Understanding and Managing Social–Ecological Tipping Points in Primary Industries

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Global environmental change and humanity's growing demands for resources have generated concerns regarding how much pressure Earth systems can absorb without drastic, potentially irreversible consequences. In natural resource production systems, tipping points can generate immediate threats to human well-being. However, empirically exploiting conceptual tipping point models, and applying that learning to management has proven challenging. We argue that primary industries are characterized by a set of social and ecological features that predisposes them to tipping points and motivates studying them as a special class of social–ecological systems. Several primary industry features and feedback loops can explain why some resource systems face a high risk of tipping points, how social responses can affect the detection of early warnings, and how tipping points may cascade among primary industry subsystems. New understanding of resource resilience could be gained by complementing current research with a primary industry perspective. We discuss challenges and solutions for this research agenda.

Keywords: tipping point, primary industry, social–ecological system, regime shift, natural resources

Rapid increases in natural resource consumption have driven substantial changes in the Earth systems that support human societies. Over the coming decades, humanity is facing an enormous challenge in meeting the resource demands of an increasing human population while avoiding irreversible environmental degradation. An increased scarcity of natural resources is a relatively predictable outcome of their overuse. However, human adaptation to resource decline is likely to be additionally complicated by increased frequency of biophysical tipping points, because of global environmental changes and increasingly prevalent human pressure (table 1; Rocha et al. 2015a).

Tipping points are a common feature of complex systems and occur when an ecosystem crosses a critical threshold, whereby it shifts abruptly and often unexpectedly to alternate states, driven and maintained by feedback processes that can generate hysteresis (see box 1; Scheffer et al. 2001). Examples of ecosystem tipping points include lake eutrophication and collapse of animal populations under gradual stress. Although anthropogenic drivers are not necessary for biophysical tipping points, these nonlinear dynamics are frequently triggered by human action and often alter the provision of benefits obtained from nature (Lade et al. 2013, Selkoe et al. 2015). In primary industries (i.e., industries that obtain or provide natural resources for economic gain, here taken to include biosphere-related industries such as agriculture, fisheries, forestry, commercial horticulture, pastoralism, customary harvest, aquaculture), tipping points can generate immediate, persistent, direct, and indirect threats to human well-being through resource collapse or the loss of a supporting element to resource provision, such as fertile soil.

Understanding interlinked biophysical and social dynamics is the fundamental goal of social–ecological systems (SES) research, which has increasingly used the tipping point concept to describe ecological, social, and social–ecological state shifts (Milkoreit et al. 2018). The precise characteristics and definitions of *tipping points* have been debated (Hughes et al. 2013, van Nes et al. 2016, Kull et al. 2017, Montoya et al. 2017, Milkoreit et al. 2018; see box 1 for the definition we use in the present article), and considerable efforts have been made to identify generic patterns and predictors of tipping points (Boettiger and Hastings 2013). However, applying tipping point theory to natural resource or ecosystem management is challenging (Thrush et al. 2009). We believe that this challenge is caused by overuse of the term *tipping point* to describe a variety of distinct phenomena, resulting in linguistic uncertainty (*sensu* Regan

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Table 1. Risks of natural resource tipping points in the main primary industry sectors.	
Primary industry	**Tipping point**
Agriculture	Globally, national *per capita* food provision has increased over the past 50 years, in large part because of the Green Revolution, and it is expected that the world can produce even more food. A number of tipping points have been identified as agricultural production depends on soil, water and weather, and at present needs to adapt to changing climate, growth of biofuels, narrowed diversity in crop species and spatial decoupling of animal production from the supporting natural resource source. Circa 80% of the world's agricultural land is now suffering from moderate to severe erosion, and during the past four decades, 30% of the world's arable land has become unproductive with considerate efforts needed for restoration. High-efficiency, industrialized agriculture may lack resilience to environmental variability; for example, invasive species and pathogens can decimate fruit production in an entire country, or spread to a whole range of crops worldwide. In cases where few countries dominate production of specific crops, climatic stressors may lead to increases in globally simultaneous production losses.
Capture fisheries and aquaculture production	Although the yield from capture fisheries has remained relatively stable for the past three decades (with some uncertainty), aquaculture has contributed to impressive growth in the supply of fish for humans. A "fisheries crisis" is widely acknowledged for marine capture fisheries, and there is robust evidence of fish stock collapses with relatively long recovery times or no recovery. However, uncertainty remains on the global trends, and numerous estimates have been presented for the actual occurrence rate of fish stock collapses both at present and in the future (including global scenarios). Climate change is expected to result in changes in the productivity and distribution of fish stocks, and, consequently, in economic gains and losses both locally and globally. For aquaculture, concerns have been raised over the reliance of aquaculture on wild fish and terrestrial crops for animal feeds in aquaculture (potentially contributing to "fish for food or feed" social inequalities). Although aquaculture has in general contributed to resilience in sea food provision, ecological limits to the provision of wild-caught fish (forage fish for aquaculture), increase in fed aquaculture and global diet shifts may in the future cause a tipping point in feasible seafood supply.
Forestry	Over recent years, global wood production has accelerated. Global forest area (natural and planted) has decreased, although regional differences in forest change and recovery trends are notable. Forest ecosystems have reportedly been increasingly undergoing changes from one ecosystem state to another because of human action, and common tipping point examples include fire-mediated shifts to alternate states and Amazon forest dieback. Global-scale tipping points of forest ecosystems are considered unlikely, but at local and regional scales forestry-related examples include pathogen spread that leads to loss of keystone forest species (e.g., kauri, *Agathis australis*, dieback in New Zealand) and extensive spread of introduced conifer species into nonforest ecosystems.

Note: Global trends are for largely the accumulated result of local events and processes. Key references to support these generalizations for each primary industry can be found in supplemental table S1.

et al. 2002; Kull et al. 2017, Milkoreit et al. 2018) and by the application of generic rules to a rich diversity of complex SESs with diverse interdependencies (table 2) and behaviors (Boettiger and Hastings 2013). In addition, we believe that understanding tipping points in any system requires a pluralistic methodological approach that blends observation, conceptual modeling, narratives, and simulations (Bowman et al. 2015).

Here we argue that primary industry SESs must be considered as a specific class of SESs to better operationalize theoretical concepts of tipping points, and, therefore, to increase our ability to understand tipping point risks as well as to be better able to avoid, or adapt to, tipping points in natural resource provision. These arguments are congruent with propositions that even limited system-specific information can dramatically improve interpretation of real-world tipping points (Boettiger and Hastings 2013). The utility of such a focus is demonstrated by research applied specifically to tipping points in marine ecosystems, which has enabled synthesis of their drivers and impacts and led to clear management recommendations (Conversi et al. 2014, Rocha et al. 2015b, Selkoe et al. 2015). We consider that a focused research approach is key to improving our understanding of tipping points in primary industries, because their tight social–ecological coupling distinguishes them from primarily ecological or social tipping points and many other SESs (e.g., urban social–ecological systems, abandoned production systems, nature parks). Furthermore, acknowledging the inherent social–ecological connectivity of primary industries enables detection and management of processes that may accelerate change and hinder recovery (e.g., feedback loops) but would not exist or be detectable (or, possibly, be altered) in uncoupled ecological and social systems.

In this vein, we present arguments for the importance of a focused social–ecological research perspective to tipping points in primary industries and outline barriers and opportunities to understanding and managing them. We begin by briefly introducing why tipping points in SESs have dynamics different from those in uncoupled social and ecological systems. We then outline the motivation and value of examining production system tipping points through a primary-industry lens—a research perspective that embraces the coupled and interdependent nature of SES in tipping point dynamics and acknowledges that humans play a larger role in the dynamics of primary production systems than in many other ecosystems. To present these views, we move throughout the discussion from the scale of an ecosystem to the scale of global social–ecological systems. Finally, by identifying the research barriers to adopting such a view, we suggest future research directions that may allow us to move toward a management perspective that embraces the coupled nature of social–ecological tipping points in primary industry. In so doing, we discuss tipping points from

Box 1. Glossary.

