Article

Terence P. Hughes, Lance H. Gunderson, Carl Folke, Andrew H. Baird, David Bellwood, Fikret Berkes, Beatrice Crona, Ariella Helfgott, Heather Leslie, Jon Norberg, Magnus Nyström, Per Olsson, Henrik Österblom, Marten Scheffer, Heidi Schuttenberg, Robert S. Steneck, Maria Tengö, Max Troell, Brian Walker, James Wilson and Boris Worm

Adaptive Management of the Great Barrier Reef and the Grand Canyon World Heritage Areas

Conventional perceptions of the interactions between people and their environment are rapidly transforming. Old paradigms that view humans as separate from nature, natural resources as inexhaustible or endlessly substitutable, and the world as stable, predictable, and in balance are no longer tenable. New conceptual frameworks are rapidly emerging based on an adaptive approach that focuses on learning and flexible management in a dynamic social-ecological landscape. Using two iconic World Heritage Areas as case studies (the Great Barrier Reef and the Grand Canyon) we outline how an improved integration of the scientific and social aspects of natural resource management can guide the evolution of multiscale systems of governance that confront and cope with uncertainty, risk, and change in an increasingly human-dominated world.

INTRODUCTION

Ecosystems provide crucial natural capital assets that sustain human societies. However, the global-scale degradation of terrestrial and marine environments has highlighted the urgent need to change the way people exploit and manage natural resources. Land degradation, declining water quality, overharvesting, climate change, and other human-induced drivers have resulted in major alterations to the species composition and trophic structure of ecosystems, leading to a severe decline of many ecosystem services (1). Moreover, based on current trajectories and model-based projections, virtually all of these drivers of ecosystem modification are set to get stronger. For example, the proportion of the world's population living within 100 km of the coast is predicted to double to 50% by 2030, leading to markedly increased pressure on maritime resources during the next 25 years (2). Similar trends are evident for the projected consumption of energy and freshwater resources, and even the most conservative climate change predictions imply major environmental disruptions in coming decades (3). Under these scenarios, it is clear that new paradigms, policies. and governance systems will be essential for sustaining the capacity of the world's ecosystems and for securing future economic and societal development (4–8).

All of earth's major ecosystems are increasingly impacted by social and economic drivers (9, 10). Conversely, natural and human-induced environmental shifts such as salination of soils, the collapse of fisheries, and global warming have profound effects on human societies. These linkages—between the needs and activities of people and the condition and dynamics of their environment—highlight the necessity of an interdisciplinary focus for effective management of natural resources. To date, however, the artificial separation between ecology, social sciences, and economics continues to be a major impediment to understanding how a sustainable flow of ecological goods and services can be achieved (5, 11).

In this review, we explore how a better understanding of the linkages and feedbacks between social and ecological systems can guide the emergence of improved systems of natural resource management. We argue that successful management of complex ecosystems requires governance structures and institutions that are flexible, with the capacity to respond and adapt to change (4). By definition, adaptive management cannot be static, but rather must learn how to adjust appropriately to a continually shifting world. In some circumstances, ecological shifts provide the incentives and opportunity to improve the governance system that makes adaptive ecosystem management possible (12, 13). We focus here on the concept of resilience, that is, the ability of linked social-ecological systems to persist, buffer, and adapt to recurrent shocks without fundamentally changing, often unpredictably, into highly altered systems (14). We argue that *i)* managing uncertainty, coping with environmental and climate change, and sustaining ecosystems will require a much greater focus on the integration of ecosystem ecology with the human dimension across multiple ecological and social scales (12, 15), and *ii)* a renewed role for science will emerge from an adaptive governance framework that enables and supports collaborations among scientists, other stakeholders, communities, and government agencies. We discuss how scientific and technological uncertainties can be informed and resolved through trials, appropriately-scaled experiments, and learning from elsewhere. Extending that testing and learning into social, political, and economic domains is key to improved stewardship of natural resources.

DIVERSITY AND REGIME SHIFTS IN SOCIAL-ECOLOGICAL SYSTEMS

In the ecological realm, sudden and unexpected changes are ubiquitous, including population crashes or explosions, invasion of exotic species, and other biological and physical disturbances. In the socioeconomic domain, changes in price, market demands, and operating costs can also result in abrupt shifts between financial profit or loss, wealth or bankruptcy. Increasingly, economic outcomes are influenced by global as well as local markets. Societal and cultural changes include the swamping of indigenous peoples by colonialism and mass migration, shifts from hunter-gatherer and agricultural cultures to industrial and urbanized societies, and the transition to a global marketplace (5). These complex dynamics in ecological, social, and economic domains often defy expectation, other than the logical anticipation that surprises are inevitable.

