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Walker, B. H., L. H. Gunderson, A. P. Kinzig, C. Folke, S. R. Carpenter, and L. Schultz. 2006. A handful of heuristics and some propositions for understanding resilience in social-ecological systems. *Ecology and Society* **11**(1): 13. [online] URL:http://www.ecologyandsociety.org/vol11/iss1/art13/

Insight, part of a Special Feature on Exploring Resilience in Social-Ecological Systems

A Handful of Heuristics and Some Propositions for Understanding Resilience in Social-Ecological Systems

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ABSTRACT. This paper is a work-in-progress account of ideas and propositions about resilience in social-ecological systems. It articulates our understanding of how these complex systems change and what determines their ability to absorb disturbances in either their ecological or their social domains. We call them “propositions” because, although they are useful in helping us understand and compare different social-ecological systems, they are not sufficiently well defined to be considered formal hypotheses. These propositions were developed in two workshops, in 2003 and 2004, in which participants compared the dynamics of 15 case studies in a wide range of regions around the world. The propositions raise many questions, and we present a list of some that could help define the next phase of resilience-related research.

Key Words: *resilience; social-ecological systems; change; propositions; synthesis; theory; adaptatability; transformability*

INTRODUCTION

The comparisons of the 15 regional case studies described in this special issue (Walker and Lawson 2006) gave rise to an emerging understanding about how such systems change and how resilience could be gained or lost under different circumstances. An initial, tentative set of statements about change came from a first workshop in 2003 in Sweden. That set was then discussed and evaluated during a second workshop in 2004 in Australia, leading to a somewhat more refined set of statements together with a set of research questions. Because they are still tentative and lack rigorous testing, we called them “propositions,” i.e., statements that can be true or false. They are an attempt to make explicit our present understanding and our underlying mental models of change. They provide a starting point for us and others to test concepts of how change occurs in complex social-ecological systems. We expect that these propositions will be elaborated, modified, or discarded as more information becomes available about change in social-ecological systems. We will be disappointed if this paper does not seem obsolete in a few years.

This paper summarizes the propositions. Length limitations preclude anything but a fairly general overview. However, each of the papers that follow in this *Special Issue on Exploring Resilience in Social-Ecological Systems* examines a subset of the following propositions in greater detail, offering more examples and exploring nuances.

FIVE PRELIMINARY HEURISTICS

The propositions derive from prior work aimed at understanding abrupt change in managed resource systems (Gunderson and Holling 2002, Berkes et al. 2003, Walker et al. 2004, to cite just three from a long list). That prior work suggests that social-ecological systems sensu Walker et al. (2004) are neither humans embedded in an ecological system nor ecosystems embedded in human systems (Westley et al. 2002), but rather a different thing altogether. Alhough the social and ecological components are identifiable, they cannot easily be parsed for either analytic or practical purposes. Case studies (Gunderson et al. 1995, Berkes and Folke 1998, Gunderson and Holling 2002) and models (Carpenter 2003, Carpenter and Brock 2004) indicate that pathologies of management occur when the stabilization of key ecological processes

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for economic or social goals leads to a loss of resilience. The loss of ecological resilience (Holling 1973, 1996) tests the adaptive capacity of the human dimensions of the system. Patterns of abrupt change (Gunderson 2003) are described, in a handful of heuristics, by (1) an adaptive cycle, (2) panarchy, (3) resilience, (4) adaptability, and (5) transformability. The first two describe the dynamics of systems within and across scales, whereas the last three are the properties of social-ecological systems that determine these dynamics. Each is described in the following sections, and together they provide the foundation for the subsequent propositions.

Adaptive cycle

Over time, the structures and functions of systems change as a result of internal dynamics and external influences, resulting in four characteristic phases described by Holling (1986, 2001) for the dynamics of ecological systems. The first is a phase of growth (*r*), characterized by readily available resources, the accumulation of structure, and high resilience. As structure and connections among system components increase, more resources and energy are required to maintain them. The second phase is thus one in which net growth slows and the system becomes increasingly interconnected, less flexible, and more vulnerable to external disturbances. This is described as the conservation phase (*K*). These two phases, *r* to *K*, called the fore loop, correspond to ecological succession in ecosystems and constitute a development mode in organizations and societies. Disturbances lead to the next phase, a period of release of bound-up resources (Ω) in which the accumulated structure collapses, followed by a reorganization (α) phase, in which novelty can take hold, and leading eventually to another growth phase in a new cycle. These two phases are referred to as the back loop. The new *r* phase may be very similar to the previous *r* phase, or it may be quite different. Many systems appear to move through these four phases, described as the adaptive cycle, including ecosystems (e.g., Holling 1986), social systems (e.g., Westley 2002), institutional systems (e.g., Janssen 2002), and social-ecological systems (e.g., Gunderson et al. 1995, Holling et al. 2002).

