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Resilience: The emergence of a perspective for social–ecological systems analyses

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Abstract

The resilience perspective is increasingly used as an approach for understanding the dynamics of social–ecological systems. This article presents the origin of the resilience perspective and provides an overview of its development to date. With roots in one branch of ecology and the discovery of multiple basins of attraction in ecosystems in the 1960–1970s, it inspired social and environmental scientists to challenge the dominant stable equilibrium view. The resilience approach emphasizes non-linear dynamics, thresholds, uncertainty and surprise, how periods of gradual change interplay with periods of rapid change and how such dynamics interact across temporal and spatial scales. The history was dominated by empirical observations of ecosystem dynamics interpreted in mathematical models, developing into the adaptive management approach for responding to ecosystem change. Serious attempts to integrate the social dimension is currently taking place in resilience work reflected in the large numbers of sciences involved in explorative studies and new discoveries of linked social–ecological systems. Recent advances include understanding of social processes like, social learning and social memory, mental models and knowledge–system integration, visioning and scenario building, leadership, agents and actor groups, social networks, institutional and organizational inertia and change, adaptive capacity, transformability and systems of adaptive governance that allow for management of essential ecosystem services.

Keywords: Resilience; Social–ecological systems; Adaptive capacity; Transformations

1. Introduction

Humanity is a major force in global change and shapes ecosystem dynamics from local environments to the biosphere as a whole (Redman, 1999; Steffen et al., 2004; Kirch, 2005). At the same time human societies and globally interconnected economies rely on ecosystems services and support (Millennium Ecosystem Assessment (MA), 2005). It is now clear that patterns of production, consumption and wellbeing develop not only from economic and social relations within and between regions but also depend on the capacity of other regions' ecosystems to sustain them (Arrow et al., 1995; Folke et al., 1998). Therefore, a major challenge is to develop governance systems that make it possible to relate to environmental assets in a fashion that secures their capacity to support societal development for a long time into the future (Costanza et al., 2000; Lambin, 2005). It will require adaptive forms of governance (Dietz et al., 2003; Folke et al., 2005).

This paper will address the challenge using work related to the concept of resilience (Holling, 1973, 1986, 2001). A lot of work on resilience has focused on the capacity to absorb shocks and still maintain function. But, there is also another aspect of resilience that concerns the capacity for renewal, re-organization and development, which has been less in focus but is essential for the sustainability discourse (Gunderson and Holling, 2002; Berkes et al., 2003). In a resilient social–ecological system, disturbance has the potential to create opportunity for doing new things, for innovation and for development. In vulnerable system even small disturbances may cause dramatic social consequences (Adger, 2006). Old dominant perspectives have implicitly assumed a stable and infinitely resilient environment where resource flows could be controlled and nature would self-repair into equilibrium when human stressors were

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removed. Such static equilibrium center views provide little insight into the transient behavior of systems that are not near equilibrium (Holling, 1973). The resilience perspective shifts policies from those that aspire to control change in systems assumed to be stable, to managing the capacity of social–ecological systems to cope with, adapt to, and shape change (Berkes et al., 2003, Smit and Wandel, 2006). It is argued that managing for resilience enhances the likelihood of sustaining desirable pathways for development in changing environments where the future is unpredictable and surprise is likely (Walker et al., 2004; Adger et al., 2005).

The purpose with this paper is to provide an overview of the emergence of the resilience perspective and the context within which it has developed. It will not be a paper for those that look for simple, clear-cut explanations about resilience in a technical sense. The paper is more of a narrative that starts with presenting the ecological or ecosystem resilience perspective, and its early influence on other disciplines and how it contrasts with more narrow interpretations of resilience in ecology. The second part puts resilience and system dynamics in the context of complex adaptive systems, with emphasis on cross-scale interplay and the two interacting sides of resilience as both sustaining and developing. The explorative nature of resilience research and the role of the perspective as a way for organizing thought and inquiry are emphasized. The third section reports ongoing efforts and explorative work in resilience research toward understanding social–ecological system dynamics and its implications for sustainability, a research integration that is still in its infancy. Research challenges and policy implications are raised in the concluding remarks.

2. The roots of the resilience perspective

The resilience perspective emerged from ecology in the 1960s and early 1970s through studies of interacting populations like predators and prey and their functional responses in relation to ecological stability theory (Holling, 1961; Morris, 1963; Lewontin, 1969; Rosenzweig, 1971; May, 1972). Ecologist C.S. Holling in his paper on resilience and stability in ecological systems illustrated the existence of multiple stability domains or multiple basins of attraction in natural systems and how they relate to ecological processes, random events (e.g. disturbance) and heterogeneity of temporal and spatial scales (Holling, 1973). He introduced resilience as the capacity to persist within such a domain in the face of change and proposed that "resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist" (Holling, 1973, p. 17).

In an email communication in 2003 with a few colleagues C.S. Holling wrote the following history (with permission from the author)

"The 1973 paper emerged from a series of earlier experimental studies and papers analyzing a particular process, predation. The goal was to see how far one could go by being precise, realistic, general and integrative. That did well, turning up a way to classify categories of predation into four types of functional and three types of numerical responses. The categories and resulting simplified models seemed to apply to everything from bacteria foraging for food to mammals hunting prey. But none of that was ecosystem research. It was all traditionally experimental and analytical, but at least it was synthetic.

But a bridge to ecosystems started once I shifted to combine the predation equations with others concerning other processes in order to make a population model. That is when, suddenly and unexpectedly, multi-stable states appeared. Non-linear forms of the functional responses (e.g. the Type 3 S-shaped response) and of reproduction responses (e.g. the Allee effect) interacted to create two stable equilibria with an enclosed stability domain around one of them. Once discovered it was obvious that conditions for multi-stable states were inevitable. And that, being inevitable, there were huge consequences for theory and practice. Single equilibria and global stability had made ecology focus on near equilibria behavior, fixed carrying capacity with a goal of minimizing variability. The multi-stable state reality opened an entirely different focus on behavior far from equilibrium and on stability boundaries. High variability became an attribute to maintain existence and learning. Surprise and inherent unpredictability was the inevitable consequence for ecological systems. Low-density data and understanding was more important than high-density. I used the word resilience to represent this latter kind of stability.