Many ecological and social systems (or linked social-ecological systems) exhibit multiple "alternate" regimes, each with their own set of dynamics and feedbacks (16, 17). A resilient system by definition continues to absorb disturbances without undergoing a regime shift. In many social-ecological systems, regime shifts are often associated with the loss or gain of ecological, social, and cultural diversity. For example, overharvesting of tropical herbivorous fishes can make coral reefs reliant on grazing by just a few species of sea urchins that control the biomass of fast-growing fleshy seaweeds (18). Overfished reefs may harbor large populations of sea urchins, which can erode calcareous substrates, thereby inhibiting the replenishment of juvenile corals and locking the system into a new configuration (19). Similarly, in social cooperative systems, sudden shifts can be promoted by an increased conformity of opinions among individuals, analogous to the increased instability caused by the loss of biological diversity (16, 17, 20). Likewise, centralization of natural resource agencies can also lead to the erosion of social-ecological resilience as compared to more diverse and multiscale systems of governance (21).

SCALE, THRESHOLDS, AND FEEDBACKS

Processes that contribute to unexpected regime shifts operate at different scales, creating complex interactions and feedbacks that are a key component of the dynamics of linked social-ecological systems. These cross-scale links can occur from small to very large scales, and *vice versa*. For example, large-scale migration and transport of propagules such as larvae or seeds are crucial processes for understanding local trends in the composition of biological assemblages (22, 23). Conversely, when local patches of habitat undergo regime shifts, the species composition of the propagules they export changes, modifying the larger-scale patterns of connectivity among patches. Cross-scale interactions can also create abrupt threshold dynamics in intricate ways (24). For instance, if enough local patches of habitat collapse, a system-wide threshold may be exceeded that causes a larger-scale regime shift. In the sea, overfishing of breeding aggregations at small scales may cause widespread stock collapse. Similarly, on land fragmentation of forest habitat from land-clearing can cause regional-scale extinctions if too few remnants remain. For example, in eastern Amazonia, where incremental loss of forest fragments continues today, feedbacks between forest cover and regional climate characteristics may eventually lead to a long-term, system-wide shift from tropical forests to savanna (25).

Thresholds are dynamic and difficult to anticipate or monitor, because they change in response to both local and larger-scale processes. In general, ecosystem changes and regime shifts appear more gradually (but are more catastrophic) at larger scales. Maintaining the social capacity to adapt when change is slow and incremental is relatively straightforward. When changes are rapid, recent history and local information are likely to be less informative for guiding innovation than lessons learned elsewhere. The defining challenge for adaptive management is building the capacity to anticipate environmental, social, and economic change and to steer among alternative pathways.

ALTERNATE REGIMES, TRAPS, AND ECOSYSTEM RESTORATION

The growing recognition of regime shifts and threshold (rather than linear) behavior raises challenging issues of desirability of alternate outcomes and the feasibility of restoration after environmental degradation. Alternate ecological regimes can sometimes be viewed consensually as desirable or undesirable, or conflict may arise among diverse stakeholders (e.g., recreational and commercial fishers or hunters, conservationists, tourists, old and new residents, indigenous groups, etc.) as to which regime configuration is preferable. Questions of desirability are contested in many institutional settings, and across scientific, social, economic, and political domains.

Undesirable states may be extremely resilient, becoming traps that constrain future options (26). For example, governments typically respond to declining catch rates in marine fisheries by subsidizing an increased fishing effort, creating a feedback that worsens rather than solves the problem (27). Ironically, widespread attempts to maintain a reliable supply of fish to the marketplace (e.g., by serial depletion and substitution of stocks) has increased instability, because longer-lived species are typically replaced by short-lived recruitment-driven species further down the food chain (28). Furthermore, the continued widespread use of simple production models for maximizing yields of a few targeted species ignores the incidental removal of bycatch, the broader indirect impacts of overfishing on the trophic structure of ecosystems, and the physical destruction of benthic habitats by fishing gear. Aquaculture of finfish and prawns, viewed erroneously by many governments as a technological solution to overfishing, further deepens the trap because the huge global demand for fishmeal places additional pressure on wildfish stocks (29).

Many powerful players favor restoration efforts, in part because it gives them license to destroy ecosystems in the first place—if they can be subsequently recovered. In reality, reversing environmental degradation at meaningful scales may no longer be possible in many cases, and the path back is likely to be very different and slower than the one forward, a phenomenon known as hysteresis (6, 30). For example, ecological extinction of long-lived megafauna cannot be reversed (e.g., by removing hunting pressure or restoring habitat) either quickly or throughout their former geographic range. Although this conclusion may seem obvious, there is nonetheless a persistent but naive expectation that a pristine wilderness will once more emerge whenever local human pressures are ameliorated. Some environmental changes such as salination and desertification are virtually impossible to reverse. Furthermore, most attempts at restoration are too small to be self-sustaining or to account for larger-scale processes. Even large-scale ecosystem restoration (such as the USD 8 billion restoration plan for the Everglades (31) may or may not be biologically achievable or cost-effective, depending on the complexity of the system. No one has ever successfully rebuilt a coral reef coastline, and intuitively such a task is inherently more difficult and costly than restoration of a few hectares of grassland or rebuilding the relatively simple trophic structure of a lake. Despite the rhetoric, ecologists have not yet achieved the laudable goal of restoring complex ecosystems at consequential scales, and pretending they have is both dangerous and misleading. Nonetheless, some management agencies are beginning to apply frameworks for understanding and managing complex resource systems that go beyond belated small-scale interventions.