Panarchy

Social-ecological systems have structures and functions that cover wide ranges of spatial and temporal scales. Most structures are not scale invariant, but rather occupy discrete domains in space or time. All of these structures are posited to change in the phases described in the previous paragraph at a given scale. Structures and processes are also linked across scales, based on the interactions between slow and broad structures and processes as well as those that are fast and small. These interactions can be characterized as either hierarchical confinement or panarchical relations. Hierarchical confinement is demonstrated when slow, broad features constrain and shape the small, fast ones (Allen and Starr 1982, O'Neill et al. 1986). Panarchical relations suggest that both top-down and bottom-up interactions occur (Gunderson and Holling 2002). The dynamics of a system at a particular scale of interest, i.e., the focal scale, cannot be understood without taking into account the dynamics and cross-scale influences of the processes from the scales above and below it. Examples include disturbance dynamics such as forest fires (Peterson 2002), forest pest outbreaks (Ludwig et al. 2002), or Native American societies (Delcourt and Delcourt 2004). Recent work on resilience suggests that many of the observed shifts, crises, or nonlinearities observed in ecological systems are from processes and structures interacting across scales (Gunderson and Holling 2002, Walker and Meyers 2004).

Resilience

Resilience is the capacity of a system to experience shocks while retaining essentially the same function, structure, feedbacks, and therefore identity. It follows Holling's (1973) notion of resilience as the amount of disturbance a system can absorb without shifting into an alternate regime. Social-ecological systems exhibit thresholds that, when exceeded, result in changed system feedbacks that lead to changes in function and structure. The system is said to have undergone a regime shift (e.g., Scheffer et al. 2001, Carpenter 2003) that may be reversible, irreversible, or effectively irreversible, i.e., not reversible on time scales of interest to society. The more resilient a system, the larger the disturbance it can absorb without shifting into an alternate regime.

In general, the state of a system at any one time can be defined by the values of the variables that constitute the system. For example, if a rangeland system is defined by the amounts of grass, shrubs, and livestock it contains, then the state space is the three-dimensional space of all possible combinations of the amounts of these three variables. The dynamics of the system are reflected as its movement through this space. In complex ecological and social-ecological systems, the term “alternate states” is a misnomer. Configurations of states in which the system has the same controls on function, i.e., the same feedbacks, and essentially the same structure represent different states within the same system regime. Configurations in which the kinds or strengths of feedbacks differ and in which there are different internal controls on function represent alternate system regimes with thresholds between them. These alternate regimes can have significantly different implications for society and so, from a purely human point of view, may be considered desirable or undesirable. That desirability can be expressed in economic terms (Carpenter and Brock 2004); in ecological terms, i.e., the flow or production of ecosystem services (Walker and Meyers 2004); or in social terms (Scheffer et al. 2000, 2002). Some system regimes may be considered desirable by one segment of society and undesirable by another. In addition, some regimes that are considered undesirable can also be very resilient, e.g., harsh dictatorships and desertified regions of the Sahel.

Adaptability

Adaptability is the capacity of the actors in a system to manage resilience. Complex adaptive systems are generally characterized by self-organization without system-level intent or centralized control. Humans, however, are unique in having the capacity for foresight and deliberate action, and self-organization in complex social-ecological systems is therefore somewhat different from that in ecological or physical systems (Westley et al. 2002). On the one hand, it can be argued that, although the dynamics and direction of change in such systems are influenced by individuals and groups that have intent, the system as a whole does not, as in the case of a market. However, because human actions dominate social-ecological systems, the adaptability of such systems is mainly a function of the individuals and groups managing them. Their actions influence resilience, either intentionally or unintentionally (Berkes et al. 2003). Their capacity to manage resilience with intent determines whether they can successfully avoid crossing into an undesirable system regime or succeed in crossing into a desirable one.

Transformability

Transformability is the capacity to create a fundamentally new system when the existing system is untenable (Walker et al. 2004). Social-ecological systems can sometimes get trapped in very resilient but undesirable regimes in which adaptation is not an option. Escape from such regimes may require large external disruptions or internal reformations to bring about change (Holling and Gunderson 2002). The transformation of a social-ecological system can be in response to the recognition of the failure of past policies and actions, triggered by a resource crisis, or driven by shifts in social values (Gunderson et al. 1995). Although transformations generate novel system configurations, the pathways and mechanisms that drive transformations are not well understood and are one of the foci of the case comparisons in this volume.

