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Adaptive Management of Ecosystem Services for Multisystemic Resilience

Iterative Feedback Between Application and Theory

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Introduction

Society and the natural world are irrevocably intertwined forming social-ecological systems. One set of interactions between society and ecosystems relate to the reliance people place on the environment to provide critical ecosystem services (ES). ES are broadly defined as "the benefits people obtain from ecosystems" (Millennium Ecosystem Assessment, 2005) and include provisioning (e.g., food, water, and fiber), regulating (e.g., climate regulation and pollination), cultural (e.g., spiritual, aesthetic, and recreational value), and supporting (e.g., soil formation) services. These services were valued at US$125 trillion globally per year in 2011 and are critical to human well-being (Costanza et al., 2014).

However, ecosystems' capacity to support and provide ES is under pressure, with important implications for the ongoing delivery of services on which society relies; the value of ES is estimated to be declining at a rate of US$4.3 trillion to US$20.2 trillion per year due to environmental change (Costanza et al., 2014). In light of ongoing global climate change, increased population and resource extraction, and environmental degradation (Steffen et al., 2015), it is crucial that society effectively manages social-ecological systems to support ES delivery now and in the future.

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Some ES can be replaced by engineered solutions, for example, storm barriers, levees, and dams can be used to provide protection from storm surges. Similarly, water purification traditionally provided by wetlands that filter out pollutants or excess nutrients may be replaced by water treatment facilities. However, technology can only replace some ES and only to a limited extent. Thus, managers require tools to work within social-ecological systems supporting the ecosystems from which ES are derived, and the people and communities that use these services.

In this chapter we synthesize research, both theoretical and applied, that has led to the development of these management tools. First, we provide a brief overview of historical management approaches. Next, we examine the theoretical underpinnings of ecological resilience in social-ecological systems, covering topics ranging from complex adaptive systems to adaptive cycles and panarchy. We then discuss the adaptive management model for ES management that will support multisystemic resilience of social-ecological systems and that draws on this body of theory. We conclude with a discussion of emerging and future research directions that will directly influence our capacity to support the multisystemic resilience of social-ecological systems.

Historical Management Paradigm

Historically, management of ES has focused on a single service such as grazing and made decisions using an equilibrium-based thinking, where an ecosystem follows a single, linear predictable trajectory of succession and is ecologically “recoverable” following disturbance, regardless of size of the area or the nature of the disturbance (Twidwell, Allred, & Fuhlendorf, 2013). This approach supports the assumption that small, isolated ecosystem remnants provide the same ES as large, intact ecosystems and can be managed in perpetuity for maximum yield of single benefits (such as food production like corn and soybeans). Associated management interventions tend to focus on controlling the system and maintaining the status quo (Holling & Meffe, 1996). In reality, ecosystems are dynamic and nonlinear across space and time, sometimes experiencing seemingly sudden or catastrophic shifts in structure and function becoming new, unrecognizable systems (Anderson et al., 2009; Gunderson, 2000). As a result, these command-and-control type management approaches often result in unintended consequences for ES delivery and the social-ecological system as a whole (Holling & Meffe, 1996). The inconsistent outcomes provided by historical management of ES has led to the development of new management approaches for social-ecological systems, focusing on complex adaptive systems, multisystemic resilience, and adaptive management, which we explore in this chapter.

Theoretical Underpinnings for Managing Social-Ecological Systems

The notion of complex adaptive systems is fundamental to social-ecological systems. A complex adaptive system has (a) independent, interacting components; (b) selection process(es) at work among and between components; and (c) variation and novelty through changes in components (Levin, 1998). This leads to a system in which a change in one part of the system can, through a series of feedbacks, lead to adaptation of the entire system. Another level of complexity is added when we consider scale, which is defined in ecology as "the spatial extent and temporal frequency, of a specific set of processes or structure" (Angeler & Allen, 2016, p. 620). Management results within social-ecological systems can become maladaptive if social (i.e., individual, organizational) and ecological (i.e., patch, ecosystem) scales are mismatched, creating process dysfunction, inefficiency, or loss of system components (Cumming, Cumming, & Redman, 2006).

Social-ecological systems are linked, interacting human and ecological communities that must be considered and managed together. These coupled systems change across scales of time and space in complex ways, which cannot necessarily be predicted. In such complex adaptive systems, long-term sustainability of ES is reliant on acknowledging, learning from and working with this change rather than trying to suppress it (Biggs et al., 2012; Walker & Salt, 2006). This is a fundamentally different way of managing ES from the one taken traditionally, which more typically manages ecosystems to suppress variability and change to provide a reliable and consistent stream of products, such as food or timber at often arbitrary scales (Gunderson et al., 2017; Holling & Meffe, 1996).