Next, we compare two iconic ecosystems, with strong linkages to social, economic, and political domains, to illustrate how insights into social-ecological resilience are being applied to management. One example is the Great Barrier Reef in Australia (Fig. 1a), the other is the Grand Canyon of the Colorado River in North America (Fig. 1b). We focus on the science-management interface, a key component of these two regional-scale resource systems.

CASE STUDY 1: THE GREAT BARRIER REEF

The Great Barrier Reef (GBR) is the largest coral reef system in the world, extending for 2000 km along the eastern seaboard of Queensland, Australia. It encompasses approximately 2900 individual reefs that are separated on average by a few tens of

Figure 1. The Great Barrier Reef and Colorado River are both regional-scale natural resources with strong links to social systems. (a) Eight adjoining offshore reefs on the northern Great Barrier Reef. Photograph courtesy of the Great Barrier Reef Marine Park Authority. (b) The confluence of the Colorado and Little Colorado Rivers, Grant Canyon National Park, US. Photo: M. Lellouch.

kilometers or less (Fig. 1a). The GBR is of enormous economic, social, cultural, and aesthetic value, a national and international icon that contributes USD 4 billion to the Queensland economy each year, primarily through tourism (32). This income is set to grow strongly, particularly if reefs elsewhere continue to decline. The GBR provides a valuable exemplar of a system undergoing rapid changes to its ecology, which has triggered a transformation of management approaches. Changes have also been made to support a more flexible and collaborative system of governance for the GBR, including new interactions among scientists, environmental managers, tourism and fishing industries, and the broader community.

The GBR system is showing symptoms of ecological change and increased vulnerability that warrant concern (33). Earlier export fisheries that flourished after European colonization (e.g., for sea cucumbers, pearl shell, Trochus snails, dugongs, and turtles) have collapsed or are no longer commercially viable. In the past 40 years, large-scale outbreaks of crown-of-thorns starfish have occurred three times, reducing coral cover (Fig. 2). Public concern about the impact of starfish and proposals for drilling and mining on the GBR led in 1976 to the establishment of a federally-funded body, the Great Barrier Reef Marine Park Authority (GBRMPA). Fishing regulations and land-based activities are primarily the responsibility of the State of Queensland, which initially challenged the federal government's jurisdiction in Australia's High Court, but lost. Today, state and federal agencies work closely together along with a system of locally-based citizen advisory groups. The state government retains jurisdiction for fishing regulations and for all land-based activities such as farming and coastal development. The principle management approach of GBRMPA for the past 30 years has been based on a permitting and zoning system that ranges from total exclusion of people (e.g., on a handful of islands that are important rookeries for birds or turtles) to large areas that are open to highly-regulated commercial fishing. A user-charge system offsets the expense of reef management and contributes to the cost of applied environmental and social research.

Figure 2. Outbreaks of crown-of-thorns starfish, *Acanthaster planci*, have damaged many reefs throughout the Indo-Pacific Oceans in the past 40 years. The white coral skeleton is exposed when the starfish consumes the overlying soft tissues. Photo: M. Nyström.

The major current threats to the GBR are enhanced runoff of sediment and nutrients from agriculture and urban development, depletion of megafauna (especially dugongs, sharks, and turtles), declining fish stocks, and coral bleaching and mortality caused by global warming (34). Major bleaching events from climate change struck the GBR in 1998, 2002 and to a lesser extent in 2006, causing damage to more than 600 individual reefs. Rapid growth in recreational and commercial fishing has reduced the biomass of targeted fish species, especially inshore, where fish biomass in no-take reserves is up to six times higher than adjacent heavily-fished areas (35). In 1997, a series of ongoing seascape-scale experiments was initiated to examine the efficacy of fishing reserves or no-take areas using 24 replicated reefs that were open, closed, or reopened to fishing. The scope of this innovative experiment was such that it required extensive public, state, and federal consultation (and an act of parliament) before and during its implementation—an interesting example of a multiscale adaptive governance system that was willing to experiment. At the same time, new research has highlighted the functional role of fishes, the top-down effects of harvesting on foodweb structure and dynamics, and the bottom-up influence of added nutrients.

