CHAPTER 4

Resilience Science

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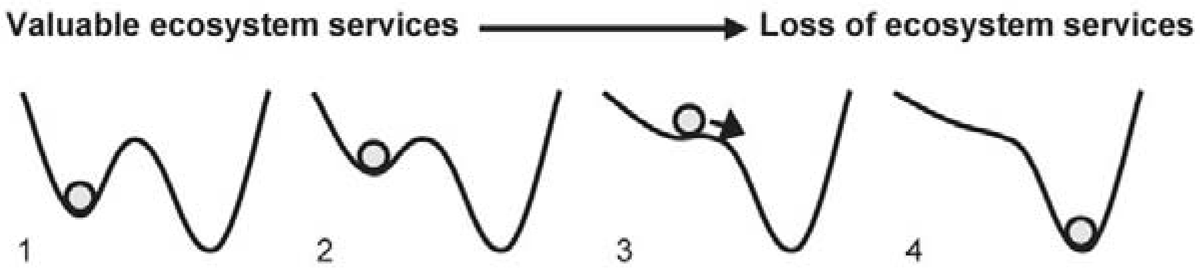
A key feature of ecosystem-based management (EBM) is the ability to manage or adapt to change. Embracing change requires us to better understand what influences the responses of systems, both human and natural, to a range of natural and human-caused disturbances. Will a system resist disturbance, rebound quickly, slowly degrade, or shift to a completely new state? Once a threshold is crossed, is it possible for a system to return to a preexisting state; in other words, is the change reversible, and with what effort? Thus, understanding *resilience*—the extent to which a system can maintain its structure, function, and identity in the face of disturbance—can enable us to better predict how systems will respond not only to a growing array of perturbations, but also to a range of management strategies.

Resilience science is a conceptual framework that can contribute to more sustainable interactions between people and terrestrial, freshwater, and marine ecosystems throughout the world (Walker and Salt 2006). With roots in ecology and complex systems science, the framework arose from the recognition that a given ecological system could exhibit two or more fundamentally different states (Holling 1973). For example, in the coastal marine environment, reefs in the Aleutian Islands have been shown to alternate between kelp-dominated and urchin-dominated systems (fig. 4.1; Estes and Duggins 1995). For a system to absorb perturbations and remain in a functionally similar state requires that there be a threshold between the alternatives—a set of conditions that, once exceeded, destines the system to move from its earlier state toward a fundamentally new configuration. Such thresholds imply nonlinear behavior of the system, that is, dynamics that are qualitatively different from those experienced before. Such "lurches" or "flips" in system behavior may occur rapidly, although they needn't. Resilience in this context, then, means the capacity to avoid breaching thresholds between alternative states.

While the resilience framework has its origins in ecology, the focus is now on coupled social–ecological systems (see also McLeod and Leslie, chap. 1 of this volume; Shackeroff et al., chap. 3 of this volume). Ecological dynamics cannot be understood apart from the human activities and decisions that influence ecosystems and their functioning. Ultimately, we are interested in how resilience science can be applied to coupled systems, rather than to solely the ecosystem or the social system. However, that does not obviate the need to understand the resilience of one or the other domain, as we will sometimes do in this chapter.

To explore the benefits of resilience science for marine ecosystem-based management, we first discuss key elements of resilience science, including the coupled and dynamic nature of social and ecological systems and characteristics of these systems that contribute to their resilience, specifically diversity, disturbance regimes, and interactions (box 4.1 and below). We then explore how resilience science can help inform the development and implementation of marine ecosystem-based management efforts. These elements are further illustrated by the case studies of ongoing ecosystem-based management efforts in part 4 of the volume.



coral-dominated reefs	overfishing, coastal eutrophication	disease, bleaching, hurricanes	algae-dominated reef
kelp forests	functional elimination of apex predators	thermal event, storm, disease	sea urchin dominance
clear-water estuary	overfishing, coastal eutrophication, loss of submerged aquatic vegetation	storm, disease, hypoxia	eutrophic estuary
benthic-dominated system	rising ocean temperatures, overfishing	disease, hypoxia	pelagic-dominated system

Figure 4.1 Shifts in marine ecosystems with multiple states from a more- to a less-desirable state (1, 4), resulting in a loss of valuable ecosystem services. (2) Drivers of such state shifts include both natural and anthropogenic causes that erode resilience. (3) Perturbations that subsequently "trigger" state shifts (as indicated by the arrow) could have been absorbed by a more resilient system. Modified with permission from Elmqvist et al. 2003 and Folke et al. 2004.

The Coupled and Dynamic Nature of Social and Ecological Systems

In many modern natural resource systems, management strategies have focused narrowly on the production of a particular commodity, such as timber or fish, by attempting to reduce the variability of the resource so that maximum yields can be realized consistently through time (Holling and Meffe 1996). In systems with a single state or functional regime, such strategies may make some sense, since the system would be expected to recover eventually from any management mistakes (e.g., overexploitation), with original resource levels restored. But many social and ecological systems exhibit more than one state. For those systems, such management approaches tend to be problematic over the long term. Narrowly controlling for maximum yield and stability of a particular component of the system usually *reduces* the resilience of the system, altering the position of thresholds in the system and making a "flip" to a new state more likely (Holling and Meffe 1996; Folke et al. 2004; MA 2005). This new state is often less desirable, that is, characterized by depleted stocks of economically or ecologically valuable species or reduced ecosystem services. For example, Boesch and Goldman (chap. 15 of this volume) describe how the synergistic impacts of nutrient pollution, overexploitation, and other human impacts have resulted in depleted fisheries and diminished recreational opportunities in Chesapeake Bay. In the Gulf of California (chap. 13 of this volume), Ezcurra and colleagues observe how degradation of coastal mangroves associated with changing land uses (e.g., aquaculture, agriculture, urbanization) has led to a shift in ecosystem states, and subsequent changes in the services provided by these coastal areas. Thus, understanding the drivers of multistate dynamics in both marine ecosystems and human communities is vital to ensure the long-term provision of the full range of benefits that coastal and marine ecosystems provide.

