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Sustainability science: accounting for nonlinear dynamics in policy and social–ecological systems

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ORIGINAL PAPER

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Abstract Resilience is an emergent property of complex systems. Understanding resilience is critical for sustainability science, as linked social–ecological systems and the policy process that governs them have the capacity for nonlinear dynamics. The possibility of nonlinear change in these systems means that there is an inherent degree of uncertainty in social–ecological systems and the policy process. Abrupt, nonlinear change often results in social and/or ecological surprises that create tremendous challenges for environmental management. Thus, it is necessary to improve environmental management via a suite of mechanisms that have the capacity for adaptation. This paper suggests how we can move closer to achieving this goal through an overarching focus, including reformed and new law, adaptive management and adaptive governance, scenario planning, and leading indicators.

Keywords Sustainability · Resilience · Adaptive management · Adaptive governance · Panarchy · Policy

Introduction

Complex systems are self-organized (Levin et al. 2013). Self-organizing systems have emergent properties that cannot be predicted from the variables inherent to the system state. Resilience is an example of an emergent property of complex systems. Accounting for complexity in social–ecological systems thus means we must account for resilience (i.e., multiple regimes, and therefore, nonlinear dynamics) in these systems (Garcia et al. 2011). Resilience (Holling 1973) is the capacity of a system to withstand internal and/or external change and maintain essentially the same processes and structures. If a system is unable to withstand change, it may shift into an alternative regime with a different set of processes and structures. For instance, shallow lakes can shift from a clear water to a turbid state, and much scientific endeavor has contributed to our understanding of the underlying driving forces (nutrient enrichment) and the resulting management implications. However, for most other complex systems, particularly combined social–ecological systems, such state transitions are much less well-understood, and sudden regime shifts can therefore result in surprises that tremendously challenge management. Understanding the causes and consequences of such surprises are therefore critical for sustainability science, as the new regime, and for that matter other alternative regimes, may not have conditions that are favorable for humans. Thus, in order to serve the public interest, we must take into account that social–ecological systems may be characterized by multiple regimes.

In addition to surprise, scale is an important aspect of resilience. Scale is the discrete temporal and spatial frequency of a process or structure (Gunderson and Holling 2002). Thus, by taking resilience into account, we therefore must take into account the fact that scale matters (Garmestani et al. 2009a). What this means is that scale is a factor that should be accounted for between systems (e.g., watersheds) and within systems (e.g., ecological systems within watersheds) in order to conduct sound environmental management. Panarchy is a model that captures

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nested scales, as well as the dynamic nature of social–ecological systems, and provides a framework for scale-dependent environmental management (Gunderson and Holling 2002). A panarchy is a nested set of adaptive cycles, and an adaptive cycle describes the processes of development and decay in a system (Gunderson and Holling 2002). Each adaptive cycle operates over a discrete range of scale in both time and space and is connected to adjacent levels (adaptive cycles) (Garmestani et al. 2009a). Since adaptive cycles operate over specific ranges of scale, a system's resilience is dependent upon the interactions between structure and dynamics at multiple scales (Garmestani et al. 2009b). Further, since scale matters, policy should be tailored for the scale of the intended effect. The panarchy model may allow us to delineate scale and reconceptualize social–ecological systems in a manner that has the capacity to better match governance to the environment.

The possibility of nonlinear change in social–ecological systems means that there is an inherent degree of uncertainty in social–ecological systems. Abrupt, nonlinear change often results in social and/or ecological surprises that create tremendous challenges for environmental management. A complicating factor in this calculus is the fact that not only are social–ecological systems often characterized by multiple regimes and the capacity for nonlinear dynamics, but also policy is sometimes characterized by multiple regimes and nonlinear change (Hall 1993). Thus, it is necessary to improve environmental management via a suite of mechanisms that allow for adaptation in the responses to surprises. This paper highlights nonlinear dynamics in the policy process and suggests how environmental management can be improved through an overarching focus, including reformed and new law, adaptive management and adaptive governance, scenario planning, and leading indicators.