In 2003 and 2004, several major initiatives were undertaken that built on this accumulation of new scientific knowledge. From 1 July 2004, the proportion of the GBR marine park that is closed to fishing (i.e., no-take fishing reserves) was increased by commonwealth legislation from 5% to 33%, encompassing for the first time at least 20% of each of 70 major habitat types (36). Simultaneously, a new 10-year multi-institutional and community-level program, the Reef Water Quality Protection Plan, was formulated to curb nutrient and sediment runoff. When the marine park was rezoned, the State of Queensland sharply reduced recreational bag limits for targeted fishes outside no-take areas and extended the new federal zones into inshore state waters. The result of this unprecedented multiscale federal-state cooperation is a dramatically enhanced management system. The public involvement was intense, including more than 1000 meetings and briefings and 31 000 written submissions to GBRMPA that were incorporated into a radically new zoning scheme.

These bold management changes comprise a rare example of an ecosystem-based approach that arose from a shift in perceptions among key individuals within various stakeholder groups about the growing vulnerability of the "pristine" GBR. The change in zoning was undertaken to cope proactively with the risk associated with future bleaching events and other uncertainties, recognizing that disturbance and change are an integral component of the GBR social-ecological system. The Precautionary Principle, adopted by the United Nations Conference on the Environment and Development (in Rio de Janeiro, 1992) recommends regulatory action without scientific certainty where the costs of future environmental and socioeconomic damage are likely to be great or irreversible. The costs of reducing fishing effort and improving water quality are small when compared to the much greater risks arising from longer-term loss of resilience and environmental degradation. Hence, ecosystem-based management and the Precautionary Principle are both incorporated in the evolving system of governance of the GBR.

CASE STUDY 2: GRAND CANYON AND THE COLORADO RIVER

Whereas the GBR management system is attempting to build resilience and avoid an undesirable phase-shift to a degraded system, the corridor of the Grand Canyon has been steered by human action to an alternative configuration that many stakeholders now wish to reverse. The Grand Canyon is one of the largest geomorphic features on the planet, created over the past 6–10 million years by the Colorado River (Fig. 1b). The canyon is almost 500 km in length, beginning upstream at the outfall from the Glen Canyon dam and ending at Lake Meade, the reservoir for the Hoover Dam. Most of the spectacular vistas are contained within the Grand Canyon National Park, which receives some 5 million visitors a year. The river flows through the Glen Canyon National Recreational Area and Native American tribal lands. Although the geological features capture the world's attention, it is the river itself that dominates the attention of managers.

The completion of the Glen Canyon dam in 1962 altered the hydrological regime of the middle Colorado River (Fig. 3). This and other dams were constructed to control annual variability in water flow and to generate electricity. The dams provide water storage (reservoirs), a management action that buffers variable input into the river while tightly regulating outflow for use among the neighboring states and Mexico. The river was historically characterized by extreme floods, large sediment loads that colored the water red (hence the origin of the name, Colorado River), and seasonally large fluctuations in temperature. Today, for hundreds of kilometers downstream of the Glen Canyon Dam the altered system has relatively stable flow, clearer water, and a near-constant temperature year-round. These physical changes in turn have led to unforeseen ecosystem shifts, such as the loss of seven species of native fish, the endangerment of four others, and a reduction of habitat diversity (37).

Contemporary ecosystem management in the canyon has focused on attempting to return the system to more desirable ecological regimes. Key objectives include better protection for a suite of native fish that are currently vulnerable to extinction, restoration of sediment input, and return of a seasonal temperature regime. These objectives have been pursued through an ambitious management program (38) that has conducted two experimental releases of large volumes of water from the Glen Canyon dam, one in 1996 the other in 2004. In conducting these experimental releases, scientists developed a better understanding of sediment dynamics and of how water temperature and introduced pests (salmonid predators) influence the recruitment dynamics of an endangered native fish, the humpback chub.

Figure 3. The Glen Canyon dam has altered water flow, sediment, and temperature regimes of the middle Colorado River for more than 40 years. Experimental releases of water have sought to reverse some of these environmental changes. For scale, the white grid lines at the top of the photograph are parking spaces. Photo: D. L. Blank.

Institutionally, a new body was developed in 1997, the Grand Canyon Adaptive Management Work Group, which uses planned management actions and subsequent monitoring data to test hypotheses and to build understanding of ecosystem dynamics. Community leaders in the Grand Canyon understand the uncertainties and complexities of the system and believe that resolution of environmental issues can only be discovered, not determined by predetermined policy. As such, they have provided vital opportunities and windows for experimentation and learning (39). This approach has generated a great deal of trust among stakeholders and provides a more open and flexible institutional setting for dealing with multiple objectives in the management of complex and large social-ecological systems.

