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Article *in* ECOLOGY AND SOCIETY · November 2003

DOI: 10.5751/ES-00650-090205 · Source: OAI

Walker, B., C. S. Holling, S. R. Carpenter, and A. Kinzig. 2004. Resilience, adaptability and transformability in social–ecological systems. Ecology and Society **9**(2): 5. [online] URL: http://www.ecologyandsociety.org/vol9/iss2/art5

Perspective

Resilience, Adaptability and Transformability in Social–ecological Systems

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ABSTRACT. The concept of resilience has evolved considerably since Holling's (1973) seminal paper. Different interpretations of what is meant by resilience, however, cause confusion. Resilience of a system needs to be considered in terms of the attributes that govern the system's dynamics. Three related attributes of social–ecological systems (SESs) determine their future trajectories: resilience, adaptability, and transformability. Resilience (the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks) has four components—latitude, resistance, precariousness, and panarchy—most readily portrayed using the metaphor of a stability landscape. Adaptability is the capacity of actors in the system to influence resilience (in a SES, essentially to manage it). There are four general ways in which this can be done, corresponding to the four aspects of resilience. Transformability is the capacity to create a fundamentally new system when ecological, economic, or social structures make the existing system untenable.

The implications of this interpretation of SES dynamics for sustainability science include changing the focus from seeking optimal states and the determinants of maximum sustainable yield (the MSY paradigm), to resilience analysis, adaptive resource management, and adaptive governance.

INTRODUCTION

We need a better scientific basis for sustainable development than is generally applied (e.g., a new "sustainability science"). The "Consortium for Sustainable Development" (of the International Council for Science, the Initiative on Science and Technology for Sustainability, and the Third World Academy of Science), the US National Research Council (1999, 2002), and the Millennium Ecosystem Assessment (2003), have all focused increasing attention on such notions as robustness, vulnerability, and risk. There is good reason for this, as it is these characteristics of social–ecological systems (SESs) that will determine their ability to adapt to and benefit from change. In particular, the stability dynamics of all linked systems of humans and nature emerge from three complementary attributes: resilience, adaptability, and transformability. The purpose of this paper is to examine these three attributes; what they mean, how they interact, and their implications for our future well-being.

An inherent difficulty in the application of these concepts is that, by their nature, they are rather imprecise. They fall into the same sort of category as "justice" or "wellbeing," and it can be counterproductive to seek definitions that are too narrow. Because different groups adopt different interpretations to fit their understanding and purpose, however, there is confusion in their use. The confusion then extends to how a resilience approach (Holling 1973, Gunderson and Holling 2002) can contribute to the goals of sustainable development. In what follows, we provide an interpretation and an explanation of how these concepts are reflected in the adaptive cycles of complex, multi-scalar SESs.

There is little fundamentally new theory in this paper. What is new is that it uses established theory of non-linear stability (Levin 1999, Scheffer et al. 2001, Gunderson and Holling 2002, Berkes et al. 2003) to clarify, explain, and diagnose known examples of regional development, regional poverty, and regional

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sustainability. These include, among others, the Everglades and the Wisconsin Northern Highlands Lake District in the USA, rangelands and an agricultural catchment in southeastern Australia, the semi-arid savanna in southeastern Zimbabwe, the Kristianstad “Water Kingdom” in southern Sweden, and the Mae Ping valley in northern Thailand. These regions provide examples of both successes and failures of development. Some from rich countries have generated several pulses of solutions over a span of a hundred years and have generated huge costs of recovery (the Everglades). Some from poor countries have emerged in a transformed way but then, in some cases, have been dragged back by higher-level autocratic regimes (Zimbabwe). Some began as local-scale solutions and then developed as transformations across scales from local to regional (Kristianstad and northern Wisconsin). In all of them, the outcomes were determined by the interplay of their resilience, adaptability, and transformability.

There is a major distinction between resilience and adaptability, on the one hand, and transformability on the other. Resilience and adaptability have to do with the dynamics of a particular system, or a closely related set of systems. Transformability refers to fundamentally altering the nature of a system. As with many terms under the resilience rubric, the dividing line between “closely related” and “fundamentally altered” can be fuzzy, and subject to interpretation. So we begin by first offering the most general, qualitative set of definitions, without reference to conceptual frameworks, that can be used to describe these terms. We then use some examples and the literature on “basins of attraction” and “stability landscapes” to further refine our definitions. Before giving the definitions, however, we need to briefly introduce the concept of adaptive cycles.

