SIXTH FRAMEWORK PROGRAMME
PRIORITY 8 - NEST
Project acronym: CAVES
Project full title: Complexity: Agents, Volatility, Evidence and Scale

Contract for:

SPECIFIC TARGETED RESEARCH PROJECT

Deliverable 6 - "Critical examination of resilience theories and measures"

Report Dissemination Level (PP)
Restricted to other programme participants (including the Commission Services).

Work Package 4

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EXECUTIVE SUMMARY

This report serves as an introduction to Resilience theory (RT) for social scientists in the CAVES project interested to use it in testing ideas about the dynamics of human networks in areas of environmental uncertainty, such as that emerging from climate unpredictabilitz. RT developed originally from ecologists' efforts to understand sudden, catastrophic, often irreversible, shifts in ecosystems to degraded and impoverished states. Originally proposed by C.S. Holling, an animal ecologist, the circle of disciplines applying RT to understand the non-linear dynamics of Complex Adaptive Systems (CAS) has expanded outside the natural sciences to include economists, sociologists, anthropologists, political scientists and psychologists. The co-evolution of RT CAS theory and Adaptive Management has developed a number of metaphors and graphic heuristics to convey abstract ideas about the structure and dynamics of Complex Adaptive Systems without recourse to mathematics. For example, the Adaptive Cycle is a graphic metaphor that radically challenges traditional equilibrium-based ecological concepts of steady progression (succession) to climax states. It portrays disturbance as a trigger that is not an external intervention but part of the natural, inherent dynamics of the system. As such it releases resources in cycles of renewal and reorganization or degradation of ecosystem. Other concepts that have proven useful in lay-science collaborations are the Panarchy concept (landscapes as complex mosaics of entities at different stages in their adaptive cycles linked by cross-scale interactions) and Stability landscapes. Such tools allowed a broader range of experience to contribute to rigorous dialogues about problematic dynamics of SES, including insight from policy makers, conservation and community activists, stakeholders that made their living (hunters, foresters, farmers, fishermen) in the ecosystems and societies under threat of collapse. Beyond teaching, research and communication benefits, the search for practical applications of RT has striven for "policy relevance" by making it more accessible to policy makers, e.g. by identifying variables that indicate resilience thresholds which can be used as policy triggers. This search has yet to find any indicators that consistently track resilience in all phases of the adaptive cycle. Instead of indicators, the term *resilience surrogate* is proposed to convey the looser but more robust links between the actual resilience of a system and the information provided by certain variables observed in the field and/or modeled using computer simulation. A policy-research framework is described that links field observation, computer models, and resilience surrogates in an iterative cycle. Such a framework is designed to assess resilience dynamically from a number of perspectives. It does so by accounting for how biophysical and socio-economic contexts change over time, along with the different paradigms operational in the community of human actors. All these sources of uncertainty are addressed in a suite of models that explore the implications of some of the key, different perspectives. Such a framework has been successfully applied to combine field data with computer model output to show how spiking variance in lake water phosphorus concentrations can predict declining resilience of lake water quality to pulsing inputs of phosphorus from the landscape. As such, the framework is useful for predicting how declining resilience presages a *regime change* from the oligotrophic (clear water) to the eutrophic (turbid water) condition. However, such an application relied on data and experience built over a century of field experimentation. To meet the limited resources and narrower needs of the

CAVES project, this report attempts to make RT accessible for the study of network dynamics in several ways. It describes social factors associated with resilience, with emphasis on regimes to represent the constellations of human networks and processes that reinforce one another. It uses a description developed by social and natural scientists of the factors influencing the phases of transition between regimes to offer a template for applying RT in examining the dynamics of the networks in their agent-based models. It proposes to apply this template in a series of steps driven by questions that allow users to bound the system of study in space and time, describe regimes (past, present or future) in terms of the networks and processes that reinforce one another in their operation, determine which variables in these regimes are linked to resilience by their vulnerability to shock and/or stress, develop hypotheses about how regime change may occur by plotting potential pathways that might link present with future regimes, identify variables or behaviors that indicate that transition is in process or has occurred. This report can only cover a fraction of RT or the approaches to its application with networks but can serve as an introduction to discussions to apply RT in models developed within the CAVES project.

1. AN INTRODUCTION TO RESILIENCE

1.1 Purpose

The CAVES project is designed to foster a number of opportunities to increase understanding of complex adaptive systems. Principal among these are chances to apply concepts and methods of complexity science in actual case studies to show their policy-relevance and efficacy in understanding how complex systems change. These applications offer an arena in which to challenge and revise both theories and methods (knowledge elicitation, analysis and modeling simulation). How such approaches of integrated analysis and modeling can inform decision-making processes about how social-ecological systems respond to shock and stress is a wider test of their policy-relevance.

Resilience theory (RT) has co-evolved with the development of the theory of Complex Adaptive Systems (CAS) (Lansing 2003) and encompasses a diversity of ideas about what factors influence non-linear dynamics in CAS. This report surveys some of these ideas and methods to apply them in ecosystems, social systems and social-ecosystems. The aim is to provide researchers and modelers in the CAVES project with tools that they can adapt in assessing resilience in CAS, such as the case studies they investigate.

RT has a history of bridging theoretical and policy debates. It began as a radical challenge to equilibrium-based paradigms, especially those that supported centralized top-down management control of natural resource systems (Gunderson et al. 1995). Its development along with Complexity Science pointed toward the inevitability of surprise in CAS as a mandate to shift from control to "…managing the capacity of social-ecological systems to cope with, adapt to, and shape change (Berkes et al., 2003, Smit and Wandel, 2006, Folke 2006)." As this report describes, development of RT and CAS have advanced our understanding of complexity, but not enough for neat and tidy proofs and summary explanations. Demands for that degree of simplicity (Klein et al. 2003) are sincere but premature, even in the face of real and urgent challenges of addressing vulnerability in the face of change. The undiminished richness uncovered in the theoretical and methodological development of Complexity Science needs a broad exploratory track. This need sustains the thrust behind the development of RT as it continues to widen the scope of scientific inquiry to include tools (models, metaphors) that organize thought and research. When much of the phenomena that influence the dynamics of CAS are not easy or impossible to observe and record, Complexity Science needs a broad exploratory framework that includes a wide array of tools to consider alternatives, even speculative metaphors as engines of hypotheses. This report describes examples of such a framework that employs metaphors, models and field observation in the assessment of resilience of social-ecological systems.

1.2 Defining Resilience

Complexity is difficult enough to appraise even if only one disciplinary approach is taken. However, numerous disciplines besides ecology have informed the refinement of RT in studying complex systems, and some of these separate perspectives have shifted as the disciplines evolved over time. While ecology provided the initial impetus, a number of other disciplines have used and improved RT in their attempts to analyze complexity. Folke (2006) notes the following separate contributions to RT (*italic emphasis is mine*).

> "…*anthropology* where e.g. 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* (e.g. Hanna et al., 1996) and also other *social sciences* (reviewed in e.g. Scoones, 1999; Abel and Stepp, 2003; Davidson-Hunt and Berkes, 2003). "

A variety of definitions for resilience has emerged from this manifold and diverse stream of research (see Appendix One for a small sampling). Folke et al. 2005 use a definition quite similar to many of those invoked by scientists approaching it from its origins in ecosystem science.

> "Resilience … defined as 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."

This definition describes resilience as something far more than a defensive capability in response to shock or stress. It includes the Janus-like twin faces of reaction (absorb disturbance) and initiative (reorganization following disturbance). It is dynamic in that the system responds "on the move" as it undergoes change. Finally, it specifies the factors that combine to build and sustain the system's identity: structure (the web of interactions that link the system's key actors or processes), function (the services or activities characteristic of the system) and feedbacks (the processes that cyclically reinforce or dampen activities in the system).

While the following section on Resilience and its relation to CAS will examine these facets in more detail, it is enough to note the difficult balance that the resilience concept tries to reach between stasis and dynamism, building and destruction, single acts or actors and collective response (see the section on Paradoxes below). Even "disturbance" is recognized for its contribution in opening gaps to be filled and creating opportunities for "recombination of evolved structures, renewal of the system, emergence of new trajectories" (Folke 2007). Decriminalizing "disturbance" and dethroning "productivity" as the mainstay of ecosystem integrity are part of the revolt that resilience has led against conventional paradigms that suggest "ecological health" is evident in monotonic and smooth trajectories within a single, static equilibrium.

The value of resilience theory is achieved if this sophisticated balance between opposites is forged in building hypotheses and models that guide inquiry into all (or a useful and significant fraction) of the aspects that influence a system's trajectory. Of special interest is assessing the potential that the system will undergo irreversible change or change that may possibly be reversed with great effort over extended periods (hysteresis). However, contrary to the contention of Klein et al. 2003, who claim it is "widely seen as a desirable system property", resilience in and of itself is neither good nor bad. Resilience simply reflects the system's potential to persist in its present identity in the face of stress and/or disturbance. If the present identity is not socially desirable (degraded ecosystem, authoritarian dictatorship) then resilience will be deplored as well in the attempt to move the system toward a new, more socially acceptable, state.

1.3. Ontogeny of the Resilience Concept

The idea that every ecosystem has one and only one equilibrium prevailed as the conventional view in ecology for most of the last century. The Clementsian (Clements 1916) concept of ecological succession best illustrates this single equilibrium paradigm (see Figure 1) which posits that every ecosystem develops along a specific trajectory toward its unique balance point, a "climax" stage. Figure 1 shows the succession from a bare field to a temperate deciduous forest over 150 years. In this light, disturbance only interrupts this development or disrupts the "natural" climax state of balance. Much ecosystem management policy was thereby directed to eliminate disturbance with a fervor of stamping out evil and "pernicious" influences. For example, for more than seventy years fire was totally suppressed in US national parks. Similar philosophies have driven the elimination or suppression of insect "pests" from forests and agricultural areas and flooding from river valleys. These policies appeared to succeed for decades before spectacular ecological collapses provoked a line of questioning that eventually developed *resilience* within the frame of complex adaptive systems to explore the roots of such surprising catastrophes.

1.3.1 Conceptual foundations – Multiple Equilibria

The potential for not one but multiple equilibria in a system offered a framework to imagine sudden and irreversible jumps to degraded states, giving traction to inquiry into such unprecedented environmental disasters. The concept of multiple equilibria, already well studied in Physics, was gaining attention in evolutionary biology (Bazykin 1969) and gained credibility in ecology when it emerged in exploration of predator-prey interactions. C.S. Holling describes how this occurred when he expanded his analysis from equations describing how predators searched to a full model of population dynamics (Carl Folke 2006):

> "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."

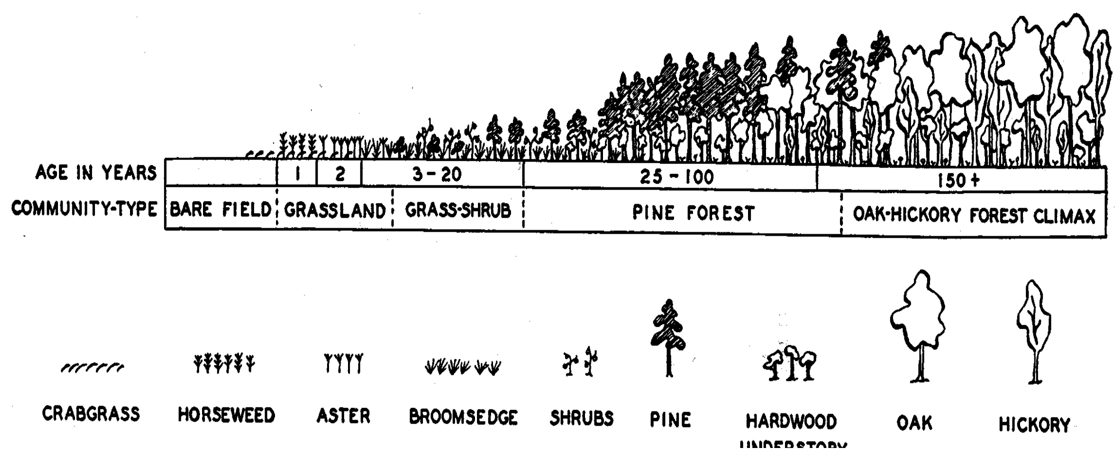


Figure 1 – Old field succession to Oak-Hickory climax forest in northern temperate deciduous forests *(After E.P. Odum 1971 Fundamentals of Ecology)*

This insight provided the impetus for Holling's seminal paper on resilience (Holling 1973), and gained further momentum and definition as multiple equilibria were consistently found in a wide range of ecosystems: boreal forest dynamics of North America (e.g Holling, 1978; Ludwig et al., 1978), the Great Lakes (e.g. Regier and Kay, 2002 dynamics and management of rangelands (Walker et al., 1981; Westoby et al., 1989), freshwater systems (Fiering, 1982) and fisheries (Walters, 1986). Folke (2006) notes: "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)." Fuller lists of examples of shifts between multiple equilibria can be found in the figures and tables of Section 3 – Regime Shifts.