LEARNING BY EXPERIMENTAL TRIALS: ADAPTIVE MANAGEMENT

A number of striking parallels exist between the GBR and the Grand Canyon systems, despite their vast physical and biological differences. Both social-ecological systems have increasingly adopted the use of large-scale trials to resolve key resource uncertainties. Failures to adopt adaptive management elsewhere are often related to a belief that further modeling and monitoring alone will resolve uncertainties or that experimentation would be too costly and risky (40). Other impediments may include opposition from special interest groups or an inability to resolve value conflicts among scientists and other stakeholders. In Australia, for example, some conservation groups opposed the experimental reopening of closed reefs (which ironically provided evidence for the efficacy of no-take areas). The subsequent rezoning and new fisheries policies on the GBR and the water releases and predator control actions in the Grand Canyon are each examples of active adaptive management that were informed by very large-scale experiments (41).

While a complex history preceded the use of adaptive management in both systems, the emergence of the current approaches can be traced to ecological crises that promoted a rapid transformation. We define ecological crisis in this context as the occurrence of unforeseen events that reveal a failure of policy (13). The ecological crises on the GBR include recurrent outbreaks of crown-of-thorns starfish, the slow ongoing decline of megafauna, degradation of inshore reefs due to runoff, and the growing threat of coral bleaching events, all leading to a sense of impending loss of social, cultural, and aesthetic values. Similarly, in the Grand Canyon, the extirpation and continued endangerment of aquatic species also required radical policy changes. In both cases, new federal (i.e., national) and state legislation was vital to enable large-scale adaptive management. The Australian and US legislation enabled an adaptive, learning-based approach that allowed resource managers to undertake initial sets of experiments through collaborative and participatory processes involving a wide range of stakeholders and agencies. The focus on adaptive responses and stakeholder integration is a different social dynamic from one where scientists and policymakers typically inform and educate each other while paying only token attention to stakeholder engagement. Broadening the social arenas for ecosystem management builds trust and cooperation, promoting adaptive governance systems that can better adjust to ecosystem change and surprise (12, 15).

The critical and evolving role of scientists and the implementation of scientific approaches in policymaking are also further hallmarks of the two case studies. Both the GBR and the Grand Canyon have multidecadal programs of applied and basic research, with much of the former being directed by government agencies. As a result, valuable information is available for the two World Heritage Areas on the structure and dynamics of ecosystems and on the status and trends of natural resources. When placed in a framework of adaptive management, monitoring key resource indicators can add to learning and adaptive governance. However, monitoring should not just supply information on whether current policy is working or failing (e.g., is biodiversity declining?). Instead, it must focus more on resolving key uncertainties (e.g., how do we reverse the decline?). To date, the former question has dominated research efforts, and much less is known about the latter. Future monitoring programs urgently need to gain a clearer understanding of thresholds, regime shifts and feedbacks, and the capacity of ecosystems to sustain ecological services, such as fisheries or tourism, in response to globally- and locally-induced disturbances. Monitoring that merely describes the current state or past trajectory of ecosystems has a much more limited value.

In both case studies, scientists, other stakeholders, and policymakers have engaged in novel ways. For example, the revised spatial zoning by GBRMPA was informed by integrated research on seafloor mapping, larval connectivity, and social and economic data, as well by as by unprecedented consultation and negotiation with indigenous, recreational, commercial, and scientific users. Similarly, the Grand Canyon Adaptive Management Work Group liaises closely with the Glen Canyon Research and Monitoring Center to direct and modify programs of research, assessment, and monitoring. Importantly, in both the GBR and the Grand Canyon, science and information are shared, assessed, and integrated into management by groups other than scientists. This changing role of science and scientists is coupled with the adoption and development of adaptive, experimental management in both cases.

Both systems appear to be well positioned to build further on nascent forms of adaptive governance. Adaptive governance of complex social-ecological systems requires four key components: *i)* a sound understanding of ecosystem dynamics, *ii)* a flexible approach to management that considers policies as testable hypotheses and management actions as experimental treatments that permit learning, *iii)* the ability to build adaptable institutions supported by multilevel social networks, and *iv)* a willingness to confront uncertainty by developing the capacity to deal with change (such as shifts in climate, global markets, and international policies) (12). Although these approaches may seem expensive and even cumbersome compared to conventional top-down management approaches, we argue that they are robust strategies for dealing with the much larger economic and social costs of environmental degradation in the long term.

CONCLUSION

Managed resource systems, by definition, have ecological, social, political, and economic dimensions that are strongly interlinked. Consequently, simplistic approaches based solely on conventional natural sciences that ignore social and economic linkages and the likelihood of unforeseen dynamics are doomed to failure. Improving ecosystem management will require large-scale trials that enable learning and adaptive governance structures that are inclusive and well-supported by society. We suggest that new roles for science and scientists are emerging to help make sense of an increasingly complex and human-dominated world. Scientists will provide crucial input in posing questions and models for testing and in developing appropriately-scaled experiments that can test and improve our understanding and provide alternative views for the future. One clear signal from both of the examples we consider is that uncertainties about resource dynamics and the effects of policies cannot be resolved solely among like-minded peers in the scientific literature, but must be explored openly through adaptive management practices that promote pragmatic learning for improved stewardship of the world's nature resource assets.