Adaptive Cycles and Cross-scale Effects

The dynamics of SESs can be usefully described and analyzed in terms of a cycle, known as an adaptive cycle, that passes through four phases. Two of them—a growth and exploitation phase (r) merging into a conservation phase (K)—comprise a slow, cumulative forward loop of the cycle, during which the dynamics of the system are reasonably predictable. As the K phase continues, resources become increasingly locked up and the system becomes progressively less flexible and responsive to external shocks. It is eventually, inevitably, followed by a chaotic collapse and release phase (Ω) that rapidly gives way to a phase of reorganization (α), which may be rapid or slow, and during which, innovation and new opportunities are possible. The Ω and α phases together comprise an unpredictable backloop. The α phase leads into a subsequent r phase, which may resemble the previous r phase or be significantly different.

This metaphor of the adaptive cycle is based on observed system changes, and does not imply fixed, regular cycling. Systems can move back from K toward r, or from r directly into Ω, or back from α to Ω. Finally (and importantly), the cycles occur at a number of scales and SESs exist as “panarchies”—adaptive cycles interacting across multiple scales. These cross-scale effects are of great significance in the dynamics of SESs.

Resilience

Resilience is the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks. As amplified below, the focus is on the dynamics of the system when it is disturbed far from its modal state. The notion of speed of return to equilibrium (Pimm 1991) leads to what has been termed “engineering resilience” (Holling 1996) and, although related to one aspect of “ecological resilience,” cannot be considered as *the* measure of resilience. Because of the possibility of multiple stable states, when considering the extent to which a system can be changed, return time doesn’t measure all of the ways in which a system may fail—permanently or temporarily—to retain essential functions. It is also important to bear in mind that “systems” consist of nested dynamics operating at particular organizational scales—“sub-systems,” as it were, of households to villages to nations, trees to patches to landscapes.

There are four crucial aspects of resilience. The first three can apply both to a whole system or the sub-systems that make it up.

1. Latitude: the maximum amount a system can be changed before losing its ability to recover (before crossing a threshold which, if breached, makes recovery difficult or impossible).
2. Resistance: the ease or difficulty of changing the system; how “resistant” it is to being changed.

3. Precariousness: how close the current state of the system is to a limit or “threshold.”
4. Panarchy: because of cross-scale interactions, the resilience of a system at a particular focal scale will depend on the influences from states and dynamics at scales above and below. For example, external oppressive politics, invasions, market shifts, or global climate change can trigger local surprises and regime shifts.

Adaptability

Adaptability is the capacity of actors in a system to influence resilience. In a SES, this amounts to the capacity of humans to manage resilience. A characteristic feature of complex adaptive systems is self-organization without intent (Levin 1998), and although the dynamics of SESs are dominated by individual human actors who do exhibit intent, the system as a whole does not (as in the case of a market). Nevertheless, because human actions dominate in SESs, adaptability of the system is mainly a function of the social component—the individuals and groups acting to manage the system. Their actions influence resilience, either intentionally or unintentionally. Their collective capacity to manage resilience, intentionally, determines whether they can successfully avoid crossing into an undesirable system regime, or succeed in crossing back into a desirable one. There are four ways to do this, corresponding to the four aspects of resilience. Actors can move thresholds away from or closer to the current state of the system (by altering (1) above), move the current state of the system away from or closer to the threshold (altering 3), or make the threshold more difficult or easier to reach (altering 2). In addition, actors can manage cross-scale interactions to avoid or generate loss of resilience at the largest and most socially catastrophic scales (altering 4).

Transformability

The capacity to create a fundamentally new system when ecological, economic, or social (including political) conditions make the existing system untenable.

EXPLANATION

Resilience: States, Attractors, and Stability Landscapes

The “state space” of a system is defined by the (state) variables that constitute the system. If, for example, we define a rangeland system by the amount of grass, shrubs,and livestock, then the state space is the three-dimensional space of all possible combinations of the amounts of these three variables. The state of the system at any time is defined by their current values.

