Social-ecological connections across land, water, and sea demand a reprioritization of environmental management

Gladstone-Gallagher, Rebecca

2022-06-08

Gladstone-Gallagher , R , Tylianakis , J M , Yletyinen , J , Dakos , V , Douglas , E J , Greenhalgh , S , Hewitt , J E , Hikuroa , D , Lade , S J , Le Heron , R , Norkko , A , Perry , G L W , Pilditch , C A , Schiel , D , Siwicka , E , Warburton , H & Thrush , S F 2022 , ' Social-ecological connections across land, water, and sea demand a reprioritization of environmental management ' , Elementa: Science of the Anthropocene , vol. 10 , no. 1 . https://doi.org/10.1525/elem

http://hdl.handle.net/10138/345958
https://doi.org/10.1525/elementa.2021.00075

ELEMENTA
Science of the Anthropocene

Gladstone-Gallagher, RV, et al. 2022. Social–ecological connections across land, water, and sea demand a reprioritization of environmental management. *Elem Sci Anth*, 10: 1. DOI: https://doi.org/10.1525/elementa.2021.00075

PRACTICE BRIDGE

Social—ecological connections across land, water, and sea demand a reprioritization of environmental management

Rebecca V. Gladstone-Gallagher[1,*], Jason M. Tylianakis[2], Johanna Yletyinen[3,4], Vasilis Dakos[5], Emily J. Douglas[6], Suzie Greenhalgh[7], Judi E. Hewitt[1,6], Daniel Hikuroa[1], Steven J. Lade[8,9], Richard Le Heron[1], Alf Norkko[10,11], George L. W. Perry[1], Conrad A. Pilditch[12], David Schiel[2], Ewa Siwicka[1], Helen Warburton[2], and Simon F. Thrush[1]

Despite many sectors of society striving for sustainability in environmental management, humans often fail to identify and act on the connections and processes responsible for social–ecological tipping points. Part of the problem is the fracturing of environmental management and social–ecological research into ecosystem domains (land, freshwater, and sea), each with different scales and resolution of data acquisition and distinct management approaches. We present a perspective on the social–ecological connections across ecosystem domains that emphasize the need for management reprioritization to effectively connect these domains. We identify critical nexus points related to the drivers of tipping points, scales of governance, and the spatial and temporal dimensions of social–ecological processes. We combine real-world examples and a simple dynamic model to illustrate the implications of slow management responses to environmental impacts that traverse ecosystem domains. We end with guidance on management and research opportunities that arise from this cross-domain lens to foster greater opportunity to achieve environmental and sustainability goals.

Keywords: Cross-domain, Cumulative effects, Ecosystem-based management, Hilltops to ocean, Tipping points

Introduction

Increasing rates of environmental change, the crisis of biodiversity, the loss of ecosystem services (ES), and the risk of surprises from tipping points (nonlinear ecological or social transformations) highlight the need to find different approaches to navigate society toward ecological sustainability (Vitousek, 1997; Scheffer et al., 2001; Rockstrom et al., 2009; Lindenmayer et al., 2010; Carpenter et al., 2015; Organisation for Economic Co-operation and Development, 2017; Filbee-Dexter et al., 2018). Despite many sectors of society striving for sustainability and balanced interactions with the environment, the current focus and effort is insufficient to generate sustainable solutions because it does not account for the whole problem. The issues that humanity collectively needs to address are relevant both to interventions that react to problems and those that seek to prevent them. Here, we explore how a focus on the social and ecological connections and feedbacks (both positive and negative) across ecosystem domains (land, freshwater, and marine) can promote resilience to multiple future threats (Biggs et al., 2011; Selkoe et al., 2017; Lenton, 2020).

Ecological and social knowledge accumulated over decades has highlighted the role of biophysical subsidies and connectivity across a “hilltops to ocean” continuum (Polis and Hurd, 1996; Ramesh et al., 2015; Gounand et al.,

---

[1] University of Auckland, Auckland, New Zealand
[2] University of Canterbury, Christchurch, New Zealand
[3] Manaaki Whenua Landcare Research, Lincoln, New Zealand
[4] School of Resource Wisdom, University of Jyväskylä, Jyväskylä, Finland
[5] ISEM, Univ Montpellier, CNRS, EPHE, IRD, Montpellier, France
[6] National Institute of Water and Atmospheric Research (NIWA), Hamilton, New Zealand
[7] Manaaki Whenua Landcare Research, Auckland, New Zealand
[8] Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden
[9] Fenner School of Environment & Society, Australian National University, Canberra, Australia
[10] Tvarminne Zoological Station, University of Helsinki, Hanko, Finland
[11] Baltic Sea Centre, Stockholm University, Stockholm, Sweden
[12] University of Waikato, Hamilton, New Zealand

* Corresponding author:
Email: rebecca.gladstone-gallagher@auckland.ac.nz

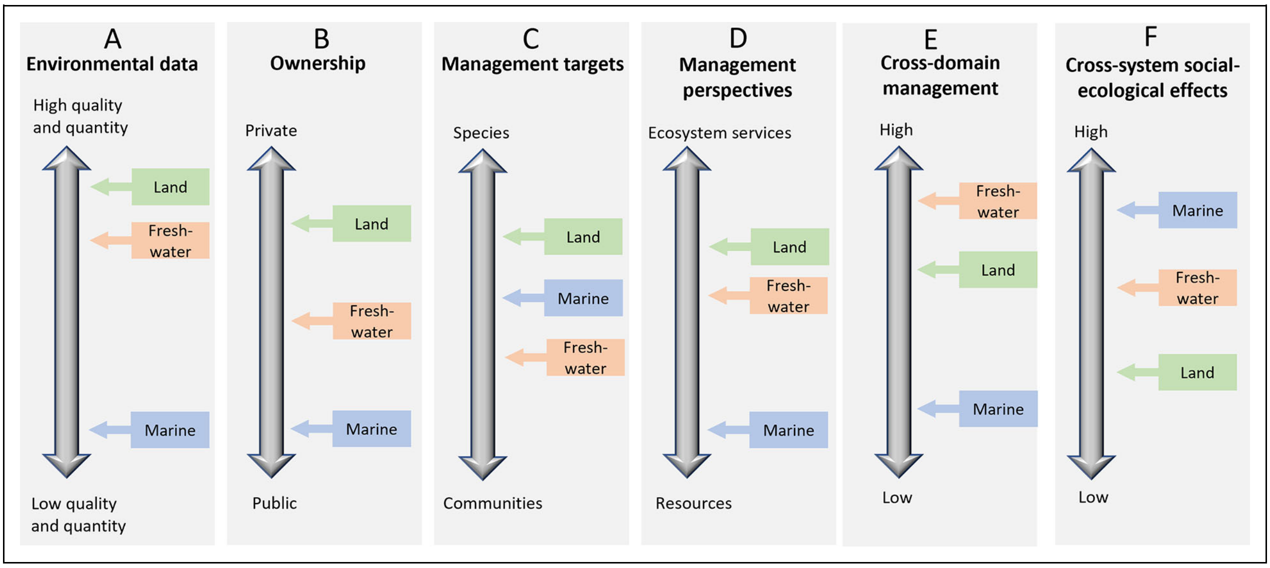

Figure 1. Disparities between land, freshwater, and marine ecosystem domains. In our experience, disparities in these social, political, ecological, and management variables between ecosystem domains contribute to the difficulties in managing to prevent tipping points. DOI: https://doi.org/10.1525/elementa.2021.00075.f1

2018). Despite this, management practice still tends to be isolated by ecosystem domain (Singh et al., 2021; Threlfall et al., 2021), often using different approaches and frameworks, with inequities in data and knowledge (**Figure 1**). Land can be privately owned, but the ocean is usually in the public domain, and this discrepancy leads to different aspirations and targets (**Figure 1B**). Environmental management on land is targeted at species (animal or plant) or habitats and focused on the ES that biodiversity provides, while in the ocean, resource extraction is prioritized (**Figure 1C** and **D**). The relative visibility of changes and ease of access to the 3 ecosystem domains also drives differences in social awareness and how we allocate science and management resources. Consequently, environmental data quality and quantity tend to be greater in volume, velocity, and variety for land than in freshwater, with both well ahead of marine (**Figure 1A**).

Systems thinking and more holistic management approaches such as ecosystem-based management are much discussed concepts but have proven difficult to implement (Christensen et al., 1996; Ruckelshaus et al., 2008; Granek et al., 2010; Thrush and Dayton, 2010). Because environmental issues are often dealt with in isolation, governments, businesses, and individuals can fail to first identify and then act on the connections that lead to and prevent abrupt unexpected state changes or tipping points. Tipping points occur when a system's environmental and social stressors (or phenomena) have intensified to the point where a system shifts to a different state (often for the worse from a human perspective). Further sudden (nonlinear) changes from that point are also possible (i.e., multiple tipping points can exist), and state shifts can trigger other state shifts in distant locations, for instance, via nutrient and water flow (Rocha et al., 2018). There is a growing realization that interactions among social and ecological components of ecosystems are crucial for fostering positive environmental outcomes where tipping points can be foreseen and prevented. For example, an extensive literature and multiple cultures highlight a deep interconnection between social and ecological systems that coevolve across space and time, allowing adaptation in times of change (Folke, 2006; Carpenter et al., 2015; Osterblom et al., 2017; Filbee-Dexter et al., 2018; Nystrom et al., 2019; Yletyinen et al., 2019).

In a highly connected world with the certainty of climate change and further anthropogenic exploitation (Nystrom et al., 2019), it is imperative to explore and implement robust management regimes. To be robust to a range of plausible futures, management should traverse land, freshwater, and marine ecosystem domains and consider their connectivity in important functions, flows, feedbacks, and impacts (Schiel and Howard-Williams, 2016). We refer to these critical connections as "cross-domain connections," and "connectivity" as the movement of materials, energy, ideas, and the expansion of social structures and practices across land, freshwater, and sea. We focus on these cross-domain connections as these represent major opportunities to improve environmental management and governance. While the level of integration of hierarchies in governance may vary both within and across domains (Singh et al., 2021), our focus is on the ecological and social linkages. This approach and framing are consistent with many Indigenous Peoples' worldview, knowledge, and practice (e.g., McGregor, 2004; Clapcott [Ngāti Porou] et al., 2018). Here, we lay out the latent opportunities for management, which currently does not adequately acknowledge these cross-ecosystem domain connections, and therefore has limited potential to enhance sustainability and the resilience needed to prevent undesirable tipping points.

The ideas presented in this perspective piece evolved from a workshop designed to address the siloed nature of the New Zealand National Science Challenges, which arguably reflect broader management and governance structures in New Zealand and globally. These National Science

Challenges were deliberately focused on separated environmental domains (e.g., marine, freshwater, and land). Our collective concern was that the connections between ecosystems were being ignored, or at least not prioritized, thus limiting research and solution sets (e.g., management interventions). The workshop involved an internationally diverse set of 17 researchers whose research spans the 3 ecosystem domains and multiple disciplines including ecology, social sciences, economics, Māori and indigenous studies, natural resource management, and systems modelling. Based on our collective experiences and discussions during the workshop, we (1) present our perspectives on the social–ecological properties of cross-domain connections that emphasize the need for management reprioritization, (2) demonstrate that the strength and speed of cross-ecosystem domain feedbacks in the social (management) versus ecological components often differ (illustrated with a simple dynamic model to demonstrate possible environmental outcomes associated with delayed management responses [relative to the generation of ecological impacts]), and (3) offer guidance for cross-domain environmental management and research priorities that aim to better prepare for and mitigate tipping points. Throughout our narrative, we connect broader concepts to 3 case study examples (**Boxes 1–3**). Importantly, we highlight the benefits of investing effort and focus on cross-domain and cross-scale (space and time) connections to identify the common threads that support opportunities for change.

The social—ecological properties of cross-domain connectivity that demand a reprioritization of ecosystem management

Humanity has known of cross-domain connections for centuries but appears to be continually surprised by their

Box 1 — Baltic Sea: Managing eutrophication.