Policy

Environmental issues such as the loss of biodiversity, water resources, and climate change manifest at a variety of scales, and thus require a diverse set of responses at multiples scales from government, the private sector, and the general public (Kraft and Vig 2006). The market system can result in externalities (e.g., loss of ecosystem function) that market mechanisms cannot account for (Kraft and Vig 2006). Thus, government must play a key role in developing sound environmental policy, as environmental problems largely revolve around public goods that cannot be treated exclusively via the private sector (Kraft and Vig 2006). Environmental policy is typically concerned with long-term goals that are not easily quantified, which makes environmental policy even more difficult to implement in the face of short-term political cycles. Even under these circumstances, U.S. history clearly demonstrates that the environment would be in far worse shape today if not for the environmental policies enacted in the 1970s and 1980s. For example, the U.S. EPA has been successful at generating improvements in environmental quality, since the early 1970s. In particular, the EPA has been able to address point source environmental pollution with good results (Cohen 2006). Cohen (2006) contends that the U.S. was able to improve environmental quality, in this context, via a decentralized federal structure that encouraged innovation at the state and local scales. Environmental policy was developed at the federal level, while monitoring and enforcement were largely delegated to the states and local entities. This management arrangement ensured that policy developed at a national level could be tailored for the specific locality to which it was to be applied.

In the policy arena, agenda setting is a key aspect of the policy process, and turns on an issue (e.g., loss of ecosystem services) reaching a heightened level of societal awareness with respect to said issue (Kraft and Vig 2006). An issue could arise as a result of, for instance demographic, social and/or technological change. A new issue could result in government action in response to dramatic change or subtle change that is elevated in priority due to pressure from organized nongovernmental entities. Dramatic change in the environment (e.g., the recent BP oil spill in the Gulf of Mexico) can create a window of opportunity which can help create the conditions for rapid policy change (Kraft and Vig 2006). Kingdon (1995) contends that there are three policy "streams" that flow through the policy process, and can be harnessed by policy entrepreneurs when conditions are ripe for policy change (i.e., a window of opportunity): (1) evidence of a problem, (2) policy already developed to deal with the problem, and (3) a political climate ripe for action. If an issue rises to the level of an "agenda," it still must go through the policy cycle, which is characterized by five steps: (1) policy formulation; (2) policy legitimization; (3) policy implementation; (4) policy evaluation; and (5) policy change (Kraft and Vig 2006). Importantly, Kraft and Vig (2006) recognize the policy process as a system characterized by change, which requires recalibration of policy in response to change, as has Gunderson (1999) who characterized the policymaking process as an "adaptive cycle of policy," in which policies are formed and implemented (r), concern manifests as policies begin to show signs of failure (K), the policies fail (Ω), and policies are reorganized (α).

The observation that there is tension between law, policy, and dynamic systems is not a new one (see Coleman 1998), but importantly remains a problem of critical importance for sustainability. The primary challenge from a sustainability perspective is allowing for organizational flexibility to manage dynamic systems, while maintaining the legal certainty necessary for procedural and substantive due process (Coleman 1998). Administrative agencies, and organizations in general, typically change via incrementalism (Lindblom 1959). Changes in policy are small because there is not enough information to make large overhauls of organization policy. Standard operating procedures (SOPs) are another mechanism that contributes to organizational inertia, as they slow the bureaucratic process (Allison 1969). Societies also often react slowly to problems that may not appear to be imminent, but in reality demand immediate attention (Scheffer et al. 2003). This phenomenon is exacerbated in societies with strong social control, as well as situations in which the problem is downplayed by a leader and by competition for attention from other problems (Scheffer et al. 2003). Divided authority in the U.S. government has also served to create stability in policy, which has enhanced the legitimacy of said policies (Kraft and Vig 2006). Further, the role of the court system in shaping environmental policy cannot be overstated, as the courts have had a profound effect on the trajectory of American environmental policy (O'Leary 2006). Policy gridlock likely occurs due to several factors, such as divergent policy views, separated powers and bicameralism, the complexity of environmental problems, a lack of public consensus, the influence of organized groups, and ineffectual political leadership (Kraft 2006, Young 2008).

Policymakers typically consider environmental problems to evolve slowly, predictably, and in a linear manner (Schroeder et al. 2008). This approach works best for budgetary and legal reasons, as certainty and predictability are needed, but not at the expense of flexibility in the face of linked social–ecological systems (Schroeder et al. 2008). While there is now extensive scholarship on nonlinear dynamics in social–ecological systems, it is critical to recognize that the policy process may also be characterized by nonlinear dynamics, further complicating environmental management.

