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Insight

Addressing surprise and uncertain futures in marine science, marine governance, and society

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ABSTRACT. On an increasingly populated planet, with decreasing biodiversity and limited new opportunities to tap unexploited natural resources, there is a clear need to adjust aspects of marine management and governance. Although sectarian management has succeeded in addressing and managing some important threats to marine ecosystems, unintended consequences are often associated with overlooking nonlinear interactions and cumulative impacts that increase the risk of surprises in social-ecological systems. In this paper, we begin to untangle science-governance-society (SGS) interdependencies in marine systems by considering how to recognize the risk of surprise in social and ecological dynamics. Equally important is drawing attention to our state of preparedness, adaptation, and timeliness of response in ecosystem governance and society, which involve fostering transformations away from rigid and nonintegrated structures of governance. More inclusive decision-making processes, deeper understanding of complexity, and colearning across SGS can help to build constructive solutions that are likely to benefit multiple stakeholders and build capacity to understand and respond to change.

Key Words: *governance; management; marine ecosystems; regime shift; resilience; science; society*

INTRODUCTION

Ecological research is often applied to find solutions to what environmental science has generally understood as environmental dilemmas. They are, however, almost invariably social-ecological dilemmas, brought about by social action and implying often-grave social as well as environmental consequences. Those individuals and agencies funding research recognize the need to engage with these dilemmas and the difficult problems that they produce for science, economy, and society and their governance. Even fundamental environment research is now increasingly tagged to social impact and economic benefit, and connected to initiatives and interventions that link ecological systems to investment processes and new regimes of governance. This paper begins from the position that although science, its funders, and its end users have begun to identify what must be addressed, they have yet to develop frameworks for posing the compelling questions that must be asked and the solutions that must be found. Research in the New Zealand context suggests that aligned with ecological principles such as resilience, the idea of the surprise provides a basis for a new, engaged social-ecological research approach that offers such a framework. The idea of the surprise forces a reconsideration of social and ecological regimes as both emergent and coevolving, and directs attention to regime dynamics and shifts.

The insights that lie behind this call for a focus on surprise as the basis for ordering interventions derive from discussions about ecosystem-based management (EBM) approaches between ecologists and geographers. These involve five generative processes of recognition. First is the identification of a series of parallels between ideas of regime shifts and cumulative impacts drawn from ecology and those of emergence, assemblage, and experimentation drawn from poststructuralist geography. A common language and attention to openness and dynamics provides new ground for building social-ecological knowledge. Second, this ground is further seeded by the shared attention paid by ecologists and geographers to the particularities and peculiarities of process dynamics in places and the context dependence of disruptions to or interventions in these processes. Thus, it becomes clear that the nature and outcomes of applied work demanded of environmental scientists in relation to local-scale restoration projects or regional- or national-scale spatial planning exercises are always context dependent, where that context is both social and environmental. Third, despite context dependence, dynamic processes operate at multiple scales, especially social processes that have been coagulated into institutionalized structures. As a result, common challenges arise across contexts, challenges that are often related to disconnects among scales of action, concern, and governance (social and environmental) and manifest in interagency and intra-agency disconnects between science and policy, and nonintegrative governance regimes more broadly. Fourth, if this scalar and governmental complexity is endemic, then the call for more engaged forms of science demands a new and novel way of actually doing engaged science that emphasizes coproduction and colearning. Here the idea of enactive science, in which knowledge, engagement, and governance occur simultaneously in workshop or field sites, is productive. These concepts point to the importance of managing for change rather than stability, which is the challenge we take up in this paper.

Regime shifts occur when a system, i.e., an ecosystem, a society, or an economy, moves from one organizational regime to another (Scheffer et al. 2001). We are often surprised by sudden and dramatic change; in the environment, this can result from unusual natural or anthropogenic events that act as external shocks to the system (e.g., eruptions or oil spills), but more worrying are the subtle yet cumulative impacts on systems that can result in changes to the intrinsic dynamics of the system that have large, abrupt consequences. Understanding the different conceptions of regimes held by ecologists and social scientists and resolving the contradictions between them promise to stimulate a fresh generation of policy-relevant social-ecological knowledge. Ecologists' view of regime shift is embedded in systems thinking and emphasizes coherence, function, and structure, and the preservation of these attributes. Implicitly any intervention is aimed at retaining or rebalancing regime integrity. Social scientists, in contrast, have been more concerned with using regime thinking to

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represent the changing world and social relations, and to theorize about the implications of change. For the most part, however, social scientists fell short of confronting the governance and management questions their critiques exposed. On the other hand, ecologists have constantly attempted to secure productive boundary relations between regime science and policy domains, including governance and management. Social science is now grappling with ideas that represent open networks, contingency, experimentation, and unintended consequence as normal. A focus on surprise as the norm challenges governance in the wider political economy at different scales of analysis and intervention.