1.3.2 Experiments in Application – Adaptive Management

The concept of resilience was challenged and improved in applications of modeling integrated with field science (as above) or linked with analysis to support policy development in response to regional environmental crises. Both streams informed one another and converged in the development of a process to integrate science and policy that came to be known as Adaptive Management (AM) (Holling 1978, Walters 1986, Gunderson et al. 1995). Starting in the 1970s the development of AM was realized in a series of stakeholder-driven dialogues facilitated by modelers and scientists and integrated with research of the large-scale ecosystems (terrestrial, freshwater and marine) that required crisis management. In addition to increasing insight into complex system dynamics, the experience of running such citizen-scientist dialogues, with all the attendant political and institutional nuances of including key decision-makers and other stakeholders, contributed to the growing awareness that surprise and uncertainty are inevitable in social-ecological systems - a cornerstone of Complexity Science. The dialogue process reflected this awareness by concentrating on learning and understanding rather than proof and certainty (Holling and Chambers, 1973; Holling, 1978; Clark et al., 1979; Walters, 1986). The challenge of facilitating learning across disciplines and sectors of society drove the development of a range of tools, from metaphors to models, to communicate ideas about complexity, including resilience. Multiple lines of experiment on AM tested and improved these tools for their capacity to support "comparative analyses of the theoretical foundations to ecosystems behavior and ecosystems management "(Folke 2006).

In summary, the resilience concept evolved through repeated and recursive examination in two streams of inquiry into complex adaptive systems: scientific research (mathematical and simulation modeling, field studies) to advance theoretical understanding of complexity, and applied science to support policy development. As shall be explained further, complexity science became policy relevant *not* because resilience concepts neatly explained causation mechanisms. Policy relevance emerged from the way that resilience in particular and complexity theory in general built a much richer picture for policy makers to consider options to research and to test in application. Through the notion of multiple equilibria resilience conveyed the risk of irreversible consequences that inspired more precautionary, recursive approaches to developing and testing policies, not simply imposing them. Resilience worked within the conceptual framework of Complexity theory to generate a wider range of questions and novel hypotheses for testing through a process of modeling integrated with field research. In this way discussion, modeling and field research could be more directly linked to policy implementation and subsequent revision. So far any attempt to trim resilience to one, tidy universal definition flies in the face of the utility gained from its capacity to inspire theoretical and applied science at several levels of meaning summarized by Carpenter et al. (2001) as

- Metaphor related to sustainability
- A property of dynamic models
- A quantity measurable in field studies

The remainder of this report examines these levels individually and as a combined approach for their capability to assess the potential for irreversible change.

2. RESILIENCE AS METAPHOR

Metaphors, for anyone charged to understand or manage complex systems, may appear like overly simplistic literary devices until we see how ideas and paradigms can dominate the agenda of research, policy and practice. Wilson (2006) notes how the conventional notion of any system as a clockwork of tight, deterministic connections has distorted our understanding and practice for ocean fisheries. A better metaphor lies at the heart of inquiry into complex adaptive systems, and he cites Holland (1995), one of the main contributors to the theory of CAS, that they should be "…conceptualized as a much looser and less predictable order that arises from the constraints generated by the evolved behavior of the biological and human elements of the system." Both resilience, and the theory of CAS within which it fits, are attempts to grasp this "hidden order" of loosely coupled systems

2.1 Theory of Complex Adaptive Systems

A wide array of disciplines has contributed to the theory of CAS and the resilience concept. Levin (1998) linked CAS to resilience, biodiversity and ecosystem ecology and notes prior contributions from an economist, Arthur et al. 1997 and a computer scientist, Holland 1995. To conceive of an economy as a CAS the former identified six characteristic properties: "…dispersed interaction, the absence of a global controller, cross-cutting hierarchical organization, continual adaptation, perpetual novelty, and far-from-equilibrium dynamics (Arthur et al. 1997, Levin 1998)." Holland (1995) developed a smaller set of basic properties of CAS: aggregation, nonlinearity, diversity, and flows. Rather than an imposition from outside, *aggregation* results from self-organization into groups and, ultimately, a hierarchical assembly of groups. Once such pattern develops endogenously, it can influence system dynamics by constraining interactions. *Non-linearity* in CAS dynamics is a consequence of how the system can self-organize by reinforcement of chance events (mutation, etc.) at different levels, thus opening the door to an enormous variety of different trajectories of development. Variety at any one level, for example biodiversity seen as the number of species, does not capture the richer sense of *Diversity* as the hierarchical assembly of different aggregations in CAS. Species are not the sacrosanct level of reference, for, as an ecologist, Levin (1998) notes: "…critical ecosystem processes will not be under the control of individual species, but may be mediated nonetheless by a small set of species that thereby form a *keystone functional group*." Finally, *Flows* of nutrients, energy and biomass are what " … transform the community from a random collection of species into an integrated whole, an ecosystem in which biotic and abiotic parts are interrelated (Levin 1998)."

Research into resilience through development of an integrated set of socio-economic ecological models (Carpenter et al., 1999a,b; Janssen and Carpenter,1999) built on the complex adaptive systems approaches of Hartvigsen et al.(1998) and Levin et al., (1998) (Peterson 2000). Resilience is seen as one of four properties that contribute to CAS dynamics: *Ecological Resilience* (the extent the system configuration persists in the face of disruption), *Complexity* (the variety of structures and processes interacting at different scales), *Self-Organization* (the ability of structures and processes to interact and mutually reinforce and sustain one another) and *Order* (the structure that emerges as self-organization of disorder into order, though cross-scale interactions, can disrupt and reconfigure ecological organization, producing complex dynamics).

2.2 Paradoxes

Sustaining a wide path of inquiry that encompasses most sources of complexity forces one to embrace paradoxes (see Appendix 3). Order emerges from disorder in non-predictable ways. Variability not regularity of key variables may be critical to a broader and looser stability. Where local species have evolved in an environment with periodic disturbance, episodic instability may in certain ways be a kind of invigorating exercise crucial to maintaining diversity and persistence (Gunderson and Pritchard 2004). As Adger, 2006).notes:

> In a resilient social-ecological system, disturbance has the potential to create opportunity for doing new things, for innovation and for development. In a vulnerable system even small disturbances may cause dramatic social consequences.

With the exception of perhaps, sustainable development (Folke et al. 2002) the conceptual framework of resilience is not fixed on any normative concept (stability/instability, disturbance/order, etc.) or at any scale in time and space. This allows one to flex inquiry toward the specifics of any specific system in question (e.g. resilience *of what* factor *to what* disturbance), but where is the normative reference point when deciding what to do? Redman and Kinzig (2003) observe that:

> Cataloguing the features that contribute to resilience will reveal attributes that depend on the temporal, spatial, and organizational scales of interest, and on the phase of the adaptive cycle in which the focal system is situated. Attributes that confer resilience in the reorganization phase may erode it in the conservation phase, whereas attributes that confer resilience at the level of the state may erode it at the level of the household. The challenge for scholarship will lie in recognizing and elucidating these apparent mismatches and paradoxes, and the key to developing resilient strategies will lie in learning how to cultivate different social and ecological attributes at different times or at different levels."

2.3 Metaphors of Complex Adaptive Systems

A number of conceptual, verbal and graphic tools have been developed to facilitate communication in the study and management of CAS. Analysis of CAS has generated many terms besides resilience (see Appendix Two) to describe different types of change or factors related to change in CAS dynamics. The path to better understanding and collaboration in analyzing and modeling CAS often starts with simple graphic models of the structure and dynamic function of CAS. Rather than causal explanations (at any level of detail) these graphics are explicitly used as metaphors or heuristics to convey the workings of CAS in a coarse but robust way. United by a consensus that the actual operation of a CAS will usually differ from that suggested by the metaphor, collaborators can use a graphic to start and/or guide discussion of alternative hypotheses with less friction over word definitions inherent in purely verbal models. Several examples of some of the key resilience concepts and their graphic models are described below.

2.3.1 Adaptive Cycle

The Clementsian view of succession was the dominant paradigm for the dynamics of large-scale systems for decades. The problem was not that it was wholly wrong, just incomplete. It did account for much of what was observed of ecosystem development post-disturbance (for example, after glacial retreat). However, it excluded both disturbance and re-organization as endogenous phases of a natural cycle. This made it hard to explain systems with predictable periodicities of disturbances, such as fires, as well as systems that suddenly changed to another kind of system post-disturbance. Holling (1986) developed the Adaptive Cycle (Figure 2) to incorporate these and other factors hypothesized to influence CAS dynamics. The *r* and *K* phases are roughly analogous to the “bare field” and “climax” phases, respectively, of classical succession. This is the so-called “forward loop” (Walker et al. 2004) with the fairly predictable dynamics of slow, accumulative development. The wide-open and loose competition of a young system gradually intensifies into the tight, entrenched standoff of highly skilled and connected veterans in a mature system. The tightness with which resources are sequestered makes the system progressively less flexible in the face of shock and so, ripe for massive change. This latter proposition modifies the traditional view of climax as a secure equilibrium and feeds directly into the hypothesis that disturbance routinely “liberates” biomass and nutrients as an endogenous “release” function in many systems. This is explicitly shown as the Ω phase, which begins a very unpredictable “back loop” of the Adaptive Cycle. Whether the liberated resources are lost to the system or captured and re-organized back into the same suite of species and functions is settled in the α phase. Too much loss or insufficient “memory” (for example a seed bank in the soil of the forest) might mean the system shifts to a “new regime” with different actors, species and functions. If the system starts on this new trajectory, then in the *r* phase self-organizing reinforcement of interactions shapes the recruitment of new actors into a new web of relations that characterizes the “identity” of the new regime or ecosystem.

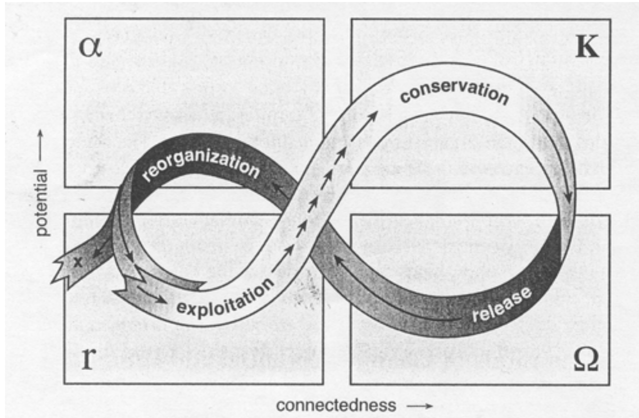


Figure 2. the Adaptive cycle (after Gunderson and Holling 2002).

The Adaptive Cycle was never seen as general phenomenon, but it has served well as a heuristic that illustrates one explanation of non-linear dynamics. Perhaps more importantly, it generated enough discussion to drive proposals of alternative models (see Cumming and Collier (2005) for a survey of alternatives). For example for Australian rangelands (Andries et al. 2002) and socio-technical transitions (see section 3.2.2) which complement it as part of a suite of hypotheses about how different systems change or persist. Attempts to use the Adaptive Cycle to understand the dynamics and resilience of diverse social-ecological systems revealed its limitations. It cannot portray entities or systems that operate at different scales and the cross-scale interactions that sometimes link them. *Panarchy* was proposed as a metaphor to address these limits (Gunderson & Holling, 2002).

2.3.2 Panarchy

Panarchy portrays a CAS not as a system moving through a single adaptive cycle but as a hierarchy of adaptive systems where the different systems are related by cross-scale interactions. Each adaptive system (or level within the Panarchy) is at its own unique position along the adaptive cycle. Lower-level systems go faster through adaptive cycles at smaller spatial scales than the higher-level systems within which they are nested. Interactions normally are confined primarily within each of the different levels, and most cross-scale interactions have little to no effect on dynamics. The slower, higher-level systems normally establish a macro-scale rhythm that constrains lower scales. For example, at macro time-scales (decades) citizens' rights (local small-scale processes) are slowly revised through parliamentary legislation (macro-scale institutions). On the other hand, the rapid cycling at lower levels usually makes little impression ("noise" that is easily ignored) at higher scales (bureaucracies usually can out-wait any individual citizen). However, occasionally during sudden and brief episodes cross-scale interactions can dramatically affect dynamics. Three separate systems operating at different scales are shown in a relatively simple panarchy in Figure 3. Should the intermediate system become overly connected and inflexible it becomes vulnerable to small-scale perturbations ("revolt") that can spread contagiously upward through the many links in the mature state. Such an "upward cascade" can precipitate the destruction and release of all the capital built up in the K-phase of the intermediate system. The largest system can influence the reorganization phase of the lower scale system as it restructures. For example, a burnt thicket can more easily regrow when showered with a rain of seeds and migrants from the surrounding landscape. This "remember" interaction provides the information around which the system self-organizes as it rebuilds. In this manner, resilience at one scale can be subsidized by resilience at a broader scale in space and/or time. Loss of biodiversity at a regional level can deprive disturbed patches with the seeds of memory around which they can regrow into the same ecosystem.