Nonlinear dynamics in policy

Policy is typically characterized by relative stasis, but that stability can be disrupted dramatically as the policy process can be subject to rapid change (Baumgartner 2008). Repetto (2008) contends that policy operates under the constraints of punctuated equilibrium. This theory, derived from evolutionary biology, helps to explain why some policy is characterized by incremental change and others characterized by rapid policy shifts. As an illustration of punctuated equilibrium in a policy arena, Baumgartner (2008) shows there was zero federal spending on energy conservation from 1947 until 1977, when spending suddenly spiked to $575 million, and then spending increased to $1.2 billion in 1978. The event that drove this shift in policy was a shock to the system in the form of a dramatic spike in oil prices, which in turn caused federal authorities to scramble and attempt to address the issue (Baumgartner 2008). Thus, policy operates in much the same manner in which other complex systems behave; sometimes characterized by nonlinear dynamics, which implies there are multiple regimes in the policy arena (Repetto 2008). There are several examples of negative feedback that serve to maintain a policy regime within its current regime, including the separation of power among federal institutions (including legislative and judicial institutions), the role of precedence in legal proceedings, constraints on bureaucratic action imposed by an open administrative process, and interest groups that rally to defend the status quo (Repetto 2008). These negative feedback mechanisms serve to maintain or increase the resilience of a policy regime, whether or not that is in the public interest. There are also positive feedbacks that can offset these negative feedbacks, and push policy into a new regime, including bandwagon effects (politicians do not like to lose, so they jump on issues that are popular with the public), social contagion and political entrepreneurship (politicians base decisions on polling of public preferences), and media mimicry (media outlets tend to converge and cover stories that competitors are covering) (Repetto 2008). A positive feedback loop can drive a regime shift in policy via a small institutional shift that leads to changes in other areas (e.g., implementation, policy image) (Ingram and Fraser 2008). Ingram and Fraser (2008) contend that a regime shift in water policy in California was triggered by a critical water agreement. There were also other factors that contributed to the policy shift including evidence of failure of the previous water policy regime (e.g., poor water quality, intermittent water supply), a shift in focus to the regional level, the creation of a new policy image that mobilized new constituencies, and leadership at multiple levels.

While negative and positive feedbacks are critical in the policy process, exogenous shocks also play a key role in determining whether a policy regime remains within its current state, or loses resilience, undergoes a systemic transformation and reorganizes into a different policy regime. Historical examples of exogenous shocks include:

(1) New scientific information that can dramatically reframe the political debate (e.g., discovery of Antarctic ozone hole)
(2) A shift in economic variables (e.g., a rise in energy prices led to energy conservation)

(3) A technological shift (e.g., catalytic converters improving air quality)
(4) Disclosure of information to the public (e.g., Toxic release inventory)
(5) A change in the macropolitical environment (e.g., election of a president with a pro- or anti-environmental platform)
(6) An act of God (e.g., Three Mile Island) (Repetto 2008).

Setting an agenda via a strong leader and then learning via technical debates are also a key aspect in policy change (Hagerman et al. 2010). Hagerman et al. (2010) in a study of forest management policy over 150 years in British Columbia, found that entrenched agency positions resulted in some poor forest management policies persisting for extended periods of time with deleterious effects. Along this line, Brock (2006) asserts that regime shifts may be driven by endogenous or exogenous change, thus identifying the type of driver is paramount. Brock's (2006) model of tipping points in policy shows how group pressure to conform can overcome free-riders (i.e., those who benefit from goods or services without paying for them) to produce regime shifts in policy. In the model, policy can remain relatively constant, but over time, small or slow changes can result in policy regime shifts.

Cashore and Howlett (2008) refer to the economics of micromotives, in which the buildup of individual preferences can result in a regime shift in public opinion. Factors that can drive these changes include slowly changing demographic variables (e.g., immigration) that can have a strong effect on the political process and public opinion (Cashore and Howlett 2008). Within this context, interest groups have the capacity to "rally the troops" and create a critical mass necessary to drive a policy shift. Further, organizational hierarchy has the capacity to influence the scale a policy shift can occur. For instance, in the Pacific Northwest from 1960 to 2000, state-level institutions had an entrenched policy that favored economic development without regard for ecological degradation. However, at the federal level, ecosystem indicators were factored into the decision-making apparatus (Cashore and Howlett 2008). There are several factors that reinforced the pro-timber policy position at the state level in the Pacific Northwest, including the role of the common law in protecting private property rights, the timber industry shaping state statutes regulating private forestlands, forestry considered to be a nonpoint source form of water pollution (not as rigorously regulated under the Clean Water Act), and private landowners under no obligation to "recover" species under the Endangered Species Act. The policy shift on timber policy in the Pacific Northwest was driven at the federal level when it became apparent that the northern spotted owl was in precipitous decline. This event triggered a cascading effect that resulted in the Pacific Northwest becoming one of the earliest attempts at large-scale ecosystem management (Cashore and Howlett 2008).