Recent regime shift research (Table 1) shows an extremely encouraging degree of commonality in recommendations, despite different perspectives. Although strong on practical suggestions about how to prepare for surprises, often undeclared are shortcomings, limits, and undeclared assumptions about how regime shifts emerge. Discussions of regime shifts as unpredicted rapid change and the difficulty of recovery to desired states often lead to despair and disillusionment in managers and concerned society. The science of regime shifts is based on abstract theory or hindsight of documented change. Nevertheless, the complex systems science that anchors our concepts of regime shifts and resilience highlights the importance of the interconnectedness of systems. Table 1 suggests productive knowledge possibilities from bringing the social science critique of regimes to the ecologist's desire to understand processes of social-ecological assemblages. At the core of the shared insights in Table 1 lie the uncertainties related to regime shifts, about which "something" has to be done. This issues new challenges to the management and governance of science systems, primarily how to govern for the inevitability of surprise. Recognizing that social-ecological dynamics tend to be contradictory and only ever partially understood, and that stabilizing them requires compromises in action, implies a need to develop new ways of thinking that accommodate the open-ended imperatives and dynamics of investment at the same time as studying the resilience of ecosystems. Here we suggest that management of regime shifts needs a science-governance-society (SGS) system framework in which knowledge is generated, advice is offered, actions are taken, investments are made, and values are realized. We begin to untangle science, governance, and society interdependencies in marine systems by considering how to prepare for change and how open our SGSs are to surprises from social and ecological dynamics.

Challenges

The language of resilience, regimes shifts, tipping points, thresholds and alternate states is confusing (Thrush et al. 2009), but from a SGS perspective the consequence is surprise. Surprise can occur for many reasons e.g., unknown relationships and connections, lack of information on the pace of change, an over reliance on techno-fixes rather than reducing drivers of change, or restricting the number of strategies that may contribute to solutions (Toth 2008). Management actions can also contribute to surprises by requiring specific assumptions that may ignore interactions between key drivers and responses. For example, fisheries management in New Zealand is focused on fish stocks and quota setting; the impacts of other stressors or habitat loss on exploited species and the role of exploited species in ecosystem dynamics have little importance in decision making. The implicit management assumptions in this and other areas of marine management often lead to an over-reliance on specific management tools that focus on simple stress or extraction-response relationships as the solution to what in reality are complex SGS problems. We argue that sectoral business-as-usual approaches to environmental management constrains how data is interpreted and tends to limit our perspective of far-reaching interdependencies and consequences (Figure 1). Too much focus on efficiency and narrowly optimised governance limits the ability to explore alternatives and options. Under these circumstances the worst situation may not occur, but the opportunity to be in the best situation may be missed. Learning how to recognise a bad compromise will be increasingly important in enabling a more diverse range of stakeholders, with very different values, to legitimately participate in decision-making. Broadening the perspective of regime shifts to SGS opens up prospects to improve our ability to forewarn of threshold changes to both manage to limit the impact of surprise, and be responsive to new opportunity. Below we discuss the challenges we see facing the disciplines striving to deal with regime shifts and surprises and the potential steps to solutions offered by a SGS system framework.

Fig. 1. The dynamics of surprise for science, governance, and society. Two scenarios are illustrated. Scenario A: (i) Ecosystem appears resilient to stress and the decision is made to push it harder; (ii) increasing variability draws attention to ecosystem change but a wait-and-see approach is taken; (iii) surprise happens and regime shift is detected with hindsight; (iv) a new state is established, recovery is difficult, and ecosystem services change and socioeconomic values and perceived benefits must adapt. Scenario B: (i) Science-governance-society system works to maintain ecosystem resilience; (ii) early warning signs of a possible regime shift are detected from monitoring data; (iii) prompt and effective actions prevent regime shift; (iv) ecosystem services and intrinsic values are retained and socioeconomic values are maintained.

