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ECOSYSTEMS

MINIREVIEW

From Metaphor to Measurement: Resilience of What to What?

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Abstract

Resilience is the magnitude of disturbance that can be tolerated before a socioecological system (SES) moves to a different region of state space controlled by a different set of processes. Resilience has multiple levels of meaning: as a metaphor related to sustainability, as a property of dynamic models, and as a measurable quantity that can be assessed in field studies of SES. The operational indicators of resilience have, however, received little attention in the literature. To assess a system's resilience, one must specify which system configuration and which disturbances are of interest. This paper compares resilience properties in two contrasting SES, lake districts and rangelands, with respect to the following three general features: (a) The ability of an SES to stay in the domain of attraction is related to slowly changing variables, or slowly changing disturbance regimes, which control the boundaries of the domain of attraction or the frequency of events that could push the system across the boundaries. Examples are soil phosphorus content in lake districts woody vegetation cover in rangelands, and property rights systems that affect land use in both lake districts and rangelands. (b) The ability of an SES to self-organize is related to the extent to which reorganization is endogenous rather than forced by external drivers. Self-organization is enhanced by coevolved ecosystem components and the presence of social networks that facilitate innovative problem solving. (c) The adaptive capacity of an SES is related to the existence of mechanisms for the evolution of novelty or learning. Examples include biodiversity at multiple scales and the existence of institutions that facilitate experimentation, discovery, and innovation.

Key words: resilience; resistance; stability; persistence; socioecological system (SES); lake districts; rangelands; sustainability; self-organization; adaptive capacity; adaptive cycle.

Introduction

In the rapidly developing area of research on ecosystem services and the people who depend on them, the term "resilience" is often used to describe the characteristic features of a system that are related to sustainability. As a technical term, the idea of "resilience" originated in the field of ecology (Holling 1973). Diverse definitions of resilience and other concepts related to stability can be found in the ecological literature (Schrader-Frechette and McCoy 1993). The concept of resilience is now used in a great variety of interdisciplinary work concerned with the interactions between people and nature (see, for examples Gunderson and others 1995; Hanna and others 1996; Ludwig and others 1997; Berkes and Folke 1998; Redman 1999; Klein and Nichols 1999; Kinzig and others 2000; Gunderson 2000; Gunderson and Holling 2001). Both "resilience" and "sustainability," however, have multiple levels of meaning, from the metaphorical to the specific. "Resilience" is often used in conjunction with "adaptive capacity," another term with multiple meanings. In our research on ecosystem management in diverse regions of the world, the

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importance of clear and measurable definitions of resilience has become paramount. Practitioners have repeatedly asked how resilience, and trends in resilience, can be measured for particular socioecological systems (SES). This paper explores definitions that are both useful and operational.

Gunderson and Holling (2001) define "resilience" as the capacity of a system to undergo disturbance and maintain its functions and controls. In their view, resilience is measured by the magnitude of disturbance the system can tolerate and still persist. They contrast this definition with that proposed by Pimm (1984), for whom the appropriate measure is the ability of the system to resist disturbance and the rate at which it returns to equilibrium following disturbance (Pimm 1984; Tilman and Downing 1994). The distinction between these two definitions of resilience has been useful in encouraging the managers of naturally variable systems to think about the persistence of such systems and has helped them to break away from their traditional preoccupation with management aimed at the unachievable goal of stability. However, we also need to consider the other, complementary aspect of persistence—resistance, which may be defined as the amount of external pressure needed to bring about a given amount of disturbance in the system. Consider, for example, those systems that are particularly persistent because they are intrinsically resistant—that is they absorb high levels of external pressure and nevertheless persist. Some examples include self-mulching clay soils and paddy rice production in Java (Geertz 1963). We agree with Gunderson and Holling (2001) that the key criterion is persistence; therefore, to assess long-term persistence, we need to also consider resistance as the complementary attribute of resilience.

In any study of resilience, we are concerned with the magnitude of disturbance that can be tolerated before a system moves into a different region of state space and a different set of controls, as originally conceived by Holling (1973, 1996). Based on this interpretation, resilience has the following three properties: (a) the amount of change the system can undergo (and implicitly, therefore, the amount of extrinsic force the system can sustain) and still remain within the same domain of attraction (that is, retain the same controls on structure and function); (b) the degree to which the system is capable of self-organization (versus lack of organization, or organization forced by external factors); and (c) the degree to which the system can build the capacity to learn and adapt. Adaptive capacity is a component of resilience that reflects the learning aspect of system behavior in response to disturbance (Gunderson 2000). Unlike sustainability, resilience can be desirable or undesirable. For example, system states that decrease social welfare, such as polluted water supplies or dictatorships, can be highly resilient. In contrast, sustainability is an overarching goal that includes assumptions or preferences about which system states are desirable.

The Adaptive Cycle and Resilience

The notion of the adaptive cycle has a key role in organizing our ideas about resilience (Gunderson and others 1995; Gunderson and Holling 2001). According to the theory of the adaptive cycle, dynamical systems such as ecosystems, societies, corporations, economies, nations, and SES do not tend toward some stable or equilibrium condition. Instead, they pass through the following four characteristic phases; rapid growth and exploitation (r), conservation (K), collapse or release ("creative destruction", or Ω), and renewal or reorganization (α).

A key feature of this metaphor is the existence of relatively brief periods during which major changes occur—the Ω and α phases. The former is a period of rapidly collapsing dynamics following a major perturbation during which some components and attributes of the system may be lost (species, memory). It is succeeded by a period of reorganization, the α phase, during which novelty can arise (new species, new institutions, new ideas and policies, new industries). In the following r phase, the system settles into a new trajectory in a well-defined basin of attraction. During the long, slow progression from r to K, there is a diminishing likelihood that any further novelty will arise, although the system may become more complex as new connections are solidified. Resilience changes throughout the adaptive cycle, and different aspects of resilience assume prominence at particular phases of the cycle (Gunderson and Holling 2001).

We view the adaptive cycle as a useful metaphor and not as a testable hypothesis. The history of interactions between humans and nature includes many cyclic patterns (Gunderson and others 1995; Redman 1999). Definition of the r, K, Ω, and α phases emerged from the need to classify regimes that are commonly seen in resource management systems (Holling 1986; Gunderson and others 1995). It is useful to classify these stages, just as biologists classify life-cycle stages that recur in species after species. If the adaptive cycle is productive of ideas, it will generate testable explanations of SES dynamics that turn out to embrace a wide range of situations.

For this reason, we have adopted a view of scientific progress similar to the one proposed by Hull (1988). Theory itself is rarely tested directly; indeed, it may not be testable in any definitive way. Instead, its success is measured by the utility of the concepts in terms of their ability to influence the research topics chosen by scientists and stimulate productive hypotheses. According to Hull (1988), progress in the definition of concepts is central to advancement of science. In this vein, our paper aims to clarify the definition of resilience used in the adaptive cycle.

Resilience and Space–Time Scales

Measurable, quantitative definitions of resilience would open new and important pathways for testable hypotheses related to the adaptive cycle. To interpret the dynamics of a particular system in terms of the adaptive cycle metaphor, so that we can try to understand the resilience of the system, we must begin by clearly defining resilience in terms *of* what *to* what. These aspects change, depending on the temporal, social, and spatial scale at which the measurement is made. A socioecological system can be resilient at one time scale because of the technology it has adopted. Iron axes, for example, probably helped emerging agricultural societies to persist over a particular span of time because they enabled their possessors to clear more forest and grow more food. But at a longer time scale, once some threshold of forest cover had been crossed, fallowing could no longer maintain soil fertility and the resilience of the system was compromised (Ruthenberg 1976). In this example, resilience in one time period was gained at the expense of the succeeding period.