PROPOSITIONS

The heuristics described in the preceding section provide a starting point for this set of propositions, which represent our current understanding of change in social-ecological systems. For simplicity and clarity, the propositions are worded as positive, direct statements. We emphasize, however, that they are tentative patterns based on limited experience. Almost certainly they will be expanded, modified, or rejected by future work.

Proposition 1: Modes of reorganization

The adaptive cycle accounts for abrupt and nonlinear change by describing phases of creative destruction and reorganization. These phases are not as well understood as are the growth (r) and conservation (K) phases. In the ecological model, release and reorganization occur when an exogenous disturbance such as a fire or pest outbreak intersects with internal vulnerability such as accumulated fuel or food in a late K phase (Holling 1986). Both the triggers and the patterns of reorganization may be different for social-ecological systems.

During release and reorganization, the system is most vulnerable to change, because it is in these phases that the effects of the linkages between the system of interest and systems at other scales become more pronounced. For example, following a fire in an ecosystem, the type of seeds that arrive post-burn and weather conditions such as rainfall determine the shape and form of the reorganization. Hence, the shape and form of the linkages outside the system during these phases are critical (Peterson et al. 1998, Adger et al. 2005).

Some resources in the system are depleted following the release phase, whereas others are recombined, reused, and rebuilt. Resources can also be acquired. The dynamics of these resources and their interrelations determine how the system reorganizes. In ecological systems, for example, nutrients and remnant seed sources are critical elements for reorganization. In social systems, resources and linkages such as trust, institutions for self-determination, social networks, physical capital, or financial reservoirs come into play during these phases.

Loss of capital of all kinds during release restricts the reorganization options for the composition of the new growth phase. Too much loss of capital can lead to system configurations that are depauperate and stable, also described as “poverty traps” (Holling et al. 2002). Parts of the Sahel are seemingly examples of such traps.

Summary proposition: Multiple modes of reorganization are possible during phases of release and renewal in a social-ecological system. Because of this, managers need to consider multiple approaches during such periods.

There are a few dominant modes of reorganization possible during phases of release and renewal. Although managers cannot completely dictate the trajectory taken, the maintenance of critical resources and the management of cross-scale linkages (see below) can increase the probability of desirable outcomes.

Proposition 2: Variations in the adaptive cycle

The adaptive cycle does not apply to all situations and is not a useful metaphor for all system dynamics. Cumming and Collier (2005) describe various kinds of systems that do not fit this “meta-model,” as they call it. Where it is an appropriate explanation, the adaptive cycle is depicted as a sequence that passes from a growth phase to a conservation phase, a release phase, a reorganization phase, and back to a growth phase. However, the pattern does not necessarily reflect a cycle, and alternative sequences of the phase transitions have been identified. For example, there may be:

- no release phase involving a loss of capitals. Alternative forms of reorganization occur. An ecosystem example is the transition from a bog to a forest as a consequence of a slowly accumulating substrate and decreasing water level. The ability of the bog to self-organize and resist invasion by trees is eventually overwhelmed, and reorganization into a forest occurs, but without any creative destruction phase involving a loss of nutrients, etc. In social systems, a democratic election can be viewed as a programmed instability, with a resulting reorganization of political power. There is a breaking of controls with room for new players, but no loss of resources.

- no conservation phase. Some systems with little structure and large resilience may be subject to reorganization. If the external disturbance is so large that it cannot be absorbed, even in an *r* phase configuration, the system becomes disordered. A vigorous young forest is resilient to storm damage without changing identity, but a major hurricane will destroy it. An emergent market may be resilient to price fluctuations and continue to develop, but a major currency drop or stock market collapse may destroy it.

- no structure emerges. Reorganization begins, but loss of capital or another external disturbance or cross-scale impact quashes innovation, and the system again becomes disordered. This is what happened in the Southeast Zimbabwe case study (Walker and Lawson 2006).

- persistent phases. Some social-ecological systems can persist in a state between *r* and *K* for long periods of time, and spend resources to buffer the system, adapt, and maintain structure.

Summary proposition: The four phases of the adaptive cycle appear to explain the dynamics of change in many systems. Nonetheless, exceptions to the adaptive cycle occur, particularly under the influence of large, external disturbances and a lack of critical forms of capital.