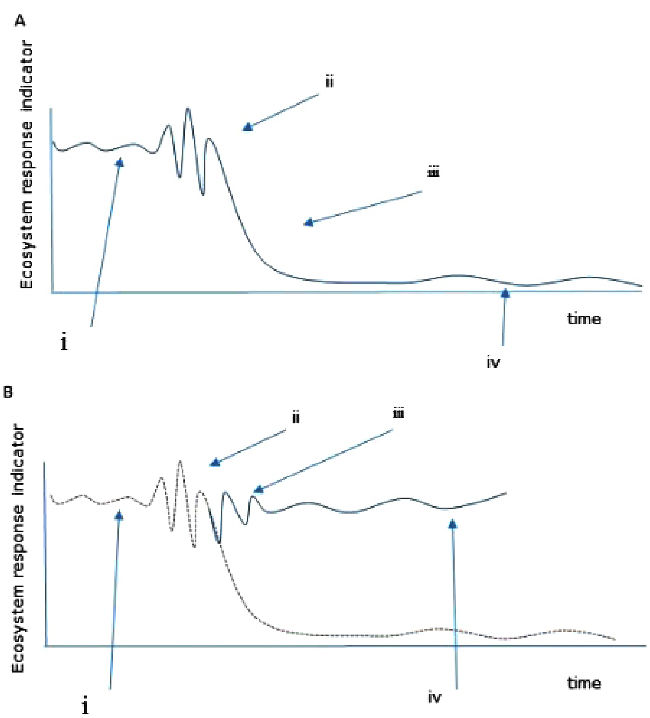


Table 1. Recommended actions to address regimes shifts derived from different perspectives of science, governance, and society.

Perspective	Recommendations
Environmental law (Craig 2010)	Monitor of multiple factors to inform decisions
	Reduce multiple stressors and cumulative impacts
	Provide incentives for adaptive behaviors
	Plan for the long term
	Coordinate across sectors
	Accept that adaptation to change might be painful
Social-ecological systems and ecosystem services (Biggs et al. 2012)	Maintain diversity and redundancy
	Manage connectivity
	Manage slow variables and feedbacks
	View social-ecological systems as complex adaptive systems
	Encourage learning and experimentation
	Broaden participation in decision making
	Encouraging polycentric governance (i.e., multiple scale, nested governing authorities)
Social-ecological systems and economics (Crépin et al. 2012)	Manage to avoid regime shifts likely to have negative impacts on society
	Increase the distance between system state and a threshold of the state of the system
	Restrict shocks (stress and disturbance)
	Monitor both system state and shocks
	Address time lags between regime shift and management response
	Address market and nonmarket values as the socio-ecosystem changes
Marine ecology and resilience (Selkoe et al. 2015)	Recognize that regime shifts can occur anywhere
	Acknowledge both intense and multiple uses
	Search for early warning indicators
	Identify change in ecosystem benefits to different users
	Weigh up the cost of management action or inaction
	Develop biologically informed management targets
	Adaptively monitoring of ecosystem state
Social vulnerability (Bennett et al. 2015)	Identify important social and ecological system components and develop criteria to evaluate
	Characterize the importance of socioeconomic and biophysical drivers
	Define exposure risk and potential impacts
	Describe interactions and feedbacks within and between social and ecological systems
	Define elements of latent adaptive capacity
	Identify potential barriers to adaptation
	Identify adaptations that enhance social-ecological outcomes
	Analyse trade-offs among social and ecological outcomes
	Identify win-win and most beneficial adaptations
	Prioritize actions based on feasibility (adaptive capacity) and desirability (values) of outcomes
	Define responsibility for implementation
	Monitor and adapt
Marine governance (Serrao-Neumann et al. 2016)	Set appropriate quotas and rules
	Developing institutions to address intergenerational equity
	Concentrate on responsibilities instead of rights
	Avoid overemphasizing short-term economic gain over scientific advice
	Develop flexibility to make context-specific rules
	Use collaborative decision making and involve local communities
	Move toward adaptive governance involving a shift from open access to marine spatial planning

The ecosystem science challenge

More and more marine ecosystems provide examples of sudden and dramatic changes or regime shifts (Andersen et al. 2008, de Young et al. 2008, Conversi et al. 2015). Often, regime shifts can be traced back to the interaction of environmental drivers with ecological processes (Scheffer et al. 2012, Thrush et al. 2014). The importance of these interactions in driving change implies that management actions that only focus on limiting levels of stress, disturbance, or the removal of organisms without also paying attention to ecosystem responses are likely to generate surprise. Although not all regime shifts are bad, changes in critical interactions can generate resistance to recovery (i.e., hysteresis, Scheffer et al. 2001), slowing recovery to a previously valued ecosystem state (Conely et al. 2007, van Der Heide et al. 2011). At the same time that they recognize the uncertainties inherent in the science of predicting dramatic change, many ecologists have moved away from thinking about stable ecological baselines. Instead, they inhabit a world of sliding baselines, continuous change, and temporal variability on multiple scales (Duarte et al. 2009).