The evidence for multiple states in coastal and marine systems has been growing for some time. We now know that both natural and anthropogenic drivers of change can contribute to such shifts (Scheffer and Carpenter 2003; Folke et al. 2004; Knowlton 2004; Hughes et al. 2005). To return to the example of kelp- and urchin-dominated reefs noted above, changes in multiple biotic and abiotic parameters can contribute to the shift between the two states. Predation by the sea otter can drastically reduce the number of urchins on a reef, enabling kelp to thrive in the absence of one of its primary consumers. But other stressors also can mediate the shift in the nearshore system, including the variation in recruitment of new urchins to the reef or the addition of novel predators (Estes and Duggins 1995; Estes et al. 1998). When killer whales began preying upon sea otters in the early 1990s, nearshore community dynamics changed markedly within a decade (Estes et al. 1998). Kelp—a structurally important, foundational species that provides habitat for many other marine species—declined dramatically throughout western Alaska as the number of sea urchins (and the intensity of their grazing) in nearshore communities increased.

Another local-scale example of alternate states comes from tropical coral reefs. There, ecologists have documented shifts caused by synergistic interactions between overexploitation, land-based pollution, and disease. These forces, acting in combination, can drive a reef from a state dominated by extensive healthy coral cover and an intact community of fish and invertebrate consumers to one dominated by macroalgae and a depauperate group of consumers (fig. 4.1; Knowlton 1992; Hughes 1994; McClanahan et al. 2002). Finally, eutrophication of coastal waters due to changes in land use and increased nutrient inputs can lead to a radically different biophysical state than that characterizing a healthy coastal ecosystem, particularly in bays and semienclosed seas (Gunderson and Pritchard 2002; Lotze et al. 2006; Boesch and Goldman, chap. 15 of this volume).

At larger spatial scales, these types of ecological shifts are potentially no less prevalent, but they are harder to detect and document. Consequently, investigators rely more on long-term observations and models to capture shifts in the composition and functioning of the system, as opposed to local-scale field

Box 4.1. Key Elements of Resilience Science

1. Human and ecological systems are closely linked, and understanding these connections can help inform environmental decision making.
2. Many systems exhibit alternate states, and changes between them can be abrupt.
3. Shifts between alternate states may be irreversible, particularly on policy-relevant time scales.
4. Given the ever-changing nature of both social and ecological systems (and our uncertain knowledge of them), management goals should focus on maintaining options into the future, rather than maximizing production of a particular commodity or ecosystem service.
5. Management strategies should focus on key system characteristics that are sources of resilience, for example, diversity, disturbance regimes, and interactions.
6. Resilience cannot be maintained at all scales at all times—vulnerabilities will remain and should be incorporated into management efforts.
7. Assessing the success of management efforts and learning from those evaluations is critical.

experiments. In the Pacific Ocean, shifts in zooplankton and fish guild structure, as well as changes in physical variables, serve as indicators of the Pacific Decadal Oscillation, a multidecadal-scale regime change in the Pacific Ocean (Hare and Mantua 2000). In the Northwest Atlantic, Collie and colleagues (2004) combined data on fisheries landings and ocean conditions with ecological models to detect a discontinuous oceanic regime shift, one of the few rigorously documented in an open ocean ecosystem. Additional examples of large-scale ecological shifts include the anchovy and sardine fisheries throughout the Pacific (Chavez et al. 2003); the decline of the Northwest Atlantic groundfish assemblage, including Atlantic cod (Choi et al. 2004; Steneck et al. 2004); and shifts from vertebrates to invertebrates and benthic to pelagic species in Narragansett Bay and Rhode Island Sound (Wood et al. 2008). In summary, scientists have observed alternative ecological states involving a diversity of marine organisms (algae, invertebrates, fish, marine mammals, and humans) in both nearshore and open ocean ecosystems, and these alternate states often generate different sets of ecosystem services. For recent reviews of alternate states in marine systems, see Knowlton (2004) and deYoung and colleagues (2008).

In the social context, the shift in local economies and social networks that occurs when a fishery- or forestry-dependent community loses access to primary resources may be analogous to the ecological shifts detailed above (Kinzig et al. 2006; Nelson et al. 2007). For example, following the collapse of the northern cod fishery off the Grand Banks of Canada, changes in the social and economic structure of coastal human communities in Newfoundland were observed (Hamilton and Butler 2001; Hamilton et al. 2004). Specifically, with the 1994 moratorium on cod fishing and subsequent closure of the fishery in 2003, hundreds of fish plant workers lost their jobs, as did fishermen themselves. Subsequently, many young people left the area to pursue education or employment elsewhere (Hamilton et al. 2004). This story has been repeated in resource-dependent communities throughout the world (Nelson et al. 2007).