The semi-enclosed, brackish Baltic Sea is bordered by 9 countries with different policy priorities and socioeconomic conditions. The Baltic is also heterogeneous in terms of biodiversity, climate, hydrography, ecosystem health, and likely future states. Decades of diffusive nutrient loading from agriculture and municipalities in combination with the Baltic's environmental history have led to large-scale eutrophication (a demonstration of Social-Ecological Properties SE-P1 and 3 in main text). Infrequent saltwater inflows from the North Sea do not dilute the nutrient rich brackish water but amplify how nutrient enrichment is manifested in the Baltic by influencing water-column stratification, vertical exchange of water masses and nutrients, and hence the spreading extent of hypoxia (Carstensen et al., 2014).

An intergovernmental convention managed by the Helsinki Commission (HELCOM, 2018) was established to address these problems. The commission represents an advancement in the way we manage waters that works to restore the upstream social–ecological feedback where land practices are managed with the health of the Baltic Sea ecosystem in mind (a step toward management and research priority P4 in main text). HELCOM builds on the long tradition of trust and collaboration between the science community and policy makers in the region (exemplifying P7 in main text; Reusch et al., 2018; Stenseth et al., 2020). The Baltic Sea Action Plan represents a positive cross-sectorial agreement to define the problem(s) and to set explicit ecosystem-based goals and objectives and accompanying indicators and targets for reaching good environmental/ecological status while "supporting a range of sustainable human economic and social activities for the marine ecosystem" (HELCOM, 2021). This has resulted in good progress on reducing nutrient inputs, addressing eutrophication, and improvements in the eutrophic state have been observed (epitomizing P3 and P6 in main text; Andersen et al., 2017). However, broader but more ambitious goals of a sea "unaffected by eutrophication" by 2021 have highlighted the difficulties in effective management even when partially complemented by comprehensive and ambitious EU legislation (Water Framework Directive [EU-WFD]; Marine Strategy Framework Directive).

While HELCOM demonstrates the positive effects of managing ecosystem connections, it also reveals how ecological and social time lags represent a major barrier to upstream social–ecological feedbacks. The time lags complicate effective management since the legacy of nutrient inputs over decadal timescales has saturated the marine ecosystem with excessive nutrients that now circulate in the system (SE-P4 in main text). This makes a direct quantitative link between present nutrient inputs from the catchment and the status of the marine environments weak. This situation frustrates both the public and policy makers. The management system is simply too slow and inert from the ecosystem and public perspectives. With ecosystem assessments conducted every 6 years, according to the EU-WFD, subsequent management feedbacks are too slow for a system experiencing rapid change (demonstrating a need for P2 in main text). Nevertheless, HELCOM remains a model of success in international environmental governance.

Climate change is rapidly reshuffling not only the structure and function of the ecosystem but also society's understanding and recognition of environmental problems. While nutrients have been a major focus of HELCOM, other pressures impacting the ecosystem, such as fishing interacting with climate change, are amplifying multiple existing regional pressures. Strategies that support ecosystem resilience rather than reducing pollutant loads are also needed. The importance of real and effective Marine Protected Areas has yet to be recognized, and progress suffers from time lags between both societal recognition and management action. Yet researchers stress that the Nordic seas (including the Baltic) must be understood and managed as an ecologically and socially connected "meta-ecosystem" (Paasche et al., 2015). Global climate change really emphasizes the importance of ramping up local and regional management efforts to conserve local biodiversity and increase resilience against harder to manage climate impacts.

consequences. For example, damming rivers in southern California reduced sediment transport to the coast, enhancing beach erosion (Sherman et al., 2002). Extraction of water for land irrigation in Australian rivers altered estuarine and lagoon circulation regimes, creating complex geochemical and physical feedbacks resulting in hyper-eutrophic states (Laurance et al., 2011). Upstream damming, sand mining, and enhanced erosion of riverbeds have led to saltwater intrusion of productive lands in the Mekong River Delta, with massive economic, social, and ecological consequences (Eslami et al., 2019). However, these unintended effects are not always deleterious for ecological sustainability. For example, the management of invasive predators on islands created unintended positive feedbacks, where removal of predation pressure on seabird populations (and their subsequent recovery) resulted in increased inputs of marine sourced nutrients, stimulating forest growth (Fukami et al., 2006).

While our current environmental management practices have had some successes (e.g., reduction of DDT pesticide in the Baltic Sea and air pollutants and acid rain in Europe and North America; Helsinki Commission [HELCOM], 2010; Grennfelt et al., 2020), global trends show that this is not sufficient to prevent tipping points. Rather than being trapped in the narrative that science needs to better inform management, we expand aspirations and view the issues through a cross-domain lens to suggest a reprioritization of management efforts. Considering even simple social–ecological properties of ecosystems through this lens can lead to improved environmental management, which may help to break the cycle of sectarian governance that currently facilitates blame and inaction (Howlett, 2014). These simple but fundamental social–ecological properties (SE-P) are as follows:

SE-P1. In general, water flows downhill

Generally, water flows from land to sea, meaning that the aquatic environment is the net recipient of change on land, and ultimately, the coastal marine environment is the net recipient of many changes in both land and freshwater ecosystems (**Figure 2**). This downstream connectivity has resulted in degradation of aquatic environments globally, which is perpetuated by disparities in ownership and accountability, governance, environmental targets, perspectives, data, management, and understanding of ecological processes between domains (e.g., see **Boxes 1–3** for real-world examples of these dynamics playing out across domains; and **Figure 1**). "Water flows downhill" is a simple axiom, and yet current environmental management of terrestrial and freshwater ecosystem domains

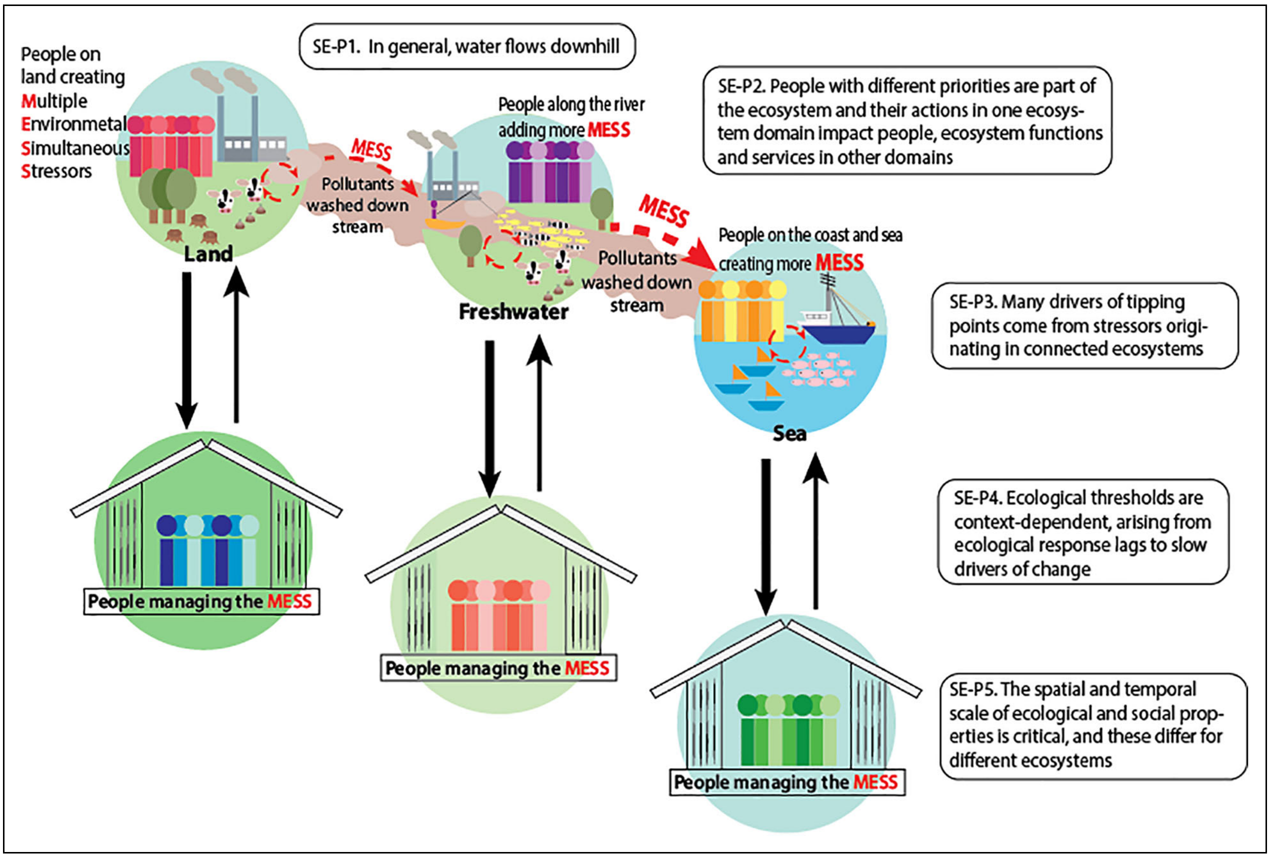

Figure 2. Diagrammatic representation of the fracturing of environmental management among ecosystem domains. The fracturing among ecosystem domains prevents social feedbacks to upstream management. The diagram lists the social–ecological properties (SE-P1–5) of cross-domain connections that demand a reprioritization of environmental management. The differential arrow thickness between people and the ecosystem domain indicates that the quantum of the "MESS" is greater than the ameliorating environmental management. DOI: https://doi.org/10.1525/elementa.2021.00075.f2

tend to devalue the considerable distal effects of land-based stressors in receiving aquatic environments (exemplified in **Box 3**'s critique of stressor limit setting; **Figure 1F**). There is a critical need to strengthen the social feedback that links downstream issues to upstream activities to sustainably manage both beneficial (e.g., subsidies) and detrimental (e.g., pollution) flows that are critical to biodiversity, and ecosystem functions and services in all 3 ecological domains (e.g., **Boxes 1** and **2**).

SE-P2. People with different values and interests are part of the ecosystem and their actions in one ecosystem domain can affect people, and ecosystem functions and services in other domains

People can be separated from the consequences of their actions by the physical segregation of ecosystem domains and governance structures (**Figure 2**). This separation becomes a problem when the benefits that an individual accrues from an ecosystem are diminished by activities in another domain, where the people creating the impacts are separated from both those managing and those affected by impacts (depicted in **Figure 2**). A decoupling of decisions from the impact location reduces the feedbacks that would change management practices (e.g., political pressure to stop a particular activity; DeFries and Nagendra, 2017). Part of this issue stems from socially constructed boundaries around physical areas and jurisdictions (e.g., privately vs. publicly owned land; regionally vs. nationally managed areas; Brunson, 1998; see **Box 2** for a discussion of values, ownership, and management scales with respect to wetland ecosystems). The perception of boundaries is not the same in the 3 ecosystem domains, leading to disparities in how people defend and protect physical areas (e.g., land, and sometimes wetlands and streams, are often in private ownership, and the ocean, and the resources it provides and sustains, are publicly owned; **Figure 1B**). People are more likely to adjust their actions to protect a forest or stream on their own property, or in a public space that is near to where they live, than a river or estuary that is some distance away (i.e., the psychological distance effect; Perry et al., 2021). Ecological processes transcend boundaries constructed by humans (DeFries and Nagendra, 2017), and this fractured social–ecological dynamic creates barriers to identifying and acting on the drivers of change and solutions.

SE-P3. Tipping points occur from multiple drivers and often from stressors originating in other connected ecosystems

The fracturing of ecosystem management across domains creates a situation where single environmental drivers (often within one ecosystem domain) are the focus of environmental impact mitigation (see **Box 3** on stressor limit setting). Policy that targets specific ecological domains ignores the abundant literature demonstrating the flow of species, resources, and environmental effects between habitats within a domain (Frost et al., 2016), and between land and freshwater (Polis and Strong, 1996; Knight et al., 2005; Bartels et al., 2012), land and marine (Polis and Hurd, 1996; Sanchez-Pinero and Polis, 2000), and freshwater and marine domains (Palumbi, 2003; Wipfli et al., 2003; Gounand et al., 2018). A siloed domain focus can make it hard to identify drivers of change (see, e.g., **Boxes 1**–**3**), and this can leave humanity unprepared for future changes that arise from multiple (often nonlinearly interacting) stressors that originate in connected ecosystem domains (Sala et al., 2000; Crain et al., 2008; Darling and Côté, 2008). For example, land management for conservation remains largely focused on focal species (typically vertebrates) or on parcels of land demarcated by the dominant ecosystem type (e.g., a forest) rather than ecosystem processes and the potential for different habitats to be connected to other ecosystems (**Figure 1C, E,** and **F**; Kortetmäki et al., 2021). Freshwater management is typically conducted at a catchment scale and explicitly considers the linkages between land and freshwater domains (e.g., nutrient and sediment flows) with a focus on processes (e.g., catchments and upstream effects; Rouse and Norton, 2016). Land and freshwater management drive change in wetlands (**Box 2**), but it does not account for how wetlands can buffer change in estuaries or be impacted by salination associated with sea-level rise. Further, since freshwater quality and quantity are the main priorities, there is little consideration of any downstream effects in the marine domain. Management of the coastal marine environment usually recognizes the connectivity and impacts of decisions on land, but there are significant time lags and barriers associated with mitigating these distal effects (**Figure 1F**; **Box 1**; Schiel and Howard-Williams, 2016; Osterblom et al., 2017).