Likelihood of surprise is increased by ignoring known relationships to simplify models, or basing predictions on averages, which can smooth ecologically important heterogeneity or ignore the consequences of extreme events. For example, in New Zealand the runoff of terrestrial sediment is now recognized as a major threat to coasts and estuaries; and the ecological effects associated with elevated turbidity, changes in habitats, and smothering of benthic communities are manifold (Thrush et al. 2004). Many of these impacts are associated with extreme events (e.g., landslide or stream back collapse) that over short periods can contribute many years' worth of annual average sediment load. A single sediment deposition event may only impact a small proportion of the seafloor, but cumulative impacts are commonplace.

The economic challenge

Models of economic behavior, incentives, and objectives provide insight into how different management actions in isolation or combination may affect economically driven responses. These models are frequently important in marine ecosystems because they are often open access systems. Surprise has been incorporated into some economic analysis; for example, early models of the cost of controlling pollution have indicated that the threat of a catastrophe should lead to increased emissions (Clarke and Reed 1994). Essentially, this economic analysis suggests that increasing the risk of regime shift makes the future uncertain, and consequently it makes economic sense to get the value out of the resource now and discount future benefits heavily. The threat of loss of ecosystem benefits may exacerbate the tragedy of the commons when the impacts of resource use are tightly coupled to the future stock of the resource (Nkuiya 2015).

Risk taking is an important part of investment activity, and theory has suggested that an increase of uncertainty can enhance economic returns (e.g., Costello and Polasky 2008). As such, investors may be economically better off under conditions of uncertainty. Resolving how the costs and benefits of different options will fall differentially on different groups within society who have different values and resource use expectations is a major challenge. Economic models usually treat these SGS challenges as low dimensional problems and seek to optimize solutions for certain groups within society. However, participation in decision making about limiting the sources of environmental problems should theoretically be increased with uncertainty (Nkuiya et al. 2015).

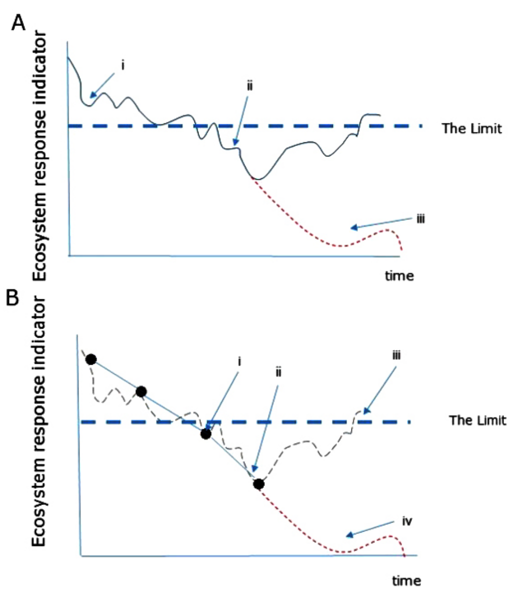
In the context of managing to avoid surprise, how benefits accrue will depend on the current condition of the ecosystem, the environmental drivers involved, the shape of the ecosystem's response curve to those drivers (i.e., whether a tipping point occurs), how nature is valued, and the social cost of avoiding or recovering from degraded state. Identifying which factors managers can and should try to control to reduce the chance of a regime shift will be influenced by both cost and the probability of success (Crépin et al. 2012). However, in all this analysis there is, of necessity, an assumption that the shape and consequences of the resource collapse curve associated with the regime shift are understood. Where costs are high or chances of success low, then it may be economically better to invest in adaptation, but these decisions are both political and multidimensional.

The management challenge

The lack of attention to how marine ecosystems may undergo sudden change threatens sustainable use and the integrity of the ecosystems. Marine resource management in developed countries has traditionally tended to develop specialized management cultures that are highly focused on specific aspects of the marine system, e.g., fisheries, pollution, transportation, or conservation or human health. Frequently such sectors also focus on a single stressor associated with an activity. For example, fisheries management tends to focus on the impact of fish extraction on species-specific population dynamics, which is clearly important to the fishers exploiting the stock, whereas the ecosystem effects of extraction, which might include habitat change, loss of biodiversity, and regulating ecosystem services, may be of more importance to other marine resource users.