Hence, the useful measure of resilience was the size of stability domains, or, more meaningfully, the amount of disturbance a system can take before its controls shift to another set of variables and relationships that dominate another stability region. And the relevant focus is not on constancy but on variability. Not on statistically easy collection and analysis for data but statistically difficult and unfamiliar ones.

About that time, I was invited to write the 1973 review article for the Annual Review of Ecology and Systematics on predation. I therefore decided to turn it into a review of the two different ways of perceiving stability and in so doing highlight the significance for theory and for practice. That required finding rare field data in the literature that demonstrated flips from one state to another, as well as describing the known non-linearities in the processes that caused or inhibited the phenomenon. That was a big job and I recall days when I thought it was all bunk, and days when I believed it was all real. I finished the paper on a 'good' day, when all seemed pretty clear. By then I guess I was convinced. The causal, process evidence was excellent, though the field evidence was only suggestive. Nevertheless the consequences for theory and management were enormous''.

Early applications of the findings were generated from the resource ecology group at University of British Columbia, particularly in relation to the insect spruce budworm and its role in boreal forest dynamics of North America (Holling, 1978; Ludwig et al., 1978), and from the Great Lakes groups (Regier and Kay, 2002), followed by examples from the dynamics and management of rangelands (Walker et al., 1981; Westoby et al., 1989), freshwater systems (Fiering, 1982) and fisheries (Walters, 1986). Applied mathematics, modeling and applied resource ecology at the scale of ecosystems were combined with inductive science and experience from field work and large-scale management disturbances (Holling, 1996).

The resilience perspective began to influence fields outside ecology like anthropology where Vayda and McCay (1975) challenged Rappaport's (1967) concept of culture as an equilibrium-based system, in ecological economics in relation to biological diversity (Perrings et al., 1992), non-linear dynamics (Common and Perrings, 1992) and the modeling of complex systems of humans and nature (Costanza et al., 1993), in environmental psychology (Lamson, 1986), cultural theory (Thompson et al., 1990), human geography (Zimmerer, 1994), the management literature (King, 1995), property rights and common property research (Hanna et al., 1996) and also other social sciences (reviewed by Scoones, 1999; Abel and Stepp, 2003; Davidson-Hunt and Berkes, 2003).

It became the theoretical foundation for the work with active adaptive ecosystem management where Holling, Walters and colleagues mobilized a series of studies of large-scale ecosystems subject to management—terrestrial, freshwater and marine. This process developed an integrative sense of the systems by using a sequence of workshop techniques for scientists and policy people to develop explanatory models and suggestive policies (Holling and Chambers, 1973; Holling, 1978; Clark et al., 1979; Walters, 1986).

The adaptive management process also provided a set of studies that allowed for comparative analyses of the theoretical foundations to ecosystems behavior and ecosystems management and became a source of inspiration, during the period at the International Institute of Applied Systems Analysis, for the interdisciplinary volume ''Sustainable Development of the Biosphere'', edited by Clark and Munn (1986). Holling's (1986) chapter in that volume developed the theoretical basis for resilience emerging from the comparison of the ecosystem studies. In his email letter Holling continues;

> ''Some of the key features of ecosystems popped out: e.g. there had to be at least three sets of variables, each operating at qualitatively different speeds. There was an essential interaction across scales in space and time covering at least three orders of magnitude. Non-linearities were essential. Multi-stable states were inevitable. Surprise was the consequence. It was the place where the ''Adaptive Cycle'' was first described and presented''.

We will return to this heuristic model of ecosystem development below.

The Sustainable Development volume with ''the science of surprise'' perspective became a source of inspiration and creation for many, including those involved in the volume like the group of the Great Lakes drainage basin developing interdisciplinary science and understanding in relation to complex systems theory (Rapport et al., 1985; Steedman and Regier, 1987; Baskerville, 1988; Edwards and Regier, 1990; Robinson et al., 1990; Kay, 1991; Kay et al., 1999), a major synthesis by Turner et al. (1990) of the earth as transformed by human actions, which continued into research on uncertainty and surprise (Kates and Clark, 1996), social learning (Clark et al., 2001) sustainability science (Kates et al., 2001), and risk (Kasperson et al., 1995) and vulnerability in human–nature systems (Turner et al., 2003), work on systems science and sustainability (Gallopín, 2003) and research at University of East Anglia by Tim O'Riordan and colleagues on, e.g., the precautionary principle and social resilience (O'Riordan and Jordan, 1995; Adger and O'Riordan, 2000; Adger et al., 2001). A workshop on surprising futures, with many of those people involved, was organized in the mid-1980s by the Swedish Council for Planning and Coordination of Research (FRN) (Svedin and Aniansson, 1987), a research council with an amazing foresight in creating research platforms for sustainability issues and in supporting the emergence of new interdisciplinary fields like ecological economics.

Holling and colleagues continued the comparative work on adaptive resource and environmental management of regional ecosystems that later led to the edited volume ''Barrier and Bridges to the Renewal of Ecosystems and Institutions'' (Gunderson et al., 1995) in which aspects of social and ecological theory and empirical practice were brought together to analyze how ecosystems are structured and behave and how institutions and the people associated with them are organized and behave. The findings of the volume emphasize the necessity to *learn to manage by change* rather than simply to react to it and the key role that individuals and small groups or teams of individuals play in this context. It implies that uncertainty and surprise is part of the game and you need to be prepared for it and learn to live with it (Carpenter and Gunderson, 2001; Berkes et al., 2003; Peterson et al., 2003a; Kinzig et al., 2003). This perspective and its relation to resilience is in stark contrast to equilibrium centered, command-and-control strategies that aim at controlling the variability of a target resource (e.g. fish populations, insect outbreaks, cattle grazing), a perspective that has dominated contemporary natural resource and environmental management. These strategies tend to solve resource problems in the short term, like declining yields, but success in controlling one variable, that often fluctuates, leads to changes in variables that operate at other temporal and spatial scales, like nutrients or food web dynamics. Such management creates landscapes that become spatially homogenized and vulnerable to disturbances that previously could be absorbed (Holling and Meffe, 1996; Gunderson et al., 1995; Holling et al., 1998). The pathology of natural resource management has been described for many resource systems including lake fisheries and forestry (Regier and Baskerville, 1986), coastal fisheries (Huitric, 2005), agricultural regions (Allison and Hobbs, 2004) and trade, globalization and growth in organizational structure in urban areas where decisions makers become distant and alienated from environmental feedback in both contemporary and ancient societies (Redman, 1999; Lebel et al., 2002).