A “basin of attraction” is a region in state space in which the system tends to remain. For systems that tend toward an equilibrium, the equilibrium state is defined as an “attractor,” and the basin of attraction constitutes all initial conditions that will tend toward that equilibrium state. All real-world SESs are, however, continuously buffeted by disturbances, stochasticity, and decisions of actors that tend to move the system off the attractor. Therefore, we think of SESs as moving about within a particular basin of attraction, rather than tending directly toward an attractor. There may be more than one such basin of attraction for any given system (for example, two or more combinations of amounts of grass, shrubs, and livestock toward which a rangeland might tend, depending on the starting point). The various basins that a system may occupy, and the boundaries that separate them, are known as a “stability landscape.” Fig. 1a depicts the first three components of resilience for a basin in a stability landscape of two state variables. A good review and summary of stability landscape dynamics in ecology is given in Beisner et al. (2003).

Both exogenous drivers (rainfall, exchange rates) and endogenous processes (plant succession, predator–prey cycles, management practices) can lead to changes in the stability landscape, such as: changes in the number of basins of attraction, changes in the positions of the basins within the state space, changes in the positions of the thresholds (edges) between basins (latitude—L in Fig. 1a), or changes in the “depths” of basins, a measure of how difficult it is to move the system around within the basin—steep sides imply greater perturbations or management efforts are needed to change the state of the system, i.e., its position within the basin (resistance—R in Fig. 1a). Moving the system around changes its position within a basin relative to the edge (precariousness—Pr in Fig. 1a), or moves it into a new basin (e.g., Fig. 1b, where, without the state of the system itself changing, the system finds itself in a new basin of attraction, owing to changes in the stability landscape). The people in this system might consider some basins to be desirable (lots of grass, few shrubs, plentiful livestock) and the objective might be to prevent the system from moving into an alternate, undesirable basin (little grass, many shrubs, few livestock) from which it may be difficult or impossible to recover.

Fig. 1a. Three-dimensional stability landscape with two basins of attraction showing, in one basin, the current position of the system and three aspects of resilience, L = latitude, R = resistance, Pr = precariousness.

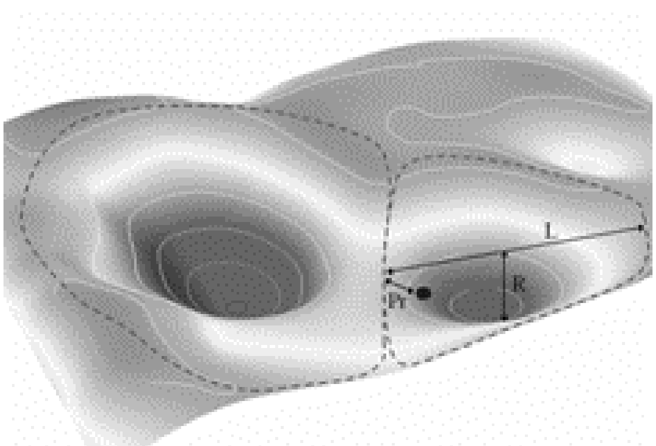
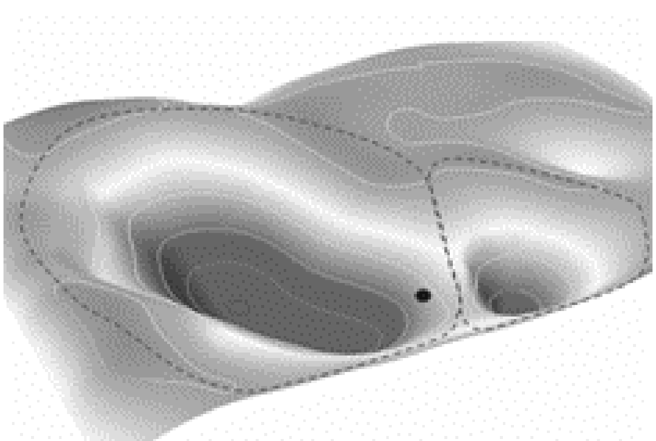


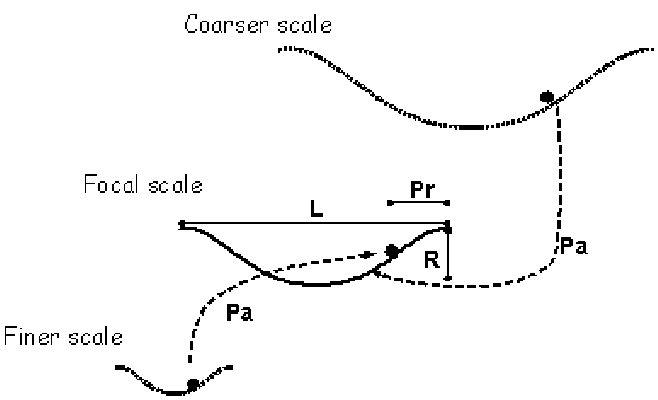
Fig. 1b. Changes in the stability landscape have resulted in a contraction of the basin the system was in and an expansion of the alternate basin. Without itself changing, the system has changed basins.