Proposition 3: Cross-scale interactions

For systems at a particular focal scale that demonstrate the phases of an adaptive cycle, their trajectory depends on both bottom-up and top-down cross-scale interactions.

Adaptive cycles at one level can be repeated if higher-level cycles of the panarchy provide “memory,” and the role of memory is strongest when the higher-level cycle is in the conservation phase. Memory in an ecological system can be in the form of a seed bank, whereas memory in a social system is held in organizations and institutions. The panarchical connection between scales provides opportunities for memory and learning from the higher scales to influence and renew lower scales, facilitating or inhibiting new trajectories in the lower scales. New adaptive cycles can emerge when this memory is disrupted because adaptive cycles at higher levels of the panarchy are themselves in a back loop, or even in an early growth phase, with many system trajectories still possible.

The term “revolt” is used to describe change that originates at smaller scales, but moves across scales to broader spatial scales or longer temporal scales. Revolts can occur either because lower-level cycles are synchronized, and thus all enter a back loop at the same time, or because they are tightly interconnected, so that a back-loop transition in one cycle triggers such a transition in the other cycles. In ecological systems, even-aged patches of vegetation at the same small scale across the landscape allow for the propagation of disturbances such as pest outbreaks or fire across large spatial scales, whereas heterogeneous landscapes stop such propagation.

Summary proposition: Cross-scale interactions critically determine the form of the subsequent adaptive cycle at any particular focal scale.

Proposition 3A: Reiterations of adaptive cycles are driven by higher-scale influences, such as memory.

Proposition 3B: Synchronization of adaptive cycles at lower levels influences the potential for upscale “revolt.”

Proposition 4: The “rule of hand”

Although social-ecological systems are self-organized through interactions among large numbers of biotic and abiotic variables, the most important changes can be understood by analyzing a few, typically no more than five, key variables (Yorque et al. 2002). This is the “rule of hand.” More complex models are not necessary to explain the key interesting patterns and, in fact, are likely to mask them. This is both because generally humans can only understand low-dimensional systems and because, empirically, it appears that only a few variables are ever dominant in observed system dynamics. The essential dynamics of all the case studies in this special issue involved fewer than five key variables at any one scale.

Summary proposition: Critical changes in social-ecological systems are determined by a small set of three to five key variables, i.e., the “rule of hand.” To understand change in systems, it is important to identify this small set.

Proposition 5: Fast and slow variables

Resilience in systems is determined by the interactions of a few key variables that operate at different scales, e.g., slower and faster rates in time or smaller or larger extents in space. Because these variables influence the overall dynamics of the system, they are therefore of direct interest to managers, who are frequently focused on fast variables. In ecosystems, the variables that control regime shifts, such as soil, sediment concentrations, or long-lived organisms, tend to change slowly. Examples, mostly from the case studies, include hydrology in Gorongoza in Mozambique and the Goulburn-Broken Catchment in Australia, sediment chemistry in Wisconsin lakes, and ecological succession to woodland/forest in New South Wales, Australia, and Kristianstad, Sweden. In social systems the controlling variables may change rapidly, e.g., fads or technology, or slowly, e.g., culture.

Two kinds of “slow” variables must be considered, and the differences between them may have important consequences for resilience. One is characterized by a slow rate of change, the other by a low frequency of change.

Summary proposition: Slowly changing variables control ecological resilience, whereas social resilience is controlled by either fast or slow variables.

Proposition 6: Ecological vs. social domains

It is unclear whether a common framework of system dynamics can be used to examine and explain both social and ecological systems. For instance, there are numerous published examples of alternate regimes and thresholds in ecological systems (Walker and Meyers 2004), but few clear examples in the social domain with the important exception of Brock (2004). Do social systems have attractors equivalent to those that have been shown for ecological systems?

Coupled social-ecological systems may have very different dynamics when compared to the ecological component, because the social domain contains the element of human intent. Management actions can deliberately avoid or engineer the crossing of actual and perceived thresholds.

Undesirable ecological attractors are often created through attempts to maintain preferred social regimes, e.g., salinized agricultural systems (Anderies 2005). If this persists or deepens in intensity, a transformative change leading to the creation of a fundamentally new system may be required. Additionally, perceptions may create attractors or repellors, as in the theory of rational expectations (Yorque et al. 2002) or in processes of envisioning scenarios or models of change (Peterson et al. 2003 *a,b*).