Importantly, from a management perspective, the new ecological or social state is often just as resilient as the previous state, creating challenges for managers interested in reversing the situation. To return to the Newfoundland coastal community, the conditions that enabled the development of a healthy coastal economy—for example, abundant fishery resources, access to markets, dockside infrastructure, and functioning social networks—may no longer be in place, creating an essentially irreversible situation on timescales of interest to most policymakers and managers. Other livelihoods and local economies would have to be developed to replace the former opportunities. In other words, resilience is not always a positive phenomenon. Many undesirable and degraded states are highly resilient (e.g., eutrophic estuaries, expansive bureaucracies), and the management challenge in such cases is to erode resilience by breaching a threshold and accessing a more desirable state. In some cases, through management of human activities, we seek to maintain or restore the resilience of ecological or social states, while in others, we implement strategies so as to reduce their resilience. Which path is pursued will depend on which states are valued by society and why (see also Kinzig et al. 2006; Moore and Russell, chap. 18 of this volume).

Documenting shifts in coupled social–ecological systems presents considerable challenges scientifically. Experiments are often out of the question, both logistically and ethically, which makes determination of potential alternate states and underlying mechanisms difficult (Scheffer and Carpenter 2003; Walker and Meyers 2004). Moreover, in a review of state shifts in social and ecological systems, Walker and Meyers (2004) found no examples where a novel threshold was predicted before it had been experienced, suggesting that further research is needed to develop tools to detect and avoid system shifts (see also deYoung et al. 2008). The development of tools to compare the impacts of system shifts, for example, to assess trade-offs inherent in different management approaches, is further along and equally important (see Wainger and Boyd, chap. 6 of this volume; McLeod and Leslie, chap. 19 of this volume). In summary, the challenges associated with anticipating and documenting system shifts highlight the importance of managing in light of resilience, that is, managing human interactions with coastal and marine ecosystems in ways that avoid shifts to undesirable ecosystem or social states, when possible. We offer suggestions for how to do this later in the chapter (see box 4.2).

This discussion about multiple states raises the question of what relevance the above discussion has for those systems that *do not* exhibit such states. First, in many cases, there may be little operational difference between a system that exhibits multiple alternative states and one that experiences a slow, albeit deterministic, recovery to the "original" state (Knowlton 2004). Moreover, the precautionary principle makes it clear that we need to recognize the potential for the existence of multiple states and act accordingly. That is, where an action threatens to do serious or irreversible damage, lack of scientific certainty should not be used as a reason to postpone actions that would prevent environmental degradation (UNCED 1992 principle 15).

As an example, consider the water filtration service provided by estuarine shellfish. This service is provided by an ecosystem state characterized by robust shellfish populations of sufficient abundance and individual filtering capacity. When shellfish populations decrease through time due to the cumulative impacts of multiple natural and anthropogenic factors, as in the Chesapeake Bay, the filtration service is impacted as well (Jackson et al. 2001; Boesch and Goldman, chap. 15 of this volume). That is, the filtration rate will be low when shellfish biomass is low, regardless of whether the system exhibits a single state or multiple states. Which situation applies, however, may play a significant role in the success of particular restoration strategies—and thus articulating these alternatives is an important consideration for management. Resilience science offers a conceptual framework for articulating these alternatives and also suggests strategies for moving forward with marine EBM in the face of such uncertainty. We will return to this issue later in the chapter.

Sources of Resilience in Ecological and Social Systems

Case studies and modeling of coupled social–ecological systems throughout the world have yielded insights on the characteristics of these systems that contribute to resilience (table 4.1). Here we highlight several that are particularly relevant to the development of ecosystem-based management in coastal and ocean areas: diversity, disturbance regimes, and interactions within and across scales. Knowledge of how and why these factors operate can help inform the development of effective management strategies and thus contribute to one of the overarching goals of marine EBM: to maintain an ecosystem in a healthy, productive, and resilient condition so that it can provide the services humans want and need (McLeod et al. 2005).

Diversity

In general, across terrestrial, freshwater, and marine systems, we see that increased biological diversity leads to increased production of ecosystem services or functioning (Hooper et al. 2005). In ecosystems, diversity is often equated with the number of species present in a given area, that is, species richness. While the majority of investigations of diversity and ecosystem functioning have focused on terrestrial ecosystems, we have an increasing number of marine cases from which to draw. These include work on how diversity influences primary production (Callaway et al. 2003), secondary production (Duffy et al. 2003), nutrient cycling (Emmerson et al. 2001; Bracken et al. 2008), and invasion resistance (Stachowicz et al. 2002). There is also evidence that diversity increases resilience to overexploitation: Worm and colleagues (2006) analyzed fisheries catch data from sixty-four large marine ecosystems worldwide and found that recovery from overexploitation was positively correlated with fish species diversity and that collapses were more likely to occur in relatively species-poor ecosystems.

In addition to species richness, two other forms of diversity are particularly important when considering ecological or social resilience: functional diversity and response diversity (Folke et al. 2004). Functional diversity refers to the variety of functions or activities occurring within a given system. In coral reef ecosystems, for example, herbivorous fish consume macroalgae and thus enable continued coral recruitment, while symbiotic zooxanthellae provide their coral hosts with energy. In estuarine environments, oysters and other reef-building shellfish that filter particulates and create habitat for other species play important and functionally distinct roles (Coen et al. 2007). Thus, resilient coral reef and estuarine ecosystems—that is, those that are able to maintain themselves through time—include these arrays of species (and functions). The functional groups described above enable production of valued ecosystem services (including tourism opportunities and seafood production, respectively).