Early warning signal. An indicator that shows detectable changes in advance of a tipping point

Feedback. A process in a system in which outcomes generated by a mechanism are returned to it as inputs. Negative feedback loops are self-damping (i.e., they reduce effects of perturbation), whereas positive feedback loops are self-reinforcing (i.e., amplify the effects of perturbation).

Hysteresis. A situation in which change in one direction differs from change in the opposite direction. In a system with hysteresis, a change needed for degradation differs from the change needed for recovery.

Intervention opportunity. A place or situation in a system at which management can significantly change the trajectory of the system. Key intervention opportunities are characterized by gaining large change with relatively small management input.

Primary industries. Industry that obtains or provides natural raw materials (for example, agriculture, capture fisheries, aquaculture, forestry, mining).

Production system. A system that directly relates to the provision and harvesting of individual crops, wild species or livestock

Resilience. The degree to which a system is capable of absorbing shocks or perturbations while sustaining its function, structure, main feedback loops, and identity (Folke 2016). Resilience in production systems can be defined as the ability to maintain production when under stress or when the resources it relies on are under stress, and to recover from disturbances when they do impact.

Social–ecological system. A system with interacting biophysical and social components

(Critical) threshold. A system state at which even small changes lead to large changes in a system

Tipping point. Any situation in which accelerating change caused by a positive feedback drives the system to a new state. In this article, we use the term tipping point for any phenomena meeting this criteria, even if the reviewed literature uses other terms or more detailed definitions. This decision follows (van Nes et al. 2016).

the perspective of shifts to undesired states rather than triggering desired social–ecological transformations. Insights in this article are drawn both from an interdisciplinary workshop among scientists, practitioners, industry representatives, and policy advisors and from published SES research.

Dynamics of tipping points in social–ecological systems

Tipping points have been documented in diverse social (Wolf 1963, Gladwell 2000) and ecological systems (e.g., Lindenmayer and Luck 2005 and the references within). A number of case studies of tipping points in SESs have been reported (see online Regime Shifts Database; Stockholm Resilience Centre 2018 and the list of literature provided by Milkoreit et al. 2018); however, these examples have seldom been systematically examined across different systems (but see Rocha et al. 2015a, Benton et al. 2017). Moreover, if tipping point research is to inform management and policymaking that creates resilient resource production systems, science must produce knowledge and information that extends beyond the idiosyncrasies of single cases. Furthermore, with the exception of fish stock collapses, we found no estimates of the frequency at which tipping points occur in primary industries, or, alternatively, any evidence for tipping points being rare, which would enable trust in the present resilience and management of production systems. Repeated recovery from localized perturbations does not provide evidence of system-scale resilience against tipping points (Scheffer et al. 2012).

Understanding the socioeconomic or biophysical dimensions of SESs in isolation of each other can only partially contribute to management decisions in primary industries because they, like many SESs, form complex adaptive systems (Levin et al. 2013). Primary industries consist of complex subsystems that adapt and interact with each other at different scales (hierarchical levels): Resource subsystems (e.g., fisheries as a system, fish species as a resource unit, and people with fish-based livelihoods and consumers as resource users) and governance subsystems (e.g., organizations and policies that govern fishing) interact to produce outcomes at the SES level, with feedback loops to the subsystems and even other SESs (e.g., the global economy; Ostrom 2009). Ignoring the ability of the ecosystem to reorganize or the ability of the social system to respond to change affects decisions about the long-term capacity of the production system to generate ecosystem services (Folke et al. 2005). For example, evaluating the outcomes of fish stock management on the basis of ecosystem state may exclude the effects of management on the community of fishers, which, in the future, will affect ecosystem resilience through harvesting (Yletyinen et al. 2018).

Seeing primary industries as complex adaptive SESs leads to at least three important considerations. First, incorporating individual decision-making, collective human behavior and institutional processes into a complex ecological and environmental context, or *vice versa*, often reveals a richer diversity of feedback loops and thresholds than occur in either social or ecological systems separately (supplemental

Table 2. Examples of SES tipping points that demonstrate the diversity of social–ecological tipping point dynamics.

Scale of change in SES	Tipping point (TP)	Main driver	Example
Tipping point in either social or ecological system	Ecological TP	Social	Sudden loss of biodiversity through habitat loss and fragmentation, driven by land conversion for human use and accelerated by habitat edge effects and changes in population structure. Intervention: habitat restoration (E), public awareness campaigns for environmentally friendly land management (S).
	Ecological TP, with influence on social system.	Biophysical	Natural climatic shifts that affect regional marine ecosystems and, therefore, the human communities using the marine resource. Intervention: adaptive resource management to mitigate social influence and increase resilience of the ecosystem to stress (S, E).
	Social TP	Biophysical	Removal of subsidies in agriculture or fisheries and adoption of a different set of rules for governing the use of an ecological resource, driven by environmental change in resource abundance. Intervention options are not presented as the social shift is itself an intervention to maintaining healthy ecological change.
Tipping point in one system, reciprocal influences	Ecological TP, causing changes in social systems	Social–ecological feedback loops	Humans introduce invasive species into healthy native ecosystems. The adverse effects of the invasive species on the native ecosystem trigger eradication efforts. Intervention: pest management (E), increasing public awareness (S), publicly approved pest eradication technologies (S, E).
	Social, causing changes in ecological system	Social–ecological feedback loops	Globalization and construction of infrastructure to access untapped natural resources leads to overexploitation of resources, with net negative effects on ecosystem resilience and provision of ecosystem services, extraction of much of the wealth acquired from the region from the community and loss of traditional ecological or harvesting-related knowledge. Intervention: sustainable resource harvesting (S, E), subsidies to traditional harvesting (S), alternative income sources (S).
Tipping points in both ecological and social systems	Ecological TP and social TP	Any combination	Overharvesting (potentially in synergy with concomitant environmental change) drives a resource collapse, which leads to consequent restructuring of social community. Intervention: sustainable resource management (S, E), consumer awareness programs (S).

Note: The table follows a threshold categorization framework by Walker and Meyers (2004). More details and key references for each example can be found in supplemental table S2. We have excluded Walker and Meyers' classes for uncoupled social and ecological systems. Abbreviations: E, ecological feedback; S, social feedback.

table S2; Lade et al. 2013). Even if social and ecological subsystems exhibit linear behavior, links between subsystems can induce tipping points in a coupled SES (Lade et al. 2013). Second, whatever the trigger, once a change is set in motion, the structure of the SES plays a major role in whether the change accelerates and becomes catastrophic (Scheffer et al. 2012). Therefore, clues to how susceptible systems are to tipping points can be gained by comparing their structure to that of systems that have proven resilient, because certain structural features may indicate fragility that typically precedes abrupt changes (Scheffer et al. 2012). Third, SES tipping points can be initiated in either the social or ecological subsystem and potentially cascade from one subsystem to another or occur in both subsystems as a coupled event (table S2; Walker and Meyers 2004).