Marine management often involves setting limits, e.g., variations around maximum sustainable yield in fisheries management or contaminant guidelines in pollution management. If adequate monitoring of ecosystem response indicators is available, the data can be integrated with information on the magnitude of stress. If a decline in ecosystem health is identified and remedial actions are taken, recovery will be rapid if the resilience of the system is sustained (Fig. 1). However, where the ecosystem indicates resilience by showing little response to specific stressors, then it is likely that resource users will argue the assimilative capacity of the system indicates the ecosystem can withstand even greater exploitation. The problem is that it is very hard to know how close to the edge a system is at a particular point in time. Even with good environmental data and appropriate management limits, decisions will still be taken actions implemented in a timely fashion (Fig. 2A). These decisions are usually made assuming that the limit-setting process is rigorous and appropriate, and that positive signs in the monitoring data reflect recovery. The foundational assumption is that there is understanding of how the system will respond to change and there is little chance of surprise. In this instance, the management and science challenges are interdependent.

Fig. 2. Implications for science-governance-society of data quality and fitness for purpose of monitoring when considering threshold risk and recovery. A. Monitoring data are capable of capturing temporal patterns and detecting trends relative to management limits. This allows for adaptation in response to knowledge of ecosystem state, but knowledge of ecosystem dynamics is needed to interpret trends and the timing of interventions. (i) Nimble actions increase the chance of recovery, (ii) delayed actions create longer recovery times, or (iii) there is a possibility of regime shift. B. Poor knowledge of ecosystem condition relative to management limits indicated by infrequent data gathering (!). Increased uncertainty in ecosystem response (i), delays in action (ii), limiting the chance of recovery (iii), and increasing likelihood of regime shift (iv).



Space is important in marine management, even though regime shifts are usually thought of as changes in time (e.g., Figs. 1 and 2A). Although some spatial indicators of impending regime shifts have been proposed (Rietkerk and van de Koppel 2008), heterogeneity in ecosystems and the connectivity within and between habitat patches can often affect ecosystem dynamics (Fahrig 2003, Thrush et al. 2008). Marine spatial planning has been advanced as a management tool for multiuse coastal ecosystems, but often the available data for mapping seafloor ecological habitats (not just sand, rock, or mud) are lacking. This, for example, limits our ability to make decisions about seafloor disturbance regimes and the potential for localized but cumulative impacts to lead to a regime shift (Thrush et al. 2008, 2013). These connections between data quality and quantity and the inferences drawn to support management (in)action are powerful evidence for the policy relevance of ecological thresholds across a wide range of ecosystems (Kelly et al. 2015). In uncertain circumstances, concepts of insurance, buffers to change, redundancy in system functions, adaptive capacity, and opportunity for innovation need to be developed. This requires a broadening of perspective to consider how activities that support ecosystem resilience and resourcefulness in social-economic systems can be implemented, rather than a focus on defining limits down to which ecosystems can be exploited.

The governance challenge

Ideally governance and decision-making strategies should be able to buffer unexpected shocks to the social-ecological systems while allowing for resource use. However, social-ecological systems are open and connected, knowledge is imperfect, and problems are multidimensional (Bennett et al. 2015). Governance processes and institutions face a challenge in acknowledging and adapting to a less predictable future. By focusing on more uncertain futures, decision making is likely to shift to more participatory processes requiring issues of power and inclusivity to be addressed. Cognizant of plausible regime shifts and the consequent loss of values for diverse sectors of society and the economy, these decision-making processes occur within the context of a cultural system with specific capacity, commitment, financial investment, and political mandate.

Extensive literature on the pathology of resource management emphasizes that narrowly focused optimization of resource use and reductionist models often lead to unintended consequences, including regime shifts to less favored ecosystem states (Holling and Meffe 1996). A recently proposed stupidity-based theory of organizations highlights how persuasion and manipulation among people can work effectively to hide uncertainty and block effective communications (Alvesson and Spicer 2012). These internal organizational dynamics can lead to ignoring real risks and opportunities, limiting our ability to cope with and respond to surprise. These characteristics imply that stupidity-based organizations are unlikely to be able to respond to profound and rapid ecosystem change, even if they are responding reactively to observed environmental change.

