Coping with Collapse: Ecological and Social Dynamics in Ecosystem Management

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The role of ecological expertise in policymaking is evolving. In fields such as engineering or medicine, long-established professional standards guide the application of expertise in public decisionmaking. Professional ecologists, however, participate in decisionmaking in variable and changing ways. Some function as technicians, providing factual information used by decisionmakers; others as detectives, drawing attention to some previously unrecognized problem; and still others as advocates, adducing information designed to support a particular position.

In some of the most successful applications of ecology, governments have actively sought the expert opinions of ecologists. In addition, scientists themselves have sometimes been able to define a broad consensus on what is known and not known, and they have clearly stated their uncertainties. Examples of effective contributions include the Intergovernmental Panel on Climate Change (Houghton et al. 1990) and numerous reports by panels of the US National Research Council (see the Web site *www.nas.edu*).

In other cases, ecological expertise has been manipulated by agencies or interest groups to serve narrow political goals (Wagner 2001, Hutchings et al. 1997). Ted Strong, director of the Columbia River Intertribal Fish Commission, commented that "science has become a commodity rather than a standard. Too many groups can go out and buy science, and then use science to reaffirm a political decision" (Dietrich 1995). Some ecologists have compounded the discipline's problems through self-serving advocacy, arguing that "more research is needed"—an argument aimed at sustaining their own funding—while delaying effective action on environmental problems (Walters 1997). Other ecologists, however, are frustrated by these abuses of expertise and by dilution of ecology's impact on public policy.

Such frustrations prompted a reconsideration of ecologists' participation in decisionmaking processes, which led to the papers in this issue of *BioScience*. In this article, we begin by looking at the contexts in which ecological expertise is ignored or manipulated to serve narrow interests.

> LIKE FLIGHT SIMULATORS THAT TRAIN WOULD-BE AVIATORS, SIMPLE MODELS CAN BE USED TO EVOKE PEOPLE'S ADAPTIVE, FORWARD-THINKING BEHAVIOR, AIMED IN THIS INSTANCE AT SUSTAINABILITY OF HUMAN–NATURAL SYSTEMS

Distortions are often associated with gridlock among powerful stakeholders (Gunderson et al. 1995). The stakeholders reach a balance of relative power, which freezes environmental policy in ways that may harm ecological goods and services and even general social welfare. That gridlock may persist until a crisis precipitates a restructuring of power relationships, creating the opportunity for new management schemes (Gunderson et al. 1995, Gunderson 1999). Alternatively, it may be possible to discover novel solutions that cause stakeholder groups to find mutual benefit in cooperative action (Gunderson 1999). Such innovations create social flexibility through "win–win" options, thereby breaking gridlock and leading to appropriate management.

How can ecologists help create new solutions and promote social flexibility? This role that ecologists might play is

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quite different from the usual one assumed in expert review panels. It has similarities to ecologists' role as teachers, especially the teaching done with small groups of students in the field, which involves multiway communication and collective discovery. This article describes how ecologists can help build communication, understanding, and social flexibility to address environmental problems. We introduce simple models of ecosystem management as one useful tool for helping achieve these goals.

Models for building understanding

Ecologists have a venerable tradition of models for both teaching and understanding complex processes. The logistic and Lotka–Volterra models, for example, represent important ecological processes such as density dependence, competition, and predation. Such models may be too simplistic to make predictions about any specific ecological situation, but they do capture complex concepts in transparent ways, which makes them superb teaching tools. Physical sciences also use simplified heuristic models, such as the "toy" models of the atmospheric sciences (Lovelock 1988).

Early applications of adaptive environmental management employed models for both data-rich assessments and more general, cross-disciplinary understanding (Holling and Chambers 1973, Holling 1978, Walters 1986). Holling and Chambers (1973) noted that models forced participants to be absolutely explicit about assumptions and biases, thereby improving communication and exposing the logical consequences of various beliefs. Walters (1994) presented computer games used successfully to help stakeholders understand collective decision problems related to overfishing. Most early models focused on sophisticated representations of ecosystems, coupled to social and economic drivers (Holling 1978). More recently, models have included increasingly sophisticated representations of social processes (Sargent 1993, Axelrod 1997, Brock and Hommes 1997, Brock and Durlauf 1999). Psychologists have used models of coupled social and environmental systems as experimental tools to probe decisionmaking processes of people confronting nonlinearity and uncertainty (Dörner 1996). Integrated assessments of global climate change have coupled climate models with models of social preferences and collective decisionmaking (Janssen 1998).