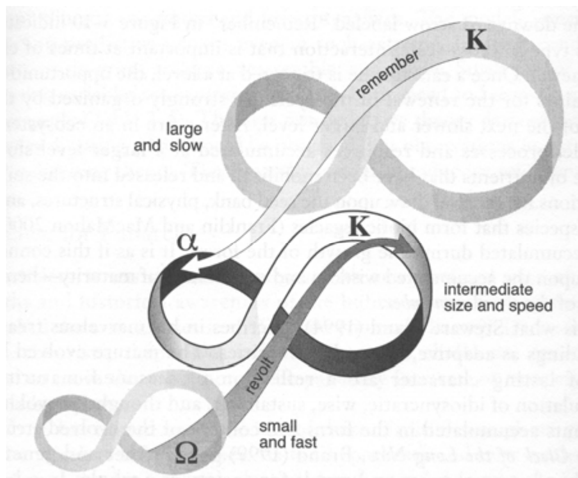


Figure 3. Panarchy (after Gunderson and Holling 2002).

Any attempt to assess resilience begins with determining what is the system of interest and what is it resilient to. Defining and bounding the system of interest involves identifying the scales in space and time at which it operates and the stage of its development (Redman and Kinzig 2003). Stommel diagrams (Schneider 2001) use a log-log plot to facilitate representation of scales that differ by many orders of magnitude in space and time. Figure 4 displays a four level panarchy graphed on a Stommel diagram to show four different factors that operate at distinct scale ranges related to the movement and storage of phosphorus in a lake landscape. Phosphorus cycles seasonally in the lake water column, over several years in lake sediments, over multiple decades in the catchment soil bank, and over millennia in relation to the movement of glaciers or soil erosion from regional geosolution. The relations between these factors depend on their scale as well as their development stage. For example, if the total storage of phosphorus in the catchment sediments (soil P) has reached the *K* (mature) stage in the Adaptive Cycle because of decades of loading by runoff from intensive fertilization, then both lower levels are vulnerable to what would normally be minor events: thunder showers. A landscape saturated with phosphorus will deliver a significant dose of P from just one major rain event, perhaps pushing a lake from a clear to a turbid state in one afternoon. So if Soil P is at the *K* stage, then the lake water may be at a very low resilience (Carpenter 2002). Conversely, if lake sediments and lake water in the α stage, with very little P accumulated, then they may both be quite resilient to Soil P, even if it is at the *K* stage of the Adaptive Cycle. The key then is to compare the scales of operation and stage of development of different factors to see how their interaction may influence resilience. Scale awareness increasingly appears important given how often decline of resilience is associated with the interaction between slow and fast variables (Carpenter et al. 2001, 2004, Redman and Kinzig 2003).

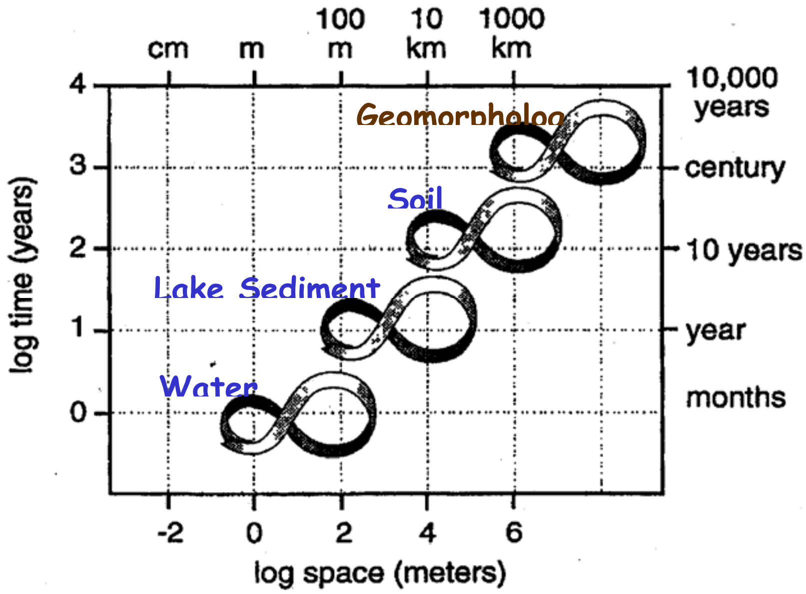


Figure 4. Panarchy of different factors related to the movement and storage of phosphorus in and around a shallow lake (adapted from Gunderson and Holling 2002).

As systems progress through the cycle they change along another dimension: *connectedness.* Figure 5 illustrates how connectedness increases as the system moves from r to K and then decreases as it moves from omega to alpha. Connectedness should not be construed as a purely physical term, such as implied when the emergence of a forest crown fire is explained as a result of the forest being "overly connected" when a ground fire can leap up the tree trunk through the dead branches (as if wicking up a candle). Rather, connectedness alludes to the degree to which system elements are connected by relations such as competition or mutualism or flows of water and nutrients. Brittleness and vulnerability to disturbance increases as the degree of tight competitive connections increases with maturation to a climax stage (K). These connections are broken as fire or insect outbreak spread a wave of mortality through the community.

The third dimension (potential) is described more completely using *stability landscapes,* a heuristic that graphically portrays system dynamics within and between stability domains and attractors (see Appendix 6).

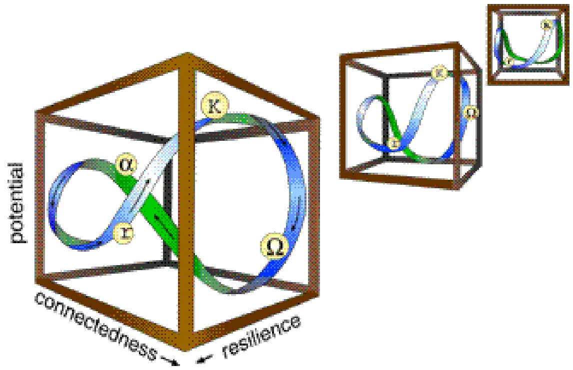


Figure 5: Resilience is another dimension of the adaptive cycle. The appearance of a figure 8 is shown to be the consequence of viewing a three-dimensional object on a two-dimensional plane (Gunderson et al 2002).

2.4 Metaphors – engines of questions

Structure and function are not static in complex systems and neither are ideas in the theories posed to probe complexity. Resilience is offered as a metaphor (Gunderson and Holling 2002) to suggest it as a soft and malleable device for exploration, not a hardened tool for strict management of ideas or ecosystems. Evolving theory and experiments may have advanced understanding of complexity, but not enough to allow these ideas to congeal into some ultimate explanation. To understand dynamic systems we may have to keep our tools broad enough to encompass all sources of CAS dynamism. Surprise "springs eternally" from CAS, repeatedly requiring us to return to such "soft" options for novelty and inspiration before we cycle back to the "hard path" of testing strict predictions. In short, to "embrace uncertainty" the conceptual framework must be kept malleable. Holling (pers. comm.) has long maintained that the key breakthroughs that herald advances come when experiment demonstrates the limits where theory breaks down, so our job is to "endanger our ideas" to reach these limits as soon as possible. Some (Klein et al. 2003) find this lack of a firm, unified structure discouraging, but it has proven an inspiration for others in a variety of fields besides ecology to experiment and try new ideas. Andries et al. 2002 proposed a three-stage cycle for rangelands. One political scientist, van der Brugge (2006) cites this open and inviting attitude of Gunderson and Holling (2002) who are …"hoping to discover where the metaphor breaks down" as the inspiration for proposing alternative explanations of the Adaptive Cycle and shifts between stability domains (hereafter referred to as regime shifts).

What are the dangers posed by metaphors? More specifically, what dangers emerge if scientific inquiry cannot progress past this "soft" creative phase that is freighted by metaphors? Nick Gotts (pers. comm.) cautions that softness as a flexible springboard to many avenues of creativity can end up stifling creativity if it is so vague or "… elastic [that] it is difficult to determine whether a particular system fits it or not." Definitive and clear advances, like reaching up to pluck novel fruit, require firm ground to stand on. Each experiment to define a system so as to measure resilience is an attempt to "firm the ground" by methodically adding rigor to our definitions and means of mensuration. As shall be further discussed, the question may reside more in the pace at which inquiry oscillates between "soft" and "hard" poles. The latter antipode promotes rigorous testing of ideas emerging from the former, and then feeds the results back into the creative phase. Over the past decade concerns that resilience science has not progressed far enough have generated a number of attempts to measure resilience. The creative phase of metaphors has loaded the piston in the engine of inquiry with fuel. Whether the engine is firing and reloading in a distinct way that pushes us forward is another question.

3. ASSESSING RESILIENCE IN SOCIAL-ECOLOGICAL SYSTEMS

3.1 Integrating Ecological and Social Aspects of SES

Inquiry into regime shifts can follow parallel lines (biophysical and social) to derive separate lines of evidence that may challenge or reinforce one another. Theory and field research can improve thereby, but the crossover interactions that span the entire CAS may be lost. How one searches and what one finds may differ greatly between studies looking separately at social or ecological aspects versus studies of entire social-ecological systems (Westley et al. 2002). As Folke et al. (2005) observe:

> "Addressing only the social dimension of resource management without an understanding of resource and ecosystem dynamics will not be sufficient to guide society toward sustainable outcomes. For example, the mobilization of Belizian coastal fishermen into cooperatives, which was socially desirable and economically successful, led ultimately to excessive harvesting of stocks of lobster and conch (46). Similarly, focusing only on the ecological side as a basis for decision making for sustainability may lead to too narrow conclusions. For example, an observed shift in a lake from a desired to a less desired state may indicate that the lake has lost resilience, but if there is capacity in the social system to respond to change and restore the lake the social-ecological system is still resilient (47,48)."

The challenge is to incorporate the separate insights and methods of these different disciplines in measurement, knowledge elicitation, and modeling to develop a synthetic overview of the entire SES.

3.2 Surrogates of Resilience

The resilience concept has matured since Holling (1973) proposed it but more from the contributions of theory and modeling than from applications in the field and policy. The promise shown in driving theory and motivating new hypotheses must be realized in practice and policy (Klein et al. 2003). Spanning the gap between theory and practice requires some "estimator" or "indicator" of resilience that offers a target (even a moving one) to measure against prediction.

The process of proposing and testing indicators of resilience is not trivial. Direct observation of conclusive events, such as crossing a threshold that precipitates regime shift, is difficult. Such events are rare, and the evidence may be dispersed in time and space. Manipulation to provoke regime shifts (remove predators, exclude browsers, add or remove water, nutrients) has been done in ecology for theoretical and management (*biomanipulation*) purposes. But it may not be ethical for entire SES where humans are involved (Carpenter 2002a, b). Deliberate experimentation that induces injury or death is not socially acceptable no matter how noble the motivation.

Direct observations of thresholds, regime shifts, and other factors related to resilience are so difficult that we are forced to infer through the use of indicators. But how to do so systematically? We can condition our inference of resilience indicators using models. However a large set of models is needed to assess resilience in any SES. Model diversity is needed to reflect the many different mental models of stakeholders as well as the range of equally plausible hypotheses about natural causes and to apply different model types (scenarios, formal, conceptual) to address different aspects and questions (Carpenter et al. 2005). Measuring resilience-related factors is confounded if the way they confer resilience depends on context (Holling 2001). This context is a web of relations that can change with time, spatial pattern, and the specifics of the local ecology or society. Carpenter and Brock 2006 summarize the difficulties in studying regime shifts and make recommendations:

> Regime shifts are difficult to study (Carpenter 2003; Scheffer & Carpenter 2003). They occur in large, spatially heterogeneous systems, and usually involve processes at more than one spatial scale. From the perspective of a human lifetime, regime shifts are infrequent events that may play out over many years, even though the change is rapid in comparison with routine ecological change. Regime shifts have multiple causes, so studies must track multiple variables simultaneously for long periods of time. Inference requires several lines of evidence, such as long-term observations or paleo-ecological data, comparisons of ecosystems across gradients of key drivers, models of various types and appropriately scaled experiments (Carpenter 2003). It takes considerable effort to build understanding of regime shifts. The kinds of evidence that are needed to understand a regime shift depend on the set of models that are believed to describe the regime shift. The appropriate evidence cannot be gathered without knowing the models, and the models cannot be assessed without the evidence. This circularity poses a challenge to researchers. It is important to design measurement programmes that could provide relevant evidence for a wide range of models, often over long periods of time and extensive spatial ranges.