Resilience

Resilience thinking is central to managing complex adaptive systems. Resilience, in this context, is commonly defined as the capacity of a system to cope with stressors and perturbations yet retain the same structure and functions (Holling, 1973). In other words, resilience is the capacity for the system to absorb disturbance and reorganize such that it retains the same function, structure, identity, and feedbacks (Walker, Holling, Carpenter, & Kinzig, 2004). Unlike in traditional equilibrium-based management, these definitions imply the possibility of more than one system state. A clear lake switching to a turbid lake provides an ecological example of multiple states.

Managing social-ecological systems effectively requires an understanding of the dynamics and resilience trajectories of different components of the system (both social and ecological; Hicks, Crowder, Graham, Kittinger, & Cornu, 2016). As a result, resilience in social-ecological systems is inherently multisystemic. For example, in the context of ES, a loss of ecosystem resilience can lead to rapid shifts or volatility in the provision of critical services, such as crop production. Thus, there is a clear link between the resilience of an ecosystem and its capacity to provide ES. However, a resilient social system that uses these ES may have the capacity to cope with rapid shifts in crop production through increased production in other areas or food systems. Thus, there is also a clear link between the resilience of society and its capacity to respond to changing ES (Tanner et al., 2014). Furthermore, an ecologically resilient system (in a desirable state) may support a more resilient society. Critically, as the resilience of a social-ecological system declines, there is greater chance of switching to a new state. An expanding body of literature now suggests that building resilience into both human and ecological systems, as well as into integrated social-ecological systems may be an effective way to cope with environmental change characterized by future surprises or unknowable risks (Cumming et al., 2014; Tanner et al., 2014; Tompkins & Adger, 2004).

Fast and Slow Variables

In exploring and managing the dynamics of social-ecological systems, it is useful to differentiate between external forces that impact on a system, and characteristics inherent to the system. Internal changes are driven by a combination of "fast" and "slow" variables (Crépin, 2007). Ecosystem services tend to be fast variables and are the focus of traditional management. However, their dynamics are influenced by other variables that tend to change more slowly over time. The dynamics of these slow variables must be accounted for to effectively manage ES delivery, as ignoring these changes may lead to perverse outcomes such as increased system vulnerability and brittleness (Gunderson & Holling, 2002). For example, crop production, a fast variable, is an important ES. The impact of external perturbations such as rainfall variability, on crop production, is mediated by organic matter levels in the soil, a slow variable (Walker, Carpenter, Rockstrom, Crépin, & Peterson, 2012). Focusing management on crop production rather than accounting for the dynamics of the soil may lead to short-term gains in yield but drive unforeseen outcomes in the long-term, such as switch between ecosystem states, known as a regime shift.

Regime Shifts

While regime shifts are often triggered by a sudden large external impact, it is the underlying changes of the "slow" variables that are typically preparing the system for such a change long before the external impact occurs (Scheffer & Carpenter, 2003). Such gradually changing conditions may create situations of reduced resilience, increasing the vulnerability of a system to smaller disturbances that it might otherwise have been able to cope with. For example, in Caribbean reef social-ecological systems, a shift from coral to algal-dominated reefs occurred following the impacts of hurricanes and a sea urchin pathogen. However, this shift was driven by the previous slow loss of herbivorous fish due to prolonged high levels of fishing by local communities focused on maximizing their access to a key provisioning ES—food. Algal growth had been controlled by herbivorous fish; however, over time, fishing had severely impacted on the herbivorous fish community and the grazing function it provided. The loss of these herbivores was largely masked by expanding sea urchin populations that became dominant in grazing on and controlling algal cover. However, a loss of corals from hurricane damage combined with a sea urchin pathogen that dramatically reduced the now-widespread urchins meant grazing rates were insufficient to control algal growth leading to a shift from coral- to algal-dominated reef systems (Hughes, Graham, Jackson, Mumby, & Steneck, 2010).

The shape of the relationship between fast and slow variables in a social-ecological system will impact the dynamics of the system over time, the outcome of declining resilience and the potential options for management of ES (Figure 37.1). Linear relationships show stepwise impacts of any external disturbance (Figure 37.1, black line). In contrast, nonlinear relationships may result in tipping points between ecosystem states (Figure 37.1, red and blue

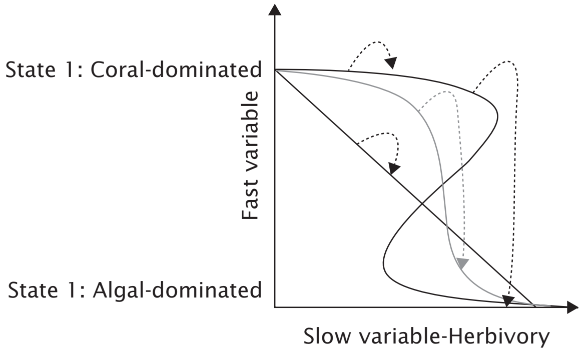

FIGURE 37.1 The relationship between fast and slow variables in social-ecological systems and the impact of external disturbance on state of the system.

lines). Where external disturbances impact resilient ecosystems, little change occurs in ecosystem state. As resilience is eroded (system moves closer to the tipping point), an external disturbance can shift the system into a new, radically different state, in a move known as a regime shift. Where more than one system state can occur for the same value of the slow variable, the system is said to have alternate stable states.