2.1. Resilience in steady-state versus complex systems

But all this work, especially in the early days, was largely ignored or opposed by the main stream body of ecology. Because it seemed easier to demonstrate shifts between alternate states in models than in the real world (Holling, 1973; May, 1977), non-linear dynamics and alternate domains of attraction were seldom on the screen of the ecological profession. Instead, work in ecology continued with implicit assumptions of one steady state and with a focus on addressing issues close to a single-equilibrium (the balance of nature view) on small scales with short-term experimentation. Returning to the email letter Holling continues

> "One early ecological response to the 1973 paper was by Sousa and Connell (1985). They asked, "was there empirical evidence for multi-stable states?" They did so by analyzing published data on time series of population changes to see if the variance suggested multi-stable behavior. They found no such evidence. This so reinforced the dominant population ecology single equilibrium paradigm, that the resilience concept was stopped dead, in that area of science. There are two problems with their analysis, however: (1) they did not ask any process question (are there common non-linear mechanisms that can produce the behavior?). That is where the good new hard evidence lay. (2) They rightly saw the need for long time series of high resolution, but, as population/community ecologists, their view of time was a human view where decades are seen as being long. That view is reinforced by a "quadrat" mentality. Not only small in time, but small in spatial scale; and a theory limited to linear interactions between individuals in single species populations or between two species populations, all functioning at the same speed (e.g. predator/prey, competitors). But the multi-stable behavior can only be interpreted within the context of at least three (but probably not more than five variables), that differ qualitatively in speed. It is therefore inherently ecosystemic. As an example, the 40 years of budworm change they analyzed seemed long to Sousa and Connell and to all those conditioned by single variable behavior and linear thinking. But the relevant time scale for the multi-equilibrium behavior of budworm is set by the trees—the slow variable. What is needed for their tests was budworm data (the fast variable) over several generations of trees (the slow variable), i.e. several centuries, at a resolution of 1 year. It is the slow variables that determine how many years of data are needed for their kind of test. None of their examples had anywhere near the length of temporal data needed."

The significance of slow variables and slow–fast interactions for understanding ecosystem dynamics and management is addressed in several publications (Carpenter et al., 2001; Gunderson and Pritchard 2002).

Not only temporal scales but their interrelations with spatial scales and spatial heterogeneity enables multi-stable behavior in ecosystems (Peterson et al., 1998; van Nes and Scheffer, 2005) sometimes addressed in the context of spatial resilience (Nyström and Folke, 2001; Bengtsson et al., 2003; Hughes et al., 2005). With the rise of landscape ecology (Turner, 1989) and insights on cross-scale interactions (Holling, 1992; Levin, 1992) along with an increasing availability of long-term records on ecosystem change and long-term degradation (Zimov et al., 1995; Jackson et al., 2001; Kirch, 2005), the window has now opened for a deeper understanding of the broader context and behavior of multiple basins of attraction in ecosystems and its relation to social drivers and dynamics, a major point emphasized in the Millennium Ecosystem Assessment (MA) (2005).

The single equilibrium view that dominated main stream ecology led to the interpretation of resilience as return time after disturbance, referred to as engineering resilience (Holling, 1996). Engineering resilience focuses on behavior near a stable equilibrium and the rate at which a system approaches steady state following a perturbation, i.e. the speed of return to equilibrium. Pimm (1991:13) defines engineering resilience as "how fast a variable that has been displaced from equilibrium returns to it. Resilience could be estimated by a return time, the amount of time taken for the displacement to decay to some specified fraction of its initial value." This definition applies only to behavior of a linear system, or behavior of a non-linear system in the immediate vicinity of a stable equilibrium where a linear approximation is valid (Ludwig et al., 1997). Engineering resilience therefore focuses on maintaining efficiency of function, constancy of the system, and a predictable world near a single steady state. It is about resisting disturbance and change, to conserve what you have. As previously stated, the single equilibrium view has substantially shaped contemporary natural resource and environmental management with attempts to control resource flows in an optimal fashion.

The engineering interpretation of resilience exists to date in many facets of ecology (McManus and Polsenberg, 2004). The resistance to change is often addressed in terms of recovery, which is the time it takes to return to the previous state following disturbance, for example to a coral dominated state after a coral bleaching event (Halford et al., 2004). But as stated by O'Neill (1999)

> "current ecosystem theory has a deceptively simple representation of recovery. In actual practice, recovery is affected by the frequency and extent of disturbances and by the spatial heterogeneity of the ecological system."

Disturbance events and spatial heterogeneity cause each recovery trajectory to be unique and the complexity of the system combined with unanticipated compounded effects can make recovery trajectories difficult or impossible to predict (Paine et al., 1998; O'Neill, 1999). The system may look similar but it is not the same system, because like any living system it is continuously developing. For reasons like these, scholars involved with resilience in relation to complex adaptive systems increasingly avoid the use of recovery and prefer the concepts renewal, regeneration and re-organization following disturbance (Bellwood et al., 2004). In the same spirit, it might be more appropriate to use words such as "regimes" or "attractors" instead of terms such as "stable states" or "equilibria" that give a sense of excluding dynamics (Carpenter, 2003).