In evolved systems that have been subjected to strong selection pressures, the three aspects of resilience have co-developed and are often strongly inter-related. For example, one dimension (axis) of the stability landscape for individual human health is temperature. (One could imagine three basins of attraction in this landscape—healthy, sick, or dead). For good physiological reasons, the optimal temperature for the body is very close to the threshold between life and death (very precarious). A hundred million years of homeotherm natural selection has ensured that there are strong negative feedbacks—temperature regulation mechanisms—making it very unlikely and difficult for the body to move across the critical temperature threshold. In other words, being precariously close to such a threshold has meant the evolution of strong resistance. Evolving toward the edge of chaos (corresponding, in this case, to the edge of a basin of attraction) is a seemingly common consequence of selection (Kaufmann 2000) for maximum efficiency. Recently developed SESs (managed fisheries and virtually all agro-ecosystems, for example) have short co-evolutionary histories. Therefore, we cannot rely on such selected relationships with appropriate feedback controls, and the likelihood of crossing thresholds is much higher (as evidenced by the many examples of collapsed fisheries and salinized or otherwise degraded agricultural regions).

No SES can be understood by examining it at only one scale. The social component of a SES consists of groups of people organized at multiple levels with differing views as to whether some basins are desirable and others undesirable. At any particular scale, the system is actually a sub-system of the whole panarchy, and the first three aspects of resilience are influenced by what is happening in the panarchy at scales above and below the scale of interest. Panarchy, the cross-scale effects, is the fourth aspect of resilience that needs to be considered (Pa in Fig. 2). For example, many lakes occupy a stability landscape with essentially two basins of attraction: one that is initially wide and cavernous, characterized by clear water, and a smaller one characterized by turbid water (Carpenter 2003). Agricultural practices within the larger SES, through application of fertilizers and manure, have gradually increased the phosphorus content of soils in some watersheds. This cross-scale effect has changed the stability landscapes of the lakes in several ways. As lake basins fill with sediment, a third basin of attraction has appeared, one in which the lake is dominated by rooted vegetation. The first basin—clear water and sparse vegetation—shrinks and nearly disappears from the stability landscape. The second basin—turbid water and frequent blooms of toxic algae—moves from being small to being wider and more cavernous.

Fig. 2. The fourth aspect of resilience in relation to a stability landscape—Panarchy (Pa); the influence of the states of the system (including where they are in their adaptive cycles) at scales above and below the focal scale, which affects the other three aspects (Fig. 1) by impacting the system directly (from the finer scale) or changing the stability landscape (from the coarser scale).



Some loss of resilience, at some scales, is an inevitable feature of the cross-scale dynamics in complex adaptive systems. Losses, however, can be managed so as to be confined to smaller organizational scales, with less consequent social and environmental dislocation. All else being equal, a system that loses resilience at small, and more societally manageable, scales of organization (e.g., patches) will be more resilient than one where these losses occur at larger scales (e.g., landscapes). Note, however, that resilience is not always a good thing. Sometimes change is desirable, generally at larger scales, and then effective management requires overcoming the resilience in the system to precipitate changes at these scales.

Components of Adaptability

As explained in the initial definition, because the dynamics and direction of change in a SES are dominated by human actions, we consider adaptability to be mainly a function of the social component—the individuals and groups acting to manage the system (see Berkes et al. 2003, for a good account). The ability to either control the trajectory of the system (change precariousness), change the topology of the stability landscape (latitude and resistance), or change the processes in response to dynamics at other scales (panarchy response), is a measure of adaptability. Consider both strategies in the case of the lake that has fallen into a turbid basin. Managers could attempt to move the ecosystem to another basin without changing the stability landscape by chemically immobilizing the phosphate in the lake. If the land-use practices of the SES change in ways that reduce phosphorus levels in soils, in contrast, the stability landscape changes, the turbid basin shrinks, and the clear water basin expands. Both purposeful movements between basins, and purposeful reshaping of the stability landscape, demonstrate adaptability. SESs can move from one basin of attraction to another either by the system crossing a threshold, or by a threshold moving across the system.