Thus to measure resilience, one needs to specify the time scale. The choice of time scale depends on the issue we may wish to investigate and ranges from evolutionary studies spanning millennia to farming system studies with a time horizon of decades. Time scale also affects the classification of system components as fast or slow, variables or parameters (see special feature in *Ecosystems* 3(6)). Topography, for example, is a parameter in models of landscape function, but in geomorphological studies it is a variable.

Just as resilience can be achieved in one time period at the expense of resilience in a succeeding period, resilience at one spatial extent can be subsidized from a broader scale. For example, it is common for a regional crisis—drought, say—to be relieved by the importation of resources from the state. The region persists, but only through external subsidy. If many such regions are being similarly subsidized, then the resilience of the state itself could be in doubt.

The history of human cultural evolution has been the story of cross-scale subsidies. As resources are exhausted in one region, they are taken from another (for example, under imperialistic regimes). In the case of fossil fuels, all current SES are subsidized by resources from a past era. Only when cultures have been isolated has their fixed-scale resilience been tested. In the case of Ukara Island, East Africa, a community isolated by the slave trade developed an innovative, labor-intensive, self-sufficient agricultural system that persisted until the end of the slave trade (Ruthenberg 1976). In contrast, the culture isolated on Easter Island did not develop a self-sufficient system and therefore became extinct (Redman 1999; Brander and Taylor 1998; Anderies 2000).

Most studies that explore resilience-related ideas have used resilience as a metaphor or theoretical construct. In a few cases, it has been defined operationally in the context of a model of a particular system (Peterson and others 1998; Carpenter and others 1999; Janssen and others 2000; Scheffer and others 2000; Peterson 1999). However, these definitions have been system-specific, and not all of them are measurable in the field (although it may be possible to calculate them in models). Although the metaphorical concept of resilience has the power to inspire useful analyses of socioecological systems, much more insight could be gained from empirical analyses, which would require an operational, measurable concept of resilience. Operational definitions of resilience should be consistent with the metaphorical or theoretical uses of the term. Furthermore, because knowledge can be gained from cross-system comparisons, operational definitions of resilience for different socioecological systems should be as similar as possible.

The purpose of this paper is to explore the possibilities and limitations of measurable operational definitions of resilience for socioecological systems (SES). We will address this issue in the following four sections. First, we provide the background of two case studies, one from the lake districts of North America and one from the rangelands of Australia, that will be used throughout the paper to inform and focus the discussion. Next, we discuss the concepts of resilience and the adaptive cycle in the context of models for each of the examples to show that useful parallels can be drawn between radically different SES. Then, we attempt to develop pathways by which some useful resilience measures for SES might be devised. Finally, we describe some of the pitfalls and limitations of resilience measures and offer some remarks on the future of work in this area.

Background: The Ecosystems and the Services They Provide

To focus our discussion, we will compare two well-studied SES—the agricultural lake districts of North America and the rangelands of Western New South Wales (NSW) in Australia. These two areas are marked by sharp contrasts in climate, ecosystem structure and function, ecosystem services, and management institutions. They are similar in that both SES exist in democracies with traditions of science-based management. Previous papers have analyzed the systems in detail, so we have a rich body of models and analyses on which to draw.

Lakes and Agriculture in North America

The lake districts of the Great Lakes region of North America encompass productive farm lands as well as thousands of lakes. The ecosystem services of the region include agricultural production and freshwater used for irrigation, municipal water supplies, pollution dilution, and recreation, including valuable sport fisheries (Postel and Carpenter 1997; Wilson and Carpenter 1999). Agricultural and aquatic ecosystem services are in conflict. Agriculture generates nutrient runoff that causes the eutrophication of lakes, leading to higher costs for water treatment, fish kills, and loss of recreational benefits (Carpenter and others 1998). Intensive nutrient use is related to manure yield from high densities of livestock, as well as the use of commercial fertilizers (NRC 1993; Vitousek and others 1997; Bennett and others 2001). Intensive fertilization and high densities of livestock are associated with economies of scale that favor the consolidation of large industrial farming operations (NRC 1993). In economic terms, agriculture communizes the costs of nutrient treatment by disposing of excess nutrients in common-property streams and lakes (Scheffer and others 2000). It is subsidized through a complex system of price supports and regulations intended to stabilize production and make farming profitable. The value of lost freshwater resources is often large relative to the value of the farm products (Wilson and Carpenter 1999; Carpenter and others 1999).

Two states of lakes are of interest—a clear-water or oligotrophic state and a turbid-water or eutrophic state (Carpenter and others 1999; Scheffer and others 2000). Both states can be resilient. For a lake in the clear-water state, the challenge for managers is to increase or maintain the resilience of the clear-water state. For lakes in the turbid state, the challenge is to break down the resilience of the turbid state or shift the lake into the clear-water state. Here we will focus on the resilience of the clear-water state.

Phosphorus (P) is the most critical nutrient for the eutrophication of lakes in the Great Lakes region (Carpenter and others 1998). Excess P is imported to farms in the form of fertilizer and animal feed supplements (Bennett and others 1998, 2001). P is added to the soil as inorganic fertilizer or manure. Most of the excess P accumulates in soil, which may be transported to streams and lakes during runoff events associated with snowmelt or rainstorms (Bennett and others 1998, 2001). Thus, P plays a key role in determining system resilience, both in models and in practice.

Western New South Wales Rangelands

Rangelands are socioecological systems in semi-arid regions where the native vegetation sustains extensive grazing and browsing by domestic livestock. In the rangelands of western NSW, the major ecosystem service since the late 19th century, when Aboriginal peoples were displaced by pastoralists, has been wool production based on grazing by sheep, with limited use of woody browse. In this paper, we will consider the resilience of the wool production system and—rather more broadly—the resilience of pastoralism of all kinds to broader-scale economic and climate changes that affect this region.

The establishment of the rangeland wool production system was dependent on imported finance, which was used to buy sheep, establish infrastructure, and import technology. The subsequent resilience of the socioecological system was in part the consequence of the transport systems, stock routes, and artificial watering points that enabled the stock to be moved around. Further subsidies have been given to avert or dampen crises caused by drought. A federally managed price support scheme, paid for by the producers, was instituted to dampened fluctuations in wool prices and later to support them. Without cross-scale subsidies from the outset at state, national, and international scales, a persistent wool industry could not have been established.

Biophysically, resilience at the local level is dependent on the ability of the landscape to maintain infiltration, water storage capacity, and nutrient cycles (Tongway and Ludwig 1997), all of which are threatened by soil loss and structural change. An inherently resilient pastoral property would therefore contain soils that are physically resistant to change despite heavy grazing pressure.

Resilience at the local level also depends on vegetation structure. Rangelands are comprised of mixtures of grasses and woody plants (small trees and shrubs). The dynamics of the wood:grass ratio are driven by fire and grazing pressure under highly variable rainfall (Walker 1993). The long-run equilibrium state of a prehuman rangeland, set primarily by the soil moisture regime (which is dependent on rainfall and soil type), is thought to have consisted of shrubs and trees with a mix of age classes and a well-developed grass layer that allowed for periodic fires. The fires would have created a dynamic mosaic of age classes and vegetation structures. When burning by Aboriginal peoples increased the fire frequency above the natural, lightning-induced regime, a more open, grassy state was established. The subsequent exclusion of fire under pastoral management caused an increase in woody biomass at the expense of grass.