We use a family of models to explore the interactions of social, economic, and ecological systems. Models have been developed around conflicts in management of water quality, fisheries, and rangelands (Carpenter et al. 1999, Janssen and Carpenter 1999, Janssen et al. 2000), and more examples are under development. Although the models differ substantially in detail, they have three common features: (1) an ecosystem with at least three components having different turnover rates; (2) a society of diverse agents, each making independent decisions while attempting to learn about a world the agents create together; and (3) a capacity for assessing the ecosystem and the economy, forecasting future performance, and transmitting this information to decisionmakers. Each of these components has its own rich literature. When combined to form integrated models of social–economic–ecological systems, they exhibit novel behaviors that would not be expected from the isolated models of sociology, economics, or ecology.

The models are set up as computer games. The objective of a game is to maintain, for an extensive period of time, a society interacting with an ecosystem. This objective is difficult to achieve because the system is inherently cyclic, and the goals can be met only by guiding the cycles within a desirable range of social and ecological conditions. Responses of the system to management action can be understood by experimentation. The necessary experiments require give-and-take among competing interest groups. Often the people operating the computer take the role of decisionmakers, viewing the technical information and choosing policy for the next iteration of the game. However, the game player could also take the role of ecologist, economist, farmer, fisher, and so forth. Some examples of our models can be downloaded from the Internet (Carpenter et al. 1999).

These models are tools to study the generic behavior of coupled social–economic–ecological systems. They are useful for teaching general concepts of sustainability, ecosystem resilience, social flexibility, and experimental ecosystem management. They are not intended to provide site-specific predictions of the dynamics of any particular system. We have found that our goals of multiway communication and collective discovery are best served by simple, flexible models that are quickly solved and easily modified "on the fly." In contrast, site-specific management predictions usually involve models that are more complicated and data intensive than those we describe. Such models are valuable for certain specific tasks, but they tend to be too unwieldy and rich in detail to explain general concepts effectively.

Example: Adaptive versus fixed policy

Management of lake fisheries is closely linked to management of shoreline activities that affect fish habitat. Development of homes and businesses along shorelines leads to loss of shoreline vegetation, thereby increasing erosion of nutrients into lakes and reducing inputs of fallen trees (Novotny and Olem 1994, Christensen et al. 1996). Tree boles and branches in nearshore waters of lakes are crucial habitat for fishes (Christensen et al. 1996, Schindler et al. 2000). It could take decades or centuries to replace lost woody habitat for fishes. Thus woody habitat is a slowly changing variable that affects the dynamics of fish populations. To help illustrate the interactions between shoreline habitat management and management of a lake fishery, we developed the model shown in Figure 1.

The model depicts a fish stock of a lake subject to exploitation by resident anglers and tourist anglers (Figure 1). A manager sets a bag limit each year, with the goal of sustaining both the fish stock and the people in the system. The bag limit is the maximum number of fish an angler may harvest per day of fishing. In the diagram shown here, the game player (i.e.,