These three SES characteristics demonstrate how general research on SES tipping points increases our understanding of systems problems in these multilevel and multiscale systems. However, we should be cautious with blueprint approaches in tipping point management, even if simple solutions to complex problems appear attractive (Ostrom 2007). Because of their dependency on natural resources and because humans play a larger role in the dynamics of production systems than in many other ecosystems, tipping point research focused on primary industries must be carefully contextualized. Through extraction of resources, primary industries are among industries that influence and manage the environment directly, whereas many other industries that rely on natural resources (e.g., secondary sector of the economy: retail, insurance etc.) influence environmental management indirectly through, for example, market pressure. Understanding and managing the resilience of primary industries is especially important now that they face unprecedented environmental and regulatory changes in addition to conventional biophysical, economic, and societal pressures. We believe that research with a "primary industry lens" on tipping points in production systems will support decision-making (cf. Thrush et al. 2016) better than general SES perspectives or standalone case studies. Furthermore, improved understanding of primary industry tipping points may contribute to ecosystem management, as resource harvesting practices (e.g., fertilizer use) commonly contribute to driving ecosystems to tipping points (Rocha et al. 2015a).

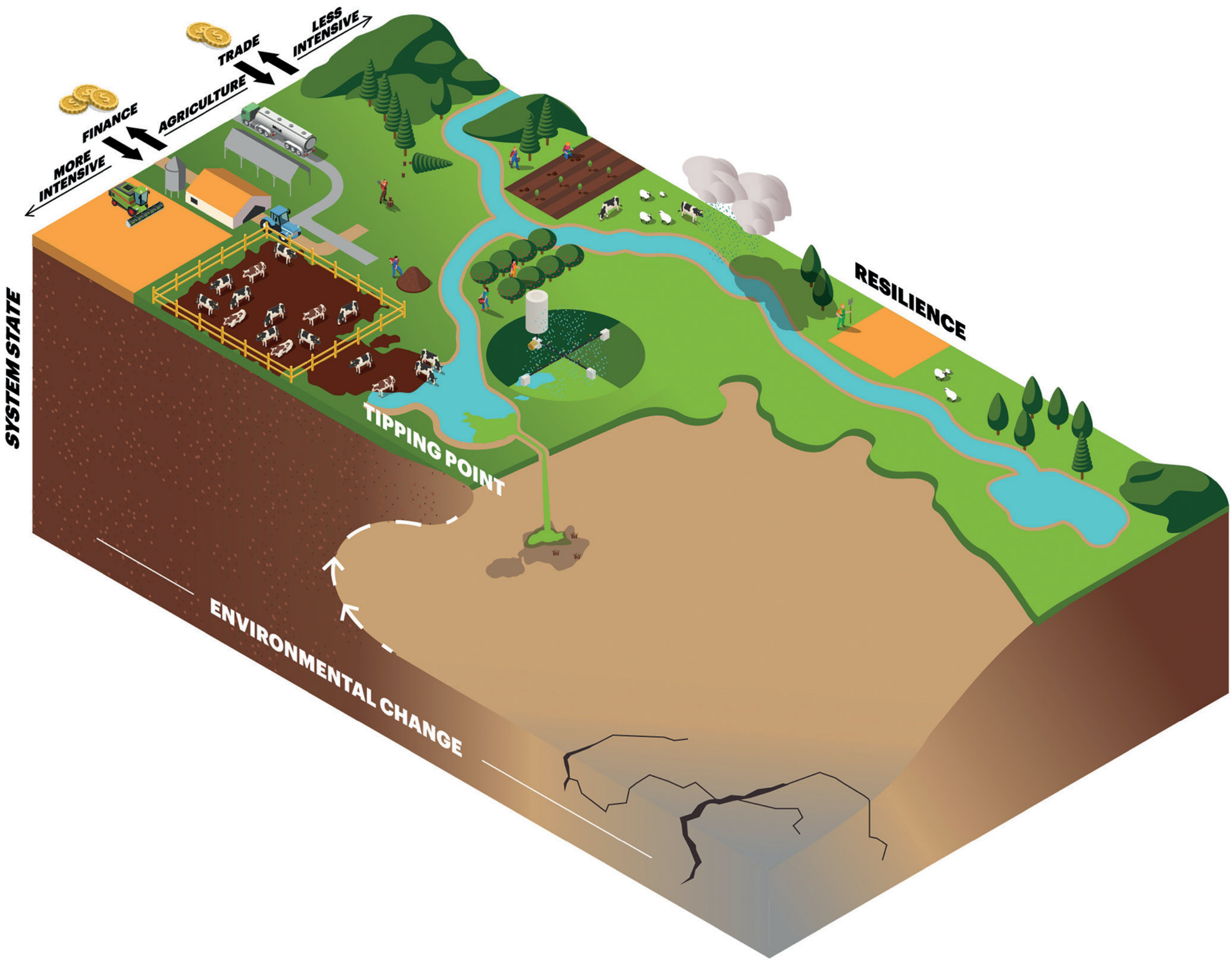

Figure 1. ***Primary industries are characterized by a set of social and ecological features and complex social–ecological interdependencies that may predispose them to tipping points. Intensive agriculture provides an example of a heavily modified ecosystem where ecosystem structures have arisen through resource use and management, and lack many characteristics considered important for maintaining resilience to environmental change or failed management.***

Tipping points through a primary industry lens

Resilience allows an ecosystem to persist in its current state through adaptation and self-organization (Folke 2016). Intensively managed ecosystems, however, have structures that have arisen through management rather than through biophysical self-organization; therefore, in the absence of specific adaptive responses to stress, they are more vulnerable to stressors (figure 1; Levin 1998). Evaluating changes in resilience may be challenging. For example, irrigation reduces water stress and increases the productivity of water-demanding crops, but irrigation may reduce the ability of an ecosystem to manage drought response when irrigation is no longer possible. Recognizing this vulnerability is key to evaluating risks for tipping points in primary industry because production ecosystems are frequently modified and often lack (some of) the characteristics (e.g., species diversity) considered important for maintaining resilience against shocks or failed management (Fischer et al. 2006). In many cases, ecological feedback loops contribute to maintaining the present state of a system and should (if the present state is desirable) not therefore be altered (Perry 1995). For example, deforestation in the Amazon may break a hydrological cycle, which in synergy with other drivers can transform rainforests into savannas (Davidson et al. 2012). It is important to acknowledge, however, the varied extent of ecosystem modification across production systems. For example, timber production in natural forests often allows natural regeneration of trees, and reforestation can be managed to sustain a near-natural mix of native species. Another example is ecosystem-based management, which prioritizes maintaining ecosystems that sustain a resource over the resource itself. However, operationalizing these management principles has proven difficult (Tallis et al. 2010).

Although social institutions usually respond to ecosystem degradation through restorative management, the incentive to such management in primary industries could be undermined by a need or desire to maximize production or maintain preferred social states (e.g., culling whales for fisheries yield; Gerber et al. 2009). Prioritizing production may cause actual or perceived ecosystem tipping points to be crossed or influence how and when a tipping point unfolds (Walker et al. 2006). A well-known case is "command-and-control" management of natural resources, which reduces the range of natural variation of systems (structure, function or both) in an attempt to increase their predictability or stability, but in so doing replaces natural ecological control with engineered constructions and manipulations—a practice that has often led to undesirable ecosystem states (Holling and Meffe 1996). For example, intensive monoculture agriculture suppresses ecological succession and modifies nutrient cycles through the use of fertilizers to achieve high production; however, at longer time scales, it is highly vulnerable to pest outbreaks, market fluctuations, and soil degradation (Lin 2011). Another example is implementation of Green Revolution agriculture in traditional rice farming, which significantly contributed to problems in water distribution and pest outbreaks that used to be regulated by traditional practices (Schill et al. 2017). Furthermore, pressure to provide employment and (increase) profits may result in unsustainable harvest levels, and a tragedy of the commons may prevent individual landowners from environmentally sustainable harvesting. Efforts to maximize ecosystem outputs can create or break crucial social–ecological feedback loops (table 2). At the extreme, ecosystem modification may create new ecological feedback loops or alter the strength of the existing feedback loops to reinforce the modified ecosystem, making it resilient to rehabilitation even if management for production ceases (e.g., agricultural legacy effects).