Cultural conservatism may be an example of a slow social variable. Within institutional frameworks, constitutional and structural changes in governance, e.g., devolution, are much slower than changes in particular rules of use and access to natural resources.

Thus it seems likely that fundamental ideas of scale, relative rate of change, and thresholds apply to social and ecological systems as well as social-ecological systems, although, of course, the specific dynamics may be infinitely varied among such systems.

Summary proposition: The ecological and social domains of social-ecological systems can be addressed in a common conceptual, theoretical, and modeling framework.

Proposition 7: Functional and response diversity

In relation to the dynamics and stability of social-ecological systems, it is useful to recognize two kinds of diversity: (1) functional diversity, i.e., the number of functionally different groups, which influences system performance, and (2) response diversity, i.e. the diversity of types of responses to disturbances within a functional group, which influences resilience.

Functional diversity

In self-organized natural systems, performance in the ecological domain is related to the diversity of functional groups of species. Productivity in savannas, for example, is enhanced by having grasses, nitrogen-fixing forbs, shrubs, and trees with different rooting depths (Scholes and Walker 1993). The structure and function of coral reefs depend on having fish that graze algae, fish that can crunch up dead coral, and fish that eat urchins, i.e., all fish, but each type in a different fuctional group (Bellwood et al. 2004). In simplified agro-ecosystems, performance is narrowly defined as, e.g., crop yield, and increasing the diversity of functional groups does not necessarily enhance performance, although there are examples of multi-cropping tropical systems in which this is true.

In the social domain, performance is related to the diversity of functional actor groups. The concept is simple: The more different types of actors there are, the more functions are performed.

Response diversity

Response diversity, sometimes referred to as "functional redundancy," is the diversity of responses to disturbance among species or actors contributing to the same function in the social-ecological system, i.e., the species within the same functional group. Resilience is enhanced by response diversity (see Elmqvist et al. 2003 for examples from forests, rangelands, lakes, and coral reefs).

In self-organized ecosystems as opposed to, e.g., managed agro-ecosystems, response diversity has been demonstrated across a wide range of examples. In the social domain, the role of social redundancy is unclear. There is some evidence that redundancy in resource governance contributes to resilience in the form of response diversity. It may be that the relationship between resilience and response diversity in the social domain exhibits an inverted U shape, as it does for functional diversity above.

Overlapping, albeit less efficient, governance structures can enhance the resilience of social-ecological systems to external ecological or social shocks and add to the resilience of adaptive governance (Berkes et al. 2003, Dietz et al. 2003, Folke et al. 2005, Ostrom 2005).

Efforts to increase the efficiency of production in, e.g., agro-ecosystems or of performance in, e.g., business operations or governance structures tend to focus on removing apparent redundancies and can thereby reduce resilience.

Summary proposition: Two types of diversity are important for social-ecological systems: (1) functional diversity, which influences system performance, and (2) response diversity, which influences resilience.

Proposition 8: Components of adaptability

Preventing a system from crossing a threshold, or being able to change the underlying structure of the system to move a threshold, requires innovation and skills, agreement on what to do, and a combination of options in terms of access to natural capital, financial resources, and infrastructure. If any or all of these are severely limiting, crossing a threshold may be unavoidable.

Governance, i.e., creating the conditions for ordered rule and collective action (Stoker 1998), and the system of informal rules that constitute the social system's institutions strongly influence the ability of a social-ecological system to respond to disturbances and to changes in resilience. Institutions for monitoring and responding to environmental and social changes, for instance, determine the tightness of feedbacks among social and ecological components.

Social capital is a complex and particularly important aspect of adaptability (Ostrom and Ahn 2003, Pretty 2003). Here we focus on one part of social capital: the social capacity to respond to change. Initial comparisons of the case studies identified three major determinants of social capacity: leadership, social networks, and trust.

Leadership

Given the varying conditions of the different stages of an adaptive cycle, there is no single style of leadership that guarantees adaptability and transformability. Rather, leadership needs to be a dynamic process, including changes in leaders, that is responsive to prevailing social and biophysical conditions.

Typically, a leader defines the visions and goals and may initiate action, but consolidation of the goals is often best done by others. Therefore, a single, well defined leader is unlikely to be able to maintain a resilient system; multiple leadership roles, vested in different individuals or groups, is usually required.

Social networks

Motivation and co-operation depend strongly on the structure of social networks and the flow of information within them.

Trust

Lack of trust and interference with the information flow or the structure of the social network reduce resilience. Examples of negative influences include propaganda, duress, restriction of freedom of association, and corruption.