Models: Resilience and the Adaptive Cycle

Resilience is a theoretical concept that was originally envisioned using models. In this section, we review resilience in models of lakes and rangelands, before turning in later sections to empirical measures.

Resilience in the Lake System Model

Phosphorus in soil is a large, slowly changing pool that affects the magnitude of input events from land to freshwaters (Bennett and others 1998; Reed-Anderson and others 2000). Once P enters the lake, it may be taken up by primary producers (including the undesirable blue-green algae that are symptomatic of eutrophication) or added to the sediments. P in the lake cycles continually among organisms, the water, and the sediment. Recycling from sediment to the overlaying water is a key flux that is subject to nonlinear changes in rate (Nürnberg 1984; Carpenter and others 1999). When P levels in the water are low, oxygen concentrations stay high throughout the summer and P remains bound in iron complexes in the sediment. When P levels in the water are high, the production of algae is high and decomposition of sinking algae depletes oxygen near the surface of the sediment. The iron–P complexes are chemically reduced, releasing the P in soluble form to support further algal growth. This shift between negative and positive feedbacks produces alternate stable states—one with low water P, low recycling, and high water quality; the other with high water P, high recycling, and poor water quality (Carpenter and others 1999).

Resilience is measured by plotting the equilibria of the system on axes of the rapidly changing variable (water P) and a more slowly changing variable

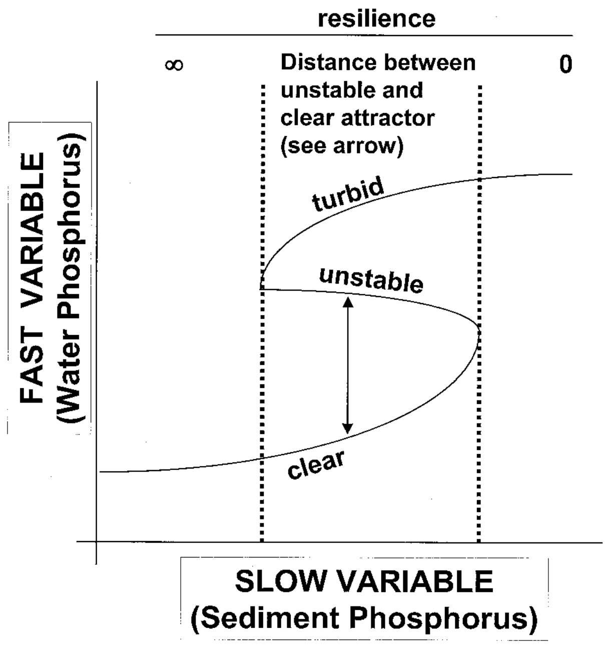

Figure 1. Water phosphorus versus sediment phosphorus, showing equilibria and resilience of the clear-water state. Vertical dashed lines show where the resilience of one of the stable states becomes zero.

(sediment P) (Figure 1). The plot shows upper and lower sets of stable states (one for clear water and one for turbid water) separated by an unstable set of equilibria (Carpenter and others 1999). Because there are multiple stable states, to evaluate resilience, one must specify which stable state is being considered. Assume that we are interested in the resilience of the clear-water state. The vertical dashed lines in Figure 1 delimit three zones of resilience for the clear-water state. In the leftmost zone, the system will move parallel to the fast variable axis toward the clear-water state from any starting position (we assume that the component of motion parallel to the slowly moving axis is negligible). In this zone, resilience of the clear-water state is infinite. In the rightmost zone, the system will move to the turbid-water state from any starting position, including starting positions with very low water P. In this zone, resilience of the clear-water state is zero. The only way to restore the clear-water state is to decrease the amount of sediment P. In the middle zone, the system will move to the clear-water state only from starting positions below the unstable line. If the system is perturbed above the stable line, it will move to the turbid-water state. In the middle zone, we define the resilience of the clear-water state as the distance from the unstable equilibrium to the clear-water equilibrium. A perturbation that increases water P by more than this amount will tip the system into the basin of attraction for the turbid-water state.

Note that the shape of the equilibrium curve in Figure 1 depends on the status of other variables that change even more slowly, such as the amount of P in watershed soils. Changes in soil P therefore affect the resilience of the clear-water attractor. If soil P is extremely low, the curve will straighten so that the unstable equilibria disappear, causing the resilience of the clear-water state to be infinite for all values of sediment P. Similarly, if soil P is extremely high, the curve will straighten in a way that makes the resilience of the clear-water state zero for all levels of sediment P. Intermediate levels of soil P produce curves like that of Figure 1. Soil P also affects the probability distribution of runoff events, the perturbations that could move the system from the clear-water basin of attraction to the turbid-water basin of attraction (Carpenter and others 1999). Higher levels of soil P increase the probability of large pulses of P input. Thus, soil P affects the stability of the clear-water state in two ways: by affecting its resilience, and by affecting the probability distribution of disturbances. Therefore, soil P content is a powerful control variable for lake eutrophication (Bennett and others 1998, 2001).

In field studies, the attractor depicted in Figure 1 is difficult to measure. However, soil P is measurable and is inversely associated with resilience. Agencies concerned with agriculture or soil management often measure soil P on a routine basis. These measurements are a useful surrogate for resilience.

The Adaptive Cycle in the Lake System Model

Models of the lake–agriculture SES exhibit cycles that resemble Holling's (1986) adaptive cycle (Carpenter and others 1999) (Figure 2). In the social system, the cycle is evident in the intensity of agriculture, the regulatory activity directed at control of nonpoint pollution, and the net social utility derived from freshwater and agricultural ecosystem services. In the biophysical system, the cycle is evident in water quality. In theory and in the model, resilience is tracked as the size of the attractor for the clear-water condition. In practice, resilience could be tracked by monitoring the slowly changing ecological variables that control the clear-water attractor, which are P levels in lake sediment and catchment soils. Note that the turbid-water state, which has low utility, is also quite resilient. Avoiding, or escaping from, this resilient, low-utility state

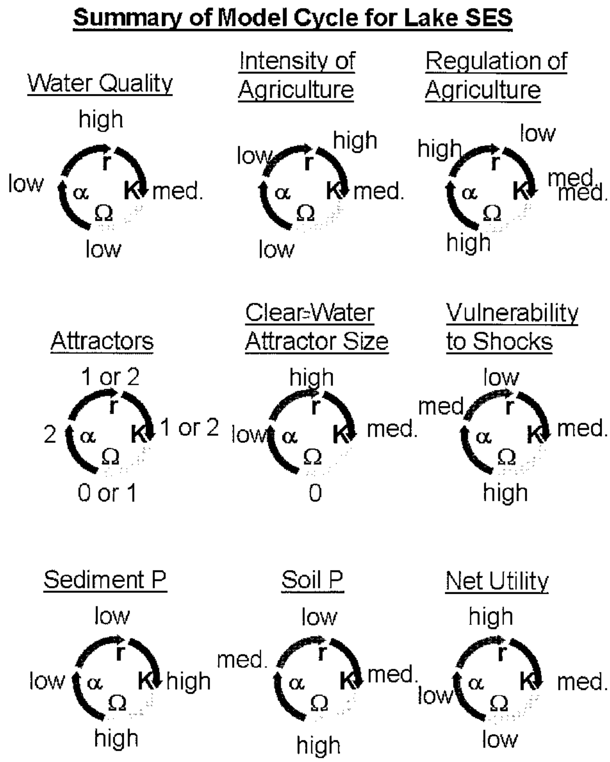

Figure 2. Summary of model results. Status of nine indicator variables during the adaptive cycle of the socio-ecological system of a lake district.

is the major objective of management (Osgood 2000).