For these and other reasons (Table 1), resilience indicators will differ from traditional ecological indicators in a number of respects.

Table 1 – Contrasting characteristics of resilience and ecological indicators

Proposed Resilience Indicator	*Traditional Ecological Indicator*
Must be forward-looking	Can be retrospective or reflect current state
Must map on to theory	Not necessarily
May change with respect to resilience over time	Must change monotonically with quantity it is supposed to indicate

Contextual complexity mandates that multiple models and multiple estimators be used in conjunction to measure different aspects of resilience. From this diversity of views and data a broad and robust picture of resilience can be derived. The term *indicator* is too narrow to reflect this more systematic approach, so Carpenter et al. 2005 propose the term *surrogate* of resilience. They conclude: "… the relationship between resilience and any particular surrogate may be dynamic, complex, and multidimensional. In general, practitioners will need a suite of resilience surrogates that jointly represent the key features of resilience, in context, for the particular SES at hand."

The idea of a suite of resilience estimators is not new. For a lake-rich agricultural landscape Carpenter et al. (2001a) have previously proposed the use of model insights to identify a suite of resilience surrogates that are: ecological (soil phosphorus, animal stocking densities, built area), institutional (best practices, education, enforcement or innovation), economic (markets for water quality, soil runoff) and social (networks to facilitate appropriate action, power asymmetries between interest groups). However, the resilience surrogate approach extends to link estimators with a diversity of many different model types: "…the diverse individual models held by people in the SES; soft models such as art, stories or scenarios; technical diagrams; maps; heuristic mathematical models, simplified for rapid understanding; and detailed integrated system models (Carpenter et al. 2005)." This use of models by multiple stakeholders allows one to make concrete abstractions from diverse perspectives, to manipulate those abstractions in a transparent way and then compare them with observations and other models. The overall approach of synthesizing a composite picture of resilience from the interplay between models, observations and surrogates is summarized in Figure 8.

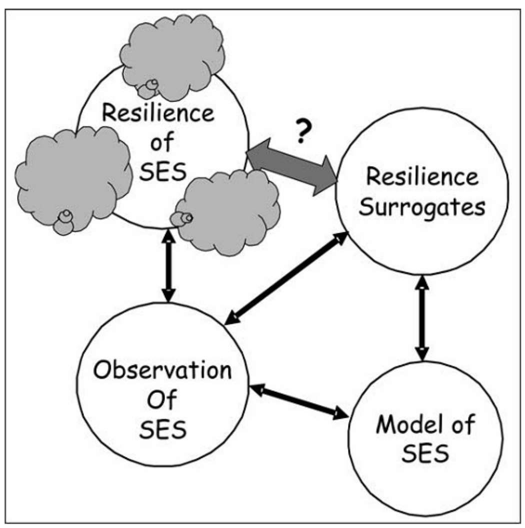


Figure 6 – Estimating SES resilience through the combined use of observations, models and surrogates (after Carpenter et al. 2005)

The process of proposing and testing different resilience surrogates against multiple models and types of observation will require careful orchestration without the benefit of known standards for comparison. Carpenter et al. (2005) propose a set of questions to check the consistency of surrogates across all these efforts.

- Are the surrogates consistent with resilience in modeling exercises?

- Are the surrogates consistent with long-term observations of the SES?
- Are the surrogates consistent in comparisons across SESs?
- In cases where SES have changed substantially, thereby revealing thresholds, were the surrogates consistent with the observed changes?

3.2.1 Alternative Paths to Develop and Use Surrogates of Resilience

A diversity of tools (concepts, methods of analysis and modeling) has been developed to capture as many aspects of the complexity of SES as possible in the assessment of resilience. The power of all these diverse approaches to detect meaningful pattern or gain novel insights can be amplified when they are usefully combined. Carpenter et al. (2005) list a few paths that can be used alternatively or in conjunction for developing and assessing resilience surrogates, which we directly cite below:

- *Stakeholder assessments*: Aspects of SES resilience or vulnerability are identified through workshops aimed at building a common understanding of change in the SES.
- *Model explorations*: Models of the SES (such as scenarios or computer simulation models) are used to explore the potential thresholds for change, and identify measurable aspects of the SES that have systematic relationships to the modeled thresholds.
- *Historical profiling*: History of the SES is assessed to classify more-or-less distinct dynamic regimes, and analyze events during the transitions. At these crucial times when resilience mattered, what changed and how?
- *Case study comparison*: SESs that have many similarities, but appear to be changing in different ways, are examined to assess observable properties that may be related to resilience. What is different among systems that appear to have quite different resilience?

Surrogates of resilience are purposefully developed *not* to be definitive, normative or any of the "neat and tidy" tools to summarily simplify complexity. They are an attempt to expand the scope of estimators to capture complexity by increasing the number of perspectives with which it is viewed at the same time. These perspectives emerge not from the estimators or the field data or the models by themselves but from their combined use. Such coarse approaches may reveal insights that are still too complex and coarse to encapsulate in an index or a regulatory threshold or a definitive policy. But they reflect the mood of researchers working at the sources of information, sampling lakes and interviewing fishermen, who are suspicious of overt simplicity imposed on an evolving complexity. Surrogates may not immediately deliver policy-ready estimates, but their use and refinement by scientists and stakeholders may generate the deeper understanding on which good policy is built.

3.3 Application - Defining Regimes and Transitions

The diversity of approaches enabled by the resilience surrogate approach outlined by Carpenter et al. (2005) cannot be documented here. This section simply lists a few possible approaches that may prove useful for developing resilience surrogates using agent-based modeling or may suggest useful alternatives that agent-based modelers can modify for their purposes. Several approaches are described which offer opportunities for qualitative assessment along with one example of quantitative assessment of resilience.

3.3.1 Example of Qualitative Assessment of Resilience: Australian Rangeland

How resilience can change as the result of the interplay of institutional and ecological processes is described in a study of Australian rangeland management (Walker et al. 2002). Resilience appeared to be a useful concept since it offered explanations for evidence for regime shift that was broadly accepted in both academic, government management and rancher circles. Lay experience and scientific research had convincingly established that rangelands can shift from grassland to shrub–dominated landscapes. These shifts were not abrupt but were not easy to reverse. Furthermore, there was a common suspicion that such regime shift was associated with crossing a threshold in the ratio of grassland to shrubland. As illustrated by the crossing region of the dotted lines of Figure 7, a threshold appears to exist at which there is no longer enough grass to sustain the fires that suppress shrubs. The breadth of the threshold is not precisely known, but even if it is broad the system appeared to have a momentum that would carry it through such a threshold unless drastic fire management measures were applied.

The dynamics of the Australian rangeland depends on far more than ecological understanding or management interventions. Many ranchers make independent decisions based on market prices and government subsidies to support “best practices.” Scientific understanding, policy (management and government subsidy), market dynamics and local practice are but a few of the streams that combine to influence regime shift in rangelands. However, Walker et al. (2002) use these to apply a simple conceptual model of economic and ecological relations that might affect the resilience of ranchers. The model (see Figure 7) describes a resilience space based on economic and ecologic axes. The ecological axis measures the amount of shrub-land or woody vegetation, with no precise threshold defined to mark the breakpoint for regime shift. The economic axis records the rancher’s debt/income ratio, again with no arbitrary threshold indicating the point of precipitous increase in vulnerability to economic problems. The locations or regions identify such thresholds can be the subject of discussion, interviews and other forms of knowledge elicitation.

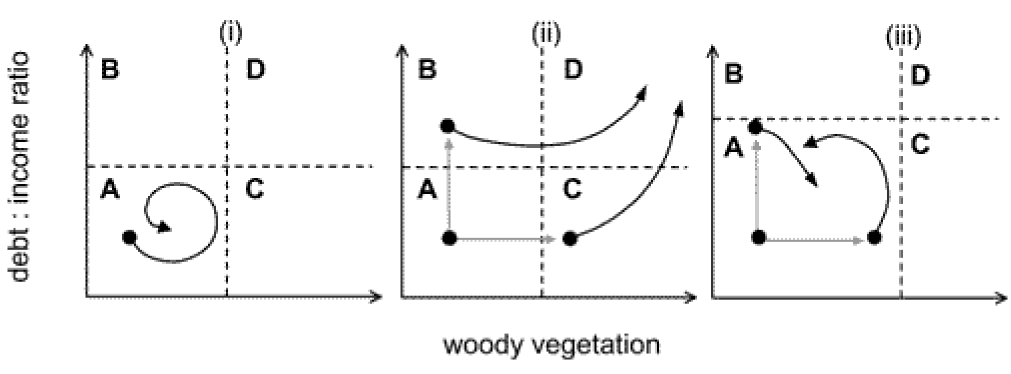


Figure 7**.** Possible trajectories of a 2-variable system through time. The positions of the dashed lines on the axes represent critical threshold levels of the sort depicted in Fig 13. (taken from Walker et al. 2002).

The primary point Walker et al. want to make is that a simple but robust government policy could emerge even from a simple conceptual model of regime shifts and resilience. Rather than enforce some particular ecological condition or encourage certain practices to maximize production, government strategy could look in a qualitative way at the conjunction of ecology and economy. The four quadrants in the figure illustrate broad definitions of different stability domains that the rancher might fall into. The least vulnerable would be A, where low debt and woody vegetation mean the rancher can easily graze his animals on abundant grass with little expense for shrub management or debt repayment. By contrast, region D is the least desirable where high debt constrains options to manage or innovate and high woody vegetation means management is expensive or impossible because fire will not carry over the landscape. The two intermediate states, B and C, show the transition zones where the rancher is in danger of falling into D either from losing income because there is not enough grass (C) or failing to manage because of too much debt (B).

The more robust approach for government might be simply to try to enlarge A rather than narrowly focus on maximizing production or ecological status (Figure 8 iii). This might be done by: a) lowering the debt/income ratio by fostering alternative income sources, or b) increasing the sophistication of management practices such that ranchers can cope with higher shrub densities without the system irreversibly sliding into the shrub-dominated state. This example shows a two-axis approach to illustrate ecological – social interactions. It could be applied at one or many axes depending on how many dimensions seemed appropriate or practical. The promise of such an approach is that it does not exclusively depend on quantitative data from research surveys or experiments. Such regions could be based on stakeholder interviews that broadly define thresholds and/or such regions themselves.

3.3.2 Example of Quantitative Assessment of Resilience: Shallow-water Lake

The sets of processes that control a system's structure and function and are involved in regime shifts in lakes have been studied for more than a century in Wisconsin at the level of whole ecosystems and continue today in parallel experiments in the Netherlands (Carpenter and Scheffer 2003, Scheffer et al. 2001). The studies have used control, replication and whole-system manipulation[1] to accumulate extensive data sets and experience in testing ideas and developing explanatory models. Decades of evidence support a broad set of models that explain regime shift as a switch in dominance from one set of processes to another. Table 2 lists the two sets of processes, each set combines in a set of reinforcing feedbacks to maintain a certain ecological condition: either clear or turbid water. These process sets are mostly biophysical reflecting the authors' attempt to define hypotheses about ecological causes of regime shift in lakes. The economic and social aspects that combine with biophysical factors to influence the dynamics of social-ecological systems are examined elsewhere (Carpenter 1999, 2000). Note: "membership"

[1] Entire lakes have been divided into halves to provide control in study the effects of whole-system changes (addition or removal) of nutrients, species, and functional groups. Experimental division started with a crude earth dike in 1900 and currently use plastic curtains.

in one regime does not strictly rule that one is absent when the other regime dominates. One may be present but in small numbers or infrequently, or one may be present but still not contribute anywhere near as much to system dynamics as when one participates in the kinds of feedback loops that reinforce one's own regime.

The combination of data (both laboratory and field), causal models and theory, revised and improved over a century, has built a knowledge base sufficient to explain the cast of characters ("members of the regime junta") and many linking causal mechanisms, but prediction remains elusive. Some lakes that had shifted from clear to turbid in the 1970s and were bio-manipulated to successfully shift back to a clear state, have oscillated back and forth in ways that are hard to explain and still impossible to predict (Scheffer 1998, 2001). It is clear there may be other actors and processes involved at scales or across-scales in ways that must be determined. But there is probably no more complete set of data, models and experience on ecological regime shifts than that in freshwater lakes.