Summary proposition: Adaptability is primarily determined by (1) the absolute and relative amounts of all forms of capital: social, human, natural, manufactured, and financial; and (2) the system of institutions and governance.

Proposition 9: Mental models

In combination with ethical standards, mental models provide the framework for perceiving and judging the direction and desirability of system change. Consequently, they play a central role in the development of formal scientific models and hypotheses about system structure, processes, and interactions. They evolve over time through learning and generational change, but they can also change suddenly, as in the "tipping points" following a crisis (Brock 2004, Brock et al. 2004).

Although multiple mental models can be beneficial when understanding is incomplete, too many competing mental models, particularly when the sensible actions suggested by each are very different, can stifle cooperation or action. Common elements of competing mental models can allow convergence of view and purpose for dealing with competing desires.

In the social domain, crises need to be perceived as such to have an impact on mental models, because large-scale changes that are not perceived as crises do not challenge the prevailing mental models. The Kristianstad case study is an example in which a common mental model formed in response to an impending crisis in an ecosystem state, leading to a change in the scale of operation and a successful intervention to avoid the change in the ecosystem state (Olsson et al. 2004).

Summary proposition: Mental models drive change in social-ecological systems, and adaptability is enhanced through partially overlapping mental models of system structure and function.

Proposition 10: Learning

Learning through experimentation and innovation is necessary to develop and test knowledge and understanding for coping with change and uncertainty. The capacity to adapt and to manage resilience requires learning and the ability to make sense of things, especially in arenas of collaborative learning, using a combination of various sources of information and knowledge. Both social processes and actors, e.g., knowledge brokers, are needed to combine information and knowledge from multiple sources and a range of scales through experimental approaches such as adaptive management.

Adaptive co-management makes it possible to develop resilient, adaptable systems. It combines the dynamic learning characteristic of adaptive management (Holling 1978) and co-management, or the sharing of management power across organizational levels (Carlsson and Berkes 2005), with the linkage characteristics of cooperative management (e.g., Pinkerton 1989, Jentoft 2000) and collaborative management (e.g., Buck et al. 2001). It relies on the collaboration of a diverse set of stakeholders operating at different levels, often in networks, from local users to municipalities to regional and national organizations and even to international bodies. Adaptive co-management extends adaptive management into the social domain and is a way to operationalize adaptive governance (Folke et al. 2005). Whereas adaptive management focuses on understanding ecosystem dynamics and feeding ecological knowledge into management organizations, adaptive governance conveys the multi-objective reality when handling conflicts among a diverse set of stakeholders, and at the same time adapts this social problem to dynamic ecosystems (Dietz et al. 2003).

Summary proposition: Learning is a key component of adaptability and is enhanced by careful experimentation in the form of active adaptive management.

Proposition 11: Adaptability vs. resilience

High adaptability can unintentionally lead to a loss of resilience in three ways:

1. Increasing adaptability in one place may lead to a loss of adaptability and resilience in another place, or over a larger area. In the New South Wales rangelands, for example, introducing a government-guaranteed "floor price" for wool made individual pastoralists more resilient in the face of market fluctuations, but led to a large stockpile of wool that reduced economic resilience at the scale of the region and the industry as a whole, with eventual catastrophic consequences for many individuals.

2. Increasing adaptability to specific or regular shocks may “optimize” the system to this class of shock or regime of shocks, decreasing its general resilience to unknown shocks. This is akin to the notion of “highly optimized tolerance” (Doyle and Carlson 2000). As a simple example, frequent application of fire or grazing in an ecosystem at one time of the year leads to a change in species that makes the system resilient to such disturbances in that season, but may reduce its resilience to disturbance at other times or to other kinds of disturbance.

3. Where adaptation leads to efforts to increase efficiency of resource use, it may result in the loss of response diversity. This is an extension of proposition 7.2; extensive areas of mono-cropping with a single genotype is an extreme example.

Summary proposition: Efforts to deliberately enhance adaptability can (unintentionally) lead to loss of resilience.

Proposition 12. Multiple thresholds

Social-ecological systems have multiple thresholds, at different scales and in different domains, e.g., social, ecological, economic. The various combinations of the alternate regimes associated with each threshold mean that a social-ecological system can theoretically exist in a number of possible regime combinations. However, not all possible regimes are equally accessible. Cultural constraints may preclude the social configurations necessary to attain certain ecological states; for example, social values may constrain options for abating agricultural pollution from runoff. Conversely, ecological states may preclude certain social configurations, e.g., threatened loss of endangered species may limit options for land-use changes. In addition, crossing a threshold in one domain or at one scale may trigger other threshold crossings that alter the possible future states of the system. Legacies of past manipulations and constructions contribute strongly to the practical limitations of future possible regimes.