Mechanisms for sustainability

The policy process, in addition to social–ecological systems, can be subject to nonlinear dynamics, and environmental policy has typically been based upon past conditions, rather than possible future conditions (Chapin et al. 2006). In living complex systems, the structure and dynamics of a given system are only partially known (Williams 2003). Thus, policy designed for stable, linear, well-understood systems, with a limited number of possible decision options, is simply not appropriate for living, dynamic systems characterized by an inherent degree of unpredictability (Williams 2003). In social–ecological systems, there is uncertainty that must be accounted for in policy development (given uncertainty in system structures and processes), and uncertainty in the dynamics of the socio-political regime governing a given social–ecological system (Williams 2003). There is a historical record of failure in conservation policy, combined with a limited number of successes, which provides part of the impetus for the exploration of new polices for environmental management (Ludwig et al. 1993; Williams 2003). A critical consideration for sound environmental management is the importance of monitoring. Monitoring is not only important for social–ecological systems, but also should be invoked to assess the policy process. Monitoring can allow for adaptation to occur as new information is accumulated and can be used to maximize learning and reduction of uncertainty, if management interventions for social–ecological systems and policies in the policy process are treated as hypotheses to be put at risk with monitoring data. In the following section I discuss mechanisms that are promising in this regard for conducting environmental management in the face of nonlinear dynamics in social–ecological systems and the policy process.

Reform of law and legislation

The current legal framework in the United States does not possess the necessary flexibility to accommodate our current understanding of the dynamics of social–ecological systems and the policy process (Garmestani and Benson 2013). Thus, the law will need to be reformed to allow for law to be proactive rather than reactive. Legal reform which allows the law to behave in an iterative manner would be more effective for linked social–ecological systems. For example, administrative law will need to be reformed to allow for effective use of adaptive management and adaptive governance (Karkkainen 2005).

In addition to legal reform, entirely new law will also likely be necessary in order to manifest a transition to sustainability. For example, Flournoy (2010) has proposed a National Environmental Legacy Act which would create the ability to establish legally enforceable thresholds for the conservation of natural resources. The Act would preserve and protect publicly owned resources, and include "a clearly articulated mandate for conserving some defined quality and quantity of key public natural resources…" (Flournoy 2010). Natural resource agencies would be required under the Act to identify thresholds in processes essential for human survival (Rockstrom et al. 2009; Flournoy 2010). Importantly, Flournoy (2010) makes the key observation that where a natural resource agency has a duty to prevent degradation or depletion of a resource and that duty conflicts with the overall duty under the Act to manage for resilience, the duty to manage for resilience prevails. Further, the Act would require monitoring and subsequent assessment of cumulative effects on ecological systems, which creates an enforceable mandate to manage for resilience. Also, the risk associated with the uncertainty surrounding the use of a specific resource will be bourne by the party wishing to use said resource (Flournoy 2010).

Adaptive management and adaptive governance

Adaptive management is an environmental management strategy that is an iterative process of decision making and attempts to reduce the inherent uncertainty in ecological systems via system monitoring (Holling 1978). Adaptive management is proactive, rather than reactive, which makes it a very attractive option for sound environmental management (Garmestani et al. 2009b). Adaptive management uses models based upon current information to develop management interventions. The system is then monitored at a rate appropriate to the system of interest, and the results evaluated. From this information, models are improved and management of the system is adapted to the new information in an iterative process. Although adaptive management is a key aspect to fostering resilience, it is only one part of the institutional and organizational changes necessary for resilience-based governance (Cosens and Williams 2012), and one of those essential changes is utilizing adaptive governance.