Response diversity, or redundancy within functional groups or species, also has been

Table 4.1. Characteristics that contribute to ecological and social resilience

Ecological systems

- Biological diversity[1]
  - Genetic diversity[2]
  - Species-rich biological communities[3]
  - Functional diversity[1,4]
  - Response diversity[1,5]
- Biological legacies[6]
- Intact disturbance regimes[7]
- Intact interactions and feedback loops[8]
  - Among species[9]
  - Among biological communities and ecosystems[6,10]
  - Across spatial, temporal, and organizational scales[11,12]
- Modularity among populations and ecosystems[8,13]

Social systems

- Adaptability of individuals and institutions[14,15]
- Bridging organizations[16]
- Capacity for collective action[17,18]
- Clearly defined ecological boundaries[17]
- Clearly defined property rights[17,19]
- Diversity[14]
  - Institutional[17,20]
  - Livelihood options [21,22]
  - Sources of knowledge[23]
- Equitable distribution of benefits and costs[17,24]
- Leaders and other key actors[14,16,25]
- Multiscale governance[14,17]
- Social memory[23]
- Social learning[16]
- Social networks[16]
- Social capital (e.g., trust, reciprocity)[16,17]

Sources: The above information was synthesized from diverse sources, including Adger 2000; Folke et al. 2004, 2005; Nelson et al. 2007; Olsson et al. 2004; and Ostrom 1990. References were selected to be illustrative rather than comprehensive.

[1]Folke et al. 2004; [2]Hilborn et al. 2003; [3]Worm et al. 2006; [4]Hughes et al. 2003; [5]Bellwood et al. 2006; [6]Nyström and Folke 2001; [7]Holling and Meffe 1996; [8]Hughes et al. 2005; [9]Sandin et al. 2008; [10]Mumby et al. 2004; [11]Roberts 1997; [12]Elmqvist et al. 2003; [13]Levin 1999; [14]Folke et al. 2005; [15]Nelson et al. 2007; [16]Olsson et al. 2004; [17]Ostrom 1990; [18]Acheson 2006; [19]Berkes and Folke 1998; [20]Low et al. 2003; [21]Pomeroy et al. 2006; [22]Hilborn 2004; [23]Olsson and Folke 2001; [24]Adger et al. 2001; [25]Gladwell 2000.

demonstrated to contribute to the functioning of ecosystems and continued production of services in the face of disturbance, that is, to resilience. This redundancy within groups increases the possibility that at least one species within a functional group will be well adapted to current conditions (Walker 1995; Elmqvist et al. 2003). Work by Ray Hilborn and colleagues in Bristol Bay, Alaska, has shown that the robust yields of sockeye salmon in the bay over a number of decades can be linked with the varied performance of subpopulations of salmon within the bay (Hilborn et al. 2003). Different populations respond in a variable fashion to environmental change, particularly the Pacific Decadal Oscillation.

In the social context, functional and response diversity are also both important and have been shown to enable human communities to buffer themselves from disturbance or adapt as necessary. For example, in their study of the post-2004 tsunami response in rural coastal communities in Southeast Asia, Pomeroy and colleagues (2006) contend that those households with diversified livelihood strategies, where people had varied sources of income (including but not limited to fishing), were better able to adapt to the changing ecological and economic conditions after the disaster. Also, in response to environmental variability and fluctuations in target species, Pacific coast fishermen historically shifted from one species to another, including salmon, halibut, herring, shrimp, groundfish, and crab, during the course of a year, thereby diversifying their economic opportunities (Hilborn 2004).

The rule of thumb may be that more diversity is better, but the details of this need to be examined within a particular system. Most ecologists would not agree that importing nonnative species to increase diversity would necessarily increase functioning or resilience; the relationships among organisms can be critical, and at least some low-diversity systems are highly resilient (e.g., desertified savannas or rice paddies that have been harvested for millennia). Moreover, there are likely to be tradeoffs among the different types of diversity; for example, enhancing functional diversity may mean decreasing response diversity or altering interactions across scales or other attributes of the system that are desirable (Levin 1999).

In sum, the importance of diversity is multifaceted: While intact biological communities (and thriving societies) both benefit from a sheer variety of components (or opportunities), the functional roles played by particular entities within the system and their range of responses to change are also critical.

Disturbance Regimes

By *disturbance regimes* we are referring to frequency and impacts of biogeophysical processes (e.g., hurricanes, coastal flooding, bioturbation) as well as those generated by human activities (e.g., offshore oil development, fishing, removal of drift materials from barrier beaches). Human activities often alter the disturbance regimes under which ecological systems have evolved (MA 2005). Based on investigations of fossilized coral reefs, John Pandolfi and colleagues (2006) found that the corals in Papua New Guinea experienced mass mortality less than once every fifteen hunded years—a disturbance frequency that contrasts quite markedly with the episodic bleaching events of recent decades caused by global warming. Worldwide, an estimated 40% of marine ecosystems are strongly impacted by human activities ranging from fishing to coastal pollution to climate change; no place in the world's oceans is untouched by human activities (fig. 4.2; Halpern et al. 2008a). These increases in the frequency, magnitude, and extent of disturbances to ocean ecosystems raise questions: How are marine systems responding to these changed disturbance regimes? Are they recovering? If not, what management strategies might enable restoration of functioning?