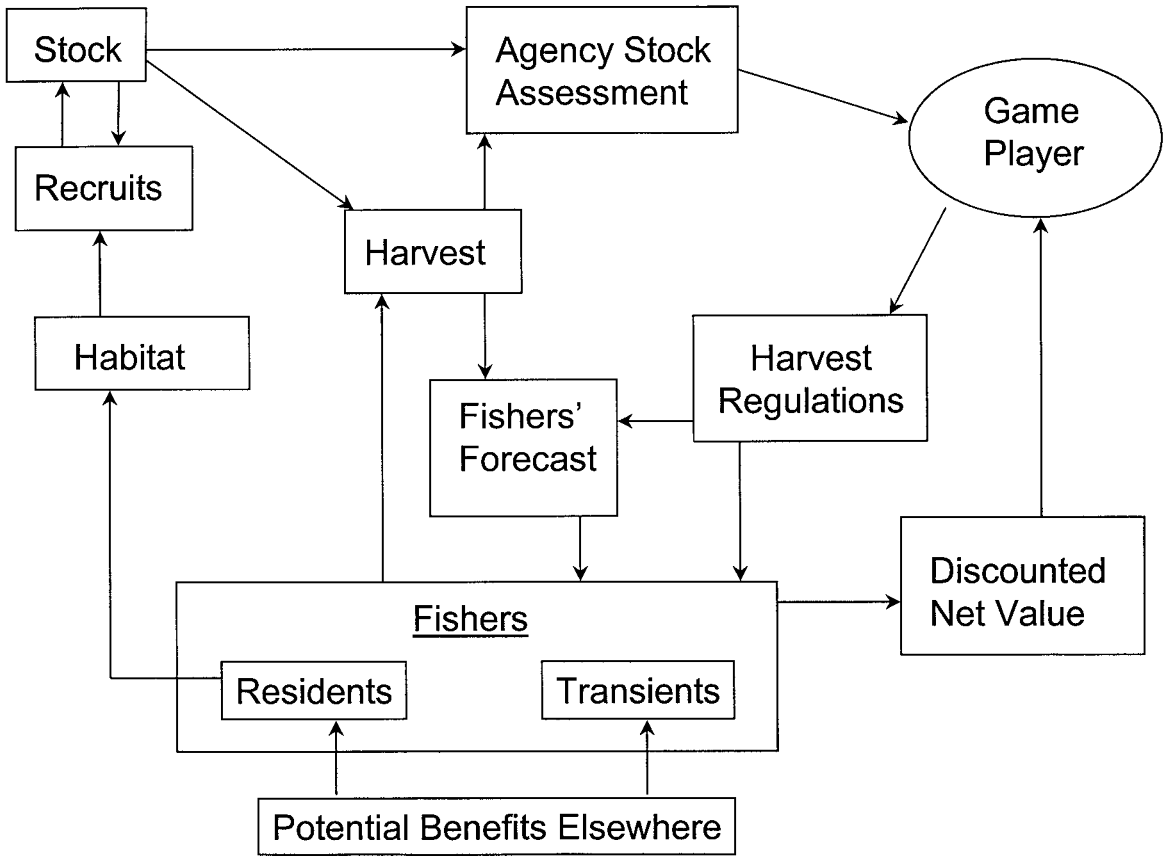

Figure 1. Flowchart of the fisheries model.

the operator of the computer) is the manager. However, in other versions of the program, the game player may be a resident, a tourist, or a scientist. At each time interval, the manager receives information from a fisheries stock assessment as well as social information (population, housing market, fishing activity) on the human agents (residents, tourists). The manager uses this information to set a new bag limit.

The fishers belong to two groups that differ in their ability to change fishing locations over time. Tourists choose where to fish on a day-by-day basis, based on their personal predictions of fishing opportunities at the focal and nearby lakes. They derive these personal predictions from recent experiences. The residents choose whether to purchase or sell property on the focal lake, based on their predictions for future fish catches and on opportunities at nearby lakes. Residents evaluate the catch rate and make forecasts over a longer time horizon than do tourists, and the residential market involves a time lag in purchasing or selling property. The number of residents affects the input of downed trees into the lake, with a long time lag due to the slow growth of the trees (Christensen et al. 1996). Residents do not like to have too many trees on the shoreline or in the lake near shore, because these interfere with boating and fishing activity. However, fallen trees in the lake are directly related to the production of fishes. The fish population dynamics in the model depend on habitat (fallen trees), harvest, and stochastic annual variations in recruitment.

If the manager adopts a fixed policy, the system oscillates widely (Figure 2). The fish stock cycles from undetectable lev-

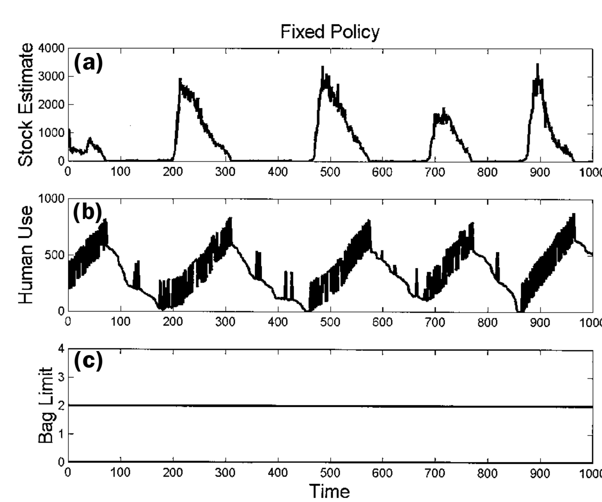

Figure 2. Fisheries model dynamics with fixed policy. (a) Stock estimate (fish per 10-ha sampling unit) versus time; (b) human use (people per year) versus time; (c) bag limit, the variable controlled by policy, through time.

els to thousands of individuals, and human use varies from just a few people per year to hundreds. In this case, a fixed bag limit of two fish is near the level corresponding to maximum sustainable yield, or MSY (Clark 1990). However, the dynamics do not resemble the stable point envisioned by managers seeking MSY. Instead, the dynamics fluctuate widely because of the dynamics of a slowly changing variable (the woody habitat) and their nonlinear connections to the rapidly changing variable of interest (fish production).