Ecologists use "ball and cup" diagrams to illustrate alternative states in ecosystems (Figure 37.2). In these diagrams, the state of the system is represented by a ball, which can roll into any of several "cups" (valleys). The depth and width of the valley determine the system's capacity to remain in its current state or retain its current identity, despite disturbances (i.e., the resilience of the system; Cumming et al., 2005; Gunderson, 2000). External disturbances shake the ball and create opportunities for it to move to a new valley. The shape of valleys can change over time due to changes in the larger social-ecological system (Gunderson, 2000). In the previously described case of the coral reef, one valley represents the coral-dominated state, and the other, the algal-dominated state. The shape of the valleys is determined in part by the amount of fishing of herbivorous species. Disturbances such as hurricanes removing coral and urchin disease causing high mortality of grazing urchins catalyze the regime shift between states, with implications for both provisioning ES such as fisheries and cultural ES such as tourism.

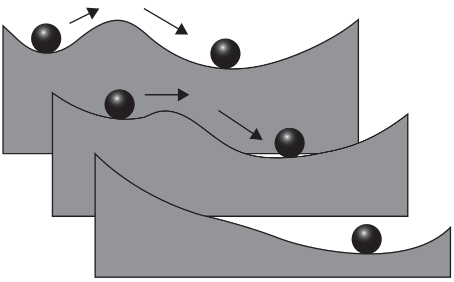

FIGURE 37.2 Ball and cup model. Modified from Gunderson (2000.)

Adaptive Cycle and Panarchy

Tipping points and regime shifts provide us with useful tools to explore certain characteristics of change in a social-ecological system. A complementary conceptual model that explores how system resilience varies over time is the adaptive cycle. This model combines information on the trajectory of resilience with information on the potential and connectedness of a social-ecological system into a three-dimensional space (Carpenter, Walker, Anderies, & Abel 2001; Holling, 1986). In this context, potential refers to the range of possibilities or capital inherent to a system, for example, the resources or diversity. In contrast, connectedness refers to the presence and strength of linkages between elements of the complex adaptive system and thus impacts on the degree to which internal and external forces impact on system behavior (Gunderson & Holling, 2002). Critically, understanding where a system is in the adaptive cycle allows decision makers to choose appropriate management interventions (Walker & Salt, 2012).

The model describes the dynamics of social-ecological systems in four phases (Figure 37.3). The first two phases of the cycle describe the slow front loop of relatively predictable system dynamics. These are a growth and exploitation phase (r) and the conservation phase (K). The r phase is characterized by low potential and connectedness and high resilience. During the K phase, resilience declines, the system is less flexible, more rigid and more responsive to external shocks. External shocks that overcome the resilience of the system in K state trigger a move into the back loop, with the collapse and release phase (Ω). During the Ω phase, there is a release of the energy and potential that accumulates within the system during the K phase. Following collapse and release, there is the reorganization (α) phase, during which innovation and new opportunities are possible and resilience is increasing (Figure 37.3; Holling, 2001). During the α phase, the state of the system may change to a new state. It is at this stage, that links can be drawn to the concept of regime shifts, with reorganization leading to a new regime (Walker & Salt, 2012).

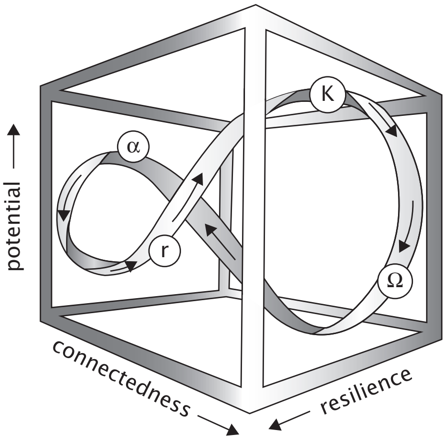

FIGURE 37.3 The adaptive cycle, showing the exploitation (r), conservation (K), release (Ω) and reorganization (α) phases in the three dimensional space provided by system potential, connectedness and resilience. Reproduced from Gunderson and Holling (2002).

The adaptive cycle has largely been used to conceptualize the behavior of social-ecological system. However, there are emerging empirical examples of a range of different types of systems following the adaptive cycle (Sundstrom & Allen, 2019). For example, phytoplankton communities in the Baltic Sea have been demonstrated to reliably follow patterns of growth, organization, and conservation and collapse over time (Angeler & Allen, 2016). It is, however, important to note that while the adaptive cycle is often visually displayed as a predictable route, the reality is that systems can move among the phases in a variety of ways, both forward and backward (Burkhard, Fath, & Müller, 2011). Furthermore, many of these cycles will interact within and across systems at multiple scales, leading to dynamic cross-scale effects on the behavior of social-ecological systems in what is known as a panarchy.