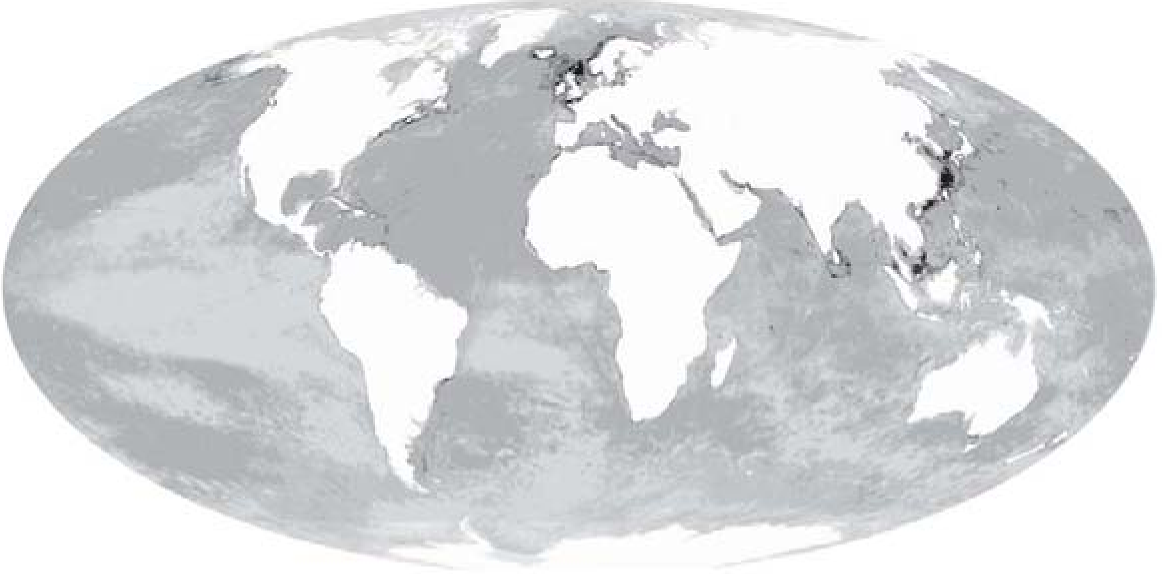


Figure 4.2 Cumulative impacts of human activities on the Earth's coastal and marine ecosystems, where the darker shading indicates the heaviest impacts overall. Adapted from Halpern et al. 2008a and reprinted with the permission of the American Association for the Advancement of Science (AAAS).

Systems may be characterized as having specific or general resilience to a particular set of stressors or disturbances (Levin 1999; Anderies et al. 2006; Walker et al. 2006). Specific resilience refers to the capacity of a system to absorb a particular perturbation, or set of perturbations, and continue to remain in a functionally similar state. The system may have high resilience to that particular perturbation, but not others. General resilience refers to the capacity of a system to absorb a broader range of perturbations, including novel or surprising perturbations. General resilience is achieved by investing in adaptive capacity or flexibility, while specific resilience is achieved by investing in the properties of a system that confer robustness against a particular stressor. Investing in general resilience will increase capacity to deal with a wide range of perturbations, but the capacity to deal with any particular perturbation will be lower than if one had invested in specific resilience toward that perturbation (Levin 1999; Nelson et al. 2007; Guichard and Peterson, chap. 5 of this volume). Conversely, investing in specific resilience may confer high resilience with respect to one particular perturbation but lower the system's capacity to deal with other, qualitatively different disturbances (Walker et al. 2006). This can be true across spatial or organizational scales as well; investing in increasing resilience at one scale may mean reducing it at others (Levin 1999).

Thus, not all functions or features of a system can be maintained in the face of disturbance, and not all functions or features will be equally valued or valuable. Some features may need to give way in order for others to be maintained. Thus, one must always ask, Resilience of what, to what? (Carpenter et al. 2001). If disturbance regimes are well known and fairly consistent over time, then one should manage human interactions with marine ecosystems to build specific resilience vis-à-vis those disturbances that most threaten valued components.

If disturbance regimes are changing and uncertain, one might more fruitfully manage for general resilience over specific resilience, or invest in some combination of general and specific resilience (they aren't discrete categories, after all, but rather a continuum). Moreover, if a system were impacted by a large array of disturbances, particularly if they were potentially interacting in a synergistic or otherwise unpredictable fashion, one would want to proceed in a precautionary fashion and manage for general resilience (see Halpern et al. 2008b for further discussion of the interacting cumulative impacts of multiple stressors). The point is that not all hazards can be avoided; there will always be trade-offs in management and disturbances to which the system will be vulnerable (Anderies et al. 2006). The only attainable goal is to reduce those vulnerabilities, rather than to eliminate them. One example of how to do this comes from McClanahan and colleagues (2008), who offer an innovative framework for integrating knowledge of ecological and social vulnerabilities into coral reef conservation by combining multiscale information on bleaching and adaptive capacity.

In terms of operationalizing these concepts, the approach of The Nature Conservancy and partners in coral reef systems is instructive. They are focused on the threat posed by coral bleaching and have published a handbook to guide managers and other practitioners in managing coral reefs so that they are "specifically" resilient to this type of disturbance (Grimsditch and Salm 2005). In this publication, Grimsditch and Salm highlight several mechanisms by which coral reef ecosystems may avoid or resist bleaching events, as well as factors that contribute to ecosystem recovery following bleaching events. They suggest that conservation practitioners focus protection on reefs that exhibit these characteristics and thus are less prone to bleaching or more likely to successfully recover. Where multiple types of perturbations (e.g., habitat degradation, pollution, and overexploitation) are of equal concern, developing strategies focused on general resilience (e.g., no-take marine reserves and other types of protected areas [PISCO 2007]) may be more appropriate.

Uncertainty about the future behavior of many coupled social–ecological systems—both in terms of large-scale drivers such as climate change and globalization and as responses of humans and other strongly interacting species—shows that a focus on general resilience is warranted. In some cases, however, as illustrated by the coral reef example above, a consensus emerges on what the primary threats to a system are. *If* these assessments are correct (see Boesch and Goldman, chap. 15 of this volume, for a more complicated story from the Chesapeake Bay), a focus on building specific resilience of desirable ecological and social states to those threats may be in order. Realistically, however, management strategies will be developed in the face of multiple uncertainties related to ecosystem responses, human behavior, and other factors. Consequently, it is best to proceed within an adaptive management framework, that is, where management interventions are implemented and evaluated as large-scale "experiments" (see also Guichard and Peterson, chap. 5 of this volume; Kaufman et al., chap. 7 of this volume). Articulating the trade-offs between managing for specific and general resilience—and doing so adaptively—is an area where little systematic work has been done, and where collaboration among scientists, managers, and resources users would be particularly fruitful.