SE-P4. Ecological thresholds are context-dependent and can arise due to lags in slow ecological responses to chronic and subtle drivers of change

Ecological thresholds in one ecosystem domain often do not apply to other domains, and hence, a focus on stressor limit setting is unable to prevent threshold responses and tipping points (see **Boxes 2** and **3**). For example, the ecological limits for land-based sediment and nutrients into freshwater ecosystems are irrelevant for assessing the coastal marine environment's response to these stressors. Being blind to the importance of understanding ecosystem responses and processes that drive differences in responses between domains has resulted in ecosystems passing tipping points (Rocha et al., 2015; Hicks et al., 2016; e.g., **Boxes 1**–**3**). Once ecosystems pass these tipping points, complex feedbacks and interactions often lock them in an undesirable state for indefinite periods and recovery can be impossible or extremely slow. For example, the slow accumulation of land-based nutrients and the severe eutrophication in the coastal waters of the Baltic Sea have occurred over centuries, but the benefits of management actions to curb the input of land-based nutrients will not be realized for decades due to the legacy effects in the system that slow recovery (**Box 1**). Often critical to these legacy effects are the slow growing ecologically important (e.g., habitat forming) species and associated biodiversity and ecological processes (Biggs et al., 2012; Andersen et al., 2017). Part of the problem with focusing on the stressor instead of the ecological processes (such as resilience and recovery dynamics) is that it eliminates the ability to generalize ecological responses spatially and temporally, or to identify interactive drivers of change and the legacy effects that result in recovery lags (Lindenmayer et al., 2010; Biggs et al., 2012).

SE-P5. The spatial and temporal scale of ecological and social properties differ with ecosystem domains and social—ecological scale mismatches are common

There is no universal "right" scale for management, but identifying scale disparities between temporal and spatial, and social and ecological scales highlights a need for a different approach to environmental management. Scale in ecology has both spatial and temporal dimensions and reflects different levels of biological organization—individual organisms, populations, communities, and ecosystems (Levin, 1992). Scale in society and social science also has spatial and temporal dimensions in, for example, human relations, actions, governance, ownership, and politics (Clark, 1985; Gunderson and Holling, 2002; Cash et al., 2006; Cumming et al., 2006; Pyyhtinen, 2017). These structural scales of environmental management have political and social consequences that affect environmental processes and management. For example, management of environmental issues at a global (e.g., climate change) or a national scale (e.g., fisheries or pollution) can remove responsibility or power to act at a local scale even if the impacts are felt locally (Brashares et al., 2014; Haarstad, 2014). Further, these scale mismatches can create situations where actions to mitigate one environmental problem (e.g., demand for bioenergy for climate change mitigation) can yield negative consequences for other important aspects of the environment (e.g., land uses and biodiversity; Pörtner et al., 2021). Similarly, broad-scale acquisition of data to inform management can prevent adaptive responses to ecological processes that occur at local scales. The negative consequences of scale mismatches (Cumming et al., 2006) could be better addressed through local, place-based management that considers connections and linkages (Herse et al., 2020; Pörtner et al., 2021).

Ecosystems on land are often managed at local/regional scales, but marine ecosystems are managed at national to international scales. National to international scale governance disempowers local actors from effecting change or driving adaptation (Pisor et al., 2022) and instead places responsibility on governments or intergovernmental agencies, leading to, for example, differences in the way people extract resources from land versus sea (Singh et al., 2021). The issue is not the specific scale of management but rather in the scale mismatches between management and ecological and social processes (discussed in **Boxes 2** and **3**). However, there are also potential negative consequences of increasing connectivity in the social structures of governance. For example, some ecosystems maintain their healthy state through the application of rules and knowledge of local people, whose sustainable environmental governance systems may then be challenged or eroded by new governance approaches (Young et al., 2006; Longo, 2012), which tend to be at larger scales where people are separated from the consequences of their actions or management decisions (see SE-P2 above).

Recognizing connections across domains and scales offers opportunities to target social–ecological connections that could change the practices that currently obstruct aspirations of ecological sustainability and associated management actions. However, these opportunities only represent possibilities because the social–ecological context is complicated by the social constraints and path dependencies arising from existing policy and institutional frameworks (e.g., **Box 1**—Baltic Sea; Blenckner et al., 2015). Such critical impediments often sit at the interface between science, governance, and society (Thrush et al., 2016; Stenseth et al., 2020). The exceptions are responses to visible and immediate impacts such as whale stranding, oil spills, or wildfires. Oceans are possibly at greatest risk from scale mismatches due to 2 factors; first, the fallacy that oceans are too big to fail, having infinite capacity for recovery, and the ability to dilute and disperse contaminants, and second, that many of the effects on marine ecosystems are not in the public consciousness (due to a lack of visibility), and often arise from multiple stressors (Thrush et al., 2016; Selkoe et al., 2017). Common to all domains are impacts that generate immediate economic consequences (e.g., invasive species affecting industry), are highly visible (e.g., oil spills, severe eutrophication, land erosion, desertification, and wildfires), and elicit an emotional response (e.g., whale stranding), which show faster social feedbacks than slow insidious impacts exemplified by climate change and biodiversity loss. The slow and insidious impacts are often discounted as problems of the future but can lead to intergenerational injustice (Treves et al., 2018). This reactive and near-sighted management prioritization generates a focus on the short-term immediate impacts (e.g., the oil spills) rather than the chronic subtle cumulative effects on ecosystem components that have long-term effects because they affect slow to recover processes (e.g., over-fishing and terrestrial run-off into coastal waters remove key species and reduce regional biodiversity, which are generally very slow to recover). These slow changes also alter our perceptions of what ecological recovery looks like and the targets we set (i.e., shifting baseline syndrome; Soga and Gaston, 2018).

The dynamic implications of slow responses to slow problems

While the principles above may seem complicated and numerous from a management perspective, important insight can be gained by focusing on 2 critical elements that run through the principles and examples (**Boxes 1**–**3**): (1) the recognition of cross-domain connections as drivers of change and (2) the importance of protecting the slow-to-recover ecosystem elements (species and processes) that are often eroded by chronic and cumulative stressors (Heinze et al., 2021). There are examples globally of environmental management incorporating cross-domain

Box 2—Wetlands: Management of a dynamic system.

Wetland ecosystems lie at the interface of freshwater and terrestrial environments. These are ecosystems that for many have transitioned in value over the last 40 years. They are reservoirs of biodiversity and provide critical ES such as water purification, long-term carbon storage (e.g., in peats), and culturally valued species. However, globally, wetland ecosystems are in decline, and Aotearoa New Zealand (NZ) is no different (Myers et al., 2013). Why? And how do they challenge management?

Wetlands are dynamic entities whose presence in the landscape and the services they supply change over time. Such changes can be slow (e.g., the formation of peat and storage of carbon over millennia) or relatively rapid (e.g., the damming of a river by a landslide triggering wetland formation). The NZ landscape covered by wetlands is now just 10% of the wetland area that existed when humans settled in New Zealand in the mid-13th century, and this decline continues (McGlone, 2009). Many stressors interact to drive wetland decline and loss (**Figure B2.1**). The widespread loss of wetlands across New Zealand has been driven by their transformation into agricultural and urban land. The decline of ecosystem quality in wetlands involves a complex suite of processes, including altered water, sediment and nutrient flows, disturbance, and invasion by weeds and predators. These stressors interact to drive systems across tipping points and may arise from well beyond the wetland itself (e.g., land-use change; an example of Social-Ecological Properties SE-P1 and 3 in main text). For example, increased nutrient flux due to land-use changes in a catchment may shift species composition and alter biogeochemical fluxes, facilitating invasion of weeds. These feedbacks may be lagged (exemplifying SE-P4 in main text). Thus, as with many complex systems, tracing the causal pathway from symptom to the underlying mechanisms is not easy (Bowman et al., 2015). This separation of cause and effect can contribute to psychological distancing of stakeholders and managers from environmental issues (Perry et al., 2021; SE-P2 in main text). Historical change may not be sufficient to predict wetlands' future. Many wetlands sit adjacent to the coast and thus under climate change and sea level rise scenarios are prone to salination and associated shifts in species distributions and disturbance regimes.

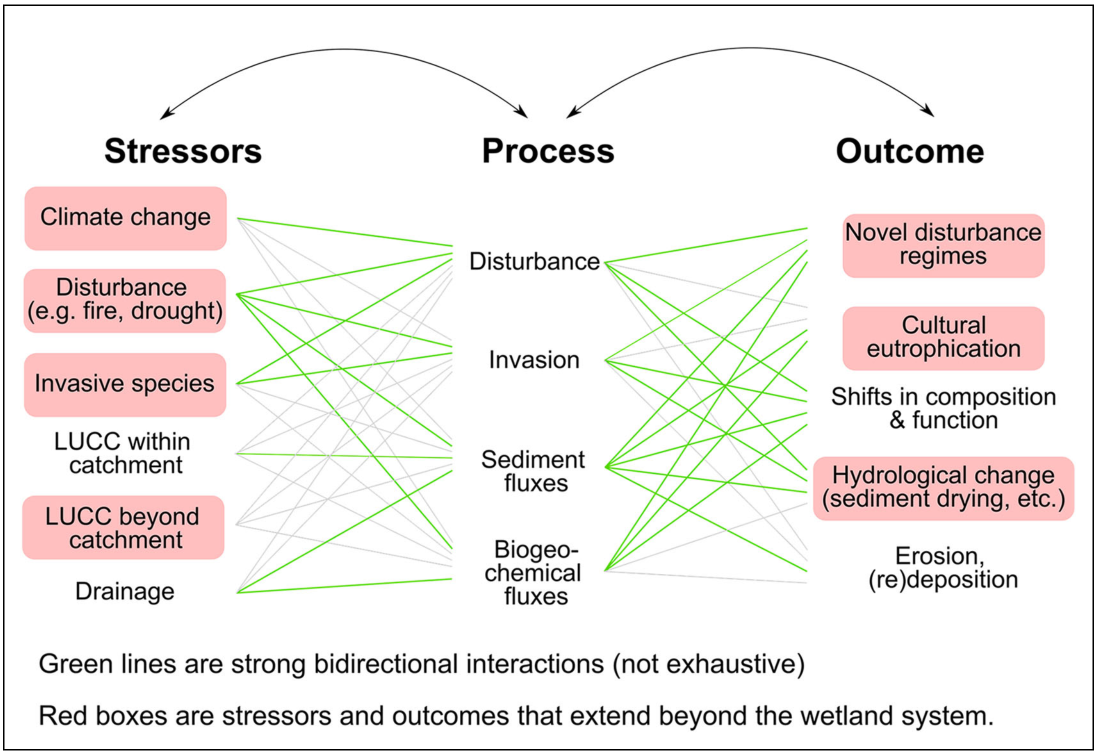

Figure B2.1 Schematic view of some of the stressors, processes, and outcomes (not exhaustive) operating in NZ's wetland ecosystems. The green links are those with strong reciprocal feedbacks (e.g., fire favors some invasive weeds, which favors fire), and red boxes are components with spatial disjunctions between cause and effect. In some cases (e.g., disturbance regimes), the same suite of entities is a stress, process, and outcome. LUCC = land use/land cover change. DOI: https://doi.org/10.1525/elementa.2021.00075.fB2.1

Our ability to manage wetlands effectively also has sociocultural components. There are fundamental issues, at least in New Zealand, about defining wetlands, and areas designated in regulation and policy as "wetlands" often have strict conservation planning associated with them. Second, the perceived value of wetlands varies from them being mere swamps to irreplaceable suppliers of ES, many of which accrue slowly. These differing views result in a contest between reclamation (of otherwise useful land) and restoration (Williams, 1994; a real-world example of SE-P2 in main text). Third, where changes in one part of the landscape affect another, potentially with long lags, patterns of land ownership and management responsibility are important. In New Zealand, although the largest wetlands tend to be in public ownership, the smaller ones tend to be on private land and may not even be recognized as wetlands. Governance of public and private wetlands differs and varies regionally as does the legislative emphasis placed on different stressors (e.g., dams vs. stock intrusions; Myers et al., 2013). Those tasked with managing a given wetland may have limited agency in the parts of the landscape where change is initiated (SE-P5 in main text). Another potential disconnect is that effective wetland management requires a holistic ecosystem-level approach (e.g., Peacock et al., 2012), but the intellectual origins of wetland sciences are in wildlife management (Euliss et al., 2008). Successful management for wildlife is unlikely to be the same as successful management for wetland ES.