In the model output, water quality, net social utility, and the resilience of the clear-water state are high during the r phase (Figure 2). As the system moves into K phase, water quality declines somewhat and the resilience of the clear-water state declines. The drive for incremental increases in efficiency of agriculture slowly increases soil P. The magnitude of weather-driven stochastic runoff events increases with increasing soil P concentration. Thus, the magnitude of potential shocks is rising as the resilience of the clear-water state is declining. Eventually, a large runoff event tips the lake into the turbid state, the attractor for the clear water state disappears entirely, or both. This triggers the Ω phase, characterized by poor water quality, low utility, strong regulation of agriculture, and a tumult of confusion, debate, and evaluation of the problem. This leads to an α phase in which new lake restoration measures are combined with new approaches to agriculture. Eventually, these activities cause the clear water attractor to reappear. Once the clear-water attractor exists, management activities can move the system into the clear-water state. At this point, the social system relaxes regulatory pressure on agriculture and a new r phase commences.

The preceding narrative is a general account of a cycle that can take on other patterns in the model. For a richer description of model dynamics, including different configurations of the SES and downloadable programs, see Carpenter and others (1999). In gaming exercises with the model, the lake can be managed in an active adaptive way, using careful, brief experiments to probe the sensitivity of the system to changes in agricultural policy. Active adaptive management leads to low-amplitude cycles that can keep the system in the clear water–high utility attractor for longer than laissez-faire management (Carpenter and others 1999).

Resilience in Rangelands Models

We consider first the resilience of wool production to the effects of fire, grazing, and rainfall on rangelands where shrub growth limits production. We have used woody cover to illustrate some of the principles underlying the measurement of resilience. Walker and Abel (2001) describe some of the other biophysical and socioeconomic sources of resilience.

If grazing pressure is increased in a system with sparse woody cover, the root and crown reserves of perennial grasses are depleted. Perennial grasses therefore tend to be replaced by annual plants that do not support fire. Meanwhile, woody plant density increases due to reduced competition with perennial grasses and a reduction in fire frequency and intensity. The establishment of shrubs is also aided by good rains.

Fire has very different effects on grasses and woody plants. It occurs when the grasses are dormant, and thus removes only their aboveground dead shoots, causing little or no harm to the plant. Woody plants, on the other hand, are highly susceptible to fire. If grazing pressure is reduced soon enough, the grasses recover, fire management can be resumed, and the shrub cover is reduced (see, for example, Ludwig and others 1997; Anderies and others 2002). The increasing woody cover is vulnerable to fire up to some threshold of woody biomass, but beyond this level, even in the absence of livestock, the resulting reduced grass cover is insufficient to carry a fire. The system stays in the woody state until some of the shrubs begin to die (Ludwig and others 1997). The important variables are the grass shoot biomass (leaves and stems, on which wool production depends). The grass root/crown reserves (hereafter called "roots"), and shrub cover. Grass shoots are the fastest-changing variable (annual), followed by roots (2–5 years), and finally shrubs (decades). Anderies and others (2002) have developed a model of this system that illustrates the changes in the resilience of the desirable attractor (high grass root biomass) as a function of woody biomass (Figure 3). Grass shoot production depends on the levels of root reserves, and these, in turn, either increase or decrease as a function of how much shoot biomass there is. Heavy grazing, which keeps shoot biomass low, leads to reduced root biomass and eventually to the death of the grass. As indicated in Figure 3, as shrubs increase, the resilience of the grassy state declines markedly.

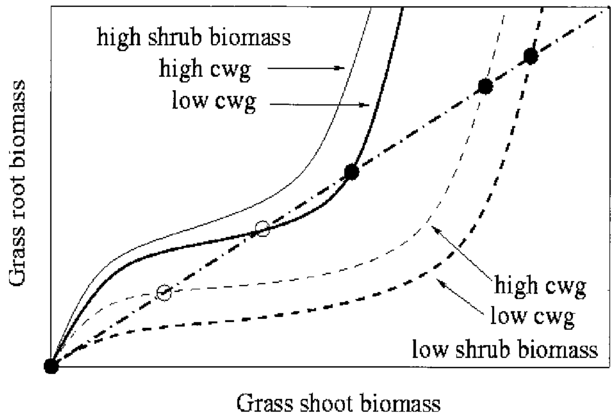

Figure 3. Grass root–shoot isoclines from the model of Anderies and others (2002). The straight line is the root isocline. The curved lines are shoot isoclines under varying conditions of shrub density and competitive effect of shrubs on grass growth (cwg). Equilibria occur where the root isocline intersects a shoot isocline. Open circles denote unstable equilibria; filled circles denote stable equilibria.

The Adaptive Cycle in the Rangelands Model

Models of the rangeland SES that combine a biophysical component and pastoralists (modeled as adaptive agents) illustrate a form of the adaptive cycle (Janssen and others 2000). We define the r–K dynamics as the changes in grass roots and crown. We are interested in the resilience of grass to changes in grazing pressure under fluctuating rainfall, in the face of increasing amounts of shrubs. In the absence of high densities of domestic livestock, the dynamics of such a system resembles a form of the adaptive cycle. Under low grazing pressure, uneaten grass accumulates as fuel; and after some years, the fuel load is such that the probability of fire is very high. Fire then occurs, either through lightning or human action. In either case, the woody vegetation is reduced to a low level, and the grass cover begins a period of rapid growth and accumulation. Depending on the pattern of rainfall, woody plants also begin to increase, but fire occurs before it reaches the threshold of dominance. In the models, this form of the adaptive cycle can be maintained by commercial livestock grazing, providing that the grazing pressure is kept low, or periodically removed, before the woody vegetation exceeds the threshold that removes the grassy basin of attraction. If we focus on grass as the ecosystem service of concern, this form of the rangeland adaptive cycle, at the scale of a paddock or landscape, can be seen as a series of repetitive, small cycles of fairly short duration. The Ω phase is very rapid (1–2 months), with little loss of memory or species, and the α phase offers a small but significant opportunity for various grass species to reestablish themselves.

The introduction of sheep and water points and the removal of Aboriginal burning changes the system to a new trajectory. It progresses from the grassy r phase into a K phase marked by a thicket state. Thickets persist until canopy trees begin to be established. The larger trees control shrub density and, with the senescence of the shrubs, patches arise in which perennial grasses become reestablished. This condition allows fire to initiate the α phase in which shrubs are replaced by grasses. An r phase ensues, and whether the new trajectory is one involving the accumulation of grass fuel and a fire within a few years or the multidecadal trajectory through the thicket state depends on the stocking density and the fire policy practiced by the system's manager.