If the manager adjusts the bag limit experimentally, the oscillations of the dynamics can be greatly reduced (Figure 3). Stock estimates range from about 100 to 500 fish, and human use ranges from about 300 to 500 people per year. These ranges are far smaller than those shown in Figure 2. Here, the game player has chosen bag limits for a period of time with two goals in mind: First, the bag limit is intended to maintain a balance between fish and people, by shifting one component or the other up or down. Second, the manager is deliberately learning the relationship between bag limit and the variables it controls—fish stocks and human use. This relationship is not fixed in time. It changes, depending on the underlying slow variables. By adjusting the bag limit from time to time, the manager is able to track changes in the responsiveness of the system, and thereby make better decisions.

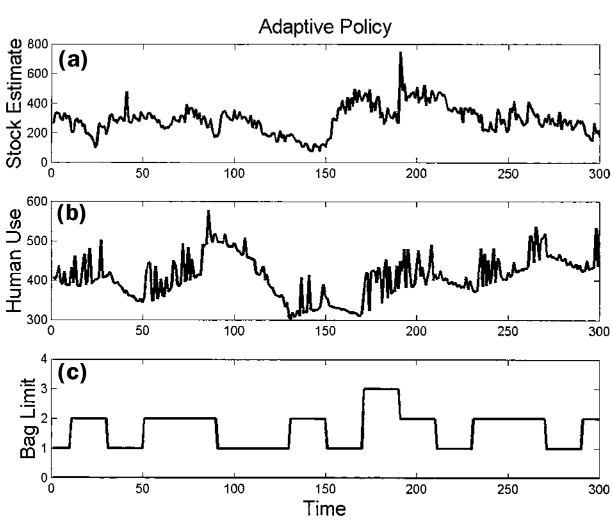

Figure 3. Fisheries model dynamics with adaptive policy. Only 300 years are plotted so that the relatively small fluctuations can be discerned. (a) Stock estimate (fish per 10-ha sampling unit) versus time; (b) human use (people per year) versus time; (c) bag limit, the variable controlled by policy, through time.

Ball-and-cup diagrams are a useful metaphor for these simulations (DeAngelis and Waterhouse 1987, Scheffer 1997). Cups represent attractors into which the system, the ball, is drawn. The ball is continually vibrating in response to external shocks from variations in weather or other factors. Some attractors are desirable and others are not. In the fixed-policy case, the desirable cup (productive fish stock and moderate human use) gradually shrinks while the undesirable cup (collapsed fish stock and diminished human use) does not change (Figure 4). Eventually the system shifts into the unwanted attractor, human usage drops, and a few decades later the system has recovered for another cycle of exploitation. In the adaptive-policy case, the manipulations reveal how the cup size is affected by changes in policy (Figure 5). Using this information, the desirable cup can be adjusted so that the ecosystem is likely to stay within it. It is important to recognize that the stability surface (the shape and location of the cups) is changing continually, slowly and unpredictably. Thus ongoing experimentation is needed to track the desirable cup.

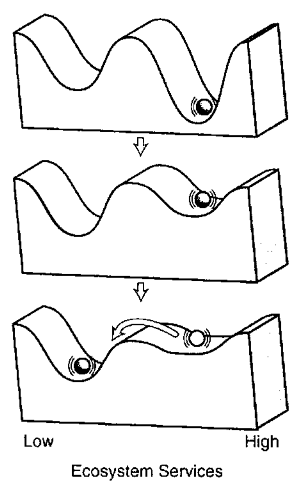

Figure 4. Ball-and-cup diagram showing how changes in the size of the desirable cup under a fixed policy shift the system (the ball) into the undesirable cup.