Interactions

The resilience of a social or ecological system is very much a product of interactions across scales of time, space, and organization—from individual ecosystems to large marine ecosystems and from individuals and households to entire communities (see fig. 1.1; McLeod and

Leslie, chap. 1 of this volume). Here we highlight several types of interactions of particular importance to system resilience: interactions between rapidly and slowly changing characteristics of a system, interactions between social and ecological systems and across multiple geographic scales, and feedback loops.

The interaction between rapidly and slowly changing characteristics of a given system can help inform understanding of a system's resilience at a given point in time, and how it is likely to change (Levin 1999; Carpenter et al. 2001; Carpenter 2003; Folke et al. 2004). For example, investigations of the sources of ecological resilience in lakes indicate that changes in the water clarity and biological community of the lake are impacted not only by rate of nutrient loading into the lake from agriculture and other land use activities, but also by longer-term changes in the nutrient storage capacity of lake sediments (Carpenter 2003). Thus, to maintain the specific resilience of the lake system to nutrient pollution, managers and stakeholders need to consider not only the current rates of nutrient loading and the factors influencing those rates, but also how the concentration of phosphorus in the sediments is changing and ways to alter that long-term storage capacity. While understanding of the importance of slowly changing variables is growing in marine systems as well (see, for example, the case studies in part 4), this knowledge has not been as widely applied as in freshwater and terrestrial systems.

Interactions across multiple geographic scales also influence resilience. It is for this reason, in part, that scientists recommend that no-take marine reserves and other marine protected areas be implemented in a network (Lubchenco et al. 2003 and papers therein). Not only is it vital to maintain the flows of materials and propagules among local ecosystems, but, in addition, many marine populations are structured as metapopulations. In other words, populations are maintained on a regional scale through the dispersal and movement of individuals among local habitats (Kritzer and Sale 2006). Even though individual populations go extinct, the regional population is maintained through time by the movement of individuals among local habitats. Note that modularity, or spatially distinct populations and ecosystems, also has the potential to confer resilience (Levin 1999; Hughes et al. 2005). Allison and colleagues provide guidance on how to operationalize this knowledge for reserve network design (Allison et al. 2003).

Interactions between ecological and social systems can affect the resilience of coupled systems, as well. The dynamics, disturbances, and performance of ecological systems cannot be readily parsed from the dynamics, disturbances, and performance of social and economic systems. Disturbances that originate in the social or economic realm—even at small scales—can have profound consequences for the ecological domain (Kinzig et al. 2006). For example, the dry forests of the Androy region in southern Madagascar are becoming increasingly fragmented, in part due to changes in land use, demographics, and ultimately, decline in the traditional belief system and informal institutions linked with forest stewardship. With loss of forest cover, highly valued ecosystem services (e.g., agriculture crops and habitat for biodiversity) are in turn declining at the local scale. Kinzig and colleagues (2006) suggest that such local-level changes in the ecological and social domains could have larger-scale consequences for the functioning of the region's ecological and human systems.

Mismatches of ecological and institutional scales can lead to loss of resilience and subsequent decline in ecosystem services (Cumming et al. 2006; Wilson 2006). Wilson (2006), for example, describes how marine fisheries in the Northwest Atlantic tend to be managed species by species and at a broad, single spatial scale. Yet many exploited species (e.g., Atlantic cod, longfin squid) are composed of spatially structured populations (Ames 2004; Buresch et al. 2006), making the assumption of a single, large stock implausible. The spatial heterogeneity of fisheries and marine ecosystems has implications for the magnitude and spatial distribution of fishing effort (e.g., see Wilson et al. 2007) and thus for food production and the provision of other marine ecosystem services. Wilson (2006) proposes that management institutions be reconfigured so as to incorporate such cross-scale ecological dynamics.

Feedback loops are interactions of particular importance to system resilience (Levin 1999). Feedback loops can exist within or between trophic levels, between biotic and abiotic components of a system, across social and ecological domains, and across scales of space and time. They can be either positive or negative—with positive feedbacks serving to reinforce an initial disturbance, and negative feedbacks serving to dampen them. Feedbacks can also be tight or loose; tight feedbacks have consequences (positive or negative) that reverberate quickly through the system. Loose feedbacks may only create noticeable changes in more distant time. In general, feedbacks between ecological and social systems have become looser in recent times—for example, due to globalization (Levin 1999).

In the ecological context, for example, the loss of herbivorous fish can facilitate settlement and growth of macroalgae, which in turn overgrow living coral. In addition, the spread of macroalgae on the reef can inhibit recruitment of new corals to the reef (Hughes 1994; McClanahan et al. 2002). Thus the initial "success" of the macroalgae is reinforced through a positive feedback loop, enhancing the abundance of the algae and leading to further decline in coral cover.

Socioeconomic feedback loops are often more complex, as they can change with institutional and economic contexts. For example, in the face of declining fish catches, fishermen may reduce fishing effort or shift to another target stock. The reduced pressure on the stock often leads to a rebound in fish abundance, resulting in a negative feedback loop. The more common case in response to declining catches, however, is an increase in fishing effort, which is often driven by subsidies, market prices, or other incentives (e.g., see Berkes et al. 2006). This latter response generates a positive feedback whereby the stock declines further. The phenomenon of "shifting baselines" is another example of a loose positive feedback loop: Management decisions are made based on the current state of the ecosystem, as people do not recognize that the current state is a degraded shadow of the original system (see Pauly 1995; Jackson et al. 2001; but also Campbell et al. 2009). As time passes, the "bar" for ecosystem restoration may fall lower and lower (Pauly and Maclean 2003).