Organizations responsible for making environmental management decisions and monitoring ecosystem response to change tend to be large and often contain groups involved in different aspects of data gathering, analysis, policy implications, and decisions. In many cases, multiple agencies may be involved in decision making, and each may employ their own suite of experts; often, these institutions are poorly integrated in terms of decision making. Moreover, integrated approaches to management that offer responses to regime shifts can be difficult to address across management or governance units (Pahl-Wostl 2007, 2009). Justifiably, resource users and other stakeholders should be engaged in the decision-making process. Although scientific data on how ecosystems respond to change are increasingly used as evidence of the need to change practice, there are many situations in which entrenched relationships lead to inappropriate data being used in decision making (Bonneuil and Levidow 2012). Similarly, science can simply go unheeded because it represents an inconvenient truth (Oreskes and Conway 2010). Science can also be used to generate inaction by the requirement for more data that effectively transfers and defers decision-making responsibility. Having the ability to make wise decisions with limited information is more likely to lead social-ecological systems down sustainable pathways and away from destructive outcomes (Polasky et al. 2011).

Challenges for all

Whether for business, recreation, education, or culture, many people have a stake in the health of our coasts and oceans. Often, such groups are referred to as stakeholders, but this term alienates some and implies a sense of exclusivity. There are many stakeholders e.g., science user groups, policy user groups, management user groups, investor user groups, culture user groups. Whether values are supported by personal interaction with the marine environment, investment, an appreciation of the wonder and beauty of remote places, or knowledge of the ecosystem service benefits, all those who consider themselves involved with the ocean should be able to make valued contributions to decisions and choices. The different user groups that promote these values are often the collective in the background. This opens up new opportunities for discussion and knowledge generation that could reveal possible surprises and offer different consideration of the consequences of nonlinear change. To maximize the potential for innovative solutions from diverse user groups, it is important to find common ground in their ability to view social-ecological and socioeconomic aspects, and in translating risk and opportunity in the context of ecosystem response to cumulative stress and disturbance (Davies et al. 2015). Diverse user groups represent a complex mix of values. New processes need to be developed to build the capability and capacity of this collective to be informed and make decisions responsive to the possibility of nonlinear change. Science, governance, and society create a landscape for social dynamics within which understanding how different users have the potential to change or reorganize their activities in response to surprise and how this in turn will feed back on science, policy, and economy (Bennett et al. 2015) can be developed.

KEY ELEMENTS TO ENHANCE SGS LINKAGES IN RESPONSE TO SURPRISES

The multiple papers that offer different perspectives of managing systems that can undergo regime shifts do show a degree of commonality in their recommendations (Table 1). However, recommendations may fall on deaf ears because they rely on theory or simplification of inherently complex problems. Here we focus on first steps to enhance SGS linkages and allow management focused on regime shifts: Acknowledge that surprise can happen; gather data to understand dynamics and search for warning signs; pay attention to ecosystem responses; move toward integrative risk assessments of cumulative effects; build capacity and responsiveness to change; and integrate governance structures with science and society.

Acknowledge that surprise can happen

Acknowledging the potential for surprise starts us searching for new interactions in SGS. This helps to reveal the connections between marine ecosystems, their intrinsic value, ecosystem services, and investment-institutional frameworks (Lundquist et al. 2016). This will also open the door to rethinking what preparedness might mean in ecosystem and investment-institutional terms. Although we are urging that more attention is paid to keeping ecosystems functioning above thresholds, surprises can always happen. The idea that multiple factors interact to affect specific properties of a system and the need to maintain resilience have changed how optimization of resource use and efficiency in management actions are considered (Armitage et al. 2012*a*). Narrowly focused strategies that lead to self-reinforcing controls can constrain adaptive capacity (Scheffer and Westley 2007, Carpenter and Brock 2008). Lock-in to specific strategies may create path dependencies that limit options and future adaptation (Craig 2010). Moving to systems analysis based on complex adaptive systems rather than those of systems that exhibit steady and predictable changes is critical to dealing with surprises (Stirling 2010). Too much focus on optimizing resource use limits the role of functional heterogeneity in the system to buffer change, increasing the risk of regime shift (Carpenter et al. 2015).

Gather data and search for warning signs

That surprising changes exist in nature is supported by empirical data, but such changes are usually only revealed with the benefit of hindsight. To address this problem, theoretical models have been interrogated to identify indicators that might forewarn of a regime shift (Dakos et al. 2012, van de Koppel et al. 2012, Kéfi et al. 2013). These approaches require good empirical time-series data, and different indicators appear to be more effective at indicating the shift in different circumstances (cf, Litzow et al. 2008, Hewitt and Thrush 2010, Lindegren et al. 2012). This implies a need to use a consortia of different early warning indicators, including how to prioritize actions when different indicators are tripped. A number of the recommendations identified in Table 1 assume that the distance a system may be from a state change can be assessed. This implies we have extensive system knowledge, but typically this information is not available. A big challenge is balancing crying wolf based on imperfect data against offering advice only when certain a transition has occurred. Either option risks losing the credibility of science and governance.