Panarchy introduces cross-scale dynamics by connecting multiple adaptive cycles in a nested hierarchy (Figure 37.4; Gunderson & Holling, 2002). The smaller, faster adaptive cycles invent, experiment, and test, while the larger, slower levels stabilize and conserve accumulated memory of system dynamics. In this way, the slower and larger levels set the conditions within which faster and smaller levels function. These cross-scale linkages are related to the within-scale system position within the adaptive cycle (Allen, Angeler, Garmestani, Gunderson, & Holling, 2014). That is, during reorganization at one scale, conservative structures at larger scales provide a form of memory that encourages reorganization around the same structures and processes rather than a different set (i.e., rather than a new regime). During the Ω (release) phase at a one scale, "destructive" processes can affect larger scales, sometimes leading to revolt and release at these scales as well (Allen et al., 2014).

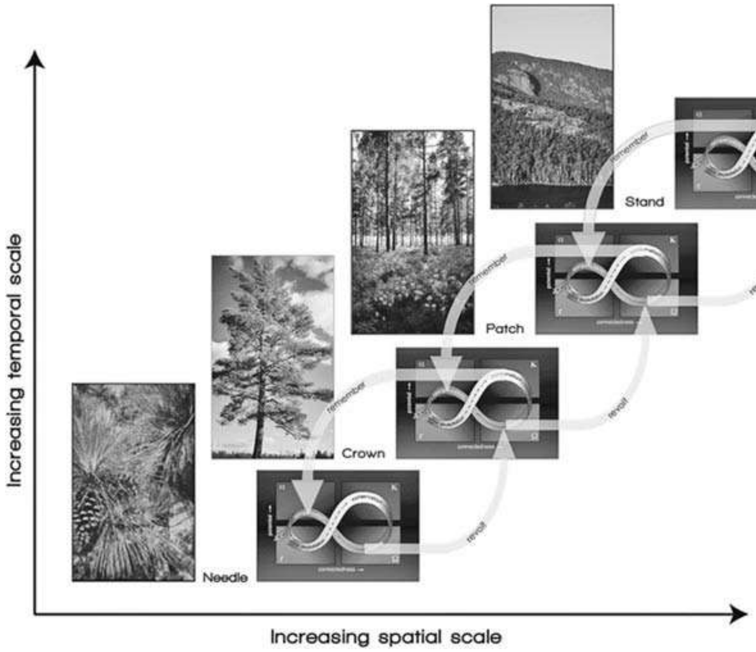

FIGURE 37.4 A conceptual diagram showing the relationship between scales of ecological structure and the nested adaptive cycles comprising a panarchy for a pine dominated forest ecosystem. Adapted from Allen et al. (2014).

Managing for Resilience

Resilience thinking, and the theoretical foundations, as previously discussed, have fundamentally changed the framing of sustainability science from seeking to achieve and maintain a static optimal state toward managing for change and accounting for tipping points (Selkoe et al., 2015; Walker et al., 2004). Nevertheless, while resilience, the adaptive cycle and panarchy are often used as metaphors to help us conceptualize ecosystem management, there is increasing interest in operationalizing these ideas (Gunderson et al., 2017), such that managers of social-ecological systems are able to translate these concepts into management approaches and practices on the ground. In this section, we first discuss broad principles of resilient systems that suggest management actions that may support the desired state of a system. We then explore a whole approach to management that enables learning in the face of uncertainty and change.

Characteristics of a Resilient System

Where managers have an understanding of the specific types of disturbances they are likely to face, they may be able to put in place targeted measures to increase the system's resilience to these disturbances (Adger, Hughes, Folke, Carpenter, & Rockström, 2005). For example, if one knows that flooding is a problem, resilience can be increased by better information about storm systems, reducing building in the flood zone, adding wetland areas to absorb some storm surges. This type of management approach focuses on "specific resilience" (i.e., resilience of a specific system state to a specific set of disturbances). It is considerably more challenging to manage for "general resilience," which provides greater capacity of a system to respond to many different types of disturbances, some of which will undoubtedly be a surprise (Adger et al., 2005; Anderies, Walker, & Kinzig, 2006; Walker & Salt, 2006, 2012). To assist managers address this challenge, seven principles have been identified as key to building the general resilience of social-ecological systems: maintaining diversity and redundancy, managing connectivity, managing slow variables and feedbacks, fostering complex adaptive systems thinking, encouraging learning, broadening participation, and promoting polycentric governance systems (Biggs et al., 2012). Some of these principles have already been discussed, such as managing slow variables, fostering complex adaptive systems thinking and encouraging learning. The remaining principles are discussed more here and may be split into those that have an impact on both the social and ecological components of a system, and those that are relevant to society.