Despite these challenges, there are examples of successful wetland management and restoration. Such successes are typified by a holistic view, centered on ecosystem-level processes (demonstrating a need for management and research priority P1 in main text). There is evidence that overarching (national) policies do positively influence wetland condition (United Nations Environment Programme World Conservation Monitoring Centre, 2009). At a regional level, effective wetland governance will need to be alert to potential scale mismatches (Folke et al., 2007), acknowledge diverse value positions (Bataille et al., 2021), and be responsive to spatial and temporal disjunctions between cause and effect (P2, 4 and 6 in main text). Successful management and restoration at the site-level will require careful selection of targets and ongoing investment in monitoring—challenges that bedevil nearly all ecological monitoring (Biber, 2013; P2 in main text).

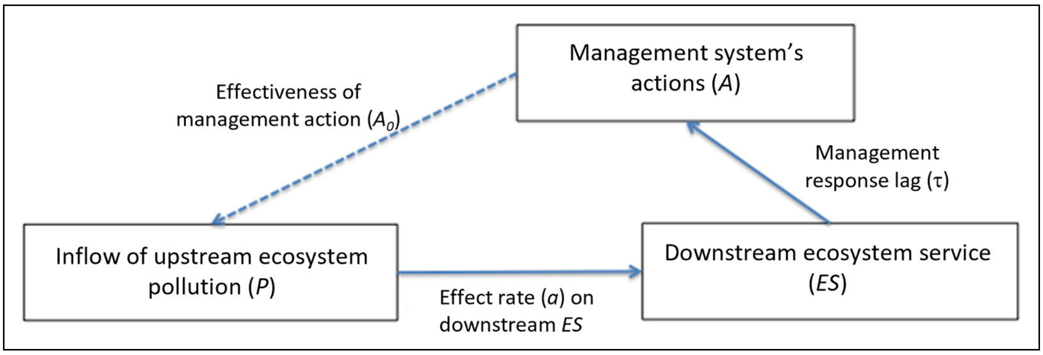

Figure 3. Stylized control theory model. To illustrate the implications of slow management actions, we analyze a simple control theory model of a social–ecological system. In the model, pollution input from an upstream ecosystem (*P*) affects a downstream ecosystem service (ES). The impact of *P* on ES is regulated by *a* (the effect of the pollution on the downstream ES). A management system responds to changes in ES with adaptive actions (*A*), at some timescale represented by a management response lag (τ). Management actions (*A*) alter the inflow of pollutants to the downstream ecosystem. The dashed line indicates that these management actions may be weak, which we quantify with a management effectivity rate (A_0). The management dynamics and ecosystem processes are modeled within the "management system actions" and "downstream ecosystem service" boxes, respectively. Full explanation of terms, model equations, and units are given in Appendix 1. DOI: https://doi.org/10.1525/elementa.2021.00075.f3

connections (reviewed in Threlfall et al., 2021), and these examples provide insight. For example, **Box 1** highlights some lessons in managing eutrophication in the Baltic Sea where collaborations across countries and agencies have begun to address the downstream effects of agriculture and urbanization on the Baltic Sea eutrophication status.

To illustrate the dynamic implications of slow management responses to ecological degradation exemplified by those outlined in **Box 1**, we present a simple control-theory model (**Figure 3**) to demonstrate how ecological connectivity, slow/mismatched management timescales (between environmental change and management actions), and different management actions can influence environmental quality in connected ecosystems.

A set of differential equations (see Appendix 1) was used to represent a downstream ecosystem (e.g., a coastal fishery) whose quality is biophysically affected by an upstream ecosystem, such as nutrient loading in an agroecosystem (e.g., a situation like that described in **Box 1**). For the dynamics of the downstream ecosystem, we assumed a classic tipping point behavior of the environmental quality of greatest value to humans (i.e., an ES), where this quality can be downgraded by the loading of nutrients in an upstream system (e.g., Thrush et al., 2021). A social–ecological feedback is present, whereby degraded quality of the downstream ecosystem may lead to management actions (*A*) that limit runoff of nutrients from the upstream ecosystem (and therefore the concentrations of nutrients in the downstream ecosystem). These management actions could be triggered by environmental concern, decline in income, or loss of other benefits from the ES.

As expected, the ecological connectivity between upstream pollution and the downstream ecosystem can trigger transgression of a tipping point in the downstream ecosystem (**Figure 4**, black line). A sufficiently strong upstream feedback (A_0) on the "social" side of this social–ecological system can stabilize the downstream ecosystem against this collapse by creating actions that decrease nutrient levels in the downstream ecosystem (e.g., riparian planting and/or the restoration of wetlands; **Figure 4**, blue and red lines). Strong upstream feedbacks can prevent regime shifts and tipping points (no bistability in red line in **Figure 4**). That management or human behavioral feedbacks can shift the position of an ecological regime shift or remove it entirely has previously been demonstrated in theoretical (Lade et al., 2013) and empirical (Lade et al., 2015) social–ecological systems. The strength of this upstream feedback will depend on several factors such as sufficiently strong incentives, trust in management agencies, and public support.

The speed of management response also strongly influences the emergent social–ecological dynamics (**Figure 5**). Specifically, if the management response is strong but delayed, an oscillatory dynamic can result. In response to a disturbance, such as a sudden inflow of nutrients or change in policy affecting land clearing, management actions are likely to bounce between under- and overresponding with similar consequences for the quality of the ecosystem (**Figure 5**, red line). A faster management response (i.e., greater temporal matching of management to changes in ecosystem state) eliminates this oscillation (**Figure 5**, blue line). A moderate delay and a moderate management response (**Figure 5**, green line) could result in a permanent shift in ecosystem condition due to the system passing a tipping point prior to any management action.

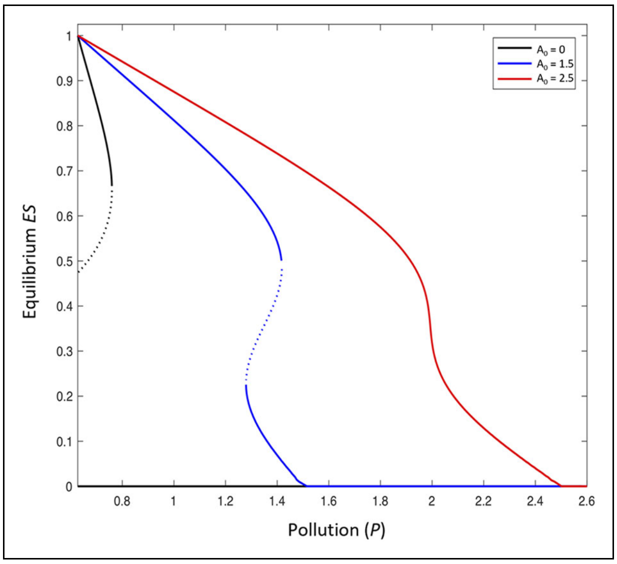

Figure 4. Bifurcation plots of our upstream-downstream social–ecological system model. The stronger the management effectiveness (higher values of A_0), the more upstream pollution loading the system can tolerate before shifting to a low ES state. For strong management effectiveness ($A_0 = 2.5$), there is no bistability (i.e., the ability for the ecosystem to be in different states at the same upstream pollution loading indicated by the dotted line). DOI: https://doi.org/10.1525/elementa.2021.00075.f4

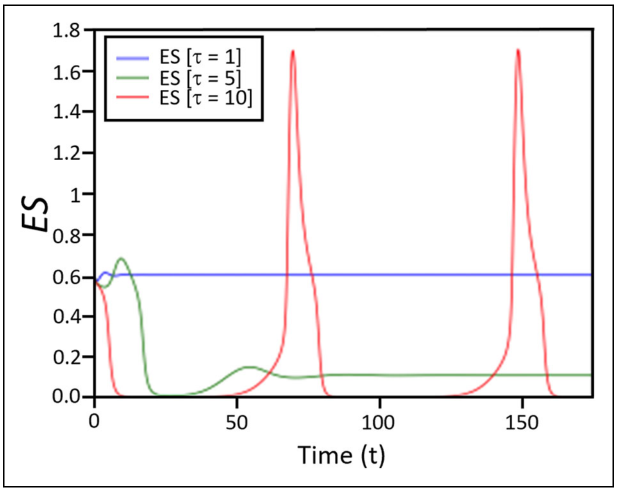

Figure 5. Modeled ecosystem service (ES) quality as a function of different management response lags (τ). Mild perturbations at t_0 (a 5% pulse reduction from the ES equilibrium) could have different effects depending on the management response lag to a change in ES in the system (i.e., temporal scale mismatch). This example demonstrates the time evolution of ES quality under 3 different lags. For short response lag ($\tau = 1$, blue line), the system recovers quickly (no danger). For moderate response lag ($\tau = 5$, green line), the system gets into a divergent trajectory but hits the basin of attraction of the alternative low-quality ES and gets trapped there (regime shift). For long response lag ($\tau = 10$, red line), the ES diverges initially to a very low quality, then oscillates but is not trapped in the alternate state. DOI: https://doi.org/10.1525/elementa.2021.00075.f5

Slow changes in pollutant loads, resulting in slow changes in environmental quality, challenge environmental management (Hughes et al., 2013). Over long time scales, environmental management often fails to respond to slow environmental changes even if the absolute change has been large. This is sometimes known as the "shifting baselines" syndrome (Soga and Gaston, 2018). Ecological time lags have hindered effective management in the Baltic Sea (see **Box 1**), for example, because the legacy of nutrient inputs over decadal timescales has saturated the marine ecosystem and "slow to recover" ecological processes that facilitate removal mediated by key species and regional biodiversity are the most affected.

The management interventions modeled here correspond to the reactive solutions that are often used in practice. In the model, once the intervention ceases, then pollutant inflows return to previous levels. Instead, future-response-focused management that aims at transformative changes, such as fundamental changes in agricultural systems or landscapes (e.g., riparian planting and buffer zones), should be a goal for long-term sustainability. We used this simple model to illustrate the importance of cross-domain connections, but it is important to note that it studies only a single stressor, whereas much of the complexity of environmental management stems from the presence of multiple stressors (Côté et al., 2016; Thrush et al., 2021; see **Boxes 1–3**).

A way forward: New management and research opportunities arising from a focus on cross-domain connections

While an ecosystem-based approach to management has been promoted by the research community for almost 20 years (Christensen et al., 1996), implementation has been slow and patchy. We argue that a focus on the social–ecological properties of cross-domain connections demands new management and research priorities, and this will assist effective implementation. These priorities include the need to recognize, in governance and in actions, the dynamic implications of slow decision making across linked

Box 3 —That's the limit: Simple limit-based policies versus ecological complexity.

Across all environmental domains, limits are a common strategy used to manage impacts. We can have limits for air or water quality, changes in land use, contaminant effects, and resource extraction. Limits can be defined as biophysical bottom lines of acceptable pollution, disturbance, resource use, or extraction. Limits can also be defined as levels of acceptable maximum harm. This has become an established approach to management because of its simplicity and has worked in situations where cause and effect are direct and tightly coupled. However, when causal pathways are more complex, there can be nontrivial problems in defining what is acceptable, particularly when dealing with more abstract concepts such as ecosystem health or integrity, which are multivariate rather than the single variable to which the limit pertains. Often limits are bounded by a buffer zone to reflect uncertainty, but often the uncertainty in this uncertainty is uncertain. In ecological systems, change can be nonlinear, making limits more difficult to implement, which is further exacerbated by multiple and cumulative stressors generating complex responses that are difficult to predict and mitigate. A policy focus on limit setting has shaped how we assess the risk to ecosystems, where the focus is on the activity that generates the stress and the stressor rather than on the complex mechanisms that generate context dependencies of responses (exemplifying Social-Ecological Properties SE-P3 and 4 in main text).