Implications of Resilience Science for Marine Ecosystem-Based Management

Some ecological and social states are more desirable than others, as they enable the delivery of ecosystem services that people value. Given the dynamic nature of ecological and social systems, it is advisable to implement management strategies that preserve the integrity and resilience of desirable states. So then the central question emerges: How can decision makers develop marine policies and management programs that preserve the integrity and resilience of valued states? We see opportunities for integrating resilience science into all stages of marine ecosystem-based management, including planning, implementation, and evaluation (see box 4.2).

Planning

Marine EBM recognizes that people are part of ecosystems and that, ultimately, we are managing human interactions with coastal and

Box 4.2. Applying Resilience Science for Marine Ecosystem-Based Management

Planning

1. Integrate knowledge of the ecological and social domains.
2. Identify sources of resilience in the social and ecological systems of interest.
3. Use multiple approaches to anticipate shifts in system states.
4. Consider a range of management strategies to build or erode resilience, as appropriate.
5. Develop both mitigation and adaptation strategies.

Implementation

6. Proceed in an adaptive fashion.
7. Prepare for and capitalize on opportunities for change.

Evaluation

8. Assess progress in an integrated manner, using biogeophysical, social, economic, and institutional information.

marine environments, rather than ecosystems themselves (McLeod et al. 2005). Consequently, integrating knowledge of the ecological and human domains in a particular region is vital in order to develop effective management strategies and to assess them accordingly (see fig. 1.1 in McLeod and Leslie, chap. 1 of this volume). Knowledge integration is best done by an interdisciplinary team of scientists, practitioners, and stakeholders, and it is particularly important that the relevant social sciences (e.g., economics, anthropology, sociology, geography), humanities (e.g., history, philosophy), and sources of local and indigenous knowledge (Kliskey et al., chap. 9 of this volume) are engaged from the outset of the process. This way, the EBM planning process will take full advantage of the relevant sources of knowledge for the design and implementation of more ecosystem-based approaches to ocean management.

Stakeholders engaged in marine EBM, as in all management processes, need to articulate a vision of what they are working to achieve. Scientists can help stakeholders understand the plausibility and likely scenarios to achieve such visions. Resilient ecosystems and human communities are often part of such visions (POC 2003; USCOP 2004; case studies in part 4 of this volume). In order to manage for resilience of coupled social–ecological systems, we need to understand the system characteristics that contribute to or inhibit system resilience. We focused on several key ones here, including diversity, disturbance regimes, and interactions (see also table 4.1). A formal resilience assessment can provide an opportunity to explore these elements in greater depth (RA 2007).

To anticipate and potentially avoid shifts to alternate (particularly undesirable) ecological or social states, it can be helpful to try to identify thresholds between these states and the drivers that contribute to such shifts. A number of statistical techniques can be used to identify changes in system state from field observations, but importantly, these cannot be used to establish causality among different variables (Scheffer and Carpenter 2003; Kemp and Goldman 2008). Consequently, field experiments and conceptual and quantitative models are critical complements to observational data. To date, these techniques have primarily been used to document shifts that have already occurred, rather than to forecast future changes. But Carpenter and Brock (2006) illustrate how increasing variance of a slowly changing variable (in this case, lake-water phosphorus) can be used to predict ecosystem shifts in advance. This area is strongly in need of further research and application.

In the selection of management strategies, we urge that both mitigation and adaptation strategies be considered. Mitigation refers to the capacity of managers to avoid the probability of a particular outcome. It requires that those forces influencing the system be under at least partial managerial control. Managers can, for instance, reduce the probability of collapse in fishing stocks by controlling fishing pressure; this would be mitigation. Adaptation refers to actions taken to alter the impact, or value, of an outcome, rather than its probability. For instance, local or regional managers can do little to influence the global course of climate change, that is, to alter the probability that it will occur. But they may be able to alter the impact climate change will have on their system, for example, by establishing a marine reserve, building general resilience, or reducing other, more locally driven pressures. This would be adaptation. In other words, mitigation is possible in the domains and on the scales that managers can directly influence. In other cases, when global forces influence local dynamics, local managers must plan for adaptation and work with higher levels of government to implement mitigation measures. We see this dual-strategy approach in the climate change community, where policymakers recognize the need to develop mitigation measures that reduce carbon emissions, as well as adaptive strategies like improved coastal responses to flooding.

Implementation

Resilience science can provide guidance during the implementation stage of ecosystem-based management, as well. Given the challenges of predicting ecosystem responses to management, let alone human behavior in the face of local-scale management interventions as well as climate change, globalization, and other large-scale drivers of change (see also Shackeroff et al., chap. 3 of this volume), we suggest that maintaining system resilience should be an explicit objective of EBM. The strategies used to build system resilience (e.g., habitat restoration, no-take marine reserves and other protected areas, ocean zoning, and outreach and education), are no different from those used in more traditional ocean management. The difference lies in the formulation of the objectives, the ways in which progress toward those objectives is assessed, and ultimately, improvements in the condition of the social and ecological systems of concern.