Maintaining diversity and redundancy focuses on supporting the variety of actors or elements within a social-ecological system. This can lead to increased resilience as the loss of an actor is compensated for by another actor playing a similar role. Managing connectivity among elements of a social-ecological system pays attentions to the trade-off between the recovery potential of well-connected systems and the rapid spread of perturbations in overly connected systems. Encouraging learning includes the concept of adaptive management and iterative learning and decision-making, which is discussed in depth in later sections. Broadening participation focuses on the benefits derived from a diverse group of people being involved in management processes as this can support the development of trust and a richer, more integrated understanding of the system (Biggs et al., 2012). Finally, polycentric governance systems are collections of decision-making bodies that are connected informally (Ostrom, 2010). Promotion of this type of governance system is thought to support collective action and provide redundancy in decision-making, just as maintaining diversity supports redundancy in both social and ecological elements of a system.

These principles provide managers with potential tools to manage for resilience within social-ecological systems. However, it should be noted that resilience of a system state is not inherently desirable. Certain states may be highly resilient but have negative implications for social-ecological systems or for certain groups within a system (Glaser et al., 2018). For example, international food retailers ensure the resilience of their supply chains by developing production hubs in multiple territories, thereby reducing the risk of production losses from extreme weather events. However, this has led to the acquisition of large areas of land in developing, food insecure countries (European Environment Agency, 2015). In this context, the resilience supporting economic returns of global companies is extremely detrimental to vulnerable communities (Oliver et al., 2018). As a result, effective management requires the development of an understanding of the system configuration one wants to support. Where systems are in a desirable state, the focus will be on supporting the current state. In contrast, where a system is in an undesirable state, managers may focus on eroding resilience and using disturbances to shift the system into a more desirable state (Graham et al., 2013).

Adaptive Management and Ecosystem Services

The previously discussed principles inform potential management actions to support resilience, but they do not necessarily provide a framework for learning in the face of social-ecological change. We currently know little about how the dynamic natural systems that provide ES will influence the resilience of social-ecological systems, and the inherent complexity of social-ecological systems makes generalization difficult (Palomo, Felipe-Lucia, Bennett, Martin-Lopez, & Pascual, 2016). This, coupled with increasing global stressors and change (Steffen et al., 2015), makes improving our ability to sustainably manage ES across scales and systems even more critical. Historical single-state ecosystem management has struggled to address these stressors and complexity, as there is no inherent framework within the philosophy for acknowledging and embracing the inevitability of surprise, uncertainty, and change. In recent decades, the philosophy of adaptive management has emerged as a way to improve our understanding and ability to manage ES for resilience, while acknowledging and accounting for unknown sources of variability. Adaptive management (AM) provides a way for managers to explore system resilience and dynamics while continuing to addressing management objectives by using purposeful experiments that improve learning and lessen uncertainty over time (Allen, Fontaine, Pope, & Garmestani, 2011).

AM is a structured, iterative process through which natural resource and ES management decisions can be made and lessons learned (Holling, 1978; Walters & Hilborn, 1978). Critically, AM follows a purposeful structure, whereby predefined objectives are used to assess management progress and lessons learned in a defined but iterative learning loop: plan, do, monitor, and learn (Stankey, Clark, & Bormann, 2005; Webb, Watts, Allan,

& Warner, 2017). It is unique in that it explicitly assumes incomplete knowledge and the inevitability of uncertainty and follows decision with action by increasing knowledge of the system under management, thereby also decreasing uncertainty in future management actions (Allen & Gunderson, 2011). AM also makes consideration of trade-offs explicit and critical when assessing how management actions will impact the complex relationships between different ES (Birgé, Bevans, et al., 2016; Rodriguez et al., 2006), which we will discuss later in this chapter. Early work in fisheries (Beverton & Holt, 1957) first discussed the process of adaptive decision making as a potential solution for overexploited fish stocks. The concept was later formalized into AM as a framework that embraces uncertainty and surprise in complex systems (consider the Ω collapse and release phase of the adaptive cycle) and acknowledges that managers must act with incomplete knowledge while taking steps to better understand the system (Figure 37.5; Allen, Fontaine, Pope, & Garmestani, 2011).

Researchers and practitioners are increasingly interested in using adaptive management to address natural resources and ES issues (McFadden, Hiller, & Tyre, 2011; Peterson et al., 2007; Tyre et al., 2011). However, use of the AM framework over the last couple decades has been limited by ambiguities and barriers (Allen & Gunderson, 2011). Like many