Transformability

At times societies or groups may find themselves trapped in an undesirable basin that is becoming so wide, and so deep, that movement to a new basin or sufficient reconfiguration of the existing basin becomes extremely difficult. At some point, it may prove necessary to configure an entirely new stability landscape—one defined by new state variables, or the old state variables supplemented by new ones. For instance, in the rangeland case—defined originally by the amount of grass, shrubs, and cattle—a new stability landscape could be created by introducing new ways for earning a living, such as ecotourism, based on wildlife and rivers. This is what occurred in southeastern Zimbabwe (Cumming 1999) where, after many decades of cattle ranching, the rangeland ecosystem had changed undesirably for livestock and terms of trade had declined. A severe drought in the early 1980s triggered a transformation from many individual cattle ranches to a few wildlife “conservancies” with all livestock and fences removed and managed collectively for tourism and hunting. The capacity to create such a new stability landscape is known as transformability—the capacity to create untried beginnings from which to evolve a new way of living when existing ecological, economic, or social structures become untenable. New variables are introduced or allowed to emerge. The changes cascade through and may transform the whole panarchy with all its constituent adaptive cycles. There are many examples of SESs becoming locked in and unable to transform until it is too late (salinized agricultural systems; dams, floodplains and flood control; forest fire suppression at ever larger scales). How can society develop transformability and avoid such lock-ins?

Examples of globally new phenomena at large time/space scales are the dramatic jump that saw the replacement of dominance by reptiles with dominance by mammals (the transformational success of homeothermy in the course of biological evolution), and, at scales in the course of human civilization, the agrarian revolution, the emergence of cities, and the industrial revolution, all examples of transformative changes. But consider more local or regional situations, as in the following example.

Scenario planning is a process of envisioning plausible transformations and bringing them into social decision processes (Peterson et al. 2003). As part of a project on resilience analysis and governance in the Northern Highlands of Wisconsin, USA, a diverse group of local people and scientists evaluated possible futures of the region and envisioned four plausible transformations (http://lakefutures.wisc.edu): a tourism-based theme park region ("Annaheim North"); a region with an environmentally induced drop in population followed by gradual reorganization around tribal initiatives ("Walleye Commons"); an expanded and diversified population leading to resource conflicts being resolved by allocating recreational lands and lakes for certain specified uses ("Northwoods Quilts"); and a region in which terrorism in Chicago leads to population growth, as well as more governmental control of resource use ("Refugee Revolution"). The scenarios, widely covered in local media, evoked spirited debate about change in the region, and whether and how the local people can or should manipulate change. They helped overcome a fundamental problem in thinking about transformation in a coherent way. With so many changes happening simultaneously, the very complexity of the situation became a barrier to understanding and action. The scenarios organized information about transformation in a comprehensible way that facilitated discussion and action. Knowing if, when, and how to initiate transformative change, before it is too late to escape a seriously undesirable and deepening basin of attraction, is at the heart of SES transformability.

A tension will exist between maintaining the resilience of a desired current configuration in the face of known (and some unknown) shocks, and simultaneously building a capacity for transformability, should it be needed. How can we foster or maintain the flexibility that will be required to cope with unforeseen challenges? It is nevertheless likely that there is overlap in the attributes that promote adaptability and transformability. In addition to such common attributes (e.g., diverse and high levels of natural and built capital), we speculate that attributes required for transformability will emphasize novelty, diversity, and organization in human capital—diversity of functional types (kinds of education, expertise, and occupations); trust, strengths, and variety in institutions; speeds and kinds of cross-scale communication, both within the panarchy and between other systems elsewhere. Such attributes are implicit (although not specifically identified) in Stiglitz"s (2002) comparison of "good" and "bad" outcomes of socio-economic transformations following the fall of communism in Russia and the Southeast Asian economic crisis. He highlights the role played by sequencing of institutional development and economic rules—attributes that fall within the crucial area (for resilience) of adaptive governance, a good account of which is given in Dietz et al. (2003). We return to it later.

A RETURN TO THE DEFINITIONS

Using the concepts of basins of attraction and stability landscapes, we can now offer more precise definitions of resilience, adaptability, and transformability:

Resilience

Resilience is the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks—in other words, stay in the same basin of attraction. Resilience has multiple attributes, but four aspects are critical for these definitions:

- Latitude: the maximum amount the system can be changed before losing its ability to recover; basically the width of the basin of attraction. Wide basins mean a greater number of system states can be experienced without crossing a threshold (L, Fig. 1).
- Resistance: the ease or difficulty of changing the system; related to the topology of the basin—deep basins of attraction (R, or more

accurately, higher ratios of R:L) indicate that greater forces or perturbations are required to change the current state of the system away from the attractor.