Adaptive governance integrates adaptive management into governance, and incorporates formal institutions, informal groups/networks (e.g., bridging organizations) and individuals at multiple scales for environmental management (Folke et al. 2005). Olsson et al. (2004) studied adaptive comanagement in Sweden and Canada and found that management of ecological systems was most effective when there was (1) leadership with vision for the system of interest, (2) legislation that created the environment for adaptive management, (3) funding for adaptive management, (4) information flow (i.e., cross-scale linkages), (5) a combination of a variety of knowledge sources, and (6) a venue for collaboration. Since a degree of uncertainty is inherent in social–ecological systems, the generation of adaptive capacity in management entities is a good "insurance policy" for sustainability (Gunderson 1999). Adaptive capacity in social–ecological systems is characterized by past history and local knowledge, as well as open and frequent lines of communication between entities at multiple scales. Perception of a particular policy can also play a significant role in whether it is accepted by critical stakeholders in a social–ecological system (Marshall 2007). Engaging stakeholders, implementing change at a suitable rate, and providing outreach to keep the public informed are all important for new environmental policy to be perceived of as positive and for a successful transition to a new policy regime (Marshall 2007).

Wood and Doan (2003) assert that defining how an issue becomes perceived as a public problem is critical to agenda setting. Wood and Doan (2003) found that if most individuals accept a particular condition, negative feedback works to maintain public opinion in that particular regime. The tendency to lock into a particular behavior for a society can partially be explained by the observation that once a threshold has been crossed and a system shifts to another regime, lock in allows for consistent behavior (Scheffer and Westley 2007). Sunk costs play a big role in maintaining a system in a particular regime, even if that regime does not exhibit favorable conditions. Organizations sometimes continue to sink money into projects that have limited chance for success because of path dependence, due to the amount of resources already "sunk" into a particular project (Scheffer and Westley 2007). However, if the individuals in the regime develop a critical mass of distaste for a particular issue, public opinion can cross a threshold and reorganize into an alternative regime. Importantly, interest groups, the media and other agents can have an effect on agenda setting and creating the climate necessary for a shift in public opinion (Wood and Doan 2003). There are critical roles to be played by individual actors in shifting policy from one regime to an alternate regime. Individuals who are well-connected, innovators and/or charismatic have the capacity to help create the conditions necessary for change (Scheffer and Westley 2007). For instance, social networkers that share information freely, individuals that have numerous, diverse connections, and individuals with powerful ability to persuade, play key roles in policy change (Gladwell 2000). These individuals can interact to create the conditions necessary for regime shifts in public policy. Zellmer and Gunderson (2009) assert that the leadership needed to foster a transition to adaptive governance isn't necessarily the work of one individual. Rather, the leadership necessary for sound environmental governance is often encompassed by several individuals and entities (Zellmer and Gunderson 2009).

According to Kingdon (1995), there are two types of policy windows: a problem-driven window and a politically driven window. A problem-driven window opens when a policymaker believes that a policy is necessary for a specific issue. A politically driven window is driven by a particular theme adopted by a policymaker who looks for problems that fit within the theme. Kingdon (1995) contends that significant changes in policy occur when conditions (e.g., problems, solutions, and politics) converge at the same time, which creates the window of opportunity for change. In Sweden, social and ecological changes at one scale triggered cross-scale effects which resulted in a window of opportunity for the transition to adaptive governance (Olsson et al. 2006). In adaptive governance, decision making is not top down, but rather emerges from outreach and group meetings with stakeholders (Steelman and Tucker 2005). In order for adaptive governance to be effective, the policy requires strong leadership, communication, and incorporation of uncertainty, which allows for adaptation to changing circumstances (Steelman and Tucker 2005). Further, research on the mechanisms that create policy windows is critical for adaptive governance (Olsson et al. 2008).

Scenario planning

Adaptive management and scenario planning are complementary approaches for managing social–ecological systems (Allen et al. 2011). Adaptive management works best when both uncertainty and controllability are high, while scenario planning explores the uncertainty in possible future policies, and is a good tool for dealing with systems with a high degree of uncertainty with limited to no ability to manipulate the system (Peterson et al. 2003a). Scenario planning, as defined by Peterson et al. (2003a), takes place in six stages, via a series of workshops with stakeholders in a system of interest. The stages in the process are (1) identification of a focal issue, (2) assessment of the linked social–ecological system, (3) identification of alternative scenarios for the system, (4) building three to four scenarios of the system, (5) testing scenarios via models, and most importantly, stakeholder feedback, and (6) screening policies by examining how they operate within a particular scenario (Peterson et al. 2003a). Peterson et al. (2003b) show in a model of ecosystem management that decision theory and optimal control approaches do not result in sound management, but rather drive social–ecological systems into periods of collapse and recovery. This problem is likely a result of the tendency to downplay the uncertainty in a management model, or only considering the uncertainty in the prediction errors of a model, when the model itself should be subjected to evaluation (Peterson et al. 2003b). In particular, if the model is based upon assumptions that a system is characterized by only one regime, this could lead to disastrous outcomes if the system has multiple regimes (Peterson et al. 2003b).