The phases of the adaptive cycle are another useful way of thinking about the results. The adaptive cycle describes a pattern known from many case studies of environmental management (Gunderson et al. 1995). During the alpha phase, a new, desirable attractor opens up. The r phase initiates the exploitation of this new possibility. The r phase gives way to the K phase as human use grows, resources diminish, and any surplus production is quickly extracted. In the omega phase, the desirable attractor collapses, leading to sharp reductions in human use. We have found that our models of ecosystem management resemble the adaptive cycle when plotted in three dimensions representing ecosystem state (e.g., the fish stock), human dependency (e.g., human use), and size of the desirable attractor (Scheffer 1997, Carpenter et al. 1999).

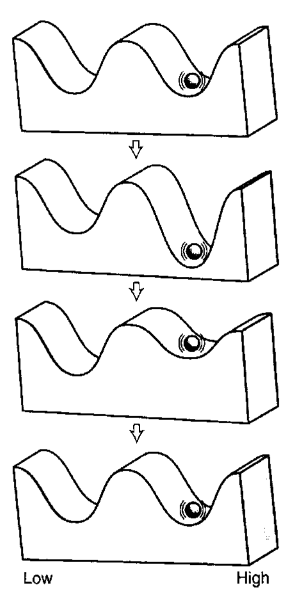

Figure 5. Ball-and-cup diagram showing how adaptive policies reveal the effect of policy choice on the size of the desirable cup.

Each cycle under the fixed policy describes an

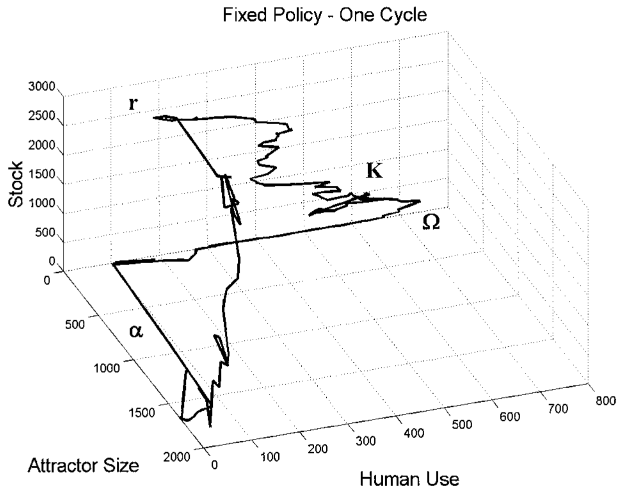

Figure 6. One cycle from the results of the fish management model with fixed policy, plotted on axes of stock size (fish per 10-ha sampling unit), human use (people per year), and size of the desirable attractor (calculated as described in Carpenter et al. 1999). Letters denote phases of the adaptive cycle. Trajectory has been smoothed by a running average.

adaptive cycle (Figure 6). The resurgence of the fish stock marks the opening of a new attractor, an alpha phase. Both the fish stock and human use grow during the r phase. During the K phase, human use continues to grow while the fish stock declines. Eventually, the stock collapses, marking an omega phase. Human use declines until stock recovery allows initiation of a new cycle.

Under adaptive management, the adaptive cycle can be discerned but the amplitude is far less (Figure 7); note the narrowness of the ranges of the axes in comparison with the ranges in Figure 6. Adaptive policies set up small cycles that are relatively safe (for fish stocks and society), compared with the wide excursions seen in Figure 6. In effect, the adaptive manager has coped with the dynamic variability while finding a way to maintain the system, with modest oscillations, through continual probing of the relationship among bag limit, fish stock, and human use. In contrast, the fixed policy, while seeking a constancy that is impossible to attain, has created extreme oscillations that are dangerous to both the fish stock and the humans who depend on it. By embracing cyclical change, the manager can sustain the system within a desirable region. Similar results have been seen in other models of adaptively managed systems (Anderies 1998, Carpenter et al. 1999, Janssen and Carpenter 1999).

Limits of certitude, command, and control

The example of the lake–fishery management system is a subset of a larger set of resource management actions that seek to control key ecological processes for a variety of human needs. At one extreme, managers try to stabilize ecosystem outputs by commanding and controlling ecological processes (Holling and Meffe 1996). In many of these cases, however, removal of unwanted variation in key ecosystem processes leads to eventual collapse. This pattern of stabilization, which leads to the loss of ecological resilience, has been called a pathology of resource management (Holling 1986).