From a practical perspective, there are countless unknown contaminants, for which limits could never be set, and there is a growing body of research on the ecological responses to emerging contaminants (Kanwischer et al., 2021). With new knowledge and shifts in social and/or biophysical context (e.g., climate change), limit setting needs to be adaptable. However, limits management is often highly path dependent, leading to set and forget policies that fixate on the limit and managing to the limit. This has led to major failures in fisheries in Aotearoa New Zealand as management fixates on fish stock, biomass, and total allowable catch (TAC) over large areas (Cryer et al., 2016; demonstrating the need for management and research priority P1 in main text). The TAC limit can be managed at scales that seem rational from the office but do not relate to the biology and ecology of targeted species let alone the rest of the ecosystem (an example of SE-P5 in main text). This potential for mismatch in context and application of limits has been acknowledged in the Australia and New Zealand guidelines for fresh and marine water quality (Australian and New Zealand Governments, 2018). Despite this, New Zealand has tried to set national limits for some stressors in freshwaters. A similar scale mismatch occurs in the management of hunting limits on waterfowl on lowland lakes in New Zealand (Herse et al., 2020).

Apart from the spatial scale over which limits are set, we can also get situations where the limits are set for one environmental domain when another is more or less sensitive (SE-P1 and 3 in main text). In New Zealand, discussions are underway to set limits on the quantity of soil that enters water ways. As the point of entry of these sediments into the aquatic systems is mainly via the stream network, limits are set as freshwater standards. While there are considerable impacts of sediments on freshwaters (Burdon et al., 2013), the ecological impacts and potential for legacy effects are much stronger in coastal and estuarine ecosystems (Reid et al., 2011).

Instead of setting limits on degradation, we can refocus and set targets for recovery. These targets would need to be set locally to address context dependencies, and in New Zealand, the aspirations of Māori (the Indigenous Peoples of NZ). Achieving targets may require a whole range of different approaches (P1 in main text), and limit setting may be one, but others include protection (e.g., reserves), and active restoration, which are common approaches on land, but these approaches have not yet become the norm in the marine and freshwater domains (which shows the need for P2 in main text). Active restoration must target the restoration of the interaction network to build resilience in the face of further stress (e.g., Barrett et al., 2021; Sea et al., 2021). No single approach will be suitable across contexts, so there is a need for risk assessments to be grounded in aligning the ecological attributes of the ecosystem with the decision options. Further, aspirations need to recognize that perceptions of ecological recovery vary through time, but recognition of ecological complexity will help in consideration of what has been lost and what we aspire to achieve.

Limits have been useful and led to the banning or control of toxic substances in some circumstances. Nevertheless, policy and management agencies need to be aware of path dependency and be open to new approaches and new data (P1 in main text). This is increasingly important as we begin to think inclusively about multiple scales of biological organization, and design management actions with a clear focus on the dynamics of connected ecosystems. The data and models used to derive limits should be accessible and open to scrutiny by all parties to ensure that circles of trust do not implode. In practice and in its simplest form, this means constantly checking on the veracity of the limit and its application, listening to multiple voices (e.g., people on the ground) and ensuring that adequate indicators are used to assess the efficacy of the limit(s) (P5–7 in main text).

domains and to enhance upstream social–ecological feedbacks, thereby reducing management response times across all ecological domains. Priorities include the following:

P1. *Research and actions aimed at redesigning governance structures away from path dependent processes that tie management (in)actions to a restricted range of decision options* (Kelly et al., 2018). For example, setting stressor limits that encourage managing up to the limit but do not open the possibility of addressing cumulative effects (**Box 3**). The social–ecological research question that follows is: What sort of governance models (e.g., polycentric; Biggs et al., 2012) might facilitate social/societal management that is more spatially and temporally targeted at appropriate scales (informed by SE-P1, 4, and 5; **Figure 2**)? Comanagement structures that combine place-based management by indigenous peoples and local communities with regional or national government policy may enable more rapid feedbacks to management at multiple scales (Herse et al., 2020), but only if power is shared in a way that allows rapid decision making and enactment of a response at the relevant scale. In practice, enabling rapid management of feedbacks requires careful consideration of comanagement roles in relation to the ecosystem processes; it can entail that local communities take engagement roles (decision making, implementation processes) and other stakeholders hold more participatory roles (e.g., designing and reviewing generic management goals, information exchange, advisory roles). For example, **Box 1** details an internationally recognized model of success in environmental management; **Box 2** details that successes in wetland management are typified by holistic views centered on ecosystem-level processes; **Box 3** discusses how a non-path-dependent management regime might look.

P2. *Management approaches that prioritize monitoring, maintaining, and restoring slow processes*—that is, the ecologically important species that are slow to recover (e.g., habitat formers and ecosystem engineers that underpin ecological function and resilience; Biggs et al., 2012; Kelly et al., 2015; Kortetmäki et al., 2021). This priority is critical for preventing tipping points and ensuring that problems other than the "crisis of the day" are recognized early so that they never become "tomorrow's crisis" (informed by SE-P3–5 in **Figure 2**). Such management approaches require institutional patience and sufficient resources to measure slow or spatially large ecosystem processes. **Box 1** describes how management of the Baltic Sea is moving toward this; **Box 2** emphasizes the need for management and monitoring to be responsive to temporal disjunctions in cause and effect; **Box 3** emphasizes restoration as a key focus for maintaining ecological resilience.

P3. *Identify the social–ecological priorities across the ecosystem domains so that multiple visions can be reconciled to help facilitate collaboration across management and governance levels.* Identifying where priorities are incompatible is an important step in managing expectations and trade-offs (informed by SE-P2 in **Figure 2**). For example, see **Box 1** for a discussion on how the countries and agencies around the Baltic Sea have reconciled visions for the future status of the Baltic Sea.

P4. *Foster collaboration, at a management and governance level, between actors and agencies who have priorities in different domains, to better recognize drivers of change earlier* (informed by SE-P1–3 in **Figure 2**; Singh et al., 2021). Such collaboration could allow the effect of changes to "upstream" domains on "downstream" domains to be assessed before impacts occur in the downstream domain (thereby utilizing SE-P1 in **Figure 2** to eliminate the response lag in the downstream domain). For example, **Boxes 1** and **2** highlight the perils of not recognizing drivers of change early enough. The collaboration could be motivated by the identification of costly outcomes of not managing cross-ecosystem connections, collective learning, or sharing of nonfinancial and financial resources, and it requires maintenance of respect and trust, shared benefits (especially as some partners are "upstream"), and commitment as the progress may be slow and frustrating. Sharing of representation and power must be agreed upon, especially if some partners may have fewer resources than others.

P5. *Ensure that new governance structures recognize and are adaptable to the differential properties of the ecosystem domains in terms of stressor residence times, limits setting, and cumulative effects, so that all ecosystem domains can be managed with equal priority* (informed by SE-P1, 3–5 in **Figure 2**). For example, see full discussion in **Box 3** about the perils of stressor limit setting for managing the marine environment.

P6. *Promote research and collaborative learning across ecosystem domains to better enable science providers to understand and provide evidence for where connections lie and the scale at which they operate, such that scales of management are relevant to scales that are ecologically meaningful* (e.g., Kelly

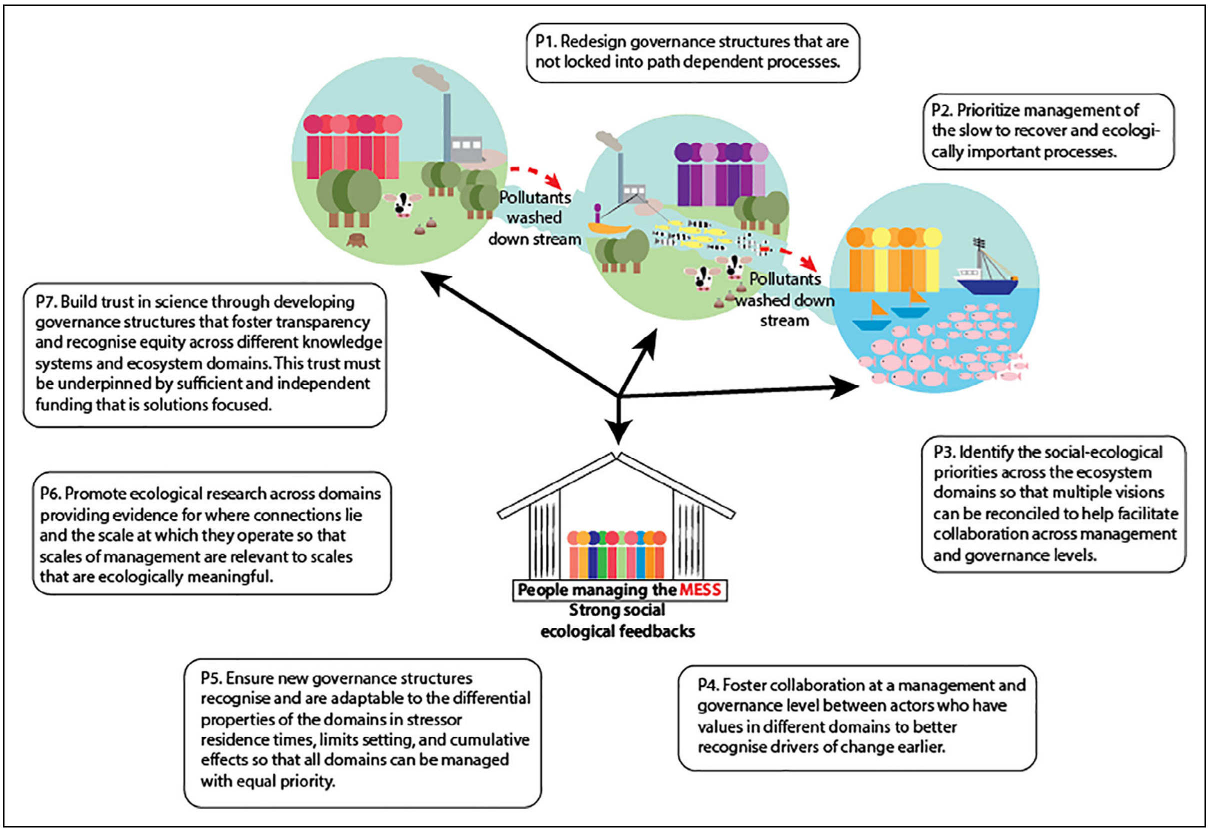

Figure 6. A diagrammatic representation of a situation where the upstream feedback is enhanced. The upstream management feedback is enhanced by explicitly accounting for cross-ecosystem domain connectivity and slow processes in management structures. The diagram includes a summary of the management and research priorities (P1–7) that are highlighted by a focus on cross-domain connections and the social–ecological properties (SE-P1–5) of these connections (summarized in **Figure 2**). DOI: https://doi.org/10.1525/elementa.2021.00075.f6

et al., 2015; Herse et al., 2020; informed by SE-P5 in **Figure 2**). In some cases, the first step may be to develop theories, models, and field methods for cross-ecosystem research and education, as well as foster collaboration across ecosystem domain-specific research fields. **Boxes 2** and **3** highlight the need for management scales to align with the ecology of the ecosystem and connections.

P7. *Build trust in science and scholarship through developing governance structures that foster transparency and recognize equity across different knowledge systems and ecosystem domains* (informed by SE-P2 in **Figure 2**). This trust must be underpinned by sufficient and independent science funding that is solutions focused. **Box 1** highlights successes in the management of the Baltic Sea that have stemmed from a long history of trust among scientists and policy makers.