References and Notes

1. Millenium Ecosystem Assessment. 2005. *Ecosystems and Human Well-Being: Current State and Trends*. Island Press, Washington DC.
2. Adger, W.N., Hughes, T.P., Folke, C., Carpenter, S.R. and Rockstrom, J. 2005. Social-ecological resilience to coastal disasters. *Science 309*, 1036–1039.
3. Watson, R.T. and the Core Writing Team. 2001. 3rd Assessment Report of the Intergovernmental Panel on Climate Change. Climate Change 2001: Synthesis Report. (http://www.ipcc.ch/pub/syreng.htm)
4. Berkes, F., Folke, C. and Colding, J. 2003. *Navigating Social-Ecological Systems: Building Resilience for Complexity and Change*. Cambridge University Press, Cambridge.
5. Berkes, F., Hughes, T.P., Steneck, R.S., Wilson, J.A., Bellwood, D.R., Crona, B., Folke, C., Gunderson, L.H., et al. 2006. Globalization, roving bandits, and marine resources. *Science 311*, 1557–1558.
6. Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L. and Holling, C.S. 2004. Regime shifts, resilience, and biodiversity in ecosystem management. *Ann. Rev. Ecol. Syst. 35*, 557–581.
7. Hughes, T.P., Bellwood, D.R., Folke, C., Steneck, R.S. and Wilson, J. 2005. New paradigms for supporting the resilience of marine ecosystems. *Trends Ecol. Evol. 20*, 380–386.
8. Folke, C., Carpenter, S., Elmqvist, T., Gunderson, L., Holling, C.S. and Walker, B. 2002. Resilience and sustainable development: building adaptive capacity in a world of transformations. *Ambio 31*, 437–440.
9. Lambin, E.F., Turner, B.L., Geist, H.J., Agbola, S.B., Angelsen, A., Bruce, J.W., Coomes, O.T., Dirzo, R., et al. 2001. The causes of land-use and land-cover change: moving beyond the myths. *Global Environ. Change 11*, 261–269.
10. Vitousek, P.M., Mooney, H.A., Lubchenco, J. and Melillo, J.M. 1997. Human domination of earth's ecosystems. *Science 277*, 494–499.
11. McMichael, A.J., Butler, C.D. and Folke, C. 2003. New visions for addressing sustainability. *Science 302*, 1919–1920.
12. Folke, C., Hahn, T., Olsson, P. and Norberg, J. 2005. Adaptive governance of social-ecological systems. *Ann. Rev. Environ. Res. 30*, 441–473.
13. Gunderson, L.H. and Holling, C.S. 1995. *Barriers and Bridges to the Renewal of Ecosystems and Institutions*. Columbia University Press, New York.
14. Walker, B., Holling, C.S., Carpenter, S.R. and Kinzig, A. 2004. Resilience, adaptability and transformability in social–ecological systems. *Ecology and Society 9*. (http://www.ecologyandsociety.org/vol9/iss2/art5/)
15. Dietz, T., Ostrom, E. and Stern, P.C. 2003. The struggle to govern the commons. *Science 302*, 1907–1912.
16. Scheffer, M. and Carpenter, S.R. 2003. Catastrophic regime shifts in ecosystems: linking theory to observation. *Trends Ecol. Evol. 18*, 648–656.
17. Scheffer, M., Westley, F. and Brock, W. 2003. Slow response of societies to new problems: causes and costs. *Ecosystems 6*, 493–502.
18. Hughes, T.P. 1994. Catastrophes, phase-shifts, and large-scale degradation of a Caribbean coral-reef. *Science 265*, 1547–1551.
19. Bellwood, D.R., Hughes, T.P., Folke, C. and Nystrom, M. 2004. Confronting the coral reef crisis. *Nature 429*, 827–833.
20. Levy, M. 2005. Social phase transitions. *J. Econ. Behav. Org. 57*, 71–87.

