern jawed vertebrates. Proc. Natl. Acad. Sci. USA, **107**(22): 10131–10135. Proceedings of the National Academy of Sciences. doi:10.1073/pnas.0914000107.

Sallan, L.C., Kammer, T.W., Ausich, W.I., and Cook, L.A. 2011. Persistent predator–prey dynamics revealed by mass extinction. Proc. Natl. Acad. Sci. USA, **108**(20): 8335–8338. Proceedings of the National Academy of Sciences. doi:10.1073/pnas.1100631108.

Salois, S.L., Gouhier, T.C., Helmuth, B., Choi, F., Seabra, R., and Lima, F.P. 2022. Coastal upwelling generates cryptic temperature refugia. Sci. Rep., **12**(1): 19313. doi:10.1038/s41598-022-23717-5.

Saravia, L.A., Doyle, S.R., and Bond-Lamberty, B. 2018. Power laws and critical fragmentation in global forests. Sci. Rep., **8**(1): 17766. doi:10.1038/s41598-018-36120-w.

Scheffer, M., Bascompte, J., Brock, W.A., Brovkin, V., Carpenter, S.R., Dakos, V., et al. 2009. Early-warning signals for critical transitions. Nature, **461**(7260): 53–59. doi:10.1038/nature08227.

Scheffer, M., Carpenter, S., Foley, J.A., Folke, C., and Walker, B. 2001. Catastrophic shifts in ecosystems. Nature, **413**(6856): 591–596. doi:10.1038/35098000.

Scheffer, M., and Carpenter, S.R. 2003. Catastrophic regime shifts in ecosystems: linking theory to observation. Trends Ecol. Evol., **18**(12): 648–656. doi:10.1016/j.tree.2003.09.002.

Scheffer, M., and van Nes, E.H. 2007. Shallow lakes theory revisited: various alternative regimes driven by climate, nutrients, depth and lake size. Hydrobiologia, **584**: 455–466. doi:10.1007/s10750-007-0616-7.

Schindler, D.E., Armstrong, J.B., and Reed, T.E. 2015. The portfolio concept in ecology and evolution. Front. Ecol. Environ., **13**(5): 257–263. doi:10.1890/140275.

Selkoe, K.A., Blenckner, T., Caldwell, M.R., Crowder, L.B., Erickson, A.L., Essington, T.E., et al. 2015. Principles for managing marine ecosystems prone to tipping points. Ecosyst. Health Sustain., **1**(5): 1–18. doi:10.1890/EHS14-0024.1.

Simenstad, C.A., Estes, J.A., and Kenyon, K.W. 1978. Aleuts, sea otters, and alternate stable-state communities. Science, **200**(4340): 403–411. doi:10.1126/science.200.4340.403.

Smol, J.P., Wolfe, A.P., Birks, H.J.B., Douglas, M.S.V., Jones, V.J., Korhola, A., et al. 2005. Climate-driven regime shifts in the biological communities of arctic lakes. Proc. Natl. Acad. Sci. USA, **102**(12): 4397–4402. Proceedings of the National Academy of Sciences. doi:10.1073/pnas.0500245102.

Stelzer, J.A.A., Mesman, J.P., Adrian, R., and 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. doi:10.1016/j.ecocom.2021.100944.

Steneck, R.S., Hughes, T.P., Cinner, J.E., Adger, W.N., Arnold, S.N., Berkes, F., et al. 2011. Creation of a gilded trap by the high economic value of the Maine lobster fishery. Conserv. Biol., **25**(5): 904–912. doi:10.1111/j.1523-1739.2011.01717.x.

Stewart, N.L., and Konar, B. 2012. Kelp forests versus urchin barrens: alternate stable states and their effect on sea otter prey quality in the Aleutian Islands. Indian J. Mar. Sci., **2012**: e492308. Hindawi. doi:10.1155/2012/492308.

Suding, K.N., and Hobbs, R.J. 2009. Threshold models in restoration and conservation: a developing framework. Trends Ecol. Evol., **24**(5): 271–279. doi:10.1016/j.tree.2008.11.012.

Thompson, P.L., Guzman, L.M., De Meester, L., Horváth, Z., Ptacnik, R., Vanschoenwinkel, B., et al. 2020. A process-based metacommunity framework linking local and regional scale community ecology. Ecol. Lett., **23**(9): 1314–1329. doi:10.1111/ele.13568.

Tulloch, V.J.D., Atkinson, S., Possingham, H.P., Peterson, N., Linke, S., Allan, J.R., et al. 2021. Minimizing cross-realm threats from land-use change: a national-scale conservation framework connecting land, freshwater and marine systems. Biol. Conserv., **254**: 108954. doi:10.1016/j.biocon.2021.108954.

van Nes, E.H., Arani, B.M.S., Staal, A., van der Bolt, B., Flores, B.M., Bathiany, S., and Scheffer, M. 2016. What do you mean, 'tipping point'? Trends Ecol. Evol., **31**(12): 902–904. doi:10.1016/j.tree.2016.09.011.

Vitousek, P.M., Mooney, H.A., Lubchenco, J., and Melillo, J.M. 1997. Human domination of earth's ecosystems. Science, **277**(5325): 494–499. doi:10.1126/science.277.5325.494.

Webb, T.J. 2012. Marine and terrestrial ecology: unifying concepts, revealing differences. Trends Ecol. Evol., **27**(10): 535–541. doi:10.1016/j.tree.2012.06.002.

Yanchilina, A.G., Ryan, W.B.F., McManus, J.F., Dimitrov, P., Dimitrov, D., Slavova, K., and Filipova-Marinova, M. 2017. Compilation of geophysical, geochronological, and geochemical evidence indicates a rapid Mediterranean-derived submergence of the Black Sea's shelf and subsequent substantial salinification in the early Holocene. Mar. Geol., **383**: 14–34. doi:10.1016/j.margeo.2016.11.001.

Yletyinen, J., Brown, P., Pech, R., Hodges, D., Hulme, P.E., Malcolm, T.F., et al. 2019. Understanding and managing social–ecological tipping points in primary industries. BioScience, **69**(5): 335–347. doi:10.1093/biosci/biz031.

Yletyinen, J., Hentati-Sundberg, J., Blenckner, T., and Bodin, Ö. 2018. Fishing strategy diversification and fishers' ecological dependency. Ecol. Soc., **23**(3). doi:10.5751/ES-10211-230328.