Measurement: Resilience and the Adaptive cycle in Practice

The Adaptive Cycle for the Lake System in Practice

In practice, very few lakes that have collapsed to the turbid state have been restored successfully to the clear-water state (Osgood 2000; NRC 1992). Lakes that are restored successfully often require ongoing intervention to maintain the clear-water state (NRC 1992),—that is to say, the clear-water state is not resilient and self-sustaining. The most common dynamic is a long r to K transition as the watershed is developed, followed by a deterioration in the water quality that is more or less permanent. While the biophysical system degrades, the social system continues on a growth trajectory. There is some debate about water quality but no effective action. The collapse of the biophysical system does not usually cause a simultaneous collapse of the local economy because the economy does not solely depend on the lake. The agricultural sector, for example, may use the lake only as a sink for wastes while extracting the water needed for agriculture from the groundwater. Other interest groups may likewise depend wholly or in part on resources from other regions. There are many reasons for the lack of recovery of the biophysical system, including the high resilience of the turbid state; the extremely slow dynamics of soil and sediment P, which maintain the resilience of the turbid state; the exclusion of water quality from the market, so the value of the ecosystem services of freshwater are not properly accounted for and do not contribute to indexes of social utility; the lack of a market for pollutant discharge, so that farmers do not have incentives or the economic means to control pollution; and mismatches of political power between environmental advocates and lobbies for the agricultural industry, realtors, and developers (Scheffer and others 2000).

The history of Lake Mendota (Wisconsin, USA) is one example of a long, slow slide to the turbid state, followed by repeated attempts to restore the clear-water state (Carpenter and others forthcoming). The process is described as a sequence of four adaptive cycles (Figure 4). Following settlement of the watershed by European immigrants around 1840, there was an immediate loss of resilience as rich prairie soils were plowed for the first time and runoff to the lake increased (Hurley and others 1992). A long transition from the r to K phases followed. There was little increase in the extent or intensity of agriculture, but the region experienced slow population growth in the watershed and gradual enrichment of the lake by sewage effluent (Lathrop 1992). Shortly after World War II, agriculture intensified sharply and urbanization in the watershed increased, triggering a collapse in water quality and the Ω phase that ended cycle 1.

After a decade of public debate, agreement was reached on a plan to divert sewage effluents from the lake—the α phase that initiated cycle 2. Sewage diversion was completed in 1971, but increases in water quality were minor. The P from sewage effluent had been replaced by nonpoint P inputs due to increased fertilizer use, increased dairy herd sizes, increased P content of soils, and sprawling urbanization. Invasion by an exotic macrophyte (Eurasian water milfoil, *Myriophyllum spicatum*) created a highly visible public nuisance. In 1978, populations of planktivorous cisco (*Coregonus artedii*) exploded, collapsing populations of the important grazer *Daphnia pulicaria* and further diminishing water quality. It was clear that sewage diversion

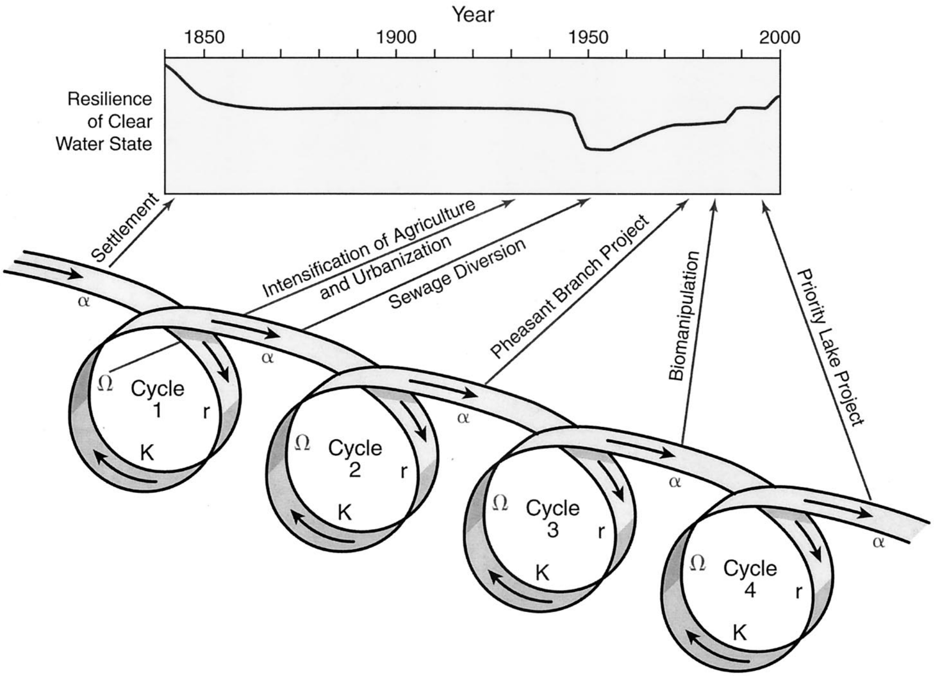

Figure 4. Cycles of management for Lake Mendota, Wisconsin.

had not achieved water-quality goals (although removal of this P source was a positive step toward improving water quality). The recognition of this failure created the Ω phase ending cycle 2. This was an institutional transition, not an ecological one.

Rather quickly, lake managers set out to tackle the nonpoint pollution problem, initiating cycle 3. The Pheasant Branch Project was designed to decrease nonpoint P loss from the most steeply sloping (and therefore erosion-prone) subwatershed of Lake Mendota. Unfortunately, farmers were not motivated to participate in the project, and there were only small reductions in the nonpoint inputs. The Ω phase ending cycle 3 came shortly after the initiation of the cycle. As before, the critical events were not ecological, but rather based on an institutional recognition that another approach was needed.

The α phase initiating cycle 4 came in the 1980s, when managers realized that biomanipulation of the lake's food web might improve water quality without the need for costly and potentially contentious interventions on private land (Kitchell 1992; Westley 2001). The biomanipulation involved stocking large numbers of piscivorous fishes (walleye *Stizostedion vitreum* and northern pike *Esox lucius*) and protecting them with restrictive size and bag limits. Whole-lake experiments in northern Wisconsin had shown that piscivores could greatly reduce numbers of planktivorous fishes, allowing potent grazers to flourish and thus reduce the concentrations of algae in the water (Carpenter and others 1987). The biomanipulation project attempted to create a similar trophic cascade in Lake Mendota that would improve the water quality. For the first few years, it was successful (Kitchell 1992). However, an unexpected intensification of fishing pressure took a heavy toll on the stocked piscivores (Johnson and Carpenter 1994). Heavy summer rains in 1993 then caused massive erosion from construction sites into the lake, causing the largest P inputs ever measured to Lake Mendota. The rains of 1993 triggered the Ω phase ending cycle 4.

At this point, it was evident that the problem would have to be confronted directly. Intensive research by both agency and university scientists culminated in the Priority Lake Project, an aggressive plan to cut nonpoint pollution in half (Betz and others 1997; Lathrop and others 1998). The initiation of this project in 1998 marked the beginning of a fifth cycle. The Priority Lake Project includes substantial cost-sharing incentives for farmer participation, funds to enforce regulations for the control of erosion from construction sites, and funds to purchase riparian easements and wetlands for restoration. At the same time, for reasons that are not understood but may be related to changes in tillage practices, soil P levels in the watershed began to stabilize or decline (Bennett and others 1998). This change has increased the resilience of the clear-water state.

It is still too early to assess the outcome of the

Priority Lake Project. Substantial reductions in nonpoint P input are possible. However, over the 10-year time frame of the project, sprawling urbanization will expand the extent of impervious cover in the watershed, potentially increasing the intensity and frequency of flood events. Thus, even as management focuses on the reduction of nonpoint P fluxes, the underlying cause of the problem may be shifting from the effects of intensive agriculture to urban sprawl and erosion from construction sites.