Table 2 – Different sets of processes controlling phosphorus inputs associated with regime shifts in shallow water lakes in temperate climates (Carpenter and Brock 2006)

Lake Condition (ecological)	*Controlling Processes (biophysical)*

Oligotrophic (clear water)	Phosphorus Inputs from catchment basin
	- Agricultural methods, intensity and history
	  - Fertilizer type and application rate
	  - Field size and shape
	  - Buffer strips on field margins
	  - Equipment size and use frequency
	- Soil deposition
	  - Soil type
	- Rain events
	  - Duration, frequency, intensity

Eutrophic (turbid water)	Phosphorus Recycling from lake bottom
	- Ecological components
	    - Benthos sediment type
	    - Macrophytes / Algae ratio
	    - Ratio bottom feeders / predators
	    - Zooplankton that eat algae
	- Physical Components
	    - Storm events (intensity and frequency)
	    - Lake morphometry (shape and depth)

<u>3.3.2.2 Measuring Changes in Variance</u>

Knowledge of all factors and interactions related to regime shifts may be incomplete, but certain patterns have been observed which do seem to herald regime shift years in advance. Cottingham and others 2001 have noticed that the variance in phosphorus concentration in a lake's water column increases several years in advance of regime shift. Baudo (2002) suggests that resilience on the population level is reflected by the density variability of the respective species. The author has interviewed farmers who claimed that the switch from inorganic to organic fertilization involved a transition period with very high fluctuations in what plant species would or would not grow in their fields. Carpenter and Brock (2006) cite studies based on observational and modeling evidence that variance, especially changes in variance, can signal impending regime shift in a variety of ecological and social systems (Table 3) and conclude:

In general, the variance of temporal fluctuations in certain state variables increases and the variance spectra shifts towards longer wavelengths (lower frequencies) just before the regime shift occurs.

Table 3 – Evidence of changes in variance signaling impending regime shift in ecological and social systems.

System	*Variance evident as Regime shift approached*	*Reference*
Ocean-circulation	Spectra shifted to lower frequencies	Kleinen et al. 2003;
Shallow lake	Variance increase in Individual macrophytes	van Nes & Scheffer 2003
Terrestrial landscape mosaic	Spatial variance of patches increased near threshold to percolation	Oborny et al. 2005
Lake Eutrophication		Brock et al. 2006
Fisheries Collapse		Brock et al. 2006
Scientific Paradigms		Brock et al. 2006. Scheffer et al. (2000), (2003) use discrete choice theory and build on the work of Brock and Durlauf (1999)
Elections		Brock et al. 2006
Monetary Policy		Brock et al. 2006
Stock Prices		Brock and Hommes, 1997

3.3.2.3 Modeling to Test Ideas about Variance and Regime Shifts

From the practical perspective of a lake manager, the knowledge that increasing phosphorus variance in the water column signals impending regime shift may not help much in correcting the situation. Such changes in variance may be difficult to distinguish from noisy signals of exogenous drivers of variance: such as nutrient inputs from the surrounding landscape. While they do not have to restore the lake, such conflicting noisy signals also challenge modelers when they explore alternative hypotheses as to what causes the variance and why it is associated with regime shift. Carpenter and Brock (2006) addressed this problem using a model of lake eutrophication that includes both noisy signals: exogenous input (P from catchment to lake) and recycling (P from sediments to water column). Despite these complications, the regime shift from clear to turbid water regimes could be detected years in advance by studying the standard deviation (SD) of phosphorus concentration in the water during summer stratification of the water column. Change in the SD could be detected by analyzing time series of phosphorus in lake water using a simple empirical model that did not require detailed knowledge of the ecosystem dynamics.

Slightly modifying previous work (Carpenter et al. 1999; Carpenter 2003, 2005; Ludwig et al. 2003) the model is a set of stochastic differential equations for phosphorus density (g m)2) in soil (U), lake water (X) and surface sediment (M) (Figure 8 and see Appendix Eight). To examine changes in the stationary distribution of X under conditions that might be observed in field studies, we simulated changes in a lake undergoing eutrophication, corresponding to changes that have been observed in many lakes Numerical analyses employ parameter estimates from field sampling in Lake Mendota, Wisconsin (Carpenter 2005) and the model is solved for successive summer stratified seasons, when stochastic events such as storms are the major drivers of P recycling. Mean and SD for stationary distributions of water phosphorus were computed by Monte Carlo simulation. Carpenter and Brock (2006) summarize: "For each estimate of the mean and SD, we simulated eqns 1–3 from each of 1000 different initial conditions for 1080 time steps (300 years with 36 time steps per year) using Ito calculus[2] and the Euler method. The 1000 final values of X (one from each of the 1000 initial points) were used to calculate the mean and SD.

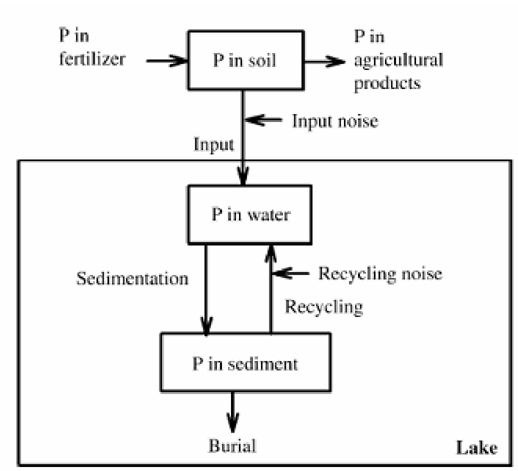


Figure 8 – Phosphorus flows for Carpenter and Brock (2006) model.

Since lakes often do not reach stationary distributions of P, Carpenter and Brock (2006) also used dynamic simulations to study changes of within-year SD under far-from-equilibrium conditions. Simulations were computed with various schedules of phosphorus input to soil (F, eqn 1 in Appendix Seven) for 300 years with 36 time steps per year, using Ito calculus and the Euler method. Because the "true" processes that actually influence P concentrations in a deterministic model are unknown, they worked with an approximate model (eqns. 7 – 11 in Appendix Seven) to distinguish between "the effects of input disturbances from other sources of variability that affect ecosystem dynamics (Ibid. p.313)."

Figure 9 presents an example of stationary distributions computed across a gradient of the loading coefficient, c (eqns 1 and 2). Carpenter and Brock (2006) note that this has practical implications in that manipulations of c (such as by restoring riparian vegetation to reduce P inputs) are sometimes used as a control parameter by lake managers. The simulation starts at equilibrium conditions: a lake that has long had a clear water

[2] For an introduction to this field, please consult this website: www-maths.swan.ac.uk/staff/at/notes/stochastics.pdf

condition and with deterministic steady-state values of soil phosphorus (U) and sediment phosphorus (M). Two alternative stable states appear as clusters of output in the low and high P input ranges, separated by a "repelling threshold" around c > = 0.00025. Variance of P, as shown by SD of the stationary distribution, rises steadily as c passes through the shift to alternate stable states. This steady rise of SD is interrupted by a sharp increase when c reaches just below the value (0.0021) where the lower oligotrophic attractor disappears. This implies that the steady rise in SD warns of the approach of a threshold and that the sharp rise in SD signals that the lake has passed the threshold and reached a new stable state around a turbid water attractor.

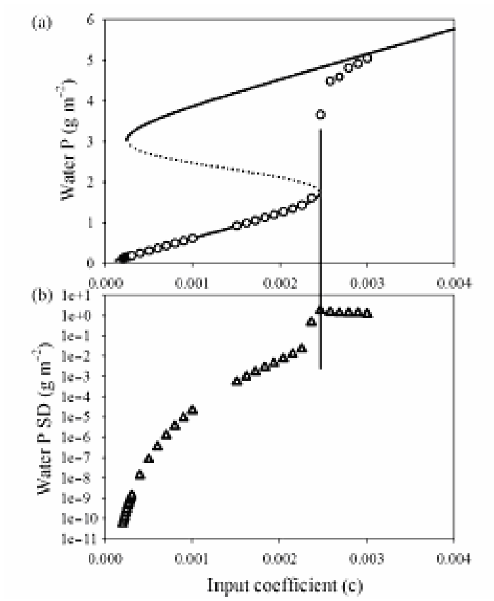


Figure 9 - (a) Equilibria of water P vs. input coefficient (c). Stable equilibria are solid lines, unstable equilibria are the dotted line, and open circles are mean values of the stationary distribution from Monte Carlo simulation. Vertical solid line shows the relationship between the eutrophication threshold and the standard deviation. (b) Standard deviation of the stationary distribution versus input coefficient (c). Note log y-axis. (taken from Carpenter and Brock 2006).

In a situation where one can observe fast-cycling of water P but little information about slow dynamics of sediment and soil P or the true ecosystem dynamics (eqns 1 – 6), an analyst can use a simplified approximation (eqns 7 – 10) to try to tease out the different influences of fast and slow variables. Carpenter and Brock did so by calculating two measures of variance: "within-year SD around the annual mean (within-year SD), and the other is the within year SD around the prediction of the DLM (DLM SD)." The former includes the complicated influences of multiple P inputs and gives only some indication of an impending regime shift (Figure 11) The latter reflects mostly the effects of within-lake P-recycling, and shows a much sharper increase in variance in advance of regime shift.

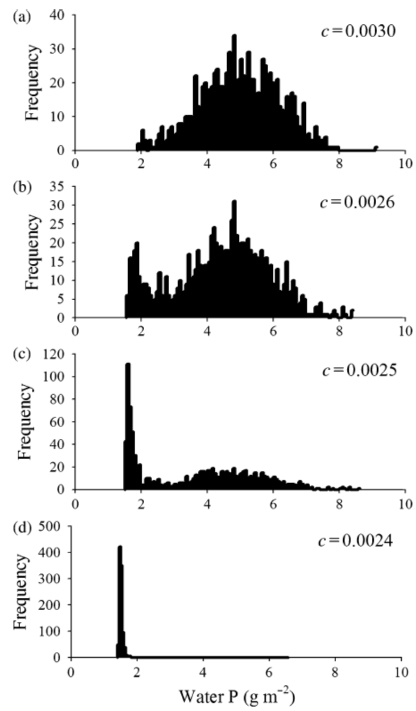


Figure 10 – distributions of water phosphorus from Monte Carlo simulation at four values of the input coefficient (c) near the threshold for eutrophication at c ¼ 0.0025. (taken from Carpenter and Brock 2006).

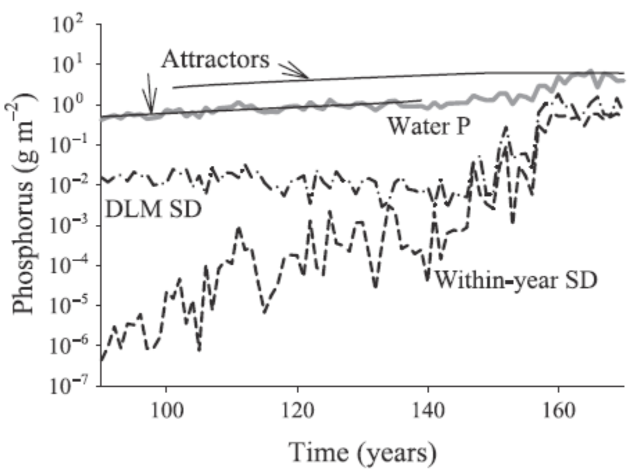


Figure 11 - Simulated time series near a transition from the oligotrophic to the eutrophic state. Note log scale for the y-axis. Equilibria were computed for the sediment + water subsystem, assuming that changes in soil phosphorus are slow enough to make equilibria meaningful for the faster variables. Water P is the thick grey line, and the stable equilibria for water P are the thin black lines. The within-year standard deviation (SD) is shown by the dashed line, and the within-year SD around predictions of the dynamic linear model (DLM) is shown by the dash-dot line.

3.3.2.4 Discussion – Field data and modeling results

Inquiry into resilience surrogates involves using both field data and multiple models to test hypotheses and look for patterns associated with regime shift. Field data had already associated increases in variability with regime shift in lakes. Whole lake manipulation by artificial forcing with added phosphorus exhibited increases in variance in phytoplankton biomass (Cottingham et al. 2000), and measures of variance in phosphorus recycling rates foretold threshold crossings one to two years in advance (Carpenter 2003). However, the use of modeling to tease apart the different influences of P input gives an earlier warning of regime shift. The modeling (Carpenter and Brock 2006) of the SD of water phosphorus appears to signal threshold crossings a decade or more in advance.