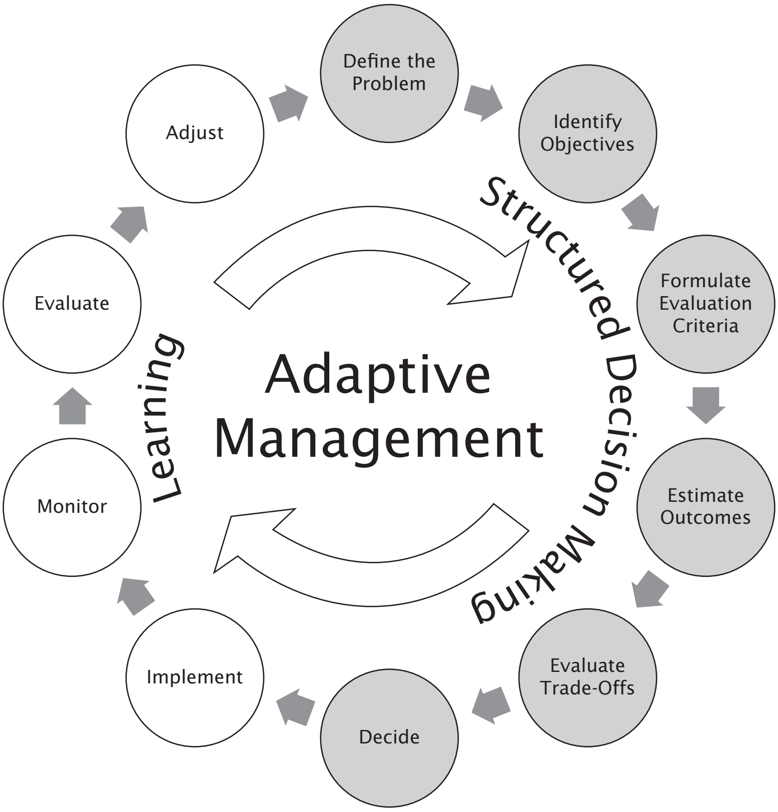

FIGURE 37.5 The adaptive management process. Used with permission from Allen et al. (2011)., available from https://www.sciencedirect.com/science/article/pii/S0301479710004226).

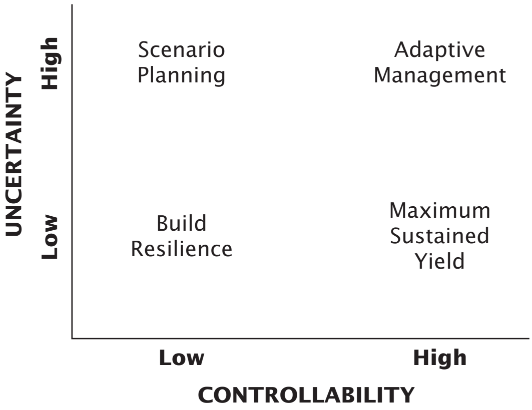

FIGURE 37.6 Different management approaches according to levels of system uncertainty and availability. Used with permission from Allen et al. (2011), available from https://www.sciencedirect.com/science/article/pii/S0301479710004226).

other proposed philosophies and frameworks, AM has been considered a silver bullet solution for any and all natural resource issues, when, in fact, it is only effective when applied at certain scales across space and time (Birgé, Allen, Garmestani, & Pope, 2016) and depends on stakeholders, researchers, and managers all being able to agree on a common vision and principles for guiding the iterative "learning by doing" process. AM is appropriate where the potential for learning is high and where the system is at a scale in space and time where it can be manipulated (Figure 37.6; Birgé, Bevans, et al., 2016). This contrasts with situations where either uncertainty is high but controllability is low (scenario planning is beneficial) or when uncertainty is low and controllability is either low (building-specific resilience is important) or high (a maximum sustainable yield approach may be suitable).

Adaptive Management in Social-Ecological Systems

The fundamental logic supporting adaptive management's modern framework has been utilized by societies that long precede modern notions of ecosystem service management (Berkes, Colding, & Folke, 2000). Furthermore, recent research suggests that this adaptive way of viewing and interacting with the natural world can improve the provision of ES critical for social-ecological systems in the 21st century (Ruhl, 2016). AM approaches to ecosystem service concerns have met with success in several areas, primarily within aquatic resources management.

The AM process has been applied in multiple watersheds in the Southeast United States where some combination of severe drought, water quality concerns, and threatened and endangered aquatic species co-occurred (reviewed in Peterson et al., 2007). Rivers are classic examples of natural resources that are prone to surprises such as drought (high uncertainty), but highly regulated by water laws that operate at multiple scales of government (high controllability). This coupled with the fact that they provide multiple ES (i.e., water quality and quantity, energy production, habitat, and recreation) lends river systems well to adaptive management approaches.

The case studies reveal common themes within successful adaptive management. These include scale-appropriate government support (municipal to federal) given the issues of concern, stakeholder involvement, and discussion of ecosystem service trade-offs, and modeling predictions that created information flow and reduced uncertainty (Allen et al., 2011). Stakeholders developed hypotheses on the results of management actions and designed monitoring plans to test the hypotheses and thus support further iterations of management planning. Further examples of adaptive management of aquatic resources highlight the benefits of AM even given logistical or cultural concerns, such as reluctance to adapt to new management or data restrictions. For example, studies focusing on marine reserves (Grafton & Kompas, 2005) and watersheds in Idaho (Tyre et al., 2011) have shown how modeling techniques can, through quantifying uncertainty, highlight and clarify both broad visions and questions of ES tradeoffs in multiuse systems, thereby alleviating certain sources of concern.