Current global trends in environmental degradation are sobering and necessitate a significant shift in our efforts to curb the damage. We argue that these 7 priorities can help to navigate research and management toward the situation depicted in **Figure 6**, where cross-domain connections and feedbacks are explicitly addressed in environmental management. This situation would lead to ecosystems that are more resilient to stress (blue and red lines in **Figure 4**) and management decisions that are effective at stabilizing and preserving ecosystem functions and services (blue line in **Figure 5**). Importantly, leveraging cross-domain linkages as early warning signals of future downstream change may alleviate temporal scale mismatches (lags) in management responses to change. The social subsystem may provide an important nexus for managing multidomain social–ecological systems, though this will require researchers and policy makers to step outside of traditional domain boundaries.

Aotearoa New Zealand's research system has contributed to addressing these priorities through its National Science Challenges. These are large, collaborative, transdisciplinary projects involving extensive codevelopment. However, they were domain constrained by the funding agency, and this article is a product of a workshop to explore commonalities and connections across 3 of these challenges ("Biological Heritage" [Terrestrial], "Our Land and Water" [Freshwater], and "Sustainable Seas" [Marine]).

Acknowledgments

We thank Jasmine Low for assistance with the artwork. We also thank the editor and 2 reviewers for their thoughtful suggestions that improved the depth and interest of the manuscript.

Funding

The workshop was funded by the New Zealand National Science Challenges: Sustainable Seas (Tipping Points Project; CO1X1515; ST) and New Zealands's Biological Heritage (Project 3.1; 1516-44-004; JT), established by the Ministry of Business, Innovation and Enterprise, New Zealand. The writing of this manuscript was also funded by the Sustainable Seas National Science Challenge Project 1.1: Ecological responses to cumulative effects (C01X1901). RG-G was supported by the New Zealand Rutherford Foundation Postdoctoral Fellowship and the Walter and Andrée de Nottbeck Foundation during the writing of this manuscript.

Competing interests

No competing interests to declare.

Author contributions

Contributed to the workshop and conception of ideas: All authors.

Obtained funding for the workshop: JT, ST.

Organized the workshop: JT, ST, JY, JH, CP.

Contributed to the model development and results: VD, SL.

Wrote the first manuscript draft: RG-G, ST, JT.

Revised the first draft and approved final submission: All authors.

References

Andersen, JH, **Carstensen, J**, **Conley, DJ**, **Dromph, K**, **Fleming-Lehtinen, V**, **Gustafsson, BG**, **Josefson, AB**, **Norkko, A**, **Villnäs, A**, **Murray, C**. 2017. Long-term temporal 622 and spatial trends in eutrophication status of the Baltic Sea. *Biological Reviews* **92**(1): 135–149.

Åström, K, **Murray, R**. 2012. *Feedback systems: An introduction for scientists and engineers*. Princeton, NJ: Princeton University Press.

Australian and New Zealand Governments. 2018. *Deriving guideline values for water quality. Australian and New Zealand guidelines for fresh and marine water quality*. Canberra (ACT), Australia: ANZG and Australian state and territory governments. Available at https://www.waterquality.gov.au/anz-guidelines.

Barrett, IC, **McIntosh, AR**, **Febria, CM**, **Warburton, HJ**. 2021. Negative resistance and resilience: Biotic mechanisms underpin delayed biological recovery in stream restoration. *Proceedings of the Royal Society B: Biological Sciences* **288**(1947): 20210354.

Bartels, P, **Cucherousset, J**, **Steger, K**, **Eklov, P**, **Tranvik, LJ**, **Hillebrand, H**. 2012. Reciprocal subsidies between freshwater and terrestrial ecosystems structure consumer resource dynamics. *Ecology* **93**(5): 1173–1182.

Bataille, CY, **Malinen, SK**, **Yletyinen, J**, **Scott, N**, **Lyver, POB**. 2021. Relational values provide common ground and expose multi-level constraints to cross-cultural wetland management. *People and Nature* **3**(4): 941–960.

Biber, E. 2013. The challenge of collecting and using environmental monitoring data. *Ecology and Society* **18**(4): 68.

Biggs, D, **Biggs, R**, **Dakos, V**, **Scholes, RJ**, **Schoon, M**. 2011. Are we entering an era of concatenated global crises? *Ecology and Society* **16**(2): 27.

Biggs, R, **Schluter, M**, **Biggs, D**, **Bohensky, EL**, **BurnSilver, S**, **Dakos, V**, **Daw, TM**, **Leitch, AM**, **Meek, C**, **Quinlan, A**, **Raudsepp-Hearne, C**, **Robards, MD**, **Schoon, ML**, **Evans, LS**, **Kotschy, K**, **Schultz, L**, **West, PC**. 2012. Toward principles for enhancing the resilience of ecosystem services. *Annual Review of Environment and Resources* **37**(1): 421–448.

Blenckner, T, **Osterblom, H**, **Larsson, P**, **Andersson, A**, **Elmgren, R**. 2015. Baltic Sea ecosystem-based management under climate change: Synthesis and future challenges. *AMBIO* **44**(3): 507–515.

Bowman, DMJS. **Perry, GLW**. **Marston, JB**. 2015. Feedbacks and landscape-level vegetation dynamics. *Trends in Ecology & Evolution* **30**(5): 255–260.

Brashares, JS, **Abrahms, B**, **Fiorella, KJ**, **Golden, CD**, **Hojnowski, CE**, **Marsh, RA**, **McCauley, DJ**, **Nuñez, TA**, **Seto, K**, **Withey, L**. 2014. Conservation policy: Wildlife decline and social conflict. *Science* **345**(6195): 376-8.

Brunson, MW. 1998. Social dimensions of boundaries: Balancing cooperations and self-interest, in Knight RL, Landres PB eds., *Stewardship across boundaries*. Washington, DC: Island Press: 65–86.

Burdon, FJ, **McIntosh, AR**, **Harding, JS**. 2013. Habitat loss drives threshold response of benthic invertebrate communities to deposited sediment in agricultural streams. *Ecological Applications* **23**(5): 1036–1047.

Carpenter, SR, **Booth, EG**, **Gillon, S**, **Kucharik, CJ**, **Loheide, S**, **Mase, AS**, **Motew, MM**, **Qiu, J**, **Rissman, AR**, **Seifert, J**, **Soylu, ME**, **Turner, M**, **Wardropper, C**. 2015. Plausible futures of a social-ecological system: Yahara watershed, Wisconsin, USA. *Ecology and Society* **20**(2): 10.

Carstensen, J, **Conley, DJ**, **Bonsdorff, E**, **Gustafsson, BG**, **Hietanen, S**, **Janas, U**, **Jilbert, T**, **Maximov, A**, **Norkko, A**, **Norkko, J**, **Reed, DC**, **Slomp, CP**, **Timmermann, K**, **Voss, M**. 2014. Hypoxia in the Baltic Sea: Biogeochemical cycles. Benthic fauna, and management. *AMBIO* **43**(1): 26–36.

Cash, DW, **Adger WN**, **Berkes F**, **Garden P**, **Lebel L**, **Olsson, P**, **Pritchard, L**, **Young, O**. 2006. Scale and cross-scale dynamics: Governance and information in a multilevel world. *Ecology and Society* **11**(2): 8.

Christensen, NL, **Bartuska AM**, **Brown JH**, **Carpenter S**, **D'Antonio, C**, **Francis, R**, **Franklin, JF**, **Macmahon, JA**, **Noss, R**, **Parsons, DJ**, **Peterson, CH**, **Turner, MG**, **Woodmansee, RG**. 1996. The report of the Ecological Society of America Committee on the scientific basis for ecosystem management. *Ecological Applications* **6**(3): 665–691.

Clapcott (Ngāti Porou), J, **Ataria (Rongomaiwahine; Ngāti Kahungunu; Ngati Raukawa), J**, **Hepburn, C**, **Hikuroa (Ngāti Maniapoto; Tainui; Te Arawa), D**, **Jackson (Ngāti Whātua; Ngāti Kahu o Whangaroa; Ngāpuhi; Ngāti Wai), A-M**, **Kirikiri (Te Whānau a Āpanui), R**, **Williams (Ngāti Whakaue, Ngāti Pikiao, Te Whanau a Maruhaeremuri), E**. 2018. Mātauranga Māori: Shaping marine and freshwater futures. *New Zealand Journal of Marine and Freshwater Research* **52**(4): 457–466.

Clark, WC. 1985. Scales of climate impacts. *Climatic Change* **7**(1): 5–27.

Côté, IM, **Darling, ES**, **Brown, CJ**. 2016. Interactions among ecosystem stressors and their importance in conservation. *Proceedings of the Royal Society B: Biological Sciences* **283**(1824): 20152592.

Crain, CM, **Kroeker, K**, **Halpern, BS**. 2008. Interactive and cumulative effects of multiple human stressors in marine systems. *Ecology Letters* **11**(12): 1304–1315.

Cryer, M, **Mace, PM**, **Sullivan, KJ**. 2016. New Zealand's ecosystem approach to fisheries management. *Fisheries Oceanography* **25**(S1): 57–70.

Cumming, GS, **Cumming, DHM**. **Redman, CL**. 2006. Scale mismatches in social-ecological systems: Causes, consequences, and solutions. *Ecology and Society* **11**(1): 14.

Darling, ES, **Côté, IM**. 2008. Quantifying the evidence for ecological synergies. *Ecology Letters* **11**(12): 1278–1286.

DeFries, R, **Nagendra, H**. 2017. Ecosystem management as a wicked problem. *Science* **356**(6335): 265–270.

Eslami, S, **Hoekstra, P**, Nguyen **Trung, N**, **Ahmed Kantoush, S**, **Van Binh, D**, **Dung, DD**, **Quang, TT**, **van der Vegt, M**. 2019. Tidal amplification and salt intrusion in the Mekong Delta driven by anthropogenic sediment starvation. *Scientific Reports* **9**(1): 18746.

Euliss, NH, **Smith, LM**, **Wilcox, DA**, **Browne, BA**. 2008. Linking ecosystem processes with wetland management goals: Charting a course for a sustainable future. *Wetlands* **28**(3): 553–562.

Filbee-Dexter, K, **Symons, CC**, **Jones, K**, **Haig, HA**, **Pittman, J**, **Alexander, SM**, **Burke, MJ**. 2018. Quantifying ecological and social drivers of ecological surprise. *Journal of Applied Ecology* **55**(5): 2135–2146.

Folke, C. 2006. Resilience: The emergence of a perspective for social–ecological systems analyses. *Global Environmental Change* **16**(3): 253–267.

Folke, C, **Pritchard, L**, **Berkes, F**, **Colding, J**, **Svedin, U**. 2007. The problem of fit between ecosystems and institutions: Ten years later. *Ecology and Society* **12**(1): 30.

Frost, CM, **Peralta, G**, **Rand, TA**, **Didham, RK**, **Varsani, A**, **Tylianakis, JM**. 2016. Apparent competition drives community-wide parasitism rates and changes in host abundance across ecosystem boundaries. *Nature Communications* **7**(1): 12644.

Fukami, T, **Wardle, DA**, **Bellingham, PJ**, **Mulder, CP**, **Towns, DR**, **Yeates, GW**, **Bonner, KI**, **Durrett, MS**, **Grant-Hoffman, MN**, **Williamson, WM**. 2006. Above- and below-ground impacts of introduced predators in seabird-dominated island ecosystems. *Ecology Letters* **9**(12): 1299–307.

Gounand, I, **Little, CJ**, **Harvey, E**, **Altermatt, F**. 2018. Cross-ecosystem carbon flows connecting ecosystems worldwide. *Nature Communications* **9**(1): 4825.

Granek, EF, **Polasky, S**, **Kappel, CV**, **Reed, DJ**, **Stoms, DM**, **Koch, EW**, **Kennedy, CJ**, **Cramer, LA**, **Hacker, SD**, **Barbier, EB**, **Aswani, S**, **Ruckelshaus, M**, **Perillo, GM**, **Silliman, BR**, **Muthiga, N**, **Bael, D**, **Wolanski, E**. 2010. Ecosystem services as a common language for coastal ecosystem-based management. *Conservation Biology* **24**(1): 207–216.

Grennfelt, P, **Engleryd, A**, **Forsius, M**, **Hov, Ø**, **Rodhe, H**, **Cowling, E**. 2020. Acid rain and air pollution: 50 years of progress in environmental science and policy. *AMBIO* **49**(4): 849–864.

Gunderson, LH, **Holling, CS**. 2002. *Panarchy: Understanding transformations in human and natural systems*. Washington, DC: Island Press.