Hence, it is important to distinguish between behavior near a stable equilibrium, a global steady state, and behavior near the boundary of a domain of attraction, which is an unstable equilibrium, reflecting behavior of complex adaptive systems (Kauffman, 1993; Holland, 1995; Levin, 1998). The definition of Holling (1973), which has been the foundation from which the resilience perspective of social–ecological systems has developed, fits with the dynamics of complex adaptive systems. Ludwig et al. (1997) provides the mathematical basis for the differences between engineering resilience and the ecological or ecosystem resilience perspective.

3. Complex adaptive systems, ecosystem resilience and regime shifts

Theories of complex systems portray systems not as deterministic, predictable and mechanistic, but as process-dependent organic ones with feedbacks among multiple scales that allow these systems to self-organize (Holland, 1995; Levin, 1999). The study of complex adaptive systems attempts to explain how complex structures and patterns of interaction can arise from disorder through simple but powerful rules that guide change. According to Levin (1998) the essential elements are; sustained diversity and individuality of components; localized interactions among those components; an autonomous process that selects from among those components, based on the results of local interactions, a subset for replication or enhancement. The dispersed and local nature of an autonomous selection process assures continual adaptation and the emergence of cross-level organization. The maintenance of diversity and individuality of components implies the generation of perpetual novelty and far-from-equilibrium dynamics (Levin, 1998). Hence, a complex adaptive system consists of heterogeneous collections of individual agents that interact locally, and evolve in their genetics, behaviors, or spatial distributions based on the outcome of those interactions (Janssen and de Vries, 1998; Janssen, 2002). Arthur et al. (1997) identify six properties of complex adaptive economic systems; dispersed interaction, the absence of a global controller, cross-cutting hierarchical organization, continual adaptation, perpetual novelty, and far-from-equilibrium dynamics. Holland (1995) identifies four basic properties of complex adaptive systems: aggregation, non-linearity, diversity, and flows. Non-linearity generates path dependency, which refers to local rules of interaction that change as the system evolves and develops. A consequence of path dependency is the existence of multiple basins of attraction in ecosystem development and the potential for threshold behavior and qualitative shifts in system dynamics under changing environmental influences (Levin, 1998). Schneider and Kay (1994) make the link between complex systems, thermodynamics and ecology.

Since the publication by Holling (1973) of multiple basins of attraction in ecology the empirical evidence, some 30 later, is now substantial, and covers a wide range of terrestrial, freshwater and marine ecosystems. Regime shifts between alternate states have been reviewed by Carpenter (2000, 2003), Scheffer et al. (2001), Beisner et al. (2003), Folke et al. (2004) and Walker and Meyers (2004). In some cases the transition is sharp and dramatic. In others, though the dynamics of the system have "flipped" from one attractor to another, the transition itself may be gradual (Walker and Meyers, 2004).

These reviews illustrate that shifts between states in ecosystems are increasingly a consequence of human actions that cause erosion of resilience (Gunderson, 2000). A combination of top-down impacts, like fishing down foodwebs or removing functions of biological diversity for self-organization, and bottom-up impacts, like accumulation of nutrients, soil erosion or redirection of water flows, as well as altered disturbance regimes, like suppression of fire and increased frequency and intensity of storms, have shifted ecosystem states (Gunderson and Pritchard, 2002) into less desirable ones with subsequent impacts on livelihood and societal development (Folke et al., 2004). Less desirable refers to their capacity to sustain natural resources and provide ecosystem services for societal development (Daily, 1997). The combined effects of those pressures make social–ecological systems more vulnerable to changes that previously could be absorbed.

Research on ecosystem resilience has also provided deeper understanding of the role of biological diversity in ecosystem dynamics. Biological diversity is essential in the self-organizing ability of complex adaptive systems (Levin, 1999) both in terms of absorbing disturbance and in regenerating and re-organizing the system following disturbance (Folke et al., 2004). In 1991, the newly established Beijer International Institute of Ecological Economics initiated a research program on the ecology and economics of biodiversity loss (Perrings et al., 1992), in particular, the role and value of biodiversity in supplying ecosystem services (Barbier et al., 1994), without which civilization could not persist (Ehrlich and Ehrlich, 1992). At that time insights from ecosystem ecologists had started to emerge on aspects of biodiversity in ecosystem function (Schulze and Mooney, 1993) and redundancy in ecosystem dynamics and development (Walker, 1992). An ecological synthesis on the role of biodiversity in the functioning of ecosystems was developed by Holling et al. (1995) as part of the Beijer program, where they argued that only a small set of species and physical processes are essential in forming the structure and overall behavior of ecosystems. Hence, it is not the number of species per se that help sustain an ecosystem in a certain state or domain of attraction, but rather the existence of species groupings, or functional groups (e.g. predators, herbivores, pollinators, decomposers, water flow modifiers, nutrient transporters) with different and often overlapping characteristics in relation to physical processes (Walker et al., 1999; Hooper et al., 2005). Species that may seem redundant and unnecessary for ecosystem functioning during certain stages of ecosystem development may become of critical importance for regenerating and re-organizing the system after disturbance and disruption (Folke et al., 1996; Bellwood et al., 2004). In addition, variability in responses of species within functional groups to environmental change is critical to ecosystem resilience (Chapin et al., 1997) a property referred to as response diversity (Elmqvist et al., 2003). Furthermore, seemingly redundant species that operate at different scales generate ecosystem resilience by connecting habitats, thereby reinforcing functions across scales (Peterson et al., 1998; Nyström and Folke, 2001; Lundberg and Moberg, 2003). The distribution of functional groups and their response diversity within and across scales enables regeneration and renewal following disturbance over a wide range of scales. Such cross-scale interplay and the emergence of discontinuous patterns, processes and structures are central issues in ecology in relation to resilience (Holling, 1992; Levin, 1992). Such perspectives on biological diversity seem to have inspired recent attempts to address institutional diversity and redundancy (Low et al., 2003; Ostrom, 2005).