What science can provide presently is a list of the major characteristics of systems and activities that increase the potential for a regime shift to occur. Focusing integrated science and management in these areas could rapidly increase the available empirical evidence required to reduce uncertainty. Moreover, there is evidence that monitoring, when used to inform adaptive management actions, can reduce the risk of surprise (Kelly et al. 2015). Monitoring is an important element of wise management because increased uncertainty often leads to decisions driven by politics and crisis (Fig. 2A and 2B). Without doubt, not all systems exhibit threshold dynamics, but where monitoring data are insufficient to reveal rapid change, then the available data will often be taken to mean "no effect" rather than an inability to detect one. This may be problematic when slow transitions into alternative states occur and presents challenges in convincing people that the transition is real before the new state gains its resilience (Hughes et al. 2013).

Pay attention to ecosystem responses, particularly where feedback processes and indirect effects may be important

Theory has highlighted the importance of feedbacks and cross-scale interactions in affecting regime shifts (Scheffer et al. 2012). In the context of SGS, empirical evidence is more persuasive than theory, and the challenge of translating simple theoretical models into applications in real world ecosystems is significant (Thrush et al. 2009, Scheffer et al. 2012). Shifting thinking from simple cause and effect relationships and single responses to considering networks of interactions and cumulative effects is particularly important. Feedbacks can exist between stressors and ecosystem components that restrict the impacts of change, but when these feedbacks fail, rapid change can occur (Coco et al. 2006, Filbee-Dexter and Scheibling 2014). Rates of recovery from local disturbance can be linked across the landscape by connectivity to the regional species pool such that, as locations become increasing isolated because of changes in the frequency, spatial extent, or magnitude of disturbance, then recovery to previous community states will slow (Pascual and Guichard 2005, Thrush et al. 2008, 2013). Once these ecosystem interactions are broken, recovery is slowed by hysteresis. For example, seagrass beds can act as a sink for suspended sediments and, thus, maintain the water clarity necessary for seagrass photosynthesis. If the seagrass dies off, fine sediments are readily resuspended, reducing light and inhibiting regrowth or restoration (van der Heide et al. 2012). Principles are emerging that would allow feedbacks to be predicted and empirically tested to see how interaction networks may change their typology (Thrush et al. 2012, 2014). The strength of interactions within a network may change with a specific intervention emphasising the need to consider multiple actions or a series of actions to guide a system.

Move toward integrative risk assessments of cumulative effects

Risk analysis is well developed for some elements of marine resource management, but needs further advancement to cope with cumulative effects and thresholds (Ban et al. 2010). Even where the interactions that will lead a healthy ecosystem to undergo a regime shift are unknown, generally the more stressors affecting a system, the more likely a regime shift response. Where interactions between individual stressors or disturbance events combine to increase the risk of surprise, case-by-case assessments of each small event will not capture the risk profile of the system (Thrush and Dayton 2010, Kelly et al. 2014). It is also important to acknowledge that a single activity may result in multiple, interacting stressors and that legacy effects can influence ecosystem dynamics and shift the risk profile of specific stressors. For example, many coastal and estuarine ecosystems have a legacy of sediment impacts associated with changes in land use (Thrush et al. 2004). Increases in the mud content of coastal sediments changes the adaptive capacity of coastal habitats to cope with other stressors, e.g., nutrients from land or ocean acidification.

Although these risks are difficult to quantify, targeting critical stressors and identifying changes in ecosystem interaction networks associated with stressors through gradient analysis (Thrush et al. 2012) or manipulative experiments (Thrush et al. 2014) lead to improved assessment of the risk of a threshold response. Risk assessments also need to incorporate community and landscape features, and nonadditive cumulative assessments (Travis et al. 2014).