But why should management that decreases variability or stabilizes system behavior lead to ecological crises or surprises? The ball and cup diagram (Figure 5) can help explain this outcome. Resilience is the width of the cup, and alternative states are depicted by alternative cups. Ecologists are beginning to understand that ecosystem resilience comes from slowly changing variables such as sediment nutrients, biodiversity, or keystone species—all of which relate to the width of the stability basin or cup. These variables are difficult to monitor and are often ignored. Hence, managers are often unaware that the size of the cup has shrunken, and are surprised when a disturbance that was previously absorbed by the system results in a change in the ecosystem.

Given that command and control management is likely to decrease the resilience of the system, it is also likely to reduce options for sustaining the coupled social–ecological system. Even if the science and control systems are perfect, these systems will continue to change in unpredictable ways, making sustainable targets not just infeasible but unlikely. Hence, the search for sustainability is less about certitude in planning and control than about ongoing learning and perpetual adaptation to an ever-changing world.

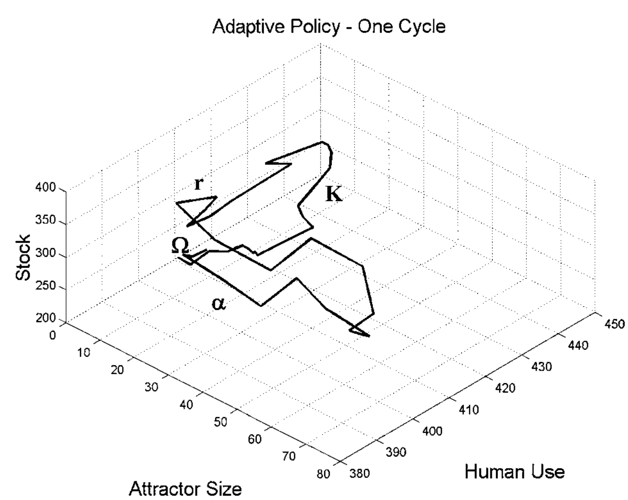

Figure 7. One cycle from the results of the fish management model with adaptive policy, plotted on axes of stock size (fish per 10 ha sampling unit), human use (people per year), and size of the desirable attractor (calculated as described in Carpenter et al. 1999). Letters denote phases of the adaptive cycle. Trajectory has been smoothed by a running average.

Learning and adapting in a changing world

Changes in the state of an ecosystem generate surprises for scientists and great uncertainties for stakeholders and policymakers. Generally, technical experts can develop plausible explanations or competing hypotheses for observed ecosystem changes. Case studies show three different kinds of response to the uncertainties of ecosystem dynamics. The first is to employ a singular command and control approach, assuming that certainty of process can compensate for uncertainty about system behavior. The second recourse is to adopt one of the hypotheses offered by the technical community, because there are other motives (social or political) affiliated with the policy implications of this preferred hypothesis. The third is to develop an integrated assessment that can independently sort through alternative explanations for ecosystem changes to develop plausible management probes to test the uncertainties.

Myopic management actions that are designed to "fix" a narrowly defined problem often backfire or evoke unintended responses. One example is from Florida Bay. A group concluded that the observed state changes in the bay were a result of increased salinity caused by decreased overland freshwater flow. Their strategy, then, was to increase water flow into and through Shark Slough to ameliorate hypersalinity in the bay. The strategy performed as intended and more water was delivered into the headwaters just northwest of the bay. However, while salinities were moderated, the increased flow generated turbidity plumes that moved in the bay, decreasing light penetration and inhibiting seagrass recolonization (Walters 1997). Fixes that backfire usually focus on a single variable, a model of simple cause and effect, and implicitly assume a single, global equilibrium.

A more insidious response occurs when stakeholders and vested interests who benefit from existing policies use the uncertainties generated by competing hypotheses to maintain the status quo. That is, these factions use the alternative hypotheses to create and maintain an uncertainty that forestalls action. Ehrlich and Ehrlich (1996) chronicle several examples of this type of behavior in various areas, among them loss of biodiversity, global warming, and carcinogenic effects of tobacco. Independent science, removed as far from politics as possible, is vital for breaking through such obfuscation and stalemate.