Management interventions should be developed and implemented in ways that recognize uncertainties and enable learning and change as needed (e.g., see Gunderson 1999; Sainsbury et al. 2000). In other words, management should proceed in an adaptive fashion (Lee 1999; Guichard and Peterson, chap. 5 of this volume). Adaptive management is a deliberate, structured process of formulating and testing hypotheses about how the world works—in this case, how ecological and social systems are connected and influence one another. Management interventions are viewed as “experiments” from which we can learn in order to improve management in the future. However, before engaging in adaptive management, it is vital that participants agree on the outstanding questions that need to be answered (Lee 1999). In addition, it is important to realize that EBM is an iterative process that requires flexibility and adaptation, as many things change over time, including knowledge, the state of the system, and the values people place on different ecosystem services.

Moreover, the resilience framework illustrates the value of identifying windows of opportunity in order to bring about change. Gunderson and Light (2006) identify three types of “policy windows” that can precipitate changes in social norms or public policy: ecological, political, and epistemic windows. The first results from an ecological state shift or following a large-scale perturbation (e.g., drought or hurricane). Political windows are created by stakeholders, managers, and other actors seeking to alter policy. And epistemic windows are created by people seeking new understanding or ways of interacting with the coupled systems of interest. As Gunderson and Light (2006, p. 332) explain, "These groups are able to suspend extant beliefs, question mental models, contrast possible futures and other such rules that allow for exploration of new and novel system configurations." An example to illustrate such windows of opportunity is provided by Boesch and Goldman (chap. 15 of this volume). The record floods of 1972 in the Chesapeake Bay region—and the slow ecological recovery that followed—raised public awareness of the failing health of the bay. Ten years later, in 1983, the Chesapeake Bay Program was established to coordinate the improvement and protection of water quality and living resources of the Chesapeake Bay estuarine system.

While the occurrence of such windows is often difficult to predict precisely, it is possible to be prepared for them. For example, Ezcurra and colleagues (chap. 13 of this volume) highlight the growing role in the Gulf of California of *Noroeste Sustentable*, a group of prominent businesspeople in the region who are facilitating a regional dialogue and building capacity to help balance environmental and development concerns in northwest Mexico. Similarly, in the Puget Sound region, Governor Gregoire and the state legislature have initiated the Puget Sound Partnership, to bring together people from public and private institutions, tribes, and citizen groups to restore and protect Puget Sound (Ruckelshaus et al., chap. 12 of this volume).

Evaluation

Given the connections between marine ecosystems and the human communities that depend on them, expanded monitoring and evaluation of social, economic, and institutional variables—as well as biogeophysical ones—is needed. Such an integrated program will increase the scientific and practitioner communities' understanding of the dynamics and drivers of the systems of interest and provide more vital information that can be used to develop scenarios for the future behavior of the coupled systems (Boesch and Greer 2003; Peterson et al. 2003).

The development of more resilience-based EBM also requires broadening monitoring and evaluation, in order to document the crossing of thresholds and, ideally, to anticipate and respond to such shifts. Thus, ecological monitoring programs should include traditional indicators of physical and chemical processes, community structure, and biomass and relative abundance of ecologically and commercially important species, but they also need to incorporate information on the ecological processes that sustain biodiversity patterns (e.g., recruitment, dispersal, and cross-scale interactions) as well as information on the relative abundances and composition of functional groups that have strong effects on ecosystem functioning. Like all indicators, resilience indicators should be clearly defined and relevant to key stressors or drivers in the system of interest (Carpenter et al. 2001, 2005). Carpenter and colleagues (2001) note that indicators of resilience often are slowly changing variables, for example, the long-term nutrient storage capacity of a lake or the extent of social networks that can be used to address natural resource dilemmas. Ideally some indicators will provide "early warning" of potential changes in the system and enable managers to anticipate that the ecosystem or social system of interest is approaching a state where abrupt, nonlinear responses to policy and management actions are more likely. Needless to say, such expanded monitoring and evaluation programs must be implemented with awareness of the relevant institutional and scientific constraints (see the case studies in part 4 and Kaufman et al., chap. 7 of this volume for further discussion of monitoring programs for marine EBM).

Concluding Thoughts

In looking to the future and how to integrate resilience and related ideas into the science and practice of EBM, three areas stand out. First, there is a need for a broader dialogue within and among the scientific, policy, and stakeholder communities about what EBM outcomes should be (see also Leslie and McLeod 2007; Moore and Russell, chap. 18 of this volume). Without clear goals, it is very difficult to track progress and to adapt policy and management efforts as needed. Second, for resilience science to be applied, scientists need to engage with other stakeholders in applying these concepts, for example, through participatory scientific investigations and synthesis and communication of existing knowledge. A participatory mode of doing science is not the standard one and will be aided by changes in expectations and norms within the scientific community itself (Leslie and McLeod 2007) as well as by the development of entities like boundary institutions, which can help bridge the gaps in knowledge, culture, and values between diverse communities of scientists, policymakers, and other stakeholders (Cash et al. 2003). Moreover, by engaging stakeholders in the practice and translation of science, scientists will become more familiar with marine policy and management processes and with the constraints and opportunities facing resource users, managers, and policymakers. Finally, in the course of moving from broad theory to place-based science and practice, it is vital to continue to develop the theoretical framework and tools that will enable the empirical data from diverse situations to be critically evaluated and synthesized. While examples of key characteristics of systems that contribute to resilience are available for some ecosystems (e.g., freshwater lakes, coral reefs, rangelands), their roles have not been evaluated comprehensively. Moreover, understanding of social resilience has lagged behind that of ecological resilience. Through interplay between empiricism and theory, scholarship and practice, we will be in a better position to contribute to sustaining the coasts, oceans, and other vital ecosystems on which human life depends and to contribute to effective marine ecosystem-based management efforts.

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