The practical implications are significant, because a manager or an analyst could uncover such warnings without knowing the exact mechanisms that produced the regime shift. The second, simplified model only used equations 7 – 10 and water phosphorus time series data to estimate the variance (SDs) and compute the leading indicator of regime shift. Such behavior seems generally applicable to a wide range of models of regime shifts (Horsthemke & Lefever 1984; Berglund & Gentz 2002a,b; Kleinen et al. 2003; Brock et al. 2006). Carpenter and Brock (2006) conclude that "…increased variance may be an important clue of regime shifts even in cases where the appropriate model is unknown. Furthermore, the true model for ecosystem dynamics is unknown and inferences about changing variance must be drawn from approximate models."

Another avenue of research to keep in mind is suggested by previous research that indicated that as a threshold is approached the variance spectrum (as measured from system state variables) shifts to longer wavelengths and lower frequencies (Kleinen et al. 2003). Rich time series data make this feasible and appropriate. Carpenter and Brock (2006) chose to estimate SD instead because lake ecological data was too sparse to estimate spectra.

The dynamics observed in lakes and other ecosystems can be explained using theories of Complex Adaptive Systems and resilience. This summary by Carpenter and Brock (2006) suggests that the interplay between slow and fast variables should be a leading question to investigate in locating thresholds and identifying the causes of regime shifts:

"Thus the relative speeds of interacting slow and fast variables is important for anticipating the regime shift in advance (Rinaldi & Scheffer 2000). The mechanism that underlies the increasing variability near the threshold occurs in diverse physical, ecological and social systems (Brock et al. 2006). The mechanism depends on having two or more attractors which change slowly because they depend on a slowly changing variable, and a fast variable which relaxes quickly to equilibrium after small shocks (Rinaldi & Scheffer 2000). If the attractors change gradually so that a regime shift becomes more likely, the variance (or SD) of the fast variable will increase. In the lake case, the slow dynamics of soil and sediment lead to gradual change in the attractors, while water phosphorus equilibrates rapidly after small shocks. As the system moves closer to the regime shift, the variance of water phosphorus rises."

4. REGIME SHIFTS

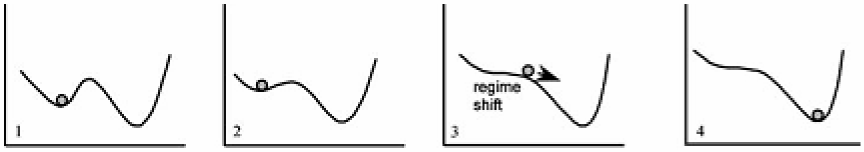
Not all systems shift suddenly and radically into new regimes. Some, like the krumholz forests in Tasmania (Holling 1986), may only change in the event of massive exogenous influences not from endogenous interactions. Resilience is a conceptual tool developed to probe across multiple scales for the potential for regime shifts, but how does one recognize a potential large enough to warrant further probing? Given that some shifts are the result of slow and barely perceptible change over large scales or of small-scale processes suddenly and episodically cascading up to large scales, this potential for profound disturbance and release may not be easy to recognize. The capacity to "remember" and self-organize as the same system identity may also be difficult to assess. The following section discusses attempts to meet these challenges.

4.1 Regime shifts from an ecological perspective

The notion of regime change was first suggested by profound and sometimes irreversible collapses of large-scale ecosystems, fisheries, forestry, lakes and agriculture (Holling 1978, Gunderson et al. 1995, see Figure 5 for a small sampling). Early research identified the actions and outputs attendant on such shifts. The actions associated with such shifts could be, individually or in combination, top-down management interventions (fishing down foodwebs or removing functions of biological diversity that normally serve self-organization), bottom-up (accumulation of nutrients, soil erosion or redirection of water flows) or the alteration of disturbance regimes (suppression of fire and increased frequency and intensity of storms). After decades of research the multi-scale interactions that produce such shifts still remain unclear, and assessing the processes that suppress regime change has not proven simple either. For example, biodiversity as *n* (e.g. species number) appears far less important than functional groups (e.g. predators, herbivores, pollinators, decomposers, water flow modifiers, nutrient transporters) with different and often overlapping characteristics in relation to physical processes (Peterson et al. 1998).

Broadly speaking, regime shift is recognized in ecosystems when such endogenous processes as rates of birth, mortality, growth, consumption, decomposition, leaching change in their rate and extent of operation and in their relationship to one another, such that the system state (defined by the dynamics of the variable of interest) begins to change from one attractor to another. Once the threshold between attractors is passed, the system has switched from one array of reinforcing feedbacks to another. The new array of feedbacks reinforce a new set of relations between the key actors, variables and related endogenous processes, and the system's trajectory is now set around a new attractor.

As the study of regime shift has expanded to all continents a database has been developed (Walker and Meyers 2004) to organize the examples into separate categories. The primary purpose of this systematic search is to help researchers to "distinguish between systems with alternate attractors and those that, although they might sometimes exist in different regimes, have only a single attractor (Walker and Meyers 2004." This survey revealed that transition rates vary far more than the initial notion of sudden regime shift, which was dominated by the shocking impression of total surprise at abrupt devastation



Desired State	**Critical Cause**	**Trigger**	**Degraded State**
clear-water lakes	phosphorous accumulation in agricultural soil and lake mud	flooding, warming, overexploitation of predators	turbid-water lakes
coral-dominated reefs	overfishing, coastal eutrophication	disease, bleaching hurricane	algae-dominated reefs
grassland	fire prevention	good rains, continuous heavy grazing	shrub-bushland
grassland	hunting of herbivores	disease	woodland
kelp forests	functional elimination of apex predators	thermal event, storm, disease,	sea urchin dominance
pine forest	microclimate and soil changes, loss of pine regeneration	decreased fire frequency, increased fire intensity	oak forest
seagrass beds	removal of grazers, lack of hurricanes, salinity moderation, spatial homogenization	thermal event	phytoplankton blooms
tropical lake with submerged vegetation	nutrient accumulation during dry spells	nutrient release with water table rise	floating-plant dominance

Figure 12 Alternate states in a diversity of ecosystems (1, 4) and the causes (2) and triggers (3) behind loss of resilience and regime shifts. For more examples, see Thresholds Database on the Web site www.resalliance.org. (after Walker and Meyers 2004)

of regional ecosystems and their related socio-economies (Holling 1978, 1986). The drama of the scale and speed of change was captured in the expression “system flip,” but this might set such a high threshold that more subtle shifts would be overlooked. A researcher schooled in sudden, large and extreme shifts like lake eutrophication or boreal forest insect outbreaks, might miss the gradual transitions from grass to shrub-dominated rangelands in Australia (Anderies, et al. 2002). Walker and Meyers (2004) illustrate (Figure 13 the difference between rapid (lake water phosphorus) and more gradual (grass in rangelands) with the dotted blue and red lines respectively.

Developers of the database have long recognized the need to extend ecosystem research to include the social systems that are part of a collective social-ecological system (SES) (Folke et al. 2002, 2005). However, this database is oriented primarily toward ecosystems, albeit with numerous links to surrounding or linked socio-economies. The database stores the fruits of decades of ecosystem research, often done from a management policy perspective that encompassed ecosystem links to social systems. The authors state categorically:

> Purely social system thresholds, that are unconnected to the dynamics of a natural system, are not included in the database. Nor are social–ecological examples that describe a change in the social system, but do not identify a change in the ecosystem. (Walker and Meyers 2004)

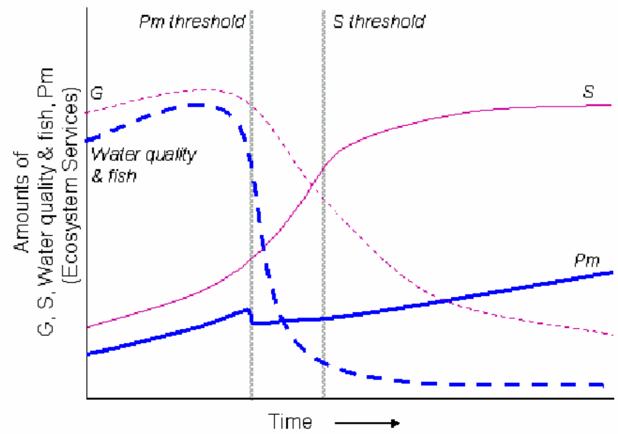


Figure 13. Stylized trajectories through time of the fast (---) and slow ( ) variables in lakes (thick blue lines) and rangelands (thin red lines) under high levels of phosphate inflow (lakes) and grazing (rangelands). In lakes, there is a very rapid change ("flip") in water quality as the threshold is passed and an associated rapid decline in water quality and fish. The amount of phosphate in the mud (Pm) shows a short-term decline as phosphate becomes soluble and is lost from the mud to the water above. In rangelands, although the feedbacks change instantly at the threshold (as in Fig. 1c), the lag effect in shrub growth rate results in slow changes of the variables (G = grass; S = shrubs). (taken from Walker and Meyers 2004)

Database use from a social science perspective may be limited to learning about the diversity of ecosystem dynamics that might be applicable to their social-ecological system (SES) of interest. The examples of ecosystem regime shifts might also inspire new hypotheses about regime shifts in SES, though the database does include some examples of social system thresholds.

While the information on social thresholds in the database needs much work and expansion, it does look at the direction of change arising from links between eco- and social-systems, particularly how changes in the one may alter variables in the other, thereby precipitating regime shift. This effect may be one- or two-way, depending on whether regime shift occurs in only one or in both the systems. Figure 14 summarizes the nine categories of regime shift identified so far and illustrates some of the hypothesized causes – from exogenous influences to feedbacks (endogenous and between systems). A more detailed explanation of the diagram and each of the categories is available in Walker and Meyers (2004) and the database it describes.

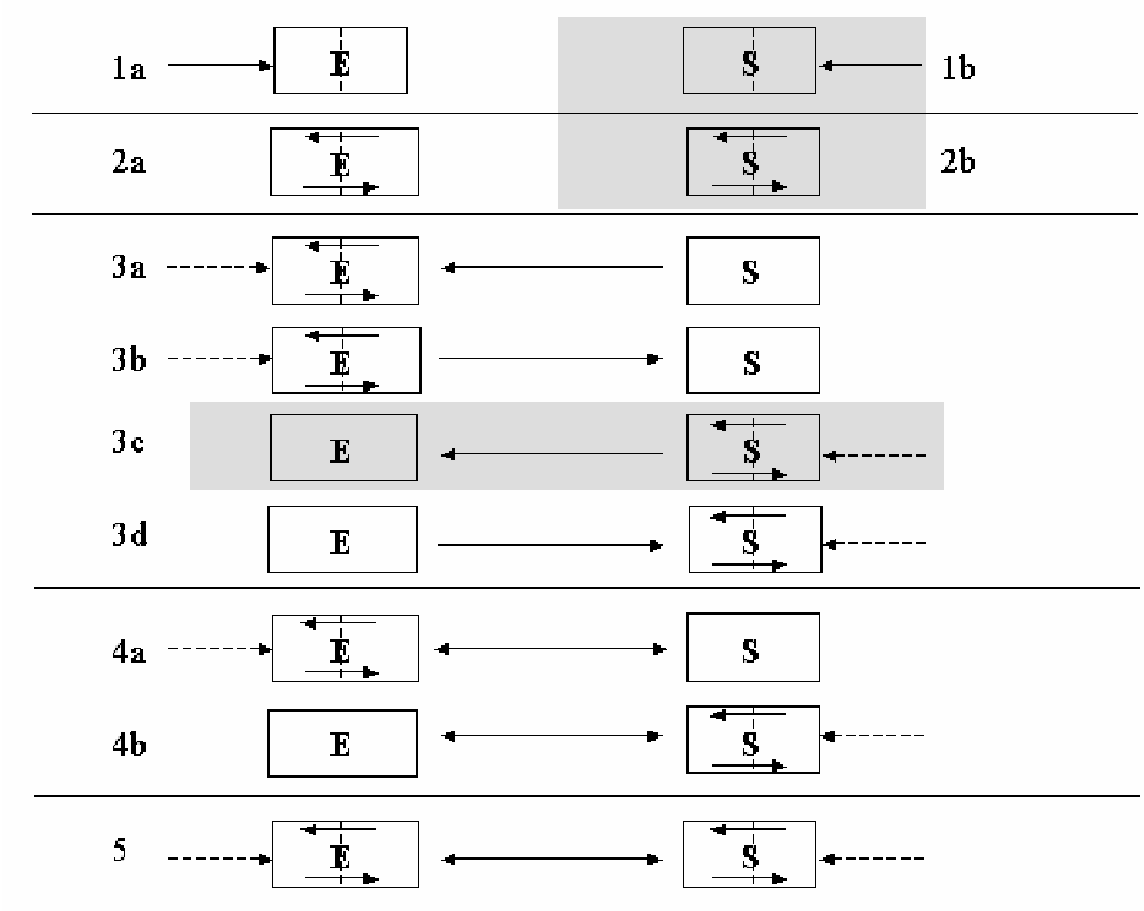


Figure 14 – Nine hypothesized categories of regime shift documented by Walker and Meyers 2004. All the possible interactions between social (S) and ecological (E) systems in relation to threshold shifts. Systems that have undergone a threshold shift to an alternate regime are split with a dashed line. The arrows within the boxes indicate that feedback mechanisms operate within the system. The arrows connecting the social and ecological systems show the direction of interaction between the systems in the development of regime shifts. Dashed arrows indicate that external influences may or may not contribute to the regime shift. The shaded categories are not included in the database, but are shown here for completion. (taken from Walker and Meyers 2004)