Haarstad, H. 2014. Climate change, environmental governance and the scale problem. *Geography Compass* **8**(2): 87–97.

Heinze, C, **Blenckner, T**, **Martins, H**, **Rusiecka, D**, **Doscher, R**, **Gehlen, M**, **Gruber, N**, **Holland, EA**, **Hov, Ø**, **Joos, F**, **Matthews, JBR**. **Rødven, R**, **Wilson, SJ**. 2021. The quiet crossing of ocean tipping points. *PNAS* **118**(9): e2008478118.

HELCOM. 2010. Hazardous substances in the Baltic Sea: An integrated thematic assessment of hazardous substances in the Baltic Sea. *Baltic Sea Environment Proceedings* No. 120B.

HELCOM. 2018. State of the Baltic Sea: Second HELCOM holistic assessment 2011-2016. *Baltic Sea Environment Proceedings* 155.

HELCOM. 2021. *Baltic Sea Action Plan 2021 update*. **HELCOM**: 31.

Herse, MR, **Lyver, POB**. **Scott, N**, **McIntosh, AR**, **Coats, SC**, **Gormley, AM**, **Tylianakis, JM**. 2020. Engaging indigenous peoples and local communities in environmental management could alleviate scale mismatches in social–ecological systems. *BioScience* **70**(8): 699–707.

Hicks, CC, **Crowder, LB**, **Graham, NA**, **Kittinger, JN**, **Cornu, EL**. 2016. Social drivers forewarn of marine regime shifts. *Frontiers in Ecology and the Environment* **14**(5): 252–260.

Howlett, M. 2014. Why are policy innovations rare and so often negative? Blame avoidance and problem denial in climate change policy-making. *Global Environmental Change* **29**: 395–403.

Hughes, TP, **Linares, C**, **Dakos, V**, **van de Leemput, IA**, **van Nes, EH**. 2013. Living dangerously on borrowed time during slow, unrecognized regime shifts. *Trends in Ecology & Evolution* **28**(3): 149–155.

Kanwischer, M, **Asker, N**, **Wernersson, A.S**, **Wirth, MA**, **Fisch, K**, **Dahlgren, E**, **Osterholz, H**, **Habedank, F**, **Naumann, M**, **Mannio, J**, **Schulz-Bull, DE**. 2021. Substances of emerging concern in Baltic Sea water: Review on methodological advances for the environmental assessment and proposal for future monitoring. *AMBIO*: **51**(6): 1588–1608. DOI: http://dx.doi.org/10.1007/s13280-021-01627-6.

Kelly, C, **Ellis, G**, **Flannery, W**. 2018. Conceptualising change in marine governance: Learning from transition management. *Marine Policy* **95**: 24–35.

Kelly, RP, **Erickson, AL**, **Mease, LA**, **Battista, W**, **Kittinger, JN**, **Fujita, R**. 2015. Embracing thresholds for better environmental management. *Philosophical Transactions of the Royal Society B: Biological Sciences* **370**(1659): 20130276.

Knight, TM, **McCoy, MW**, **Chase, JM**, **McCoy, KA**, **Holt, RD**. 2005. Trophic cascades across ecosystems. *Nature* **437**(7060): 880–883.

Kortetmäki, T, **Puurtinen, M**, **Salo, M**, **Aro, R**, **Baumeister, S**, **Duflot, R**, **Elo, M**, **Halme, P**, **Husu, H-M**, **Huttunen, S**, **Hyvönen, K**, **Karkulehto, S**, **Kataja-aho, S**, **Keskinen, KE**, **Kulmunki, I**, **Mäkinen, T**, **Näyhä, A**, **Okkolin, M-A**, **Perälä, T**, **Purhonen, J**, **Raatikainen, KJ**, **Raippalinna, LM**, **Salonen, K**, **Savolainen, K**, **Kotiaho, JS**. 2021. Planetary well-being. *Humanities and Social Sciences Communications* **8**(258): 1–8. DOI: https://doi.org/10.1057/s41599-021-00899-3.

Lade, SJ, **Niiranen, S**, **Hentati-Sundberg, J**, **Blenckner, T**, **Boonstra, WJ**, **Orach, K**, **Quaas, MF**, **Österblom, H**, **Schlüter, M**. 2015. An empirical model of the Baltic Sea reveals the importance of social dynamics for ecological regime shifts. *Proceedings of the National Academy of Sciences* **112**(35): 11120–11125.

Lade, SJ, **Tavoni, A**, **Levin, SA**, **Schlüter, M**. 2013. Regime shifts in a social-ecological system. *Theoretical Ecology* **6**(3): 359–372.

Laurance, WF, **Dell, B**, **Turton, SM**, **Lawes, MJ**, **Hutley, LB**, **McCallum, HI**, **Dale, PE**, **Bird, MI**, **Hardy, GESJ**. **Prideaux, G**, **Gawne, B**, **McMahon, CR**, **Yu, RMK**. **Hero, J-M**, **Schwarzkopf, L**, **Krockenberger, AK**, **Douglas, MM**, **Silvester, E**, **Mahony, M**, **Vella, K**, **Saikia, U**, **Wahren, C-H**, **Xu, Z**, **Smith, B**, **Cocklin, C**. 2011. The 10 Australian ecosystems most vulnerable to tipping points. *Biological Conservation* **144**(5): 1472–1480.

Lenton, TM. 2020. Tipping positive change. *Philosophical Transactions of the Royal Society B: Biological Sciences* **375**(1794): 20190123.

Levin, SA. 1992. The problem of pattern and scale in ecology. *Ecology* **73**(6): 1943–1967.

Lindenmayer, DB, **Likens, GE**, **Krebs, CJ**, **Hobbs, RJ**. 2010. Improved probability of detection of ecological "surprises." *PNAS* **107**(51): 21957–21962.

Longo, SB. 2012. Mediterranean rift: Socio-ecological transformations in the Sicilian bluefin tuna fishery. *Critical Sociology* **38**(3): 417–436.

McGlone, MS. 2009. Postglacial history of New Zealand wetlands and implications for their conservation. *New Zealand Journal of Ecology* **33**(1): 1–23.

McGregor, D. 2004. Coming full circle: Indigenous knowledge, environment, and our future. *The American Indian Quarterly* **28**(3&4): 385–410.

Myers, SC, **Clarkson, BR**, **Reeves, PN**, **Clarkson, BD**. 2013. Wetland management in New Zealand: Are current approaches and policies sustaining wetland ecosystems in agricultural landscapes? *Ecological Engineering* **56**: 107–120.

Nystrom, M, **Jouffray, JB**, **Norstrom, AV**, **Crona, B**, **Sogaard Jorgensen, P**, **Carpenter, SR**, **Bodin, Ö**, **Galaz, V**, **Folke, C**. 2019. Anatomy and resilience of the global production ecosystem. *Nature* **575**(7781): 98–108.

Organisation for Economic Co-operation and Development. 2017. *OECD Environmental Performance Reviews: New Zealand 2017*. Paris, France: OECD Publishing. DOI: https://doi.org/10.1787/9789264268203-en.

Osterblom, H, **Crona, BI**, **Folke, C**, **Nystrom, M**, **Troell, M**. 2017. Marine ecosystem science on an intertwined planet. *Ecosystems* **20**(1): 54–61.

Paasche, Ø, **Österblom, H**, **Neuenfeldt, S**, **Bonsdorff, E**, **Brander, K**, **Conley, DJ**, **Durant, JM**, **Eikeset, AM**, **Goksøyr, A**, **Jónsson, S**, **Kjesbu, OS**, **Kuparinen, A**, **Stenseth, NC**. 2015. Connecting the Seas of Norden. *Nature Climate Change* **5**(2): 89–92.

Palumbi, SR. 2003. Ecological subsidies alter the structure of marine communities. *PNAS* **100**(21): 11927-11928.

Peacock, BC, **Hikuroa, D**, **Morgan, TKKB**. 2012. Watershed-scale prioritization of habitat restoration sites for non-point source pollution management. *Ecological Engineering* **42**: 174–182.

Perry, GLW. **Richardson, SJ**, **Harré, N**, **Hodges, D**, **Lyver, POB**. **Maseyk, FJF**. **Taylor, R**, **Todd, JH**, **Tylianakis, JM**, **Yletyinen, J**, **Brower, A**. 2021. Evaluating the role of social norms in fostering pro-environmental behaviors. *Frontiers in Environmental Science* **9**: 620125.

Pisor, AC, **Basurto, X**, **Douglass, KG**, **Mach, KJ**, **Ready, E**, **Tylianakis, JM**, **Hazel, A**, **Kline, MA**, **Kramer, KL**, **Lansing, JS**, **Moritz, M**, **Smaldino, PE**, **Thornton, TF**, **Jones, JH**. 2022. Effective climate change adaptation means supporting community autonomy. *Nature Climate Change* **12**(3): 213–215.

Polis, GA, **Hurd, SD**. 1996. Linking marine and terrestrial food webs: Allochthonous input from the ocean supports high secondary productivity on small islands and coastal land communities. *The American Naturalist* **147**(3): 396–423.

Polis, GA, **Strong, DR**. 1996. Food web complexity and community dynamics. *The American Naturalist* **147**(5): 813–846.

Pörtner, HO, **Scholes, RJ**, **Agard, J**, **Archer, E**, **Arneth, A**, **Bai, X**, **Barnes, D**, **Burrows, M**, **Chan, L**, **Cheung, WL**, **Diamond, S**, **Donatti, C**, **Duarte, C**, **Eisenhauer, N**, **Foden, W**, **Gasalla, MA**, **Handa, C**,

Hickler, T, **Hoegh-Guldberg, O**, **Ichii, K**, **Jacob, U**, **Insarov, G**, **Kiessling, W**, **Leadley, P**, **Leemans, R**, **Levin, L**, **Lim, M**, **Maharaj, S**, **Managi, S**, **Marquet, PA**, **McElwee, P**, **Midgley, G**, **Oberdorff, T**, **Obura, D**, **Osman, E**, **Pandit, R**, **Pascual, U**, **Pires, APF**. **Popp, A**, **ReyesGarcía, V**, **Sankaran, M**, **Settele, J**, **Shin, YJ**, **Sintayehu, DW**, **Smith, P**, **Steiner, N**, **Strassburg, B**, **Sukumar, R**, **Trisos, C**, **Val, AL**, **Wu, J**, **Aldrian, E**, **Parmesan, C**, **Pichs-Madruga, R**, **Roberts, DC**, **Rogers, AD**, **Díaz, S**, **Fischer, M**, **Hashimoto, S**, **Lavorel, S**, **Wu, N**, **Ngo, HT**. 2021. *IPBES-IPCC co-sponsored workshop report on biodiversity and climate change*. Bonn, Germany: IPBES.

Pyyhtinen, O. 2017. Matters of scale: Sociology in and for a complex world. *Canadian Review of Sociology* **54**(3): 297–308.

Ramesh, R, **Chen, Z**, **Cummins, V**, **Day, J**, **D'Elia, C**, **Dennison, B**, **Forbes, DL**, **Glaeser, B**, **Glaser, M**, **Glavovic, B**, **Kremer, H**, **Lange, M**, **Larsen, NL**, **Tissier, ML**, **Newton, A**, **Pelling, M**, **Ramachandran, P**, **Wolanski, E**. 2015. Land–ocean interactions in the coastal zone: past, present & future. *Anthropocene* **12**: 85–98.

Reid, DJ, **Chiaroni, LD**, **Hewitt, JE**, **Lohrer, DM**, **Matthaei, CD**, **Phillips, NR**, **Scarsbrook, M**, **Smith, BJ**, **Thrush, SF**, **Townsend, CR**, **van Houte-Howes, KSS**, **Wright-Stow, AE**. 2011. Sedimentation effects on the benthos of streams and estuaries: a cross-ecosystem comparison. *Marine and Freshwater Research* **62**(10): 1201-1213.

Reusch, TBH. **Dierking, J**, **Andersson, HC**, **Bonsdorff, E**, **Carstensen, J**, **Casini, M**, **Czajkowski, M**, **Hasler, B**, **Hinsby, K**, **Hyytiäinen, K**, **Johannesson, K**, **Jomaa, S**, **Jormalainen, V**, **Kuosa, H**, **Kurland, S**, **Laikre, L**, **MacKenzie, BR**, **Margonski, P**, **Melzner, F**, **Oesterwind, D**, **Ojaveer, H**, **Refsgaard, JC**, **Sandström, A**, **Schwarz, G**, **Tonderski, K**, **Tonderski, K**, **Zandersen, M**. 2018. The Baltic Sea as a time machine for the future coastal ocean. *Science Advances* **4**(5): eaar8195.