Humans may maintain natural resources near a tipping point through strategic management that aims to avoid resource collapse but not underuse the resource (Bauch et al. 2016). The maintenance, or even increase, of resource use or harvesting pressure despite resource degradation can occur when rarity makes a resource more valuable or desirable, creating a feedback that leads to overexploitation (Courchamp et al. 2006). When harvesting pressure is not released during resource depletion, recovery may be delayed, and the resource is kept longer on the edge of collapse or in a collapsed state (Neubauer et al. 2013). Resources kept in that state may be particularly vulnerable to unforeseen natural impacts, such as plant diseases (Lontzek et al. 2016). Similarly, declining fertility or yield can drive increases in intensification, which can create a reinforcing feedback via reduced resilience (Nikolaidis 2011). In contrast, nonproduction systems that are not subjected to resource harvesting or influenced by its externalities are less likely to be maintained at the edge of a tipping point (e.g., postproduction sites, see examples in Suding 2011).

Crucially for tipping point management and forecasting, human responses to degradation can complicate the interpretation of early warning signals, or mute early warning signals of an approaching ecological tipping point in two ways (Bauch et al. 2016). First, a coupled SES has a wider array of possible outcomes than an uncoupled system, making it difficult to interpret from early warning signals to which regime the ecosystem is shifting, unless multiple indicators are used (Bauch et al. 2016). For example, an ecological early warning signal could suggest a tipping point from rainforest to a savannah. However, in the presence of resource management (i.e., human adaptation, which represents social–ecological feedback loops), ecological changes may stimulate interest in forest conservation (Thampi et al. 2018) or improved management, and the early warning can therefore suggest a shift to savannah vegetation, sustainable forestry or even a conservation area. Second, human adaptation feedback loops can mute the variability in early warning signals (Bauch et al. 2016). The human adaptation that mitigates change (forest example above) and strategic management interventions that maintain the resource system close to the critical threshold mask early warning signals (Bauch et al. 2016), likely with time lags. Monitoring generic early warning signals for a system that is deliberately maintained near critical thresholds is clearly self-contradictory; early warning signals tend to arise when a system *approaches* a tipping point (Scheffer et al. 2009), and therefore, when a system is constantly *close* to a tipping point, the indicators used to detect early warnings will constantly characterize the system as being close to a tipping point (e.g., statistical variance will not indicate change). Consequently, in addition to ecological variation, early warning signals for tipping points in primary industries could be identified in human adaptation such as technological innovations and responses to resource fluctuations (Hicks et al. 2016).

Theoretical research suggests that the more strongly subsystems are coupled, the easier it is for them to simultaneously pass critical thresholds (Brummitt et al. 2015). Because of the tight social–ecological coupling in primary industries (resource harvest and associated impacts on environment), it is essential to examine the resilience of the social subsystem to which a production ecosystem is linked. As with ecosystems, resilience in social systems is based on adaptability to environmental and societal variation. Furthermore, the structure and strength of social–ecological coupling may rapidly change through, for example, innovations. The ability to harvest diverse portfolios of natural resources may enable resource users to adapt to environmental change (including overuse of resources), and carefully designed policies can buffer negative impacts that resource users may face during ecosystem tipping points (Broderstad and Eythorsson 2014, Yletyinen et al. 2018). General principles related to resilience have been identified for social systems linked to natural resources, including the diversity and redundancy of actors and institutions (Boyd and Folke 2011, Sterk et al. 2017).

However, management outcomes and harvesting models are usually designed and assessed on the basis of ecosystem status or resource production and, therefore, overlook the adaptability of the coupled social system (Yletyinen et al. 2018). Adaptive comanagement, on the other hand, allows local social groups to share information, learn, and actively self-organize in response to environmental feedback loops (Boyd and Folke 2011).

In policymaking, mismatches between institutional and biophysical systems provide another way that the social subsystem can increase the risk of a tipping point being transgressed. For example, central management may apply one-size-fits-all solutions that are inappropriate for local resource users, respond too slowly in comparison to ecological processes (e.g., localized erosion) or be unaware of tipping-point risks and expect gradual change (Galaz et al. 2008). An example of mismatch between ecosystem dynamics and governance systems is the dust bowl tipping point event of the North American Great Plains, where increased commodity prices and legislation to expand land allowances for homesteaders drove expansion of grazing agriculture that through decrease in resilience eventually rendered the land unusable for agriculture (Kasperson et al. 1995). Similarly, spatial mismatch may occur when policies are based on local-scale dynamics and do not cover the entire areal extent of a resource system (e.g., river basin), leading to inappropriate assessments of the state of the system and inappropriate management (Sterk et al. 2017).

Finally, awareness of the global nature of primary industry trade can explain unexpected tipping points at local and regional scales. The dynamics of resource production and consumption are interlinked through trade and the global environment (Lee et al. 2012, Cottrell et al. 2019). For example, climate change impacts and extreme weather in key production centers can trigger regional food crises and global price spikes and cascade into widespread societal crises (Lee et al. 2012). Global connectivity and cross-scale links (Niiranen et al. 2018) mean that the resilience of production systems (as in many industries that depend indirectly on natural resources) is sensitive to production variability, legislation, consumer demand, and cost efficiency of production and processing, even in distal parts of the system (Ruta and Venables 2012). Furthermore, these social–ecological supply–demand feedback loops are affected by a number of social meta-feedback loops (in addition to the earlier discussed ecological feedback loops) involving issues such as fiscal crises and conflicts (Helbing 2013). Societal changes can therefore trigger changes in global trade, which lead to altered resilience in local production systems. For example, the support measures that the United States and the European Union took to encourage expansion of biofuel production contributed to changes in production of other resources in these areas, which meant that South America could take advantage of growing soybean markets in China without competition from US farmers (which, in turn, has been blamed for unsustainable land-use change in the Amazon; Lee et al. 2012). A shift to circular economy including optimized resource use, sharing and recycling could deliver dramatic changes in resource harvesting (Lee et al. 2012).

The complex interdependencies between social and ecological subsystems in the primary industries present challenges for understanding and opportunities for managing primary industry tipping points. Complex SESs cannot be controlled as such, but with appropriate interactions, adaptive feedback mechanisms and institutional settings may allow some SESs to self-organize in a guided way (Chandler 2018). An encouraging insight for tipping point researchers is that primary industries may differ from many other SESs in data availability. To sustain the supply of resources and ecosystem services, many primary industries have established monitoring of resource levels, environmental variables and harvesting to a far greater extent than what has been established for most natural ecosystems. For example, precision agriculture produces detailed data in real time on production systems in relation to management. Similarly, long-term data (covering more than 100 years) on plant pathogens in New Zealand can be used to assess effectiveness of biosecurity policies and project future trends (Sikes et al. 2018), which benefits primary industries. Adaptive resource management requires monitoring programs (Boyd and Folke 2011), so the availability of data (where accessible and not commercially sensitive) may make primary industries particularly amenable to research on adaptability, feedback loops, and thresholds.