The search for regime shifts and related thresholds may not be much farther than the "natural history" stage of identifying and cataloguing likely examples. Advances in theory coupled with modeling and fieldwork have greatly helped in identifying, analyzing and categorizing regime shifts in ecosystems. However, aside from ecosystems with fairly regular periodicities of disturbance (fire and defoliating insect outbreak), our power to predict regime shifts and thresholds is quite limited. Only three studies are known to have tested prior hypotheses about thresholds in ecosystems (Scheffer et al. 2003, Pech et al. 1992, Robblee et al. 1991). Usually it is only *after* a shift has occurred that regime shifts are observed, recorded and analyzed, sometimes comparing post-shift data with data collected before the shift. In this light, the expertise of archeological research in examining historical and pre-historical data may be quite useful. Archeological analysis may offer unique perspectives on regime shifts over such a range of scales that entire civilizations were effected. Redman and Kinzig observe (2003) that archeologists can apply specific tools for testing ideas about regime shifts, such as:

"…use information from time scales that are accessible to few other scientists and who link patterns of human response and behavior over broader levels of social organization, e.g., household to civilization, than most other social scientists. These strengths within the field of archaeology can cast new light on linked dynamics across space and time, revealing nuances, contradictions, or knowledge inaccessible over shorter time scales or narrower organizational scales."

Archeology and a range of other social science can make significant contributions to our understanding of regime shifts and related thresholds in social-ecological systems. The social sciences, and anthropologists in particular, have long been aware of the limitations of equilibrium-centered approaches. Foin and Davies (1987) examined different models of the Maring socio-ecological system. They note that the equilibrium state changes itself over time due to exogenous and endogenous factors (inventions, environmental change etc.) The evidence for regime shifts was already sufficiently compelling that they proposed future research should focus more on the causes of regime shift rather than whether regime shift occurs: "*…if this is true, empirical studies on population regulation* [of humans] *should attempt to define the regulation mechanism in force at time, with less emphasis on the equilibrium-disequilibrium issue*." (Foin and Davis 1987 p 2). A considerable literature is growing to document social factors related to resilience and regime shift (see Folke 2006 for a comprehensive summary). As a small sample of recent work we now consider several examples from economics and political science.

4.2 Regime shifts from a social perspective

4.2.1 Evidence for Tipping in Social Systems

Resilience theory offers tools one might apply to test the suspicion that one's system of study might cross thresholds and undergo regime shift. What is the basis for such a suspicion, and how might one imagine regime shift and thresholds in social systems? How much change is involved and what kind (reversible, partly reversible, irreversible)? In what ways might one characterize a shift in regime: Political regime change (revolution), dynamics of changing relationships (information exchange or power) in social networks, shifts in belief systems, paradigms or mental models, economic restructuring at levels considered profound (multi-scale)?

Some work has been done on how the "human dimension" reflects properties of complex adaptive systems, and can possibly influence resilience by changes in such factors as: diverse sets of institutions and behaviors, local interactions between actors, and selective processes that shape future social structures and dynamics (Arthur WB. 1999, Janssen and Jager 2001, Lansing, JS.2003). Brock (2006) concludes:

> "Natural and social scientists have worked hard to understand dynamical processes that produce punctuated equilibrium behavior. There are many kinds of models that do so: "sand-pile" models, "tipping point" models,

> "small world" models and other graph-theoretic models, "complex adaptive systems" models and models that produce punctuated dynamics via a hierarchy of time scales."

Some (W. Brock, pers. comm.) find the field so saturated with papers on social interactions and multiple stable states (particularly game theorists), that they have turned their attention to statistical means to garner evidence of multiple regimes and thresholds. This search is complicated by the problems of correlated unobservables and selection bias. Brock (2006) summarizes these problems as follows:

> "*Identification problem*" in econometrics: How does one use data to distinguish among observationally equivalent structures? Such an identification problem turns up in the attempt to use data to separate "true" social dynamics that produce punctuated equilibrium behavior from "spurious" social dynamics created by exogenous dynamics of unobserved variables. This identification issue is especially important in deciding whether the sluggish political system acts suddenly because of "endogenous" emergence of pressure which "tips" it or whether it acts suddenly because an exogenous change acts on it, a change that may have little to do with the punctuated equilibrium dynamics of policy change discussed by Gunderson and Holling (2002)."
>
> "*Selection effects*" refer to the general tendency for social groups to self-select because they share common preferences, experiences or constraints, many of which are impossible for an empirical scientist to observe. It is very difficult to use observational field data to distinguish the effects of commonly shared unobservables from endogenous social dynamics, which are associated with the currently popular phenomenon of social capital. In order to infer the correct policy action it is important to separate endogenous social interactions from exogenous social interactions."

Despite these challenges, evidence for regime shifts and thresholds have been found in socio-economic systems related to elections, monetary policy and stock prices (Brock and Hommes 1997, Brock et al. 2006, Carpenter and Brock 2006).

4.2.2 Regime Shifts as Cycles of Political -Technical Transition

Regime changes in SES are also studied by political scientists who have modified Holling's Adaptive Cycle to look at social transition as a series of phases. As social scientists they focus less on the role of technology and give most emphasis to within- and cross-scale interactions between institutional, economical, technological and social-cultural cross-scale developments (Van der Brugge 2005, Loorbach submitted). They study the transformation of so-called 'societal regimes', constellations of actors, with specific practices and artifacts that are embedded in social structures, performing a certain function for society. The breadth and dynamics of stability domains are strongly influenced by feedbacks, especially sets of feedbacks that reinforce each other. The process of transformation is the result of slow dynamics changing the shape of the stability domain and the distribution of innovations that act as perturbations upon the existing constellation, initiating transformation to a new attractor.

The need to modify the ecosystem perspective of regime is motivated by five critical kinds of human capacity that distinguish social- from eco-systems (Van der Brugge 2006): *Reflexivity* - Human capacity to reflect on, communicate about, and modify the roles and actions of themselves, others and the social structures they are embedded, *Foresight -:* Capacity to anticipate rather than simply react. *The use of instruments*: Human artefacts have great potential to turn into strong social structuring artefacts, *Intellectual exchange* - Human communicative skills, and *Authorization:* Authority systems specifying the rights to control events or resources are negotiated and transferred to representative authorities, themselves a social structure. It is assumed that these capabilities do not prevent the creation of domains of attraction. Therefore, the model of regime transformation as shifts between alternative states is still appealing in order to understand the non-linear process of social change.

4.2.2.2 Transitions in social systems.

While they observe periods of slow build up followed by episodes of fast, adaptive change that appear analogous to the front and back-loops of the Adaptive Cycle, they stress that such transitions emerge from adaptive responses of *social systems*. In particular, their use of the word *adaptive* connotes more decision and guidance than the term implies for ecosystem CAS. Adaptive responses can be both incremental as well as radical. Incremental in this sense refers to increased efficiency without changing the key-structure, function or feedback. Hence, remaining within a same domain of attraction. Radical adaptive responses are associated with transformation of structures, functions and feedbacks and thus with the shift to another domain of attraction. In societal systems with high connectedness adaptive responses are dominated by *transformative* processes that overcome internal path-dependency and can be managed through the deliberate introduction and nurturing of new ideas and practices (Van der Brugge 2006). However, due to high connectedness there is also much resistance towards change.

In addition to the definitive role of transformative processes, social system transitions move through a series of phases that in terms of speed of change are quite similar to the four-phase Adaptive Cycle. These phases also move through alternating slow periods that build different kinds of capital followed by fast change as the system abandons traditional practices and switches to alternatives.

1. *Pre-development* phase - system dynamics remain relatively constant but below the surface the system capital and connectedness slowly and imperceptibly change, increasing the systems' vulnerability.
2. *Take-off* phase - the potential of the system's sub-surface structural change becomes evident in emergent phenomena and changing relations between actors.
3. *Acceleration* phase - Structural changes are fully realized as new dynamic patterns resulting from the accumulation of socio-cultural, economic, ecological and institutional innovations that reinforce each other;

4. *Stabilization* phase- the new system structures are stabilized and secured through institutionalization of the new social order.

The phases are driven by four social system functions (*fixation, differentiation, bifurcation, creation*), which apply better to social transition than the functions that mark the phases in the adaptive cycle. For example, the "Release" function in the Ω phase of the Adaptive Cycle implies massive liberation of resources that precipitates ecosystem collapse after which the system re-organizes and rebuilds, either as the old ecosystem identity or as a new one. By contrast, societal systems reconfigure not by collapsing with massive release of resources but through the build-up of alternatives that anticipate changing circumstances (van der Brugge 2006)

Societal dynamics in technological transformation emerges primarily from the struggle between *Fixation (due to standardization and alignment)* and *differentiation*. The former winnows novelty down to increase productivity, efficiency and profit, while the latter generates innovation and novelty to address existing and emerging needs. Differentiation is driven by new circumstances (exogenous) and shifting ambitions (endogenous) that shift the equilibrium to the pre-development phase, where differentiation (of procedures and methods) produces knowledge about the functioning (performance, possibilities, limits and flaws) of the current system. System transformation can be smooth when low standardization and alignment allow easy integration of novelties. Otherwise, punctuated transformations occur when strongly fixated systems cannot flexibly integrate innovation. Due to the strong resistance towards innovations of these highly fixated systems, novel alternatives need to mature and structurally coupled to other novelties in –so-called-niche regimes. This process of bifurcation is needed to gain power in order to trigger social transformation. It results in the build-up of niche-regimes in terms of new structures, functioning and feedbacks through which in the end it will decrease the resistance against regime shift.

In summary, regime resistance increases as a function of fixation. However, if a novelty happens to trigger change, than it will surely cascade through a large part of the regime, transforming it and shifting the system into another domain of attraction. Then there is little chance of recovery of the old regime (backlash). Hence, in highly fixated systems, there is much resistance, but that is also accompanied by a loss of resilience. In order to force its change, the distortion must be strong in the form of larger niche-regimes. Such societal transitions can be viewed as regime shifts where each new regime qualitatively differs from the previous one in its new structural realignment (institutional, economical, technological and social-cultural). Rotmans (1994) suggests that each new (stabilized) regime can be considered a new dynamic equilibrium. The speed of change increases when *differentiation* generates new structural relations that are amplified by positive feedback loops. *Fixation* or *Standardization* dampens change through negative feedback loops. The former challenges and de-stabilizes the existing regime, almost like a disturbance, through the up-scaling of novelty in innovation networks. The decline of the structures upholding the existing regime is amplified by the loss of social capital. Trust and obligations binding key actors declines as they shift alliances, creating new alliances or niche regimes through the process of Bifurcation.

Rotmans and van der Brugge continue to apply concepts of complex adaptive systems and resilience because these frameworks help organize their observations of socio-technical systems in transition. In so doing, they help advance resilience theory by broadening the base of data and conceptual models about nonlinear dynamics of SES. This will complement the suite of models that stand as alternatives to the Adaptive Cycle from the areas ranging from building construction (Peterson 1998), political ecology (Peterson 2000) and rangeland ecology (see Cumming and Collier 2005 for a good current summary of alternative models).

4.3 Assessing the Potential for Regime Shifts

The spontaneous collapse and persistence of SES as degraded states is often associated with inflexible forms of governance that are so resistant to change they are labeled as "pathologically resilient." How do new, more flexible, regimes emerge from established and inflexible ones? This question continues to drive research on how governance can become more adaptive by change across all levels, from the bottom to the top, as opposed to management by decree from the top. *Transformability* has been proposed (Walker et al. 2004) as a term for such broad, cross-scale capacity to shift to a more adaptive regime by forging an entirely new set of system configurations with new components and novel linkages. In addition to shifts in social networks, transformation may occur also as result of changing "the state variables, and often the key cycles, that define the system" (Olsson et al. 2006). In general, transformations have been associated with ecological changes that degrade an SES (Hamilton et al. 2004), shifts in social values and resources (Scheffer et al. 2003), and economic or political change (Aberbach and Christensen 2001). Olsson et al. 2006) list some of the key shifts in social features associated with transformation:

- perception and meaning,
- network configurations,
- social coordination,
- associated institutional arrangements and organizational structures

Following largely on the work of Olsson et al. 2006, this section examines aspects that affect *Transformability* from the perspective of time (phases of transition) and then concludes by re-examining in greater detail some key elements (emergence of informal networks and of leadership) associated with navigating the phases of transition.