As with the inevitable ecological tradeoffs in adaptive management, there are also social, economic, and policy trade-offs when managing for sustainable ES within social-ecological systems (Craig, 2010; Polasky, Nelson, Pennington, & Johnson, 2011). Communities of scientists, managers, and decision makers can work toward more resilient social-ecological systems by leveraging both the perspectives of individual stakeholders and the collective vision of involved parties through adaptive management practices (Allen et al., 2011). One approach is through the development and use of bridging organizations, which are briefly defined as “institutions that use specific mechanisms such as working groups to link and facilitate interactions among individual actors in a management setting” (Kowalski & Jenkins, 2015, p. 1). Due to the complex, interdisciplinary nature of ES management concerns, there is a high social energy cost to building and maintaining the collaboration, communication, and trust necessary for both common vision and specific actions. Bridging organizations can help lower this cost by facilitating interactions, being a conduit for knowledge and information flow and building the social memory that is imperative for dealing with system surprise and change (Folke, Hahn, Olsson, & Norberg, 2005; Olsson, Folke, Galaz, Hahn, & Schultz, 2007).

AM can be difficult to visualize because it is by nature complex, iterative at multiple spatiotemporal scales and variables in practice within different social-ecological contexts. It is also not directly appropriate to systems that cover either very small or vast spatial and temporal scales such as individual plots as are common in field research or terrestrial systems that consist of thousands of square kilometers (Birgé, Allen, et al., 2016). These situations, where either uncertainty, controllability or both are low, are better approached by other management philosophies not covered in this chapter (see Figure 37.6).

Despite these considerations, adaptive management is a promising framework for pursuing sustainable ES management among diverse stakeholders that operate at scales where uncertainty and controllability are both reasonably high. Although AM is not a silver bullet solution for the sometimes wicked, large problems of 21st-century ES management, it is a highly flexible philosophy that facilitates working toward a common vision in complex, dynamic systems that often baffle more traditional single-state management approaches. We have outlined some situations in which application of AM principles has yielded significant learning, increased predictive capacity, and enhanced decision-making. In the following section, we outline five research and practice gaps which could greatly increase the potential of AM for sustainable management of the ES that underlie the well-being of humanity across the globe.

Future Research Directions

Management of social-ecological systems is moving away from management for steady states and toward adaptive management of dynamic systems (Bestelmeyer & Briske, 2012). Important next steps for research and management that embrace the inevitability of change include quantifying the resilience of social-ecological systems, determining if regime changes are imminent (Biggs, Carpenter, & Brock, 2009), improving knowledge exchange between researchers and managers in ways that account for the complexities managers face in their day-to-day work (Walker et al., 2002), and linking ecosystem service science with thinking on resilience (Bennett, 2017). A common thread through the research priorities we discuss here is the need for multisystemic, interdisciplinary, and collaborative action that extends beyond historical disciplinary problem-solving.

Perhaps because much scientific knowledge is disciplinary and static, research that truly informs decisions and improves environmental decision-making has been limited despite recent advances (Kirchoff, Lemos, & Dessai, 2013; Mauser et al., 2013). Some researchers are moving forward with co-development of knowledge, working directly with managers and decision makers in the process of scientific discovery to improve insights, lessons, and uptake by those who could use it to improve decision-making (Bennett, 2017; Future Earth, 2013). AM principles, applied to research, can facilitate this by necessitating involvement from stakeholders affected by decisions and policy shifts and requiring their input on which hypotheses and future actions will yield the most useful learning.

Another important area of research is detecting surprise regime shifts, which are notoriously difficult to predict (Biggs et al., 2009), but of critical importance as they typically involve undesirable changes to ES that people depend on and are costly or impossible to reverse (Scheffer et al., 2001). Recent work indicates that there may be several areas worth investigating further, including rising variance (Carpenter & Brock, 2006), changes in skewness (Guttal & Jayaprakash, 2008), and slower than normal rates of recovery in disturbed systems (van Nes & Scheffer, 2007). However, it is not entirely clear if these changes occur with enough advance warning to change management to avoid the regime shift (Biggs et al., 2009). The flexibility and iteration of AM, applied at appropriate scales and in contexts where results are controllable, could support insight on the dominant processes driving regime shifts and the spatial and temporal scales at which they could occur in larger systems.

There are other pressing questions of scale in current ecological and ES research. There is a great need to unravel the scales at which ecological processes (i.e., ES like soil nutrient cycling or vegetation regimes) actually occur in natural systems, and if they match the scales at which social-ecological systems choose to manage them. Since scale effects when and where

ES are provided, better understanding of the spatial and temporal dynamics that lead to sustainable ES is critical (Pope, Allen, & Angeler, 2014; Rodriguez et al., 2006).