An integrated assessment is crucial to resolution of competing hypotheses about a resource issue—especially where the observed changes in the ecosystem state create the surprise. Articulation of alternative or competing explanations helps to make the uncertainties explicit. Integrated models, such as the one described above (Figure 1), help assess these competing hypotheses and make possible more robust recommendations for subsequent actions. These models move beyond pattern recognition or qualitative descriptions into a framework that allows managers to better understand the nonlinear dynamics of these systems.

The manner of resolution of competing hypotheses dictates subsequent actions. In the best (but most rare) of all situations, all but one of the competing hypotheses can be rejected, leaving only one hypothesis which can be tested by a set of management actions. In many cases such winnowing is not possible, yet policy probes can still be structured because the competing hypotheses can be tested with similar types of management actions. Yet even when competing hypotheses can be winnowed and management probes designed, stakeholder inflexibility can halt any actions aimed at learning (Gunderson 1999).

A central tenet of the adaptive management approach is to deal with competing hypotheses by structuring management probes for learning. However, learning seems to be intertwined with cycles of policy success and failure (Westley 1995). If policies are working (or appear to be working), there is little or no emphasis on learning—after all, why should one learn from success? It is when policy fails, either dramatically or chronically, that learning is deemed necessary and given priority. The challenge of developing a capacity for learning continues to be problematic at many resource-management institutions. When that capacity is judged necessary and is sought, however, it is best achieved by focusing on understanding—not efficiency—and by networking with others who are motivated to learn.

Perhaps it is time to rethink the paradigms or foundations of resource-management institutions and to emphasize development of sustaining foundations for dealing with complex resource issues. Learning is a long-term proposition that requires a ballast against short-term politics and objectives. Another shift will very likely require a change in the focus of actions: Management by objectives and determination of optimum policies will give way to new methods for defining, understanding, and managing ecosystems. That focus should not be solely on rapidly changing variables, but rather on more enduring system properties such as resilience, social and political flexibility, and renewal capability. This framework involves both the human components of the system (operations, rules, policies, and laws) and the biophysical components of the landscape and its ecosystems. The shift of focus to learning will most likely require flexible links to a broader set of actors than technical experts alone.

Conclusions

There is a grave mismatch between the kinds of ecosystems that people want and the kinds of ecosystems that are attainable, although there may be a zone of intersection between the imagined and the possible. Ecologists can help locate that overlap, and the models described in this article can help them achieve that goal.

Explorations of this model, and other similar models, show that the road to sustainability involves forward-looking, experimental behavior. Such behavior is far easier when the ecosystem is resilient (and thus can withstand diverse experiments) and the social system is flexible enough to experiment, learn, and change in response to new information. Exploratory management will usually require some concessions by one interest group or another, motivated by the possibility of larger benefits in the future. For example, the experiments depicted in Figure 3 sometimes involve concessions by development interests (reducing bag limits) and at other times by environmental interests (increasing bag limits). In reality, such social flexibility may be difficult to achieve. Education at many levels, ranging from K–12 environmental education to outreach programs for adults, may contribute to the collective learning or social flexibility needed for adaptive management.

Collapses are going to happen—even perfect foresight cannot prevent them when social pressures or preferences push systems to the breaking point. Thus ecologists cannot claim that better information will necessarily prevent environmental disasters. It is true, however, that certain kinds of information can lead to decisions that sustain ecosystem services and the people who depend on them. Predictions at the scale of management depend on slowly changing variables and their feedbacks and on faster variables that concern people. Examples of important slow variables include evolution, pedogenesis, sediment diagenesis, dynamics of long-lived organisms, and ecological legacies such as slowly decaying logs; culture, long-lived institutions, rule of law, and enduring values are other such slow variables. Even though slowly changing variables make predictions possible, the self-organizing properties of ecosystems and social systems cause uncertainty to grow over time (Levin 1999). Understanding must continually be updated and adjusted. Methods that seemed to work in the past may fail in the future. Any environmental policy is a hypothesis masquerading as the ultimate solution. Thus it is to our advantage to treat each major management intervention as an opportunity to learn how to adapt to changing circumstances.

Acknowledgments

We thank J. Cassady for helpful comments on the paper. The models we describe could not have been developed without the insights and advice of Buz Brock and Don Ludwig. The models have been improved by suggestions from many workshop participants, particularly Jim Addis, Buzz Holling, Marco Janssen, Garry Peterson, and Frances Westley. This work was supported by the National Science Foundation through LTER and Biocomplexity Awards, and by the MacArthur Foundation through support to the Resilience Network.

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