Rocha, J, **Yletyinen, J**, **Biggs, R**, **Blenckner, T**, **Peterson, G**. 2015. Marine regime shifts: Drivers and impacts on ecosystems services. *Philosophical Transactions of the Royal Society B: Biological Sciences* **370**(1659): 20130273.

Rocha, JC, **Peterson, G**, **Bodin, Ö**, **Levin, S**. 2018. Cascading regime shifts within and across scales. *Science* **362**(6421): 1379–1383.

Rockstrom, J, **Steffen, W**, **Noone, K**, **Persson, A**, **Chapin, FS, III, Lambin, EF**, **Lenton, TM**, **Scheffer, M**, **Folke, F**, **Schellnhuber, HJ**, **Nykvist, B**, **de Wit, CA**, **Hughes, T**, **van der Leeuw, S**, **Rodhe, H**, **Sörlin, S**, **Snyder, PK**, **Costanza, R**, **Svedin, U**, **Falkenmark, M**, **Karlberg, L**, **Corell, RW**, **Fabry, VJ**, **Hansen, J**, **Walker, B**, **Liverman, D**, **Richardson, K**, **Crutzen, P**, **Foley, JA**. 2009. A safe operating space for humanity. *Nature* **461**(7263): 472–475.

Rouse, HL, **Norton, N**. 2016. Challenges for freshwater science in policy development: reflections from the science–policy interface in New Zealand. *New Zealand Journal of Marine and Freshwater Research* **51**(1): 7–20.

Ruckelshaus, M, **Klinger, T**, **Knowlton, N**, **Demaster, DR**. 2008. Marine ecosystem-based management in practice: Scientific, and governance challenges. *BioScience* **58**(1): 53–63.

Sala, OE, **Chapin, FS**, III, **Armesto, JJ**, **Berlow, E**, **Bloomfield, J**, **Dirzo, R**, **Huber-Sanwald, E**, **Huenneke, LF**, **Jackson, RB**, **Kinzig, A**, **Leemans, R**, **Lodge, DM**, **Mooney, HA**, **Oesterheld, M**, **Poff, NL**, **Sykes, MT**, **Walker, BH**, **Walker, M**, **Wall, DH**. 2000. Global biodiversity scenarios for the year 2100. *Science* **287**(5459): 1770–1774.

Sanchez-Pinero, F, **Polis, GA**. 2000. Bottom-up dynamics of allochthonous input: Direct and indirect effects of seabirds on islands. *Ecology* **81**(11): 3117–3132.

Scheffer, M, **Carpenter, S**, **Foley, JA**, **Folke, C**, **Walker, B**. 2001. Catastrophic shifts in ecosystems. *Nature* **413**(6856): 591–6.

Schiel, DR, **Howard-Williams, C**. 2016. Controlling inputs from the land to sea: Limit-setting, cumulative impacts and ki uta ki tai. *Marine and Freshwater Research* **67**(1): 57–64.

Sea, MA, **Thrush, SF**, **Hillman, JR**. 2021. Environmental predictors of sediment denitrification rates within restored green-lipped mussel Perna canaliculus beds. *Marine Ecology Progress Series* **667**: 1–13.

Selkoe, KA, **Blenckner, T**, **Caldwell, MR**, **Crowder, LB**, **Erickson, AL**, **Timothy Essington, E**, **Estes, AJ**, **Fujita, MR**, **Halpern, SB**, **Hunsicker ME**, **Kappel CV**, **Kelly RP**, **Kittinger JN**, **Levin, PS**, **Lynham, JM**, **Mach, ME**, **Martone, RG**, **Mease, LA**, **Salomon, AK**, **Samhouri, JF**, **Scarborough, C**, **Stier, AC**, **White, C**, **Zedler, J**. 2017. Principles for managing marine ecosystems prone to tipping points. *Ecosystem Health and Sustainability* **1**(5): 1–18.

Sherman, DJ, **Barron, KM**, **Ellis, JT**. 2002. Retention of beach sands by dams and debris basins in Southern California. *Journal of Coastal Research* **SI36**: 662–674.

Singh, GG, **Cottrell, RS**, **Eddy, TD**, **Cisneros-Montemayor, AM**. 2021. Governing the land-sea interface to achieve sustainable coastal development. *Frontiers in Marine Science* **8**(709947): 1–11.

Soga, M, **Gaston, KJ**. 2018. Shifting baseline syndrome: Causes, consequences, and implications. *Frontiers in Ecology and Evolution* **16**(4): 222–230.

Stenseth, NC, **Payne, MR**, **Bonsdorff, E**, **Dankel, DJ**, **Durant, JM**, **Anderson, LG**, **Armstrong, CW**, **Blenckner, T**, **Brakstad, A**, **Dupont, S**, **Eikeset, AM**, **Goksøyr, A**, **Jonsson, S**, **Kuparinen, A**, **Vage, K**, **Osterblom, H**, **Paasche, Q**. 2020. Attuning to a changing ocean. *PNAS* **117**(34): 20363–20371.

Threlfall, CG, **Marzinelli, EM**, **Ossola, A**, **Bugnot, AB**, **Bishop, MJ**, **Lowe, EC**, **Imberger, SJ**, **Myers, S**, **Steinberg, PD**, **Dafforn, KA**. 2021. Toward cross-realm management of coastal urban ecosystems. *Frontiers in Ecology and the Environment* **19**(4): 225–232.

Thrush, SF, **Dayton, PK**. 2010. What can ecology contribute to ecosystem-based management? *The Annual Review of Marine Science* **2**(1): 419–41.

Thrush, SF, **Hewitt, JE**, **Gladstone-Gallagher, RV**. **Savage, C**, **Lundquist, C**, **Meara, TO**, **Vieillard, A**, **Hillman, JR**, **Mangan, S**, **Douglas, EJ**, **Clark, DE**, **Lohrer, AM**, **Pilditch, C**. 2021. Cumulative stressors reduce the self-regulating capacity of coastal ecosystems. *Ecological Applications* **31**(1): e02223.

Thrush, SF, **Lewis, N**, **Le Heron, R**, **Fisher, KT**, **Lundquist, CJ**, **Hewitt, J**. 2016. Addressing surprise and uncertain futures in marine science, marine governance, and society. *Ecology and Society* **21**(2): 44.

Treves, A, **Artelle, KA**, **Darimont, CT**, **Lynn, WS**, **Paquet, P**, **Francisco, J**, **Avila, S**, **Shaw, R**, **Wood, MC**. 2018. Intergenerational equity can help to prevent climate change and extinction. *Nature Ecology and Evolution* **2**(2): 204–207.

United Nations Environment Programme World Conservation Monitoring Centre. 2009. The Ramsar Convention on Wetlands and its indicators of effectiveness. *International Expert Workshop on the 2010 Biodiversity Indicators and Post-2010 Indicator Development*. New York, NY: Convention on Biological Diversity (CBD): 9. Available at chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.cbd.int/doc/meetings/ind/emind-02/official/emind-02-08d-en.pdf.

Vitousek, PM. 1997. Human domination of Earth's ecosystems. *Science* **277**(5325): 494–499.

Williams, PB. 1994. From reclamation to restoration—Changing perspectives wetland management. *Wetland management: Proceedings of the international conference organized by Institution of Civil Engineers and held in London on 2–3 June 1994*. Thomas Telford Publishing: 1–6.

Wipfli, MS, **Hudson, JP**, **Caouette, JP**, **Chaloner, DT**. 2003. Marine subsidies in freshwater ecosystems: Salmon carcasses increase the growth rates of stream-resident salmonids. *Transactions of the American Fisheries Society* **132**(2): 371–381.

Yletyinen, J, **Brown, P**, **Pech, R**, **Hodges, D**, **Hulme, PE**, **Malcolm, TF**, **Maseyk, FJF**. **Peltzer, DA**, **Perry, GLW**. **Richardson, SJ**, **Smaill, SJ**, **Stanley, MC**, **Todd, HJ**, **Walsh, PJ**, **Wright, W**, **Tylianakis, JM**. 2019. Understanding and managing social–ecological tipping points in primary industries. *BioScience* **69**(5): 335–347.

Young, OR, **Berkhout, F**, **Gallopin, GC**, **Janssen, MA**, **Ostrom, E**, **Van Der Leeuw, S**. 2006. The globalization of socio-ecological systems: An agenda for scientific research. *Global Environmental Change-Human and Policy Dimensions* **16**(3): 304–316.

Appendix 1: Model methodology

We assumed that the strength of management action (A_0) changes with time delay (τ) toward a target strength T(ES), where ES is the environmental quality of the downstream ecosystem/ES. We implemented these assumptions mathematically using a first-order autoregressive model,

$$\frac{\mathrm{dA}}{\mathrm{dt}} = \frac{1}{\tau}\left(T(\mathrm{ES}) - A\right).$$

We implemented the tipping point of environmental quality using Holling Type III reproduction with linear mortality and a linear effect of pollutant inflow $r(A)$:

$$\frac{\mathrm{dES}}{\mathrm{dt}} = \frac{\mathrm{ES}^p}{h^p + \mathrm{ES}^p} - a\mathrm{r}(A)\mathrm{ES}.$$

Here, h is the approximate position of the tipping point, p is the sharpness of the tipping point, a is the strength of the inflow's impact on environmental quality, and we have normalized ES so that its maximum value is 1.

It remains to specify the linkages between the downstream environmental system and upstream management actions (A), r(A) and T(ES). For the effect of upstream management, we make the simple assumption that pollutant inflow responds linearly to management action, so that

$$r(A) = P - A,$$

where P is the pollutant inflow without management action. Any delays in response to management action can be incorporated to the delay parameter τ.

Control theory classifies the management response to changes of environmental quality into one of (or a combination of) the following types:

- Proportional control, where management action responds to the difference between the current environmental quality and a target environmental quality;
- Differential control, where management action responds to the rate of change of environmental quality (result of upper limit on timescales [generational]);
- Integral control, where management action responds to both the difference between current and target environmental quality and the time spent away from the target environmental quality.

Control theory discusses advantages and disadvantages of each of these types of control (Åström and Murray, 2012). Here, we assumed proportional control:

$$\mathrm{T(ES)} = A_0(E_0 - \mathrm{ES}),$$

where E_0 is the target environmental quality, and A_0 sets the effectiveness of management action.

Symbol	Definition	Value Used	Unit
A	Adaptive management action		Cost (in dollars, \$)
A_0	Effectiveness of adaptive management	1.5–2.5	Cost per % change of ES, (\$/%)
	Effect rate of pollution on downstream ES	1.5	Per day and cost, (1/(\$ day))
ES	Ecosystem service		% (of maximum ES)
E_0	Target ES	1	% (of maximum ES)
h	half saturation ES constant	0.5	% (of maximum ES)
P	Pollution input from upstream ecosystem	0.7–2.6	Cost (in dollars, \$)
p	Hill coefficient (defines the slope of the change in ES response)	4	–
$r(A)$	Reduction in upstream pollution input (P) due to adaptive management action (A)		Cost (in dollars, \$)
τ	Management response lag	0.1–10	Day

How to cite this article: Gladstone-Gallagher, RV, Tylianakis, JM, Yletyinen, J, Dakos, V, Douglas, EJ, Greenhalgh, S, Hewitt, JE, Hikuroa, D, Lade, SJ, Le Heron, R, Norkko, A, Perry, GLW, Pilditch, CA, Schiel, D, Siwicka, E, Warburton, H, Thrush, SF. 2022. Social-ecological connections across land, water, and sea demand a reprioritization of environmental management. *Elementa: Science of the Anthropocene* 10(1). DOI: https://doi.org/10.1525/elementa.2021.00075

Domain Editor-in-Chief: Alastair Iles, University of California Berkeley, Berkeley, CA, USA

Knowledge Domain: Sustainability Transitions

Published: June 8, 2022 **Accepted:** April 29, 2022 **Submitted:** September 9, 2021

ELEMENTA
Science of the Anthropocene

Elem Sci Anth is a peer-reviewed open access journal published by University of California Press.

OPEN ACCESS