The way forward

Difficult to predict or reverse, tipping points in primary industries pose significant challenges to society because of our dependency on the extraction and use of natural resources for well-being and long-term societal development. In this article, we have shown that focused research on primary industries enhances our understanding on their potential vulnerabilities to tipping points. There is now a pressing global need to estimate risks for biophysical tipping points and take action to avoid them or, when unavoidable, to build social and environmental capacity for adaptation. Generic SES tipping point research has provided crucial knowledge on system behavior in relation to tipping points. However, scientists and managers frequently struggle to apply generic, often theoretical, tipping point knowledge to what is practically testable or measurable in the real world (Thrush et al. 2009). At the other end of the research spectrum are case studies. Although individual case studies are highly useful in generating in-depth case-specific knowledge and general insights, accumulating knowledge needed for management with case studies can be slow, and it is limited to places where resources (funding, time) are available. It is essential to question whether producing case studies for each (or subsets of few) production system disproportionately prioritizes data quantity over data quality (e.g., Bayraktarov et al. 2019). For example, agricultural land covers the immense, approximately 37% of global terrestrial area (World Bank Group 2018) and the Food and Agriculture Organization of the United Nations monitors approximately 600 fish stocks (FAO 2011). Therefore, one of the most time-efficient actions toward improving primary industry resilience to tipping points globally is gaining knowledge also at the mesoscale (primary industries as a subset of SESs) on the features common to production systems. This approach should include synthesis of existing studies on primary industry tipping points and research agendas that produce easily comparative case studies. Future research should determine whether primary industry focus would significantly benefit from being sector-specific (e.g., agriculture, forestry; see, e.g., Cottrell et al. 2019) with consideration to cost efficiency and urgency.

Our final argument for primary industry focus is the nature of primary industries as actively managed SESs that are critical to human well-being and are embedded in dynamic, globally connected social systems. Recent studies have emphasized that tipping points can cascade (a domino effect) across systems and scales and that tipping points may be simultaneously triggered in multiple locations by shared drivers, with similar or opposing responses in resource production (Rocha et al. 2018, Cottrell et al. 2019). For example, the frequency of sudden losses to food production, driven by social and ecological drivers in synergy with the dynamics of food systems, has increased in all food-producing sectors, and can trigger tipping points that pose a significant threat to food security on global level through global trade or shared environmental drivers (Cottrell et al. 2019). Given such risks, learning to recognize the patterns and processes that are related to tipping points in primary industries is essential. As was discussed in our study, continuous human intervention in resource production systems may require researchers and managers to conduct different interpretations of system patterns and processes than what generic SES tipping point research might suggest. Integrated understanding of the primary industries is needed; isolated studies on production systems may not be able to detect cumulative risks that the extended social–ecological scale produces.

To gain improved understanding of SES dynamics and interdependencies and to encourage the use of a primary industry lens, we next describe six steps that may allow analysis of the coupled nature of social–ecological tipping points. We do not review the challenges associated with managing social or ecological tipping points separately or develop analytical frameworks for social–ecological systems in general because these topics have been examined elsewhere (e.g., Schluter et al. 2012, Levin et al. 2013).

Identify feedback loops and state variables that define tipping points. Tipping points often result from critical changes in the ways that the components of the system interact with each other (Walker et al. 2012; box 2). However, little guidance is published for designing data collection for SESs, although some frameworks offer suggestions for key variables to measure (Anderies et al. 2004, Ostrom 2009). An inadequate understanding of SES behavior can result from not knowing how the social and ecological subsystems connect or from unknowingly excluding key social or ecological variables or feedback loops. Furthermore, attention may be paid only to processes that are quantifiable rather than to the elements that may be important but not easy to measure or model (Cote and Nightingale 2012). Identifying key variables and feedback loops within and between social and ecological subsystems is the necessary first step in understanding and managing SES tipping points. This could be done by carefully creating causal loop diagrams or systematically categorizing tipping point cases (table S2; Walker and Meyers 2004, Walker et al. 2012, Bowman et al. 2015). From the perspective of primary industry tipping points, it is intriguing that agriculture, aquaculture, and extractive practices such as forestry, are often considered as drivers of tipping points—that is, external to the system rather than internal system variables (as defined by Walker et al. 2012; Rocha et al. 2015a). Instead, if resource management is considered an internal part of the system, the resource management variables too become study objectives and may be part of critical feedback loops (detailed discussion in Walker et al. 2012). As previously discussed, key interactions may span multiple spatial and temporal scales, in both environmental and socioeconomic dimensions (Niiranen et al. 2018). This first step is especially necessary in addressing the decoupling of harvest effort from ecosystem state, for example in the case of acceleration of resource extraction with resource scarcity.

Consider social structure when assessing the risk of ecosystem tipping points. Social structure refers to the social arrangement of a social group, such as relations, behavior, social norms and institutions. We have highlighted that some ecosystems may be at risk because of characteristics of the social subsystems to which they are linked. To evaluate the risk of tipping points in ecosystems associated with primary industries, it is necessary to consider the social characteristics of the principal actors in the system and how they collectively respond to environmental feedback loops and meta-feedback loops in social systems (e.g., change in consumption patterns). New opportunities for management interventions may be revealed by focusing on the social subsystem. For example, detecting bottlenecks in production supply chains (Macfadyen et al. 2015), or identifying transnational primary industry entities with disproportionately large influence on the resource sector and harvested ecosystems, may lead to the identification of key intervention points with cascading effects of improved ecosystem resilience regionally or through the entire industry (Österblom et al. 2015).

Adapt existing analytical tools to the problem of tipping points in SES, focusing on metrics that are comparable in social and ecological subsystems. Integrating analysis of social and ecological

Box 2. Quantifying feedback loops.

Given the importance of feedback loops in tipping point events, identifying feedback loops and characterizing how they operate and change through time and space may be the most important basis for management. Importantly, changes in feedback strength can drive tipping points, and the system response to some feedback loops may be lagged or slow. Furthermore, as the system state changes, the dominant feedback loops may also shift. Therefore, identification and quantification of feedback loops is essential for understanding why and when primary industry tipping points occur, for predicting the resilience of potential future states, and for evaluating intervention potential. However, although its importance has been acknowledged quantitative examination of feedback loops in SES research remains challenging.

Roe (2009) reviews the basic principles of quantitative feedback analysis in physical systems and provides an excellent presentation of the depth of system comprehension that is needed for the quantification of feedback loops in empirical research, as well as the mathematical procedures required. The approach described by Roe (2009) is based on calculating *feedback factors* (fraction of the system output fed back into the input) and *system gain* (factor by which the system response has gained because of the inclusion of feedback) in comparison to a reference system.

SESs are commonly complex, operate on large spatiotemporal scales and include diverse units of analysis. The challenge of quantitative SES feedback analyses may primarily center on the challenge of quantifying social processes (e.g., change in attitude, eroding trust) and finding an appropriate reference system. For example, with nonlinear coupling of social and ecological systems, a change in ecological variable *A* (e.g., resource abundance) can affect social variable *B* (e.g., profit from harvesting the resource) through direct *A/B* feedback, through indirect causal connection between *A* and *B* (e.g., increase in resource abundance cause a collapse of another resource, which leads to precautionary, strict harvesting policies and quotas on all local resources), or *A* and *B* may change simultaneously because of some external variable (e.g., extreme weather event affects resource abundance and also decrease the number of days harvesters are able to work outdoors). Such independencies may change periodically with, for example, seasonal trends in climate and phenology. Furthermore, human adaptation, especially in an era of unprecedented scale of interactions (e.g., global trade), creates “spill-over” effects in that social actors can move their activities to another ecosystem when needed. Therefore, variable *B* (profit) is no longer directly influenced by *A* (local resource abundance), and change in *A* now also influences other variables similar to *A* (resource systems elsewhere; Ferraro et al. 2018). Qualitative examination of such complex connections and feedback loops in SESs can be achieved with, for example, causal loop diagrams (examples available online at Regime Shift Database; Stockholm Resilience Centre 2018). However, being able to quantify the *magnitude* of codependence between each variable (feedback factors and system gain) requires a pluralistic approaches and complex modeling (c.f. Bowman et al. 2015, Ferraro et al. 2018). Fortunately, the capacity to collect data at a large scale and new technological solutions for developing and validating models are emerging, and can be carefully explored. Social–ecological feedback studies on a smaller scale include, for example, codependence between resource abundance and harvest effort and visible environmental change and conservation opinion (e.g., Thampi et al. 2018).