Although most threshold analyses focus on a particular domain, the plausibility of the various possible regimes cannot be adequately assessed without an integrated assessment of thresholds and their interactions.

A paper on multiple domains in this special issue (Kinzig et al. 2006) gives four examples of social-ecological systems with multiple possible regime shifts, two in the ecological and one each in the economic and social domains. As existing thresholds are breached, certain regimes may disappear entirely or become largely inaccessible.

Summary proposition: Social-ecological systems have multiple interacting thresholds, giving rise to multiple pairs of alternate regimes, only a few of which are feasible.

Proposition 13: Transformation

In contrast to adaptation, transformation involves changing the state space of the system by the addition of new state variables or the loss of others, which will most likely change the scales and the nature of the cross-scale relationships of the panarchy as well. It requires the emergence or development of a new kind of system, or a fundamentally new way of “making a living.”

To illustrate: A change from sheep to goat production in rangelands in the face of changes in vegetation and markets is an example of adaptation in a livestock production system. However, replacing ranching with wildlife-based ecotourism and hunting and involving joint enterprises by combining properties to operate at larger scales, as in the central United States or in southern Africa, is an example of transformation.

Summary proposition: Transformation involves changing the state space of the system and the scales of the panarchy.

Proposition 14: Determinants of transformability

Transformability is determined by a range of system attributes that enable radical, substantial changes. Four that have so far been identified in the case studies in this special issue are:

1. incentives to change vs. not to change, especially subsidies;

2. cross-scale awareness and reactivity, including networking within the social-ecological system and between the system and other systems;

3. a willingness to experiment; and

4. reserves and highly convertible assets in human, natural, and built capital.

Summary proposition: Determinants of transformability include incentives, awareness, experimentation, reserves, and governance.

RESEARCH QUESTIONS

We present here the summary proposition statements together with a list of some research questions that each of them raises. We see this list of questions as constituting a thrust of our own future research, but hope that it will stimulate others to tackle them as well.

Multiple modes of reorganization are possible during phases of rapid change in a social-ecological system.

- Can we identify a set of well described examples that can be used to establish a typology of different types of phase transitions?
- Can such a typology be used to provide clues as to how and when these different types of transitions occur, and give insights for appropriate interventions?
- Are different sets of forward-looking tools, e.g., scenario development, markets, capable of mitigating or avoiding losses of capital during phases of release and reorganization?

Exceptions to the adaptive cycle occur, particularly under the influence of large, external disturbances and the lack of critical forms of capital.

- What kinds of alternative patterns of phase changes occur in social-ecological systems?
- Can the conditions that lead to various phase changes be identified?
- Can we use this knowledge to alter the impacts of reorganization or the time spent navigating a particular phase?

Cross-scale interactions critically determine the form of the subsequent adaptive cycle at any particular focal scale.
3A. Reiterations of adaptive cycles are driven by higher scale influences, such as memory.
3B. Synchronization of adaptive cycles at lower levels influences the potential for upscale "revolt."

- Can influences from the scales above and below account for the differences between social-ecological systems that are stuck in persistent *K* phases and those in which reorganization has occurred?
- What attributes other than "memory" and subsidies have influenced the focal scale from the scale above?
- What evidence is there for the "revolt" effect from lower scales, and how common is lower-scale synchronization?

Critical changes in social-ecological systems are determined by a small set of three to five key variables, also known as the "rule of hand."

- How general is the rule of hand?
- Is the rule of hand the same for retrospective understanding and forward-looking understanding?
- Is the rule of hand a property of systems, a property of productive models of systems, or both?

Slowly changing variables control ecological resilience, whereas social resilience is controlled by either fast or slow variables.

- Are "slow" variables as important in social systems as they seem to be in ecological systems?
- Are interactions between fast and slow variables as important in social systems as they are in ecological systems?
- What is the nature of the controlling slow variables that define resilience thresholds in social systems?

- For a particular social-ecological system, are there linkages between slow ecological variables and slow variables in the social domain?

- How do the scales of variables influence resilience?

The ecological and social domains of social-ecological systems can be addressed in a common conceptual, theoretical, and modeling framework.

- Can we classify or organize the characteristics of the variables that seem to define attractors or thresholds in social-ecological systems?