Outside the realm of ecology, similar questions of scale often apply to environmental law and regulation. The scales at which laws and policies operate are often arbitrary and at a mismatch with social-ecological scales (Garmestani, Allen, & Benson, 2013). Legal systems, particularly those in the United States, do not often account for the fact that ecosystems and their services as complex, dynamic, nonlinear, and, above all, often uncertain (Allen et al., 2011). Law and policy, therefore, must develop flexibility and allow agents to adapt in the face of varying scales of change in social-ecological systems (Craig, 2010). AM and the explicit consideration of uncertainty has been effective in situations where there was support from political and regulating bodies ranging from local to federal (Peterson et al., 2007; Tyre et al., 2011). Therefore, it seems the goals of law, regulation, and adaptive management of ES are not inherently opposed; rather, the structure and support of law and policy can complement the flexibility of AM when both are approached transparently and with the goal of building trust, collaboration, and shared insight.

The quantitative frameworks necessary for learning and reducing uncertainty within the AM cycle can be highly complex and challenging due to the nuances of the social-ecological system in question (Tyre et al., 2011). Therefore, another critical area of research and practice is to develop systematic, effective teaching and training for undergraduate and graduate students in natural resources programs (Powell, Tyre, Conroy, Peterson, & Williams, 2011). Methods for accomplishing this are not well developed, but early perspectives recommend the integration of new concepts into existing coursework, including but not limited to goal-setting, complex modeling prediction, stakeholder interactions, and law and policy (Powell et al., 2011). In this way, with monitoring and evaluation of introduced curricula, the principles of AM could become more integrated into the professional research and management landscape over time.

Finally, more precise quantification of the values of ES and its connections to resilience in different social-ecological systems is critical (Polasky et al., 2011). An active area of research attempting to approach this surrounds the relationships and interactions between ES and biodiversity (Weisser et al., 2017). Although the causal relationships between biodiversity and ecosystem functioning (and therefore resilient ES) are still being investigated, there is general consensus that biodiversity does, to some extent, positively influence critical ecosystem functioning (Cardinale et al., 2012). By nature of the complex interplay among the natural, human, and built (infrastructure) capital necessary to provision humanity with ES, the approach to ES quantification must of necessity be interdisciplinary (Costanza et al., 2017; Mace, Norris, & Fitter, 2012). Therefore, the nexus of ES, biodiversity (Tscharntke et al., 2012), and the resilience of social-ecological systems (Biggs et al., 2012) is of critical importance.

Conclusion

Resilience in social-ecological systems is inherently multisystemic. Because of the interdependence of social and ecological systems, an ecologically resilient system (in a desirable state) can produce a more resilient society. Here we have reviewed the theory and practice by which the social-ecological sciences seek to sustainably manage critical ES that support human well-being. Over the last 50 years there has been significant progress in understanding the processes and feedbacks that govern change and resilience in ecosystems, but researchers and practitioners still struggle to connect this with the increasing complexity and surprises of sustainably managing the earth's resources in light of accelerating global change. We have presented a framework that will allow for the iterative testing of theory and applied practice, with each informing the other and thereby reducing uncertainty. The future research discussed in the final section are target areas for this approach, which, we believe, will produce the most critical advances in our understanding of resilient ES within social-ecological systems.

The ability of the earth system to provide the ES that confer human well-being in the face of increasingly rapid global change depends on the multisystemic resilience of the social-ecological system at multiple scales. Shifting from a static to dynamic view of systems can change the nature of ecosystem management to something much more likely to be sustainable long term, and, thus far, scientific work on resilience in social-ecological systems has developed from a need to understand the multisystemic nature of social and ecological systems to improve management. While past research has increased understanding about linked social-ecological systems and the need for flexibility and adaptability in management, there is still work to be done. In particular, we see considerable promise in research and practice focusing on feedbacks between ES and system resilience and managing resources with consideration of surprise, uncertainty, and potential system transformation.

Key Messages

1. People are dependent on the natural world to provide ES, and the ability of the earth system to provide these services in the face of increasingly rapid global change depends on the multisystemic resilience of the social-ecological system at multiple scales.
2. The multisystemic resilience of social-ecological systems is in turn affected by our ability to sustainably manage the provision of critical ES, which has historically been done by managing for maximum yield of single desired resources within ecosystems.
3. Resilience in social-ecological systems is commonly defined as the capacity of a system to cope with stressors and perturbations and yet remain in the same regime, with the same structure and functions.
4. Concepts and practices including the adaptive cycle, ball-and-cup diagrams, panarchy, scale, and adaptive management are used as key models to understand resilience by researchers and practitioners who work in social-ecological systems.
5. AM is a structured decision-making and iterative learning process by which researchers, practitioners, and stakeholders can frame hypotheses, test management actions, reduce uncertainty, and clarify further management decisions.

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