systems is a central challenge in SES tipping point research because different disciplines use different frameworks, theories, and models (Ostrom 2009). Analytical challenges and approaches for studying tipping points in complex, large SES data sets are reviewed in (Filatova et al. 2016, Polhill et al. 2016). We suggest taking advantage of existing methods that can address tipping points in SES from a variety of contexts and conditions (Filatova et al. 2016; box 3); using complementary approaches to detect and define tipping points, such as a combination of qualitative and quantitative tools to enable inclusion of qualitative social processes and stakeholder narratives (see step 5); and using consistent and reproducible methods across SES tipping point case studies to facilitate meta-analyses. Categorization and databases of SES tipping points (e.g., online Regime Shift Database; see the references cited and table S2) could provide a starting point for developing general social–ecological tipping point models for primary industries.

Communicate and question the definitions of core concepts. The term *tipping point* has multiple and contested interpretations, some of them metaphorical (van Nes et al. 2016, Kull et al. 2017, Milkoreit et al. 2018). It is important to include precise definitions of the core tipping point concepts in research reports and communication to policymakers to minimize linguistic uncertainty (cf. Regan et al. 2002). Unacknowledged conceptual differences in the use of core concepts may create the false impression of similarity in essentially dissimilar phenomena (Milkoreit et al. 2018). For example, even if both social and natural systems may experience rapid qualitative changes, tipping points in social and political domains may differ from biophysical tipping points (Milkoreit et al. 2018). Van der Hel (2018) found that in climate communication, tipping points in social systems are often presented as simple, positive, and necessary, whereas environmental tipping points are presented as being dangerous and beyond our control. Furthermore, the difficulty of fitting social processes into current tipping point research frameworks and related concepts (e.g., Adger 2000, Cote and Nightingale 2012) indicates the need for increasingly transdisciplinary development of the field and breaking down of research silos. Clearly communicated, unambiguous definitions of tipping points and related concepts in research

Box 3. Analytical tools to merge social and ecological systems.

A promising approach for social–ecological research that draws on a complex adaptive systems perspective is representing the connected components of social and ecological systems in a network and studying that network's architecture in relation to tipping points and recovery intervention. Network science has been used in both natural and social sciences and therefore provides a shared methodological approach, for example when evaluating the network structure to detect management mismatch between ecological processes and management structures.

The development of new network analysis tools in both social and ecological domains opens a variety of options for modeling. Natural resource management systems form social networks with hierarchical layers from local users to regional and national authorities. Inclusion of an ecological component adds additional layers to this hierarchy. Therefore, a highly influential framework for understanding social–ecological systems may be their representation as multilayer networks (Kivelä et al. 2014).

Network science tools such as exponential random graph modeling can be applied to multilayer SES networks to study emergence (microlevel processes and system-scale structure) and tipping point–induced changes (Yletyinen et al. 2016). A number of social–ecological motifs (network "building blocks") have been identified to represent the connectivity of social actors to ecological resources (Bodin and Tengö 2012). Early warning signals of tipping points in multilayer networks are also being developed (Jentsch et al. 2018).

Network control (Liu et al. 2011) provides a useful concept for detecting key intervention points in social–ecological networks, and some steps have been taken to apply network control methods in the context of epidemics in agrisystems (Natale et al. 2009). Controllability properties of networks are based on the topological possibility of influencing an entire network, or a large part of it, by controlling only a subset of "driver nodes." To our knowledge, network control techniques have not yet been applied to multilevel social–ecological networks, likely because technical (network structures) and conceptual (self-organization) obstacles remain (Menichetti et al. 2016).

A suite of trait-based concepts and analysis tools provide another common currency for quantifying SES. There has been a considerable ecological focus on the relationship between species traits and resilience, and there is growing evidence that traits can drive the structure of species interaction networks (Coux et al. 2016). Likewise, research on the social subsystem suggests that links among components such as adaptive comanagement are underpinned by personal traits (Brown et al. 2016). Concepts of trait redundancy and complementarity may apply equally to social and ecological subsystems, and exploring the mapping of these two may be fruitful.

reports also allows exploration of complementary analytical approaches (see step 3).

Acknowledge and build on multiple knowledge sources. Identifying and managing tipping points in SES is challenged by power imbalances, social inequalities, and personal beliefs (Walker et al. 2006). For example, indigenous peoples may prioritize intergenerational benefits in management interventions over different timescales, but this knowledge and these people's livelihoods are frequently eroded by colonization and the implementation of western resource or ecosystem management (Lyver and Tylianakis 2017). Furthermore, the high cost of participation in meetings may exclude many social groups from decision-making on tipping point management (Lynham et al. 2017). Power and beliefs influence the definition of a desirable state for an ecosystem or SES and, consequently, the appropriate management actions taken to maintain or shift the state (Walker et al. 2006, Kinzig et al. 2013), such as securing rights to a resource to local indigenous communities (Broderstad and Eythorsson 2014). Furthermore, tipping point management may be obstructed by lack of transparency in trade-offs between different potential states when the resilience of some livelihoods results in the vulnerability of others (e.g., ecotourism may limit more traditional land use activities). Management is also hindered by hidden feedback loops, and the burden of proof to policymakers to take action to avoid a tipping point or to demonstrate when a tipping point has been successfully prevented (e.g., biosecurity practices to prevent invasions). In primary industries, different priorities or interpretations of events could be revealed by economic investigations; tipping points may redistribute ecosystem or economic benefits among stakeholders or change the balance between costs of action and inaction for responding to a tipping point (Selkoe et al. 2015). Similar to careful consideration of validity in data collection, we urge increased transparency in research and policymaking in questioning whose perspective and knowledge is used to report a SES tipping point as well as in describing the benefits, costs and preferences in management.

Design and establish SES monitoring for future data needs. Multiple disciplinary perspectives are needed to analyze tipping points in SESs, and analyses are often performed with data sets that are more detailed for either the social or ecological component (Cote and Nightingale 2012). To complement existing economic and biophysical data already collected by primary industries and to initiate long-term monitoring of diverse SESs, we suggest establishing transdisciplinary investigations for identifying and measuring important social, ecological, and social–ecological elements. These investigations may need to be sector specific; for example, agricultural and marine SESs may require different types of data. For research on primary industries, the data sets should ideally enable studying both social and ecological subsystems, and both qualitative (e.g., land user interviews) and quantitative data (e.g., land cover changes) should be considered of value. Finally, making data accessible to other researchers in databases and online data repositories or by request would promote the use of complementary methods and meta-analyses.

Conclusions

The likelihood of tipping points is expected to increase in future, but their detection and effective management in SESs has been hindered by a number of technical and conceptual barriers. The examples and insights presented in the present article illustrate that the complex and dynamic social–ecological interdependencies in primary industries make them particularly vulnerable to undergoing tipping points. We argue that primary industries, where increasing resource depletion or variability in supply can be compensated for by increasing inputs (at least in the short term), will be likely to undergo unexpected tipping points rather than gradual reversible change, particularly when inputs depend on a single finite resource that itself may suffer declines (e.g., water). Moreover, the way in which many primary industries are managed can mask commonly used statistical signals of impending collapse, such as rising variance in biophysical parameters. In addition to the multitude of pathways that tipping point events may take in primary industries, we also emphasize the difficulty of detecting or predicting a tipping point in production systems with approaches that focus on the social or ecological subsystem in isolation of each other. Therefore, we have shown that a focused research perspective, a "primary industry lens," can significantly increase our understanding on tipping points in primary industries without the cost produced by conducting numerous case-specific studies. Such a focus will support management with more specialized insights to complement those produced by research across multiple industries and more widely on complex systems, and so doing contributes to building and maintaining resilience in natural resource production.