- Precariousness: the current trajectory of the system, and how close it currently is to a limit or “threshold” which, if breached, makes recovery difficult or impossible (Pr).
- Panarchy: how the above three attributes are influenced by the states and dynamics of the (sub)systems at scales above and below the scale of interest (Pa).

Throughout this paper, we use stability landscapes as a metaphor for our measures of resilience—latitude, resistance, and precariousness. But not all systems can be adequately described by a stability landscape, particularly when one must grapple with both social and ecological components playing out over several scales of space, time, and organization. Even fewer lend themselves to the formal representation of such landscapes required to accurately measure P, L, and R. In some cases, the change in regime is not from one point attractor to another. Stable limit cycles might represent very similar management challenges as do thresholds between basins (managers would try to maximize the time spent in the desirable portion of the limit cycle and minimize the time spent in the undesirable part). Nonetheless, the general concepts would still apply. Social–ecological systems can be close to, or far away from, important thresholds (P_r). They can be easy or hard to change (R). The range of dynamics that can be accommodated while still retaining basically the same system can be large, or small (L). Different management interventions would be required to enhance resilience for each of these. Although we do not believe in or advocate their separate measurement (especially because of their inter-dependencies), we do believe that substantive qualitative assessments can be made of each of these components of resilience. And considering these assessments collectively enables a more complete and better focused assessment of resilience, and what to do about it, than would be achieved without them.

Adaptability

In a SES, adaptability is the collective capacity of the human actors in the system to manage resilience. Although the system as a whole self-organizes without intent, the capacities and intent of the human actors strongly influence the resilience and the trajectory of the SES. Putting this definition in the context of stability landscapes, adaptability can take many forms, including: (i) making desirable basins of attraction wider and/or deeper, and shrinking undesirable basins; (ii) creating new desirable basins, or eliminating undesirable ones; and (iii) changing the current state of the system so as to move either deeper into a desirable basin, or closer to the edge of an undesirable one.

Transformability

The capacity to create a fundamentally new system when ecological, economic, or social (including political) conditions make the existing system untenable. Transformability means defining and creating new stability landscapes by introducing new components and ways of making a living, thereby changing the state variables, and often the scale, that define the system.

CLOSING COMMENTS

Strategies for sustainability must take many forms. There is no “one size fits all” approach to the future. Sometimes SESs are already in desirable basins of attraction, and the challenge is to ensure that the basin does not get smaller, or the system doesn’t move too close to a threshold. At other times, they are in undesirable basins and the challenge is to reduce their resilience and to move toward or enlarge more desirable basins. (Note, from the earlier discussion on regime shifts other than between basins of attraction, whatever metaphor is used, the notion of resilience holds.) Strategies will be context dependent, and will themselves have to change over time because of the inevitable changes inherent in complex, coupled SESs.

The need to know the details of the local and regional context—the particular attributes of the systems that determine the four aspects of resilience and adaptability—means a different approach to resource governance than currently applied will be required for a sustainable future. It changes the focus from seeking desirable states and the determinants of maximum sustainable yield, in its many guises (the MSY paradigm), to resilience analysis, with a simultaneous focus on adaptive resource management and adaptive governance. Adaptive governance is a process of creating adaptability and transformability in SESs. Adaptive management (Walters 1986), widely and deservedly promoted as a necessary basis for sustainable development, has frequently failed

(Walters 1997) because the existing governance structures have not allowed it to function effectively. Because the stability landscape is constantly changing, the "adaptive" part of both governance and management is required in all phases of the adaptive cycle. But, because it has received the least attention, we emphasize especially the importance of the back loop, and in particular the flexible management needed to retain critical ecological resources (adaptive management), and the evolution of rules that influence resilience during self-organization (adaptive governance).

Responses to this article can be read online at: http://www.ecologyandsociety.org/vol9/iss2/art5/responses/index.html

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Acknowledgments:

This paper results from many discussions in meetings of the Resilience Alliance. We acknowledge all our colleagues who have contributed to the development of these concepts. We thank Don Ludwig and Elinor Ostrom for helpful comments on an early draft, Art Langston for the construction of Fig. 1, and the comments of an unknown referee. The work leading to the paper has been supported by a grant to two of us (BW and SC) by the James S. MacDonnell Foundation.

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