Hence, resilience is a concept that has advanced in relation to the dynamic development of complex adaptive systems with interactions across temporal and spatial scales. This leads us to the adaptive renewal cycle of development proposed by Holling (1986) and the more recent concept panarchy (Gunderson and Holling, 2002) that explicitly takes fast/slow dynamics and cross scale interactions and interdependencies into account.

3.1. The adaptive renewal cycle and the panarchy

The Adaptive renewal cycle is a heuristic model, generated from observations of ecosystem dynamics, of four phases of development driven by discontinuous events and processes. There are periods of exponential change (the exploitation or r phase), periods of growing stasis and rigidity (the conservation or K phase), periods of readjustments and collapse (the release or omega phase) and periods of re-organization and renewal (the α phase). The sequence of gradual change is followed by a sequence of rapid change, triggered by disturbance. Hence, instabilities organize the behaviors as much as do stabilities. The exploitation and conservation phases are the parts of the adaptive cycle of renewal with which conventional resource management has largely been concerned. The release, or creative destruction phase, and the re-organization phase have to a large extent been ignored. Yet, these two phases, referred to as "the backloop" in resilience language, are just as important as the other two in the overall dynamics (Gunderson and Holling, 2002; Berkes et al., 2003). This view emphasizes that disturbance is part of development, and that periods of gradual change and periods of rapid transition coexist and complement one another.

There are those who try to use the adaptive cycle as an analytical tool and others that simply view it as a heuristic conceptual model. There are those that dislike it and interpret it as too deterministic and others become inspired by its dynamics. I belong to the latter category and in particular in relation to the panarchy of cross-scale dynamics and interplay between a set of nested adaptive cycles (Gunderson and Holling, 2002; Fig. 1). It has helped

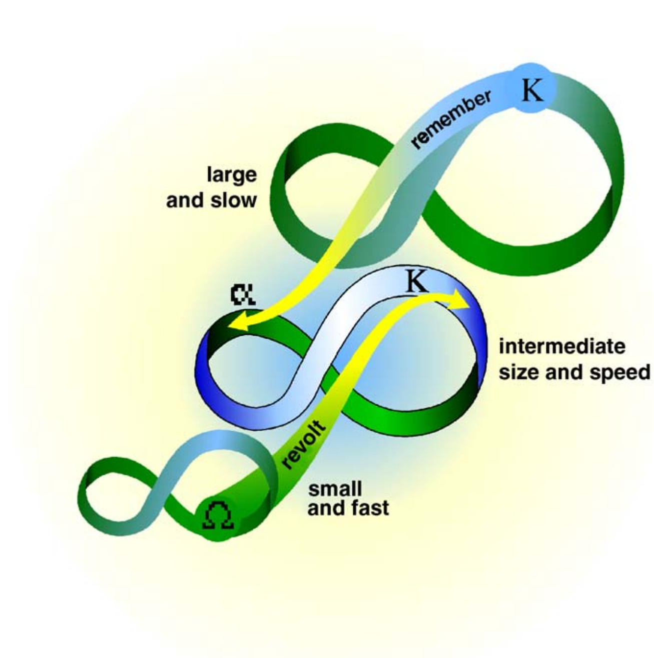

Fig. 1. Panarchy, a heuristic model of nested adaptive renewal cycles emphasizing cross scale interplay (see text for explanation) (modified from Gunderson and Holling, 2002).

me to think about structures and processes in a dynamic fashion, to move away from a steady-state world where change is looked upon as an exception, to confront complexity and uncertainty, and move further into patterns and processes that you cannot directly observe and quantify with available data and it has inspired the generation of many exciting hypotheses, and new ones to be explored.

The connections in Fig. 1 labeled ''revolt'' and ''remember'' are examples of the interplay across scales that are of significance in the context of building resilience. An ecological example of revolt is a small ground fire that spreads to the crown of a tree, then to a patch in the forest and then to a whole stand of trees. Each step in that cascade of events moves the disturbance to a larger and slower level. Remember is a cross-scale connection important in times of change, renewal and re-organization. For example, following a fire in a forested ecosystem, the re-organization phase draws upon the seed bank, physical structures and surviving species that had accumulated during the previous cycle of growth of the forest, plus those from the wider landscape. Thus, the ability for renewal and re-organization into a desired (from a human perspective) ecosystem state following disturbance will therefore strongly depend on the influences from states and dynamics at scales above and below and across time as well. Each level operates at its own pace, embedded in slower, larger levels but invigorated by faster, smaller cycles. Memory is the accumulated experience and history of the system, and it provides context and sources for renewal, recombination, innovation, novelty and self-organization following disturbance. The panarchy (Fig. 1) is therefore both creative and conservative through the dynamic balance between rapid change and memory, and between disturbance and diversity and their cross-scale interplay. It sustains at the same time as it develops (Holling, 2001).

3.2. *The resilience concept*

Appreciating the dynamic and cross-scale interplay between abrupt change and sources of resilience makes it obvious that resilience of complex adaptive systems is not simply about resistance to change and conservation of existing structures. Resilience is currently defined in the literature as the capacity of a system to absorb disturbance and re-organize while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks (Walker et al., 2004). Lot of work on ecosystem resilience has emphasized the first part of this definition, i.e. capacity to absorb disturbance, or the buffer capacity that allows persistence. It has also been used in relation to social change where, for example, Adger (2000) defined social resilience as the ability of human communities to withstand external shocks to their social infrastructure, such as environmental variability or social, economic and political upheaval. Anderies et al. (2004) used the concept robustness to mean the maintenance of some desired system characteristics despite fluctuations in the behavior of its component parts or its environment (see Table 1).

But resilience is not only about being persistent or robust to disturbance. It is also about the opportunities that disturbance opens up in terms of recombination of evolved structures and processes, renewal of the system and emergence of new trajectories. In this sense, resilience provides adaptive capacity (Smit and Wandel, 2006) that allow for continuous development, like a dynamic adaptive interplay between sustaining and developing with change. Too much of either will ultimately lead to collapse. It does not imply that resilience is always a good thing. It may prove very difficult to transform a resilient system from the current state into a more desirable one (Scheffer et al., 2001; Gunderson and Holling, 2002; Walker et al., 2004).