Building capacity and responsiveness to change

Building capacity and responsiveness to change are critically reliant on building involvement in decision-making processes. In resource-dependent communities, it appears that individuals who do not engage in decision-making process are less likely to adapt to change (Cinner et al. 2015). To manage effectively, not only ecological knowledge, but also knowledge of feedbacks and bottlenecks in social-ecological systems, is needed. Opportunities for recovery may be maximized when timed with political or environmental conditions (Gelcich et al. 2010, Nyström et al. 2012). Legal systems that weight the finite nature of resources and response to disturbance over the perils of precedent are also likely to be necessary. Marine resource managers face mounting pressure to reconcile ecological understanding of regime shifts and social forces that demand new outcomes at different scales and for different constituencies. Until this tension is resolved, progress in environment and governance will be constrained. It is critical that focus is shifted from a few easy to manage (or study) issues, while ignoring the big problems in the hope they will just go away (Polasky et al. 2011). Responsiveness and resourcefulness in the response to surprise can lead to innovation navigating us toward desirable futures and away from the undesirable, e.g., gross inequality or carbon economies.

There are limits in our ability to succeed in maintaining adaptive capacity; consequently, regime shifts and resilience thinking are tightly linked. From an ecological perspective, maintaining the adaptive capacity of valued systems is likely to involve enhancement of biodiversity, redundancy in function, and maintenance of spatial heterogeneity at multiple scales. More specifically, this includes identifying key processes, interaction networks, and the interactions that occur across scales of space, time, or organization; therefore, a sound knowledge of natural history and ecological interactions is required. From a management point of view, encouraging a diversity of activities can also provide redundancy and enhance socioeconomic resilience. However, there is potential conflict where multiple activities impacting on the ecological system in different ways lead to an increased likelihood of cumulative effects and the crossing of an ecological threshold.

Integrate governance structures with ecology and society

EBM is promoted in many scientific, political, and policy fora around the world, but working models of comprehensive implementation have yet to emerge (Knol 2010, Tallis et al. 2010, Levin and Möllmann 2015). With clear operational goals focused on long-term ecological sustainability, EBM is closely linked to resilience, the nature of change, and surprise (Levin and Lubchenco 2008, Samhouri et al. 2010). EBM recognizes humans as part of the ecosystem and has a commitment to adaptability, accountability, and inclusive decision making (Mcleod and Leslie 2009). Executed by policies, protocols, and practices, and made adaptable by monitoring of and research into the interactions between social and ecological systems, EBM is expected to improve confidence in decision making by balancing the needs and values of society in an inclusive fashion. Integrative SGS offer a way forward in the comprehensive implementation of EBM.

Developing different planning frameworks that employ plausible future scenarios using diverse teams with different experience and expertise is likely to offer different pathways to the future and identify different connections and potential surprises because of these teams' different perspectives on multidimensional problems (Le Heron et al. 2016). Getting the balance right is an iterative problem involving feedbacks between society, decision makers, and scientific knowledge. Therefore, new ways of behaving need to be developed that allow different views and beliefs to be considered in a partnership that enables colearning and fosters a commitment to adaptability and accountability. Recognizing that choices are situated in a place, a time, and a social setting where responses can be contingent and the details can matter, new ways of learning from the feedbacks between management actions and economic and ecosystem responses are also needed to foster the emergence of new governance structures. Detailed knowledge and social engagement may work for small systems, and there is some evidence that thresholds-based management is best suited to this scale (Kelly et al. 2015). However, to grapple with the vast extent of the oceans in the face of limited knowledge and funding for management is a significant challenge. Nevertheless, even small Pacific Island states are demonstrating management of extensive marine areas by creations of marine protected areas that foster recognition of use and improve spatial planning.

CONCLUSIONS

Hindsight has revealed that surprising and rapid changes in marine ecosystems have occurred, often undermining our many uses of natural ecosystems. These changes can have profound social and economic impacts. Most regime shifts arise from a set of drivers that require management at, and across, different scales (Rocha et al. 2015). However, management scales are often set by economics and politics. Broad-scale management activities are often at odds with cultural/community interests, which generally occur at a more local scale; and regime shifts affecting biodiversity, ecosystem services, and culture will likely occur first at local scales. Thus, the decision about management scale may need to be driven by social objectives and scientific realities rather than economic and political desires, suggesting the need for a strong SGS system framework. The SGS we imagine is strongly supportive of social openness and engagement, the absence of which fosters business as usual and path dependence in attitudes and approaches (Scheffer and Westley 2007). Marine governance arrangements that expect surprise are predisposed to build capacity to both buffer against potential regime shifts and increase the capacity to cope with change (Armitage et al. 2012*a*, 2012*b*, Serrao-Neumann et al. 2016). Connecting society, governance, and science to incorporate different forms of knowledge about system dynamics and change should foster more inclusive decision-making processes and deeper understanding of complexity. The colearning among stakeholders can help to build constructive solutions and build capacity respond to change.

Responses to this article can be read online at:
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