Practical Measures of Resilience in the Lake System

In principle, resilience could be measured by fitting a dynamic model to time series, calculating equilibria, and calculating the size of the basin of attraction, as shown in Figure 1. In practice, obtaining adequate fits of such models requires extraordinary data, which are not usually available (Carpenter 2001). Instead of fitting models, one can use insights from models to identify indicators of resilience. In the case of lake eutrophication, such indicators include soil P concentration, animal stocking densities, and land area under construction, which are inversely related to the resilience to the clear-water state. On the institutional side, possible indicators include the flexibility of farmers to mitigate nonpoint pollution from their lands. Can farmers afford to leave riparian lands and wetlands undisturbed? Do farmers have enough understanding and the economic means to balance the farm P budget? Is there public support for controlling nonpoint pollution? Economic indicators would focus on the degree to which externalities were captured by the market—for example, through a market for P permits or quotas (Scheffer and others 2000). Social indicators could include the existence of networks that are capable of facilitating appropriate action, or the balance of power and response time across interest groups (Scheffer and others 2000).

The Adaptive Cycle for the Rangeland System in Practice

The most common pattern of rangeland dynamics in Western NSW is not unlike that described for the lakes of Wisconsin under modern agriculture. The ecosystem goes through a steady decline in grass cover and frequency of fires until the woody stage is reached, and it tends to stay in that state. Aboriginal people used fire to open up the country, and native browsers may have helped to stimulate the growth of grassy cover. When the pastoralists arrived, they exploited this situation. Grazing, the eviction of Aboriginal peoples, the cessation of burning (and perhaps the extinction of native browsers), an increase in the density of artificial water points, and the associated increase in herbivore biomass all hastened an increase in shrub density.

Heavy grazing pressure evolved out of the pastoralists' need to remain economically viable. For 90 years, until a policy change in 1968, a close settlement policy subdivided large land holdings and reassigned the subdivisions to other leaseholders. The smaller blocks could only be viable if they were heavily stocked. After the policy was reversed to one promoting amalgamation, adverse trends in wool prices and high production costs made financial sustainability a moving target. By the late 1980s, many holdings were still too small to be viable, redoubling the incentive to stock heavily (MacLeod 1990). Heavy grazing pressure is also a consequence of grazing by other species. Total grazing pressure is often more than twice the pressure caused by sheep alone. It includes grazing by kangaroos, rabbits, and feral goats, as well as sheep. In terms of wool production, there has been a decline in the productivity of particular areas of rangeland due to the loss of perennial grasses and the expansion of shrubs.

As shown in Anderies and others (2001), if the effect of shrub encroachment on grass production is not too severe, then it actually pays the pastoralists to stay in the woody state. The costs in terms of foregone production needed to allow enough grass fuel to accumulate to enable periodic burning would actually be higher than the increased wool production obtained by keeping fire in the system. Extensive areas in the region are now infested with shrubs. Once this state occurs, the options for getting out of it are very limited. The process of letting the woody plants grow old and die, destocking, and thereby allowing fire management to be reintroduced takes too long for the pastoralists to profit by it.

The restriction of ecosystem services to a focus on wool production was due to the system of property rights established in the 19th century when the area was settled by Europeans. The region was designated as publicly owned, and it remains so. Pastoralists were granted long-term leasehold rights to grazing—and *only* grazing. The right to crop must be negotiated and licensed. Financial viability must be demonstrated. Timber is owned by society; a license must be obtained and a royalty paid to use it. Restrictions on the clearing of native vegetation under Aboriginal heritage, conservation, and endangered species legislation and statutory environmental plans reduce the inhabitants' freedom to clear the land, to maintain pasture, and to diversify into charcoal production. The cost of engaging in charcoal production is also raised by royalty payments. Diversification into nonagricultural uses may require the agreement of Aboriginal native title claimants. Finally, although graziers can purchase licenses to shoot kangaroos, the licensing arrangements are complex, and a strong market monopoly limits their freedom to sell kangaroo meat. In terms of the ability of pastoralists to survive market shocks, restrictive lease conditions reduce the overall resilience of the pastoral enterprise (as opposed to the specific case of the resilience of wool production to changes in grass production) on a generational time scale.

The transaction costs of diversification are thus high, and the potential rewards are low in comparison. As long as wool prices were high, these restrictions were not an issue, but prices declined over the last decade (at least until 2001). The declining wool prices, exacerbated by declining local-scale productivity and increasing production costs, have forced many pastoralists from the land. However, there has been a recent trend toward the conversion of sheep properties to goat operations, driven by a change in the relative prices of wool and goat meat. Due to the growing demand for goat meat, both within Australia and overseas, in the past decade goats have gone from having almost no economic value to being worth more than sheep. Also, although shrubs have a negative effect on wool production, they have a positive one on goat meat production, since goats are mixed feeders and browse on shrubs that are palatable. Browsing helps to control the shrubs, thus maintaining resilience.

We believe that three forms of the adaptive cycle have occurred in those parts of the region where shrub encroachment is an issue. First, on land systems where the competitive effect of shrubs on grass is low, the system has moved from an initial r stage with a high grass:shrub ratio (the condition under Aboriginal use) to a shrub-dominated K stage in which wool production continues, albeit at a lower level. The costs of getting back into a grass–shrub state (that is, foregone immediate wool production due to destocking to allow sufficient fuel to accumulate) are higher than the discounted future increase in wool production. Second, in a very few cases, conservative stocking has been used to keep the system in a grass–shrub state by smaller, induced Ω phases (deliberate use of fire), followed by restructuring and the subsequent maintenance of an r stage through resting and burning, coupled with browsing by feral goats. Third, those land systems where the competitive effect of shrubs on grass is substantial are now displaying an Ω to α dynamic of financial collapse (wool prices plus loss of grass production), followed by the novelty of changing from the production of sheep wool to goat meat. Over most of the region, woody density is not yet in an advanced K stage. Because adverse trends in wool prices and the high costs of production have discouraged destocking and burning to control shrubs, these land systems will not be returned to a system dominated by wool production unless there is an unexpected and sustained resurgence in the demand for wool.

The history of the cross-scale subsidization of resilience has lessons for the future use of the rangelands. Relatively nonconsumptive uses, such as tourism plus nature conservation, have been proposed as replacements for wool production. These uses are unlikely to be established without public investment—a cross-scale subsidy. However, oversubsidization would result in the overcommitment of private means of production to an industry that is also subject to declines in demand, just as wool proved to be. In these circumstances, resilience theory advises us to allow in just enough disturbance to maintain the resilience of the system. Variety in land use increases resilience.

Practical Measures of Resilience in the Rangeland System

For wool production from rangelands, the measure of resilience of the desirable state (the grass [G]–woody shrub [W] state) is the distance in Figure 3 between the unstable and stable equilibria of the grass root and shoot isoclines—the amount of change in grass root biomass before the joint stable equilibrium of roots and shoots disappears and the system flips to the attractor with no grass and abundant shrubs. Walker and others (1981) offer a related interpretation of these dynamics. As W (the slow variable in the system) increases, the amount of grass that can be used decreases. For pastoral production in general, the change to goats and other enterprises overcomes to some extent the problems posed by this particular issue of resilience. However, the dynamics of a system of grass, shrubs, and goats have yet to be played out. Goats are selective browsers; and in the absence of fire, unpalatable woody species (such as those in the genus *Eremophila*) tend to increase in relative abundance until they are dominant. The measure of resilience may therefore change from W per se to the proportion of W that consists of unpalatable shrubs. This situation raises the issue of biodiversity and resilience.