Adaptive processes that relate to the capacity to tolerate and deal with change emerge out of the system's self-organization. Furthermore, the dynamics after a disturbance or even a regime shift is crucially dependent on the self-organizing capacity of the complex adaptive system (Norberg and Cumming, 2006) and the self-organizing process draws on temporal and spatial scales above and below the system in focus (Nyström and Folke, 2001; Gunderson and Holling, 2002). This is why the concept of resilience in relation to social–ecological systems incorporates the idea of adaptation, learning and self-organization in addition to the general ability to persist disturbance. In this sense, the buffer capacity or robustness captures only one aspect of resilience (see Table 1). Following Carpenter et al. (2001) social–ecological resilience is interpreted as

(1) the amount of disturbance a system can absorb and still remain within the same state or domain of attraction,

Table 1
A sequence of resilience concepts, from the more narrow interpretation to the broader social–ecological context

Resilience concepts	Characteristics	Focus on	Context
Engineering resilience	Return time, efficiency	Recovery, constancy	Vicinity of a stable equilibrium
Ecological/ecosystem resilience social resilience	Buffer capacity, withstand shock, maintain function	Persistence, robustness	Multiple equilibria, stability landscapes
Social–ecological resilience	Interplay disturbance and reorganization, sustaining and developing	Adaptive capacity transformability, learning, innovation	Integrated system feedback, cross-scale dynamic interactions

(2) the degree to which the system is capable of self-organization (versus lack of organization, or organization forced by external factors), and
(3) the degree to which the system can build and increase the capacity for learning and adaptation.

In this sense, resilience is an approach, a way of thinking, that presents a perspective for guiding and organizing thought and it is in this broader sense that it provides a valuable context for the analysis of social–ecological systems, an area of explorative research under rapid development with policy implications for sustainable development (Folke et al., 2002). The resilience approach provides one among several arenas (e.g. vulnerability research, ecological economics, sustainability science) for generating integrative science and interdisciplinary collaboration on issues of fundamental importance for governing and managing a transition toward more sustainable development paths, one of the greatest challenges facing humanity (Lambin, 2005).

4. Resilience and research on social–ecological systems

As stated above, the resilience approach is concerned with how to persist through continuous development in the face of change and how to innovate and transform into new more desirable configurations. The resilience perspective was revived in the early 1990s through research programs of the Beijer Institute, where it came across as essential in interdisciplinary studies on biodiversity (Perrings et al., 1995; Folke et al., 1996), complex systems (Costanza et al., 1993), property rights regimes (Hanna et al., 1996; Berkes and Folke, 1998) cross-level interactions and the problem of fit between ecosystems and institutions (Folke et al., 1998; Costanza et al., 2001) and in relation to economic growth and socioeconomic systems (Arrow et al., 1995; Levin et al., 1998). As a consequence, the Beijer Institute and the University of Florida, where Holling was located, started the Resilience Network, a research program that later developed into the Resilience Alliance (www.resalliance.org) with its journal Ecology and Society (www.ecologyandsociety.org).

The Resilience Alliance is a consortium of research groups and research institutes from many disciplines who collaborate to explore the dynamics of social–ecological systems. The purpose of the Resilience Alliance is to stimulate interdisciplinary and integrative science using resilience as an overarching framework. The book Panarchy: understanding transformations in human and natural systems (Gunderson and Holling, 2002), an outcome of the Resilience Network, explores such interactions and ask questions like; Why are ecosystems not just physical systems, like piles of sand? Why are social systems not just ecosystems? And why are social–ecological systems not just social or ecological systems? The last issue is particularly relevant (Ludwig et al., 2001), because despite the huge literature on the social dimension of resource and environmental management, most studies have focused on investigating processes within the social domain only, treating the ecosystem largely as a ‘‘black box’’ and assuming that if the social system performs adaptively or is well organized institutionally it will also manage the environmental resource base in a sustainable fashion. A human society may show great ability to cope with change and adapt if analyzed only through the social dimension lens. But such an adaptation may be at the expense of changes in the capacity of ecosystems to sustain the adaptation (Smit and Wandel, 2006), and may generate traps and breakpoints in the resilience of a social–ecological system (Gunderson and Holling, 2002). Similarly, focusing on the ecological side only as a basis for decision making for sustainability leads to too narrow and wrong conclusions. That is why work on resilience stress linked social–ecological systems. The efforts to understand such systems are still in an exploratory stage and there is opportunity for creative approaches and perspectives. Examples of conceptual frameworks for analyses of social–ecological systems are shown in Fig. 2.

4.1. *An overview of work on the resilience of social–ecological systems*

There have been attempts to address social resilience in relation to coastal communities (Adger, 2000), vulnerability of cities (Pelling, 2003) and to patterns of migration (Locke et al., 2000) and work has been inspired by the adaptive cycle and the panarchy to understand management institutions and theories of social change (Holling and Sanderson, 1996; Westley, 2002), famine and assessment of vulnerability of food systems (Fraser, 2003; Fraser et al., 2005) and periods of changing and stable relationships between human groups, land degradation and their environments in an archaeological context (van der Leeuw, 2000; Redman and Kinzig, 2003; Delcourt and Delcourt, 2004; Redman, 2005). The interplay between periods of gradual change and periods of rapid change and adaptive capacity to shape change was the focus of the volume ‘‘Navigating Social–Ecological Systems: Building resilience for complexity and change’’ (Berkes et al., 2003).