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Supplemental material

Supplemental data are available at *BIOSCI* online.

References cited

Adger W. 2000. Social and Ecological resilience, are they related? Progress in Human Geography 24: 346–364.

Anderies JM, Janssen MA, Ostrom E. 2004. A framework to analyze the robustness of socia–ecological systems from an institutional perspective. Ecology and Society 9: e18.

Bauch CT, Sigdel R, Pharaon J, Anand M. 2016. Early warning signals of regime shifts in coupled human–environment systems. Proceedings of the National Academy of Sciences 113: 14560–14567.

Bayraktarov E, Ehmke G, O'Connor J, Burns EL, Nguyen HA, McRae L, Possingham HP, Lindenmayer DB. 2019. Do big unstructured biodiversity data mean more knowledge? Frontiers in Ecology and Evolution 6: 239.

Benton TG, Fairweather D, Graves A, Harris J, Jones A, Lenton T, Norman R, O'Riordan T, Pope E, Tiffin R. 2017. Environmental Tipping Points and Food System Dynamics: Main Report. Global Food Security.

Bodin Ö, Tengö M. 2012. Disentangling intangible social–ecological systems. Global Environmental Change 22: 430–439.

Boettiger C, Hastings A. 2013. Tipping points: From patterns to predictions. Nature 493: 157–158.

Bowman DMJS, Perry GLW, Marston JB. 2015. Feedbacks and landscape-level vegetation dynamics. Trends in Ecology and Evolution 30: 55–260.

Boyd E, Folke C. 2011. Adapting Institutions: Governance, Complexity and Social–Ecological Resilience. Cambridge University Press.

Broderstad EG, Eythorsson E. 2014. Resilient communities? Collapse and recovery of a social–ecological system in Arctic Norway. Ecology and Society 19: 1.

Brown P, Hart G, Small B, de Oca Munguia OM. 2016. Agents for diffusion of agricultural innovations for environmental outcomes. Land Use Policy 55: 318–326.

Brummitt CD, Barnett G, D'Souza RM. 2015. Coupled catastrophes: Sudden shifts cascade and hop among interdependent systems. Journal of the Royal Society Interface 12: e20150712.

Chandler J. 2018. Commentary the paradox of intervening in complex adaptive systems. International Journal of Health Policy and Management 7: 569–571.

Conversi A, et al. 2014. A holistic view of marine regime shifts. Philosophical Transactions of the Royal Society B 379: 20130279.

Cote M, Nightingale AJ. 2012. Resilience thinking meets social theory. Progress in Human Geography 36: 475–489.

Cottrell RS, et al. 2019. Food production shocks across land and sea. Nature Sustainability 2: 130–137.

Courchamp F, Angulo E, Rivalan P, Hall RJ, Signoret L, Bull L, Meinard Y. 2006. Rarity value and species extinction: The anthropogenic allee effect. PLOS Biology 4: e415.

Coux C, Rader R, Bartomeus I, Tylianakis JM. 2016. Linking species functional roles to their network roles. Ecology Letters 19: 762–770.

Davidson EA, et al. 2012. The Amazon basin in transition. Nature 481: 321. doi:10.1038/nature10717

Ferraro PJ, Sanchirico JN, Smith MD. 2018. Causal inference in coupled human and natural systems. Proceedings of the National Academy of Sciences. doi:10.1073/pnas.1805563115

Filatova T, Polhill JG, van Ewijk S. 2016. Regime shifts in coupled socio-environmental systems: Review of modelling challenges and approaches. Environmental Modelling and Software 75: 333–347.

Fischer J, Lindenmayer DB, Manning AD. 2006. Biodiversity, ecosystem function and resilience: Ten guiding principles for off-reserve conservation. Frontiers in Ecology and the Environment 4: 80–86.

Folke C. 2016. Resilience, Oxford Research Encyclopedia of Environmental Science. Oxford University Press.

Folke C, Hahn T, Olsson P, Norberg J. 2005. Adaptive governance of social-ecological systems. Annual Review of Environment and Resources 30: 441–473.

[FAO] Food and Agriculture Organization of the United Nations. 2011. Review of the state of world marine fishery resources. FAO Fisheries and Aquaculture Technical Paper no. 569. FAO.

Galaz V, Olsson P, Hahn T, Folke C, Svedin U. 2008. The problem of fit among biophysical systems, environmental and resource regimes, and broader governance systems: Insights and emerging challenges. Pages 147–186 in Young OR, Leslie AK, Schroeder H, eds. Institutions and Environmental Change: Principal Findings, Applications and Reserach Frontiers. MIT Press.

Gerber LR, Morissette L, Kaschner K, Pauly D. 2009. Should whales be culled to increase fishery yield? Science 323: 880–881.

Gladwell M. 2000. The Tipping Point: How Little Things Can Make a Big Difference. Little, Brown and Company.

Helbing D. 2013. Globally networked risks and how to respond. Nature 497: 51–59.

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

Holling CS, Meffe GK. 1996. Command and control and the pathology of natural resource management. Conservation Biology 10: 328–337.

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 and Evolution 28: 149–155.

Jentsch PC, Anand M, Bauch CT. 2018. Spatial correlation as an early warning signal of regime shifts in a multiplex disease-behaviour network. Journal of Theoretical Biology 448: 17–25.

Kasperson JX, Kasperson RE, Turner BL II, eds. 1995. Regions at Risk: Comparisons of Threatened Environments. United Nations University Press.

Kinzig AP, et al. 2013. Social norms and global environmental challenges: The complex interaction of behaviors, values, and policy. BioScience 63: 164–175.

Kivelä M, Arenas A, Barthelemy M, Gleeson JP, Moreno Y, Porter MA. 2014. Multilayer networks. Journal of Complex Networks 2: 203–271.

Kull CA, Kueffer C, Richardson DM, Vaz AS, Vicente JR, Honrado JP. 2017. Using the “regime shift” concept in addressing social–ecological change. Geographical Research: 1–36.

Lade SJ, Tavoni A, Levin SA, Schluter M. 2013. Regime shifts in a social–ecological system. Theoretical Ecology 6: 359–372.

Lee B, Preston F, Kooroshy J, Bailey R, Lahn G, Asia N, Asia S. 2012. Resources Futures. Chatham House.

Levin S, et al. 2013. Social–ecological systems as complex adaptive systems: Modeling and policy implications. Environment and Development Economics 18: 111–132.

Levin SA. 1998. Ecosystems and the biosphere as complex adaptive systems. Ecosystems 1: 431–436.

Lin BB. 2011. Resilience in agriculture through crop diversification: Adaptive management for environmental change. BioScience 61: 183–193.

Lindenmayer DB, Luck G. 2005. Synthesis: Thresholds in conservation and management. Biological Conservation 124: 351–354.

Liu Y-Y, Slotine J-J, Barabási A-L. 2011. Controllability of complex networks. Nature 473: 167–173.

Lontzek TS, Narita D, Wilms O. 2016. Stochastic Integrated Assessment of Ecosystem Tipping Risk. Environmental and Resource Economics 65: 573–598.