21. Gunderson, L.H. and Holling, C.S. 2002. *Panarchy: Understanding Transformations in Human and Natural Systems*. Island Press, Washington DC.
22. Nystrom, M. and Folke, C. 2001. Spatial resilience of coral reefs. *Ecosystems 4*, 406–417.
23. Nystrom, M., Folke, C. and Moberg, F. 2000. Coral reef disturbance and resilience in a human-dominated environment. *Trends Ecol. Evol. 15*, 413–417.
24. Klausmeier, C.A. 2001. Habitat destruction and extinction in competitive and mutualistic metacommunities. *Ecol. Lett. 4*, 57–63.
25. Oyama, M.D. and Nobre, C.A. 2003. A new climate-vegetation equilibrium state for Tropical South America. *Geophys. Res. Lett. 30*, 2199.
26. Allison, H.E. and Hobbs, R.J. 2004. Resilience, adaptive capacity, and the "Lock-in Trap" of the Western Australian agricultural region. *Ecology and Society 9*. (http://www.ecologyandsociety.org/vol9/iss1/art3/)
27. Ludwig, D., Hilborn, R. and Waters, C. 1993. Uncertainty, resource exploitation, and conservation: lessons from history. *Science 260*, 17–36.
28. Pauly, D., Christiansen, V., Guenette, S., Pitcher, T.J., Sumaila, R., Walters, C.J., Watson, R. and Zeller, D. 2002. Towards sustainability in world fisheries. *Nature 418*, 689–695.
29. Naylor, R.L., Goldburg, R.J., Primavera, J.H., Kautsky, N., Beveridge, M.C.M., Clay, J., Folke, C., Lubchenco, J., et al. 2000. Effect of aquaculture on world fish supplies. *Nature 405*, 1017–1024.
30. Scheffer, M., Carpenter, S., Foley, J.A., Folke, C. and Walker, B. 2001. Catastrophic shifts in ecosystems. *Nature 413*, 591–596.
31. Comprehensive Everglades Restoration Plan. 2000. (http://www.evergladesplan.org/)
32. Access Economics, 2006. Measuring the economic and financial value of the Great Barrier Reef Marine Park. (28 June 2006). (http://www.accesseconomics.com.au/reports/gbrmp.pdf)
33. Great Barrier Reef Marine Park Authority. 2 July 2006. Overview: the current status of the Great Barrier Reef. (http://www.gbrmpa/corp_site/info_services/publications/sotr/overview/)
34. Hughes, T.P., Baird, A.H., Bellwood, D.R., Card, M., Connolly, S.R., Folke, C., Grosberg, R., Hoegh-Guldberg, O., et al. 2003. Climate change, human impacts, and the resilience of coral reefs. *Science 301*, 929–933.
35. Williamson, D.H., Russ, G.R. and Ayling, A.M. 2004. No-take marine reserves increase abundance and biomass of reef fish on inshore fringing reefs of the Great Barrier Reef. *Environmental Conservation 31*, 149–159.
36. Great Barrier Reef Marine Park Authority. 2004. Representative areas program. (http://www.reefed.edu.au/rap/)
37. Gloss, S.P., Lovich, J.E. and Melis, T.S. (eds). 2005. *The State of the Colorado River Ecosystem in The Grand Canyon*. US Geological Survey Circular 1282, Reston, VA, 220 pp.
38. Walters, C., Korman, J., Stevens, L.E. and Gold, B. 2000. Ecosystem modeling for evaluation of adaptive management policies in the Grand Canyon. *Conserv. Ecol. 4*. (http://www.consecol.org/vol4/iss2/art1/)
39. Gunderson, L. 2003. Adaptive dancing: interactions between social resilience and ecological crises. Pages 33–52 In: *Navigating Social-Ecological Systems: Building Resilience for Complexity and Change*. Berkes, F., Folke, C. and Colding, J. (eds). Cambridge University Press, Cambridge.
40. Walters, C. 1997. Challenges in adaptive management of riparian and coastal ecosystems. *Conserv. Ecol. 1*. (http://www.consecol.org/vol1/iss2/art1/)
41. Walters, C.J. and Holling, C.S. 1990. Large-scale management experiments and learning by doing. *Ecology 71*, 2060–2068.
42. The Australian Research Council Centre of Excellence for Coral Reef Studies and the Beijer Institute of the Royal Swedish Academy of Sciences facilitated meetings of the authors in Townsville, Stockholm, and Cairns. This work was supported by the Australian Research Council, the Swedish International Development Cooperation Agency, and the Swedish Research Council for the Environment, Agricultural Sciences, and Spatial Planning.
43. First submitted 19 September 2006. Accepted for publication 19 March 2007.

Terry Hughes is Director of the Australian Research Council (ARC) Centre of Excellence for Coral Reef Studies and Professor of Marine Ecology at James Cook University. His address: ARC Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, QLD 4811, Australia.
E-mail: Terry.Hughes@jcu.edu.au

Lance Gunderson is Vice Chair of the Board of Members of the Resilience Alliance, member of the Science Advisory Board of the Grand Canyon Monitoring and Research Center, and Professor and Chair of the Department of Environmental Studies at Emory University. His address: Department of Environmental Studies, Emory University, Atlanta, GA 30322, USA
E-mail: lgunder@emory.edu

Carl Folke is Professor and Director of the Beijer International Institute for Ecological Economics at the Royal Swedish Academy of Sciences and Director of the Stockholm Resilience Centre. His address: Stockholm Resilience Centre, Stockholm University, SE 106 91, Stockholm, Sweden.
E-mail: carl.folke@beijer.kva.se