4.3.1 Phases of Transformation in Regime Shifts

Transformations can be described in three phases: preparing the way forward through exploration of possible new configurations and strategies, navigating transition to a new regime, and securing the transition by bolstering the resilience of the new regime (Olsson et al 2004, 2006). The phases proposed are inspired by examples from SES from four continents (North America, Asia, Europe and Australia) and could prove useful as templates to pose questions about where and how transition is occurring in actual SES or stylized models of SES.

4.3.1.1 Phase One - Preparation

If an SES is in an undesirable state, two exploratory paths can help prepare to set it on a trajectory toward a more desirable state governed by a more adaptive regime. These include research into: new system configurations and forms of governance, and strategies to identify, organize and integrate alternative approaches that support more adaptive governance. While existing networks often are locked into the paradigms, goals and operating methods that have characterized the established regime, "shadow" networks may emerge to explore these paths informally. Genuine novelty may not survive passage through the filters of orthodox doctrines and official organizational mandates, but may emerge in the shelter of voluntary associations who gather to suspend existing beliefs, identify and question their assumptions, and consider possible, alternative futures (Gunderson 1999).

Informal Networks - Both in the Florida Everglades and the Swedish lake country (Kristianstads Vattenrike (KV), informal networks were critical in the assembly of diverse expertises that built a platform for conflict management in a process of trust-building and sense-making (Olsson et al. 2006). Such platforms expand the knowledge pool of experience available for testing new ideas and deciding on considering alternative paths. They also proved crucial to establish commitment to navigate the entire transition. In the case of the Everglades, the informal network established that enough resilience remained in the system to make recovery possible within known levels of resources available to restore it. This discovery provided the assurance that propelled the network from "informality" into the daylight of politics to get the transition process rolling (Gunderson 1999). By contrast, Thailand, North America, and Australia offer examples where informal networks fail to gel and capacity building is arrested by polarization among actor groups (Olsson et al. 2006). Alternative paths of transition are hard to identify and cultivate when no network, or network of networks, can establish or maintain stable links long enough to build the knowledge pool. Such situations can further degrade when available research resources are mostly dedicated to pursuing individual political agendas rather than expanding the range of alternative configurations for a new regime.

Leadership - As shall be further discussed, such informal networks seem crucial to start the preparation process, but they are not sufficient to move transition to the next phase. That usually comes from adept leadership. Leadership can function at several scales, from individuals to groups of different sizes. Leadership functions (Olsson et al. 2006) include: integrating current experience and knowledge (including both scientific and lay understanding), summarizing that understanding at various levels (vision, goals, paths), communicating that understanding as a vision to a wider audience, and engaging and motivating key actors to help establish the direction of transition. Successful leaders, sometimes referred to as "local champions," keep the transition momentum moving forward by keeping the agenda active and prominent within the network and extending it effectively beyond the network as a rallying vision. Leadership potential increases when actors and networks coalesce into a wider network that functions at the scale at which problems operate. For example, in the Golbourn-Broken catchment in Australia, real progress on addressing soil salinity began as local networks allied in order to function at the regional level. In the final phase, leadership is vital to securing lessons learned and new innovations in methods as part of revision to institutions.

Opportunities to Seize - Superior theory and/or methods may not effectively support transition if not applied in a timely way. Rare chances to initiate policy change occur with the coincidence of four streams that normally operate independently (Kingdon 1995):

- Problems (are broadly recognized)
- Solutions (are identified and become available)
- Political climate (shifts and is ripe for change)
- Barriers and Constraints (are understood and neutralized or avoided)

The timing that brings these streams together to create these windows of opportunity is aided by two factors. First, if the scale of disturbance is sufficient to spur the emergence of a network to address the problem. Second, how the crisis is perceived relative to the scope of possible change. The Everglades exemplifies the latter case, where the network verified that anticipated impacts of the impending challenge did not exceed the resources to address it. Broad vision and active leadership are needed to foster the cross-scale interactions that bridge the separate arenas in which problems, solutions and politics operate. In practice this means functionally connecting the individuals, organizations and institutions, and doing so at multiple levels of organization (Olsson et al. 2006). The resources that must be marshaled to meet such challenges can be inferred from a list of factors that can torpedo efforts to get transition rolling.

- Short-term success of narrow (single discipline[3]) solutions eliminate the potential for alternative experiments by monopolizing available resources (funding, attention) until the window of opportunity is past. *Corrollary*: search for lowest cost solutions often promotes the same ineffective short-term solutions that make it harder to pay the bigger costs over the long term of doing it right.
- Short-sighted funding cuts hobble agencies whose knowledge and expertise and broad mandate formerly provided leadership to explore complex problems → leadership vacuum.
- Fragmentation of authority → confusion as to who is responsible (for science or policy implementation or resource use) → ignorance about state of resources or society → maximization of individual gains that often exceeds individual needs → resource wastage. This also depletes the social capital needed to deliberate and decide on courses to transition.
- Lack of funding to create the organizations or support the science and discussion processes that can drive the transition process

Over the longer term, social transformation can engender shifts in perception and awareness *as well as* in reserves of experience. This was evident in how the practice of hunting was radically transformed in the Quebec Cree when elders invoked the history of the last hunting collapse in 1910 (social memory) to alter how the younger hunters saw their relations to the resource and to each other (Berkes and Folke 1998, Berkes 2002,

[3] Initial historical examples are infamous failures due to total reliance on engineering. However, other disciplines (economics, ecology, political theory) have also been the foundations for long-term failure when they were exclusively relied on to define policy.

Berkes et al 2003). Social transformation toward new regimes often is linked to shifts in perception within the shadow networks trying to promote change (Olick and Roberts 1998, McIntosh 2000). Olsson et al. 2006 suggest that facilitating such perception shifts may "orchestrate" networking in the front loop of the adaptive cycle (see Figure 2) and that such realignments will ease the transition in the back loop (Ω to α). That is to say that changes in perception and awareness of new experience can be nuclei around which a network coalesces and can provide understanding that helps in navigating a turbulent interim period before a new regime is securely in place.

4.3.1.2 Phase Two - Navigating the Transition

Crisis can start with the turbulence of the shock of disturbance and the cascading impacts of collapse under the tension of prolonged stress. However, on-going stress and resulting feedbacks can combine to amplify the uncertainty about what is known and where the system is headed. So biophysical and socio-political processes can, independently and in reinforcing combination, create great turbulence during transition. Such an atmosphere of stress and turbulence is difficult to understand or to manage, so transitions cannot be planned, only navigated, as leaders and key networks collaborate to steer the process. Navigating relies on the preparation of the previous phase, but often needs the flexibility to depart from prior or pre-arranged ideas, procedures or policies. Such flexibility can facilitate formation of new networks, network linkages within and across scales, as well as foster new ideas and social processes to usher in a more adaptive regime of governance. Another, potentially complementary approach, is to craft management policies that function broadly (composite policies) to address problems in different domains (Westly 2002). In addition to leadership and diverse experience, Kingdon's (1995) emphasis on timing to capitalize on opportunities seems critical to this phase. For example, the "local champion" Sven-Erik Magnusson in Sweden worked within his constellation of networks to devise a set of policies that could be individually invoked should an opening occur at the right time. In keeping with the saying that "luck goes to those who are prepared" the availability of resources (funding, technical solutions from powerful organizations) can be crucial to create the capacity to exploit windows of opportunity with the ideas, experience, policies and methods of the networks trying to effect transition (Gunderson et al. 2002).

4.3.1.3 Phase Three – Securing the new regime

Transition processes may be launched with the emergence of informal networks, but the novel ideas and methods cultivated in the shadows may never be firmly secured as institutions that can endure future shock or stress. New crises from ecological collapse to economic or political realignments may sweep aside innovations that are still not fully understood and accepted. Or the inertia of the established regime can simply delay experimentation until the window of opportunity is passed. The ultimate test of transition is whether the emerging constellation of networks, ideas, methods and processes can become established as a new foundation, a new baseline for science, policy and local, living practices.

Failures to secure transition illustrate what is lost. In the Everglades, informal networks generated a wealth of new ideas for adaptive policies, but no field experimentation to test these policies (Gunderson 1999). The established reactive management regime deflected the momentum and quashed the emergence of an experimental and adaptive regime. In a similar fashion in the GMC of Australia, the established management regime rallied opinion around the traditional cultural icon: a wheat mono-culture landscape. It then funneled all resources into lowest-cost, quick solutions, starving any initiatives to address salinization through experimentation with alternative practices and landscapes (Lebel et al. 2006).

On the other hand, success can be achieved by securing the acceptance and promotion of novel approaches by established governance organizations. The new regime may include prominent elements of the previous regime, but the cast of players, actors and interacting ideas and processes has been altered. For example, in Sweden, the initiative of Sven-Erik Magnusson created the network, ideas and political momentum that convinced the Municipality Executive Board to support transition (Olsson et al. 2004, 2006). As previously noted with the Cree, lock-in to a new regime may be catalyzed by using social memory to derive a compelling story that interprets key events of a crisis (Berkes 2002) In that way the "sense-making" function of informal networks to develop persuasive alternative explanations of problems can also prove a clincher in the latter phases of transition. However, if the story on its own cannot overcome cultural inertia, leadership from the network and/or its champions must decisively advance such an alternative visions. Initiatives for experimental policies can drown in an excess of competing stories, data and experience. For example, in the New England fishery (Wilson 2002) the confusion continues between two approaches: conventional (orient on characteristics of single species of fish averaged over the whole region) and alternative (orient on the localized ecological adaptations of fish). This confusion "has created a variety of regulatory incentives that confound the goal of conservation." (Lebel et al. 2006)

4.4 Regime shifts – summary

Evidence for regime shifts and thresholds is abundant for social-ecological systems, especially from ecosystem scientists who collected and studied data and modeled marine, freshwater and terrestrial systems on every continent (Walker and Meyers 2004). A range of social scientists and economists have broadened this trend of inquiry by focusing more on the social variables and structures involved in SES regime shifts (Brock 2006, Folke 2006, Olsson et al. 2006). The longer ecosystem research effort has accumulated a picture of regime shifts supported by extensive data sets and models honed by years of testing in the field. However, the evidence from the social sciences holds enough promise to continue exploration of SES to demonstrate where the resilience metaphor "falls down" in explaining thresholds and regime shifts. That's how resilience theory will be improved or replaced.

5. PRELIMINARY RECOMMENDATIONS

5.1 Challenge of Modeling Actual SES

Deriving an estimate of resilience of an actual social-ecological system (SES) as the potential for a shift to a new regime may requires resources beyond the means of the CAVES project. The only convincing example to date, Carpenter and Brock's (2006) was for an SES but focused mostly on the ecosystem part. They modeled the variance in water column phosphorus levels as evidence of an impending shift from clear to turbid water, relying on experience and data from more than a century of in-field experimentation with replication and control. Decades of field work sustained attempts to understand through iterative testing of theory, models and methods. This effective meshing of field research, sophisticated modeling and theory eventually identified the macro-scale variables (catchment level soil phosphorus concentrations) whose slow increase imperceptibly shifted the resilience of lake water to shocks from pulses of phosphorus and/or storm turbulence. The details of the wider picture of interaction between macro-scale (catchment level) and micro-scale (lake water) phosphorus has the compelling support of models that reasonably reproduce complex, non-linear data from the field.

Social-ecological systems (SES) are even more complicated (many more variables, levels of interaction) than ecological systems. One might argue that SES are more complex, given all the inputs humans add (to name a few: *reflexivity*, *foresight, the use of instruments*, *intellectual exchange, authorization* (van der Brugge 2006)) to the ecosystems they inhabit and exploit. This raises a formidable challenge to both modeling and knowledge elicitation in the field. In a few years it is unlikely that CAVES can marshal such a suite of models supported by so comprehensive and detailed an evidence base. That may be what is required to model resilience of actual SES directly, predicting historical transitions or regime shifts.

5.2 Modeling Stylized SES

The modeling objectives of the CAVES project are limited to a practical focus on a few sectors of an SES. The primary modeling goal is dedicated to modeling only a certain part of the social sector of SES: networks of human actors, though institutions and policies might also be examined. Furthermore, network dynamics may be linked to but a few factors in other sectors. For example, in the Odra case study these might include: farming income or production (economic) and water dynamics in fields and drainage canals (biophysical). Stylized models of such simplified systems, based on data elicited from stakeholder and actor interviews, may add no power