Lynham J, et al. 2017. Costly stakeholder participation creates inertia in marine ecosystems. Marine Policy 76: 122–129.

Lyver PO, Tylianakis JM. 2017. Indigenous peoples: Conservation paradox. Science 357: 142–143.

Macfadyen S et al. 2015. The role of food retailers in improving resilience in global food supply. Global Food Security 7: 1–8.

Menichetti G, Dall'Asta L, Bianconi G. 2016. Control of Multilayer Networks. Scientific Reports 6: 20706.

Milkoreit M, Hodbod J, Baggio J, Benessaiah K, Calderon Contreras R, Donges JF, Mathias J-D, Rocha JC, Schoon M, Werners S. 2018. Defining tipping points for social–ecological systems scholarship: An interdisciplinary literature review. Environmental Research Letters 13: e033005.

Montoya JM, Donohue I, Pimm SL. 2017. Planetary boundaries for biodiversity: Implausible science, pernicious policies. Trends in Ecology and Evolution 33: P71–P73.

Natale F, Giovannini A, Savini L, Palma D, Possenti L, Fiore G, Calistri P. 2009. Network analysis of Italian cattle trade patterns and evaluation of risks for potential disease spread. Preventive Veterinary Medicine 92: 341–350.

Neubauer P, Jensen OP, Hutchings JA, Baum JK. 2013. Resilience and recovery of overexploited marine populations. Science 340: 347–349.

Niiranen S, Richter A, Blenckner T, Stige LC, Valman M, Eikeset A-M. 2018. Global connectivity and cross-scale interactions create uncertainty for Blue Growth of Arctic fisheries. Marine Policy 87: 321–330.

Nikolaidis NP. 2011. Human impacts on soils: Tipping points and knowledge gaps. Applied Geochemistry 26: S230–S233.

Österblom H, Jouffray J-B, Folke C, Crona B, Troell M, Merrie A, Rockström J. 2015. Transnational corporations as “Keystone Actors” in marine ecosystems. PLOS ONE 10:e0127533.

Ostrom E. 2007. A diagnostic approach for going beyond panaceas. Proceedings of the National Academy of Sciences 104: 15181–15187.

Ostrom E. 2009. A general framework for analyzing sustainability of social–ecological systems. Science 325: 419–422.

Perry DA. 1995. Self-organizing systems across scales. Trends in Ecology and Evolution 10: 241–244.

Polhill JG, Filatova T, Schluter M, Voinov A. 2016. Modelling systemic change in coupled socio-environmental systems. Environmental Modelling and Software 75: 318–332.

Regan HM, Colyvan M, Burgman MA. 2002. A taxonomy and treatment of uncertainty for ecology and conservation biology. Ecological Applications 12: 618–628.

Rocha JC, Peterson GD, Biggs R. 2015a. Regime shifts in the Anthropocene: Drivers, risks, and resilience. PLOS ONE 10: e0134639.

Rocha J, Yletyinen J, Biggs R, Blenckner T, Peterson G. 2015b. Marine Regime shifts: Drivers and impacts on ecosystems services. Philosophical Transactions of the Royal Society B 370: 1–12.

Rocha JC, Peterson G, Bodin Ö, Levin SA. 2018. Cascading regime shifts within and across scales. Science 362: 1379–1838..

Roe G. 2009. Feedbacks, timescales, and seeing red. Annual Review of Earth and Planetary Sciences 37: 93–115.

Ruta M, Venables AJ. 2012. International trade in natural resources: Practice and policy. Annual Review of Resource Economics 4: 331–352.

Scheffer M, et al. 2012. Anticipating Critical Transitions. Science 338: 344–348.

Scheffer M, Bascompte J, Brock WA, Brovkin V, Carpenter SR, Dakos V, Held H, van Nes EH, Rietkerk M, Sugihara G 2009. Early warning signals for critical transitions. Nature 461: 53–59.

Scheffer M, Carpenter S, Foley JA, Folke C, Walker B. 2001. Catastrophic shifts in ecosystems. Nature 413: 591–596.

Schill C, Ran Y, Ospina D, Biggs R. 2017. Balinese rice production. Regime Shifts Database. *(https://regimeshifts.org/item/60-balinese-rice-production)*

Schluter M, et al. 2012. New horizons for managing the environment: A review of coupled social–ecological systems modeling. Natural Resource Modeling 25: 219–272.

Selkoe KA, et al. 2015. Principles for managing marine ecosystems prone to tipping points. Ecosystem Health and Sustainability 1: 17.

Sikes BA, Bufford JL, Hulme PE, Cooper JA, Johnston PR, Duncan RP. 2018. Import volumes and biosecurity interventions shape the arrival rate of fungal pathogens. PLOS Biology 16: e2006025.

Sterk M, van de Leemput IA, Peeters E. 2017. How to conceptualize and operationalize resilience in social–ecological systems? Current Opinion in Environmental Sustainability 28: 108–113.

Stockholm Resilience Centre. 2018. Regime Shifts Database, Developed by the Stockholm Resilience Centre, Stockholm University, Sweden. Stockholm Resilience Centre. (*http://regimeshifts.org*)

Suding KN. 2011. Toward an Era of restoration in ecology: Successes, failures, and opportunities ahead. Annual Review of Ecology, Evolution, and Systematics 42: 465–487.

Tallis H, Levin PS, Ruckelshaus M, Lester SE, McLeod KL, Fluharty DL, Halpern BS. 2010. The many faces of ecosystem-based management: Making the process work today in real places. Marine Policy 34: 340–348.

Thampi VA, Anand M, Bauch CT. 2018. Social–ecological dynamics of Caribbean coral reef ecosystems and conservation opinion propagation. Scientific Reports 8: 1–11.

Thrush SF, Hewitt JE, Dayton PK, Coco G, Lohrer AM, Norkko A, Norkko J, Chiantore M. 2009. Forecasting the limits of resilience: Integrating empirical research with theory. Proceedings of the Royal Society B 276: 3209–3217.

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

van der Hel S, Hellsten I, Steen G. 2018. Tipping points and climate change: Metaphor between science and the media. Environmental Communication 12: 1–16.

van Nes EH, Arani BMS, Staal A, van der Bolt B, Flores BM, Bathiany S, Scheffer M. 2016. What do you mean, "Tipping Point"? Trends in Ecology and Evolution 31: 319–338.

Walker B, Gunderson L, Kinzig A, Folke C, Carpenter S, Schultz L. 2006. A handful of heuristics and some propositions for understanding resilience in social–ecological systems. Ecology and Society 11: 13.

Walker B, Meyers JA. 2004. Thresholds in ecological and socialecological systems: A developing database. Ecology and Society 9: e3.

Walker BH, Carpenter SR, Rockstrom J, Crépin AS, Peterson GD. 2012. Drivers, slow variables, fast variables, shocks, and resilience. Ecology and Society 17: 30.

Wolf EP. 1963. The tipping-point in racially changing neighborhoods. Journal of the American Institute of Planners 29: 217–222.

World Bank Group. 2018. The World Bank DataBank: World Development Indicators. World Bank. *(https://data.worldbank.org/indicator/AG.LND.AGRI.ZS)*

Yletyinen J, Bodin Ö, Weigel B, Nordström MC, Bonsdorff E, Blenckner T, Nordstro MC, Yletyinen J, Bonsdorff E, Blenckner T. 2016. Regime shifts in marine communities: A complex systems perspective on food web dynamics. Proceedings of the Royal Society B 283: e20152569.

Yletyinen J, Hentati-Sundberg J, Blenckner T, Bodin O. 2018. Fishing strategy diversification and fishers' ecological dependency. Ecology and Society 23: 28.

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