Andrew Baird is a Senior Research Fellow in the Australian Research Council (ARC) Centre of Excellence for Coral Reef Studies, with an interest in social-ecological impacts of marine disasters. His address: Australian Research Council (ARC) Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, QLD 4811, Australia.
E-mail: andrew.baird@jcu.edu.au

David Bellwood is a Program Leader in the ARC Centre of Excellence for Coral Reef Studies and professor of marine biology at James Cook University. His address: ARC Centre of Excellence for Coral Reef Studies, and School of Marine and Tropical Biology, James Cook University, Townsville, QLD 4811, Australia.
E-mail: David.Bellwood@jcu.edu.au

Fikret Berkes is Professor and Canada Research Chair at the Natural Resources Institute of the University of Manitoba. His address: Natural Resources Institute, University of Manitoba. Winnipeg, Manitoba R3T 2N2, Canada.
E-mail: berkes@cc.umanitoba.ca

Beatrice Crona recently completed her PhD studies on social and ecological linkages in coastal communities in East Africa. Her address: Department of Systems Ecology and the Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden.
E-mail: beatrice@ecology.su.se

Ariella Helfgott is a doctoral student in applied mathematics at the University of Adelaide. Her address: School of Mathematical Sciences, The University of Adelaide, SA 5005, Australia.
E-mail: ariella.helfgott@adelaide.edu.au

Heather Leslie is an Associate Research Scholar at Princeton University studying the resilience and robustness of coupled social-ecological marine systems. Her address: Department of Ecology and Evolutionary Biology, Princeton University, NJ 08544, USA.
E-mail: hleslie@princeton.edu

Jon Norberg is an Assistant Professor at the Department of Systems Ecology, Stockholm, where he studies biocomplexity theory. His address: Department of Systems Ecology and the Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden.
E-mail: jon.norberg@ecology.su.se

Magnus Nyström is an Assistant Professor working on coral reef ecosystems. His address: Department of Systems Ecology, Stockholm University, Stockholm, Sweden.
E-mail: magnusn@ecology.su.se

Per Olsson is a researcher at the Stockholm Resilience Centre and the Swedish coordinator for the UNESCO program *Man and the Biosphere.* His address: Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden.
E-mail: per@ctm.su.se

Henrik Österblom recently completed his PhD in marine ecology at the Department of Systems Ecology, Stockholm, and is Special Advisor to the Environmental Advisory Council, Swedish Ministry of Sustainable Development. His address: Department of Systems Ecology, and the Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden.
E-mail: henriko@ecology.su.se

Marten Scheffer leads the Aquatic Ecology and Water Quality Management group at Wageningen University, where he studies the mechanisms that determine the stability and resilience of complex systems. His address: Department of Environmental Sciences, Wageningen University, 6700 DD, The Netherlands.
E-mail: Marten.Scheffer@wur.nl

Heidi Schuttenberg is a doctoral student in environmental studies at James Cook University. Her address: Department of Tropical Environmental Science and Geography, James Cook University, Townsville, QLD 4811, Australia.
E-mail: heidi.schuttenberg@jcu.edu.au

Bob Steneck is a Pew Fellow in Marine Conservation and Professor

of Oceanography, Marine Biology, and Marine Policy at the University of Maine. His address: School of Marine Sciences, University of Maine, Darling Marine Center, Walpole, Maine 04573, USA.
E-mail: Steneck@Maine.edu

Maria Tengö recently completed her PhD studies at the Department of Systems Ecology, Stockholm, on social-ecological systems in Madagascar. Her address: Department of Systems Ecology and the Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden.
E-mail: mtengo@ecology.su.se

Max Troell is a Research Associate at the Beijer International Institute for Ecological Economics at the Royal Swedish Academy of Sciences and at the Stockholm Resilience Centre. His address: The Beijer Institute, The Royal Swedish Academy of Sciences, PO Box 50005, SE-104 05 Stockholm, Sweden
E-mail: max@beijer.kva.se

Brian Walker is Program Director and Chair of the Board of Members of the Resilience Alliance and an Honorary Fellow at the Commonwealth Science Industry Research Organization in Australia. His address: CSIRO Sustainable Ecosystems, Box 284, Canberra ACT 2601, Australia.
E-mail: Brian.Walker@csiro.au

James Wilson is Professor of Marine Sciences and Resource Economics at the University of Maine. His address: School of Marine Sciences, University of Maine, Orono, Maine 04469, USA.
E-mail: jwilson@Maine.edu

Boris Worm is an Assistant Professor in Marine Conservation Biology at Dalhousie University. His address: Department of Biology, Dalhousie University, Halifax, Nova Scotia, Canada B3H 4J1.
E-mail: bworm@dal.ca