- Are there examples of attractors that are jointly defined by ecological and social variables? If so, what is the nature of such combined attractors in social-ecological systems? How do they differ from those in the ecological or social domain? Are they defined by slow social variables?

- What are the mechanisms within the social domain that enable us to detect/learn about slow variables?

Two types of diversity are important for social-ecological systems: (1) functional diversity influences system performance, and (2) response diversity influences resilience.

- What are the dimensions for defining functional groups in social systems?

- Are there significant linkages between ecosystem functional groups and social functional groups?

- What is an appropriate methodology for investigating, i.e., defining and measuring changes in, response diversity and its relationship to resilience in both ecosystem and social-system domains?

Adaptability is primarily determined by (1) the absolute and relative amounts of all forms of capital: social, human, natural, manufactured, and financial; and (2) the system of institutions and governance.

- What are the institutional and governance arrangements that determine adaptability?

- How do the components of adaptability change through the adaptive cycle?

- How do the requirements for leadership change in the different phases of the adaptive cycle? What formal and informal processes are most likely to result in effective leadership?

- What characteristics of social networks support resilience? How do these social networks change in form or function at different stages of the adaptive cycle?

- How can the importance of trust and the interaction of trust with different types of social networks be evaluated?

Mental models drive change in social-ecological systems, and adaptability is enhanced through partially overlapping mental models of system structure and function.

- With regard to particular social-ecological systems, in what ways have the various mental models changed over time, and how have these changes influenced the evolution of formal models, governance arrangements, institutions, and policies?

- Under what circumstances have mental models changed dramatically, and how do these relate to the stages of the adaptive cycle at various scales in the panarchy?

Learning is a key component of adaptability and is enhanced by careful experimentation in the form of active adaptive management.

- To what extent is adaptive co-management a self-organizing process?

- What kinds of interventions and governance structures are effective for enhancing adaptive co-management?

- What are the characteristics of "safe" experiments that build resilience while avoiding unwanted breakdowns?

- What are the characteristics of useful experiments that guide either the maintenance of a desirable domain or the move from an undesirable to a desirable domain, i.e., restoration?

Efforts to deliberately enhance adaptability can (unintentionally) lead to loss of resilience.

- When do efforts to increase adaptability cross into the command-and-control pathology (cf. Holling and Meffe 1996), in which the system becomes more and more vulnerable to unknown or unexpected disturbances? How can this be avoided?

- Can we establish classes of examples in which deliberately increasing resilience in one way, e.g., X to Y, has decreased it in another way, e.g., A to B?

Social-ecological systems have multiple interacting thresholds that give rise to multiple pairs of alternate regimes, only a few of which are feasible.

- How do multiple thresholds in social-ecological systems interact to constrain or otherwise influence the possible future states of the system?

Transformation involves changing the state space of the system and the scales of the panarchy.

- Can we identify a range of transformed social-ecological systems in which adaptation was no longer a viable option?

- What changes in state variables and scales were involved in these transformations, and can we make any generalizations about them?

Determinants of transformability include incentives, awareness, experimentation, reserves, and governance.

- In social-ecological systems that have undergone transformation, what attributes were important (1) in helping to bring it about and (2) hindering it?

- In social-ecological systems that are "trapped," what factors or attributes are preventing transformation?

CONCLUSION

In the spirit of transformational change, we hope that these propositions will be augmented, modified, or rejected by future research. Such a process of sifting and winnowing should result in a set of propositions that are stronger scientifically and closer to a set of principles for resource use and management in social-ecological systems. What will be their implications for current approaches to resource development and management? Had such principles been applied, many plans for strategic development and operational management, we submit, would likely be quite different from what they are today. We return to this question in the final paper, after the propositions have been considered in more detail in the body of the papers making up this special issue. There we address how this emerging view of the resilience of social-ecological systems can be made operational, with some tentative messages for policy and management. However, before the final chapter in this volume, we hope that this set of propositions will provide grist for the articles that follow.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/vol11/iss1/art13/responses/

Acknowledgments:

The ideas presented in this paper represent the combined efforts of many people, most of them our colleagues in the Resilience Alliance. We cannot name them all here, but we particularly wish to thank Helen Allison, Steve Hatfield Dodds, and David McDonald for their contributions during the May 2004 workshop in Nagambie, Australia. We are particularly grateful to Graeme Cumming for several good suggestions. We thank two anonymous referees and the review editor for their helpful comments, which have made this a much better paper.

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