Leading indicators

Rockstrom et al. (2009) identified thresholds for nine Earth-system processes (climate change, the rate of biodiversity loss, nitrogen and phosphorus cycles, stratospheric ozone, ocean acidification, freshwater use, land use change, chemical pollution, and atmospheric aerosol), which if crossed could lead to dire consequences for human survival. They contend, taking a risk averse approach, the processes of climate change, the rate of biodiversity loss, and the nitrogen cycle have crossed the threshold for each process considered to be "safe" for a sustainable future for humanity. Estimating thresholds is not an easy task, but is necessary in order to provide guidance on the safe operating space in which to evaluate future scenarios (Carpenter and Lathrop 2008). This is important for policy, as cost-benefit analysis results in different outcomes if the potential costs of crossing thresholds are factored in (Carpenter and Lathrop 2008). Externalities in the management of social–ecological systems can be reduced by characterizing human impacts on the environment and developing policies that internalize said costs (Chapin et al. 2006). For systems where there is little data and/or experiments are not possible, it is possible to estimate thresholds based on data, models, and expert opinion, as an uncertain estimate of a threshold can serve as a baseline for the system (Carpenter and Lathrop 2008).

Associated with the identification of thresholds is recent research on the development of leading indicators of regime shifts in complex systems. There has been a fair amount of research on the subject (Biggs et al. 2009; Scheffer et al. 2012), and the value of developing these methods is of great interest, as they could potentially allow for management to make changes well in advance of crossing critical thresholds. Eason et al. (this issue) highlight a methodology based on Information Theory that appears to have great potential as a leading indicator for complex systems.

Conclusion

The modernist paradigm views the world as a machine which can be understood via reductionism and science, leading to predictability (Plummer and Armitage 2007). Therefore, the modernist paradigm of policy is based upon the assumption that policy can be designed to produce predictable outcomes (Plummer and Armitage 2007). This reactive policy model is of questionable value when developing policy for complex systems. Baumgartner (2008) correctly observes that predicting the dynamics of policy systems, let alone social–ecological systems, is inherently unpredictable because of the vast number of interacting variables.

Vulnerability can be increased when decision making is top-down, centralized, and overemphasizes reactive responses to crises; vulnerability can be reduced by cultivating adaptive capacity at multiple scales (Lebel et al. 2011). In particular, adaptive governance can play a key role in managing social–ecological systems. Institutional and policy rigidity, and the classic emphasis on control, stability and certainty in natural resources management, have the capacity to generate disastrous results over the long term as social–ecological systems are not static, but rather dynamic in nature (Lebel et al. 2011). Within this context, environmental management organizations should invest more in proactive risk management, as nonlinear change is an intrinsic feature of social–ecological systems; in other words, "surprise" happens.

There are limits to our understanding to the dynamics of social–ecological systems, and policies will therefore generate new sets of issues in time (Anderies et al. 2007). Thus, policies should be viewed as hypotheses to be tested in an iterative framework (Anderies et al. 2007). Ostrom (2007) argues that policy that proscribes panaceas (i.e., universal plans) for environmental management of social–ecological systems will not meet with success. Rather, Ostrom (2007) advocates for an iterative policy process that allows for learning, a necessary factor when trying to manage the dynamics of social–ecological systems. Since our current understanding of resilience does not provide us with a blueprint that can be used without regard to scale-specific conditions, sound environmental management rests on matching environmental policy to the scales that are best served by institutional capacity to adapt to nonlinear change (Benson and Garmestani 2011). Due to the fluid nature of social–ecological systems, it appears that the most favorable policy outcomes are achieved via a combination of policies that have some flexibility (Brock and Carpenter 2007).

Abrupt, nonlinear change creates tremendous challenges for environmental management. Improving environmental management via a suite of mechanisms, including, reformed and new law, adaptive management and adaptive governance, scenario planning, and leading indicators, is a step in the right direction.

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