Walker and others (1999) have shown that a loss of perennial grass species that occur in only very small amounts in ungrazed rangeland reduces the capacity of the rangeland to continue functioning ecologically (in terms of growth rates, water use, carbon storage, nutrient cycling) under heavy grazing. The dominant grasses tend to be functionally dissimilar (that is, they are complementary) to each other; and when dominant grass species are lost through their sensitivity to heavy grazing, they tend to be replaced, as dominants, by functionally similar species from among those that occur in only small amounts in the ungrazed ecosystem. A loss of grass species reduces the functional diversity of the grass layer and therefore its capacity to continue performing at its former levels. Little is known about the functional diversity of the woody species, beyond the fact they differ in regard to their palatability to animals, their responses to fire, and their drought-resistance. In the absence of specific information such as that given in Walker and others (1999), it is prudent to assume that a reduction in the biodiversity of the ancestral ecosystem (or a change in biodiversity to a somewhat different complement of species, albeit at the same levels) will reduce the resilience of the system in terms of its ability to keep functioning ecologically in the face of external shocks (climate, herbivores, fire).

Considering the pastoral system as a whole, two indicators of socioeconomic resilience emerge. The first is property rights. The restricted leasehold conditions for graziers reduce the resilience of the farming enterprise on a generational time scale. If they could more easily harvest wood for charcoal, market their own kangaroos, and undertake opportunistic cropping, economic resilience would be somewhat enhanced. (Cropping, however, degrades soils and can only enhance resilience over a span of a few decades.) The second of these indicators is market conditions, such that different potential uses of ecosystem services offer similar economic opportunities. Even under the regime of constrained property rights, the option to change from sheep to goats was not viable until the profitability of wool and goat meat production became roughly comparable. The greater the number and equitability of potential uses of ecosystem goods and services, the higher the resilience of the SES.

A Comparison of the Case Studies

In both lakes and rangelands, early management efforts focused on rapidly changing variables (water quality itself and grass). The slowly changing variables (soil or mud P and woody vegetation) were more difficult to recognize and also proved more difficult to manage. Several decades of research were required to establish the role of P in lake eutrophication (Smith 1998), and the trend toward increasing soil P was not clear until decades after widespread eutrophication was first described (NRC 1993; Bennett and others 2001).

In the rangelands, it took some decades after the properties were first grazed for the emergence of shrubs to become a problem. However, by the end of the 19th century, official reports expressed concern about the expansion. The problem persisted for a long time. We explained this earlier in terms of policy favoring small properties and adverse trends in wool prices and production costs. It is possible that certain strongly held (but incorrect) views about the causes of encroachment were a contributing factor. The increase in shrubs was episodic in nature and occurred concomitantly with the introduction of rabbits, cycles of droughts and flooding rains, the loss of small native herbivores that played a role in shrub dynamics, and large increases in kangaroo numbers. Because these changes correlated with shrub encroachment, any one of them could be used to explain it. But the fundamental cause had nothing to do with them: For many land systems, the woody configuration is within a stable domain of attraction determined by soil moisture. Once fire was removed, the direction of change on these land systems was inevitable. This fact was seldom acknowledged, and other firmly held viewpoints prevailed. The weight of evidence in scientific and other publications has gradually led to a merging of the real-system dynamic with various models (both tacit and explicit) of how the rangelands work.

In the lakes, the slow variable is determined by one group of people (the farmers), and the effects are felt by the community at large. In the rangelands, the whole ecological problem is internalized within the agricultural economy. The landholder must deal with the economic consequences of his or her own management practices.

In both lake districts and rangelands, the pattern is for a movement into the undesirable state without a return to the desirable state. In the lakes, there are repeated and rapid reversions from a new r phase back into Ω. So far, the SES has not developed in a way that harmonizes agriculture with freshwater ecosystem services. The incompatibilities between agricultural practice and freshwater ecosystem services are intensifying, and conflicts may become more common. In the rangelands, three versions of the adaptive cycle are thought to have occurred. Very few pastoralists have managed to get out of the woody state, but a new socioeconomic dynamic is leading to a change from sheep to goat production (an α dynamic). The new r phase is

Table 1. Resilience Measures for Lake Districts and Rangelands

Characteristic of the System	Lake District	Rangeland
Resilience *of* what	Clear-water state	Grass + shrub state
Resilience *to* what	Short-term increase in P input due to weather or human disturbance	Short-term change in climate, herbivory, fire
Measure in model	Size of basin of attraction measured as distance between stable point and unstable threshold in units of water P concentration (mass/volume)	Size of basin of attraction measured as distance between stable point and unstable threshold in units of grass root biomass (mass/area)
Biophysical field measures	Soil P (mass/volume) or stock density (animals/area)	Shrub:wood ratio (mass/area):(mass/area)
Interpretation of biophysical measures	Directly related to size of perturbation; inversely related to attractor size	Inversely related to attractor size
Socioeconomic field measures	P pollution costs represented in market	Leaseholder flexibility to obtain income from shrub clearing (e.g., charcoal); or low discount rate
Intepretation of socioeconomic measures	Incentive to stabilize soil P or decrease it if it is high	Incentive to prevent shrub cover from increasing, or to reduce shrub cover if it is high

likely to alter the ecosystem dynamics (due to the browsing capacity of goats) and reduce the sharp distinction between the grass–shrub and grass states. The rangelands system is therefore likely to be resilient in terms of pastoral production (as opposed to wool production), and the adaptive cycle will include changes in pastoral enterprises.

Challenges and Limitations of Measuring Resilience

Resilience Measures and Indicators

Although resilience assessments for lake districts and rangelands differ in their specifics, they share several qualitative characteristics (Table 1). In these cases—in fact, in *all* cases—it is crucial to specify what system state is being considered (resilience *of* what) and what perturbations are of interest (resilience *to* what). The measurements that are made in models are based on sizes of basins of attraction derived from quasi–steady-state analyses. The model-based definition of attractor size may be difficult or impossible to measure under field conditions. However, surrogate indicators can be defined that should change monotonically with resilience. In both the lake districts and the rangelands, biophysical surrogates for resilience are based on slowly changing variables. Socioeconomic surrogates are related to the flexibility of agents to negotiate local solutions to the problem and the existence of incentives to increase resilience.

Resilience measures differ in two important ways from ecological indicators as they are usually constructed. First, resilience applies to the entire SES, not just the ecological subsystem. Second, resilience focuses on variables that underlie the capacity of the SES to provide ecosystem services, whereas other indicators often address only the current state of the system or service.

Some general guidelines for resilience indicators emerge from our comparison. The likelihood that a SES will stay within a domain of attraction is related to slowly changing variables that determine the boundaries and the magnitude of disturbances that may push the system out of the domain of attraction or reconfigure the domain of attraction. In the lake district, examples are soil P, sediment P, and the frequency of large runoff events. In the rangeland, examples are woody vegetation and leasehold arrangements. Land-tenure systems and the characteristics of the culture are important slow variables in other SES (Hanna and others 1996; Scheffer and others 2000).

Indicators of the ability to self-organize should assess the extent to which system components are forced by the management regime rather than self-organizing within the management regime (Folke and others 1998). For example, in forested regions, management that rigorously suppresses fire leads to uniform vegetation and high fuel loads, thereby setting the stage for massive conflagration. In contrast, fire management that allows a mosaic to develop (while protecting buildings and people) leads to more diverse, persistent ecosystems. In both the lake district and the rangeland, economic and institutional constraints on agriculturalists limit their ability to organize in ways that would improve water quality or biodiversity, respectively. In the lake districts, farmers are locked into a path of incrementally increasing financial efficiency that will allow them to survive economically, but this "efficiency" leads to excessive fertilization, overstocking, plowing riparian lands, and increased pollutant discharges. In the rangelands, lease terms have limited the ability of pastoralists to diversify into cropping and charcoal production, both of which would have helped to control woody vegetation and maintained resilience at the generational time scale. These controls have, however, prevented soil degradation and maintained options for future generations, since shrub encroachment is a highly effective mechanism for protecting landscape function and variety is a source of resilience.