There are scholars that have interpreted social dynamics in terms of regime shifts, for example, in relation to vulnerability and collapse of ancient societies (Janssen et al., 2003), to opinion shifts in relation to leadership, social capital and learning for how to deal with complex adaptive systems (Scheffer et al., 2000, 2003) or the emergence of tipping points and multi-stable behavior of social systems (Brock, 2006). The theoretical basis and implications of regime shifts for economic systems have been described by Mäler et al. (2003) as part of a special journal issue and book, dealing with complex ecosystems and their economic management (Dasgupta and Mäler, 2003). Economic instruments applied in environmental policy work best in stable environments. Articles in the issue illustrate that existence of positive feedback leading to

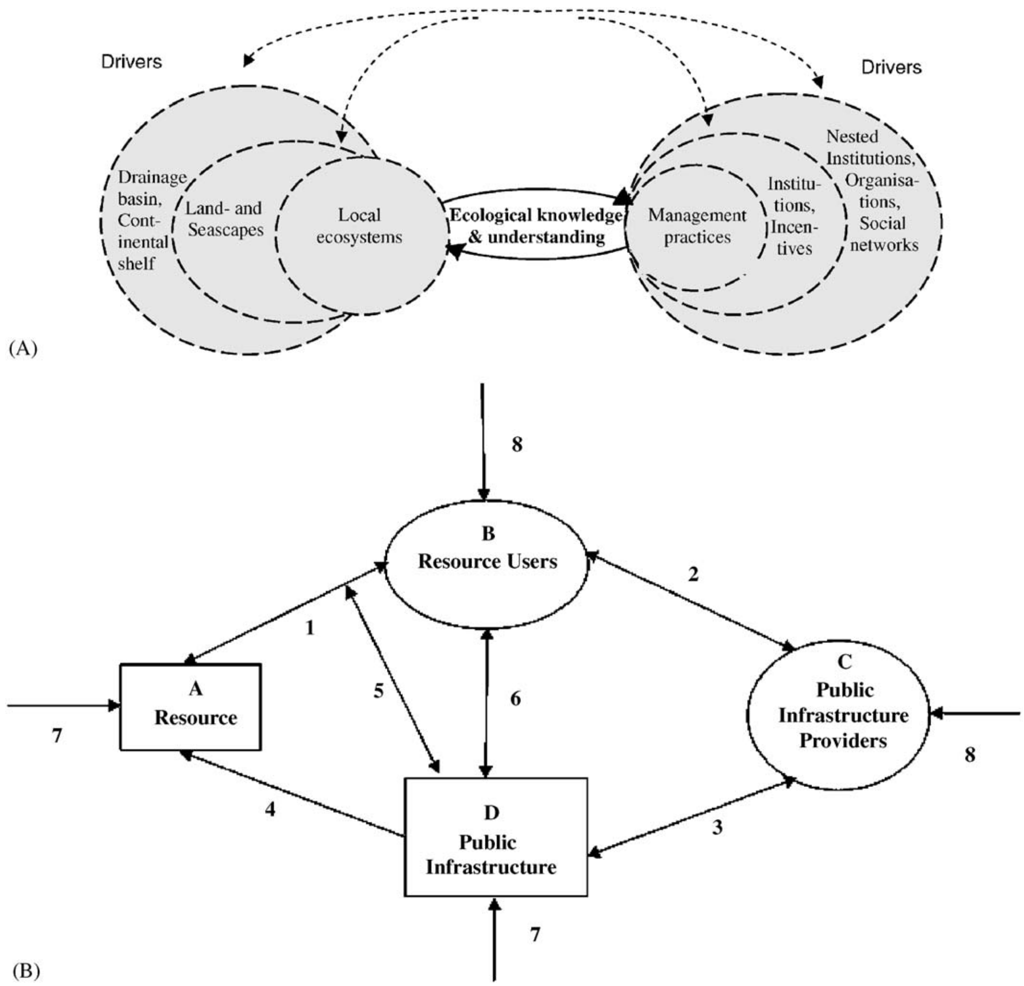

Fig. 2. There are several conceptual frameworks developed in relation to the resilience approach: (A) a framework that focuses on knowledge and understanding of ecosystem dynamics, how to navigate it through management practices, institutions, organizations and social networks and how they relate to drivers of change (modified from Berkes et al. 2003) and (B) a conceptual model in relation to the robustness of social-ecological systems. The resource could be water or a fishery and the resource users could be farmers irrigating or inshore fishermen. Public infrastructure providers involve e.g. local users associations and government bureaus and public infrastructure include institutional rules and engineering works. The numbers refer to links between the entities and are exemplified in the source of the figure (Anderies et al. 2004.)

non-linear (non-convex in economic terminology) dynamics and regime shifts make it difficult to use standard economic instruments in an efficient way (Mäler et al., 2003).

The complex adaptive systems view of nature and society has major implications for economic valuation. Most approaches to valuation attempt to capture the value of marginal change under assumptions of stability near a local equilibrium (Daily et al., 2000). They seldom take into account the inherent complexities and resulting uncertainties associated with ecosystem management (Pritchard et al., 2000) and natural capital assets in general (Brock et al., 2002) and ignore the broad-tailed and slowly changing probability distributions of critical ecosystem thresholds (Carpenter, 2002). Optimal management will often, because of the complex dynamics, be extremely difficult if not impossible to implement (Brock et al., 2002; Crépin, 2003). Whenever resilience and regime shifts are in focus it seems necessary to include risk assessment, risk valuation and uncertainty, which is seldom done (Peterson et al., 2003b).

Gunderson (2001) nicely illustrates the need for learning and flexibility in the social system when confronted with alternative and uncertain explanations of ecosystem change. There has been substantial progress in understanding the social dimension for dealing with uncertainty and change in resource and ecosystem dynamics, including organizational and institutional flexibility (Lee, 1993; Grumbine, 1994; Danter et al., 2000; Armitage, 2005; Ostrom, 2005) and social capital and conflict (Ostrom and Ahn, 2003; Adger, 2003; Pretty, 2003; Galaz, 2005). Social sources of resilience such as social capital (including trust and social networks) and social memory (including experience for dealing with change) (Olick and Robbins, 1998; McIntosh, 2000) are essential for the capacity of social–ecological systems to adapt to and shape change (Folke et al., 2003, 2005).