Indicators of adaptive capacity should address the ability of SES to cope with change. In biotic systems, adaptive capacity is related to genetic diversity (because the rate of evolution is proportional to the variability that selective forces can work on), biodiversity (for example, portfolio effects) (Loreau 2000), and the heterogeneity of landscape mosaics (Peterson and others 1998). The example given earlier (Walker and others 1999), showing how functional diversity among the grass species in a rangeland confers resilience to changes in climate and grazing pressure, is a specific example of how biodiversity enhances adaptive capacity. In social systems, adaptive capacity is related to the existence of networks that create flexibility in problem solving and to the balance of power among interest groups (Scheffer and others 2000). Folke and others (1998) have described a number of social mechanisms that create adaptive capacity. One example is the building and cultural transmission of local ecological knowledge in traditional resource management systems. In addition, an understanding of the dynamics of the SES is fundamental to building resilience (Scheffer and others 2000; Kinzig and others 2000).

In human systems, adaptive capacity is closely related to learning. The mismatch in the Australian rangelands between the various stakeholders' viewpoints and the real dynamics of the ecosystem contributed to a delay in their understanding of the problem and thus the implementation of appropriate responses. Delayed learning also appears to have been a factor in the slow acceptance by policy makers of the effects of their close settlement policy on stocking densities. Learning is central to the notion of adaptive management (Gunderson and Holling 2001). Among the key elements of this idea are the needs to consider a range of plausible hypotheses about future changes in the system; to weigh a range of possible strategies against this wide set of potential futures; and to favor actions that are robust to uncertainties, reversible, and likely to reveal crucial new information about system function. Learning is advanced by institutions that can experiment in safe ways, monitor results, update assessments, and modify policy as new knowledge is gained. The development of such institutions may be the greatest challenge to sustainability (Berkes and Folke 1998; Gunderson and Holling 2001).

Parameters That Aren't

We have discussed resilience in terms of slow and fast variables—mud and water P in the case of lakes and woody shrubs and grass in the case of rangelands. In general, we speak of systems being resilient to events (perturbations) that affect fast(er) variables.

We can conceive of the slow variables as defining the underlying structure of the system, while the fast variables reveal the dynamics of this underlying structure. In this case, we think of perturbations as displacing the system from a particular configuration and the underlying structure as determining how the system will evolve after the displacement. Does the system return to the configuration from which it was displaced? Or does it move into another configuration? In modeling these processes, it is sometimes convenient to fix the slow variables by treating them as parameters (Rinaldi and Scheffer 2000) and then analyze quasi-steady states as in Figures 1 and 3. Walters (1986) cautions us to remember that such parameters are not truly fixed, but are in fact slowly changing and are subject to alteration by policy choice. Hence, they are "parameters that aren't." Perturbations may produce a displacement and an underlying change in slow variables that alters the stability landscape and the subsequent trajectory the system will take. For example, in Figure 3, increased grazing pressure shifts the root biomass isocline upwards, which in turn reduces the resilience of the system to perturbations in root/shoot biomass. What effect would be produced by perturbations in the grazing pressure brought about by changing market conditions? It would depend on the sensitivity of the position of the shoot isocline to changes in grazing pressure. If it was highly sensitive, a small perturbation in grazing pressure could cause the domain of attraction to collapse quickly, reducing the resilience of the system.

Thus, from a measurement perspective, we must also ask how slow-variable dynamics affect resilience. For a particular fixed value of a slow variable, the system may be extremely resilient. But if the slow variable changes only slightly, the system could lose resilience quickly. Failure to recognize this situation might lead to a miscalculation of the resilience of the system.

Finally, it is important to distinguish between resilience (which is measured by the size of basins of attraction) and resistance (which is measured by the external force or pressure needed to disturb—that is, displace—a system by a given amount). Basins of attraction are measured in terms of distances in state space. This parameter does not capture any information about the magnitude of the physical disturbing force required to move the system to the boundary of the basin. Two systems (or one system at different points in time) may have the same resilience but differ in their resistance, as measured in terms of how much they are displaced (or disturbed) by a given physical force or pressure. What we want to know is how great an external force the system can withstand before it crosses the boundary of its basin of attraction. This depends on both resilience and resistance (Figure 5).

The curves in Figure 5 depict this relationship for two representative systems. The horizontal lines indicate the resilience of the respective systems in terms of attractor size. The curves depict resistance—the displacement in state space as a function of increasing physical pressure. System A is more resilient than B, but B is more resistant than A. In this hypothetical example, although system A is more resilient, system B will be more persistent than A under a given disturbance regime.

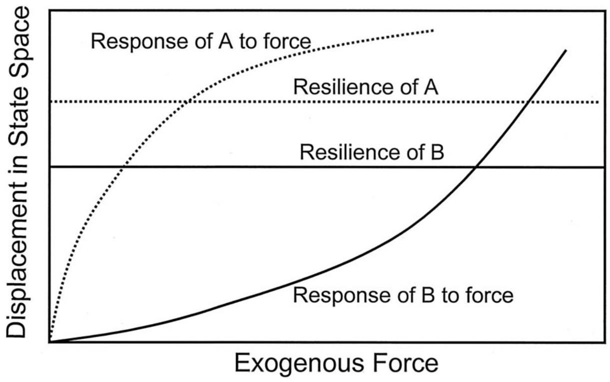

Figure 5. Displacement versus exogenous force. The curves depict the relationship between force and the distance in state space as the system moves from equilibrium for two hypothetical systems, A and B. System B is more resistant to displacement than system A. The horizontal lines indicate the resilience of the systems. System A is more resilient than system B. The intersection of a curve and line for a given system indicates its persistence—that is, the level of exogenous forcing the system can tolerate before moving to a new domain of attraction.

Future Directions

Ecosystems are ever-changing, and they are embedded in a world in which many other things are also changing continuously at various spatial scales (Levin 2000). Consequently, relationships fitted to extant observations will always become outdated as system change makes them irrelevant and misleading. Indicators of resilience that are appropriate for the current regime may become useless as ecological structures and social expectations shift. Therefore, sustained ecological research at the scale of human action is essential for resilience. A resilient monitoring program needs to invest part of its endowment in a set of indicators that seem likely to be relevant for the foreseeable future and the remainder in explorations of system function that lead to new indicators that may become important under new configurations of the SES.

It may seem obvious to expect that researchers should clearly state which aspect of resilience is being measured and what sorts of drivers are being considered. However, resilience in one time period or at a particular scale can be achieved at the expense of resilience in a later period or at another scale. Understanding these transfers across scales and time periods is a research priority. Moreover, confusion can be avoided by answering the question, "Resilience *of* what *to* what?"—that is, over what time period and at what scale.

Much of our analysis is focused on slowly changing variables—state variables with slow turnover rates or stochastic processes with long return times. Learning about slow variables takes a long time, so it is easy to miss important processes or focus attention on the wrong hypotheses. Such errors of judgment can lead to surprises in both management and basic research. The best way to cope with surprise is resilience—that is a broad basin of attraction for the socially preferred ecosystem state and the social flexibility to change and adapt whenever ecosystem services are altered in an unexpected way.

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