Berkes and Folke (1998) used the term social–ecological system to emphasize the integrated concept of humans-in-nature and to stress that the delineation between social and ecological systems is artificial and arbitrary. They addressed the interplay and problem of fit between social and ecological systems by relating management practices based on ecological understanding to the social mechanisms behind these practices, in a variety of geographical settings, cultures, and ecosystems (Berkes and Folke, 1998).

Social–ecological systems have powerful reciprocal feedbacks (Costanza et al., 2001; Gunderson and Holling (2002); Berkes et al., 2003; Janssen et al., 2003; Chapin et al., 2004). Such feedbacks and their cross-scale interactions in relation to resilience are in focus of truly integrated systems modeling of agents and ecosystem with multiple stable states (Carpenter and Brock, 2004; Carpenter et al., 1999; Janssen and Carpenter, 1999; Janssen et al., 2000; Bodin and Norberg, 2005). Recent work suggest that complex systems "stutter" or exhibit increased variance at multiple scales in advance of a regime shift (Kleinen et al., 2003; Carpenter and Brock, 2006). Such increases in variance help characterize regime shifts, and may even allow early warning indicators of some regime shifts. Furthermore, multiple thresholds and regime shifts at different scales and in different and interacting ecological, economic and social domains are proposed to exist within regional social–ecological systems (Kinzig et al., 2006). There are progress in capturing persistence or robustness of institutions in the face of change (Anderies et al., 2004) and their fit and interplay with ecosystem resilience (Young, 2000; Brown, 2003), in analyzing the role of different knowledge systems in relation to adaptive management (Berkes et al., 2003; Colding et al., 2003) in participatory approaches for managing ecosystem resilience (Walker et al., 2002; Olsson et al., 2004), in challenges for freshwater management, food production and resilience (Falkenmark and Folke, 2003) or in using scenarios for envisioning possible future directions and options (Bennett et al., 2003; Peterson et al., 2003b). The diversity of insights and discoveries of many research groups that are underway in relation to resilience are almost impossible to grasp. Two recent efforts of the Resilience Alliance are worth mentioning; a special feature of Ecology and Society–exploring resilience in social–ecological systems with results and propositions from regional case study comparisons (Walker et al., 2006) and a book on complexity theory for a sustainable future (Norberg and Cumming, 2006).

4.2. Resilience, adaptation and transformation

A vulnerable social–ecological system has lost resilience. Losing resilience implies loss of adaptability. Adaptability in a resilience framework does not only imply adaptive capacity to respond within the social domain, but also to respond to and shape ecosystem dynamics and change in an informed manner (Berkes et al., 2003). The variables and processes that structure ecosystem dynamics and sources of social and ecological resilience have to be understood and actively managed to deal with the interplay of gradual and abrupt change. It implies expanding analysis into broader spatial and temporal scales. A major challenge in this context is to build knowledge, incentives, and learning capabilities into institutions and organizations for governance that allow adaptive management of local, regional and global ecosystems. In resilience work adaptability is referred to as the capacity of people in a social–ecological system to build resilience through collective action whereas transformability is the capacity of people to create a fundamentally new social–ecological system when ecological, political, social, or economic conditions make the existing system untenable (Walker et al., 2004).

There is an increased emphasis on transformability into improved social–ecological systems as opposed to adaptation to the current situation. An emphasis on transformability implies extending the focus in social–ecological research to systems of adaptive governance (Dietz et al., 2003) in order to explore the broader social dimension that enables adaptive ecosystem-based management. An adaptive governance framework relies critically on the collaboration of a diverse set of stakeholders operating at different social and ecological scales in multi-level institutions and organizations (Olsson et al., 2004). Individual actors play essential roles in providing e.g. leadership, trust, vision and meaning, and in social relations e.g. actor groups, knowledge systems, social memory. Social networks serve as the web that seems to tie together the adaptive governance system. Adaptive governance is a major extension of conventional resource management and it consists of at least four essential parts; understanding ecosystem dynamics; developing management practices that combines different ecological knowledge system to interpret and respond to ecosystem feedback and continuously learn; building adaptive capacity to deal with uncertainty and surprise including external drivers; and supporting flexible institutions and social networks in multi-level governance systems (Folke et al., 2005).

5. Concluding remarks

The resilience perspective emerged from a stream of ecology that addressed system dynamics, in particular ecosystem dynamics, and where human actions early became a central part of understanding the capacity of ecosystems to generate natural resources and ecosystem services. The early inclusion of humans as agents of ecosystem change distinguished this ecosystem oriented branch of ecology from the main stream ecology profession. The main stream excluded humans or treated human actions as external to the system and consequently the interdependencies and feedbacks between ecosystem development and social dynamics, and their cross scale interactions, were not on the table. The resilience perspective evolved out of observation, using models as a tool for understanding and for incorporating actors and interest groups in adaptive management and learning of ecosystem processes. More recently, social scientists have started to play an active role with diverse contributions and perspectives in understanding the dynamics of social–ecological systems. Research on social–ecological resilience is still in the explorative phase. Recent advances include understanding of social processes like, social learning and social memory, mental models and knowledge–system integration, visioning and scenario building, leadership, agents and actor groups, social networks, institutional and organizational inertia and change, adaptive capacity, transformability and systems of adaptive governance that allow for management of essential ecosystem services. Research challenges are numerous and include efforts clarifying the feedbacks of interlinked social–ecological systems, the ones that cause vulnerability and those that build resilience, how they interplay, match and mismatch across scales and the role of adaptive capacity in this context. The implication for policy is profound and requires a shift in mental models toward human-in-the environment perspectives, acceptance of the limitation of policies based on steady-state thinking and design of incentives that stimulate the emergence of adaptive governance for social–ecological resilience of landscapes and seascapes. Not only adaptations to current conditions and in the short term, but how to achieve transformations toward more sustainable development pathways is one of the great challenges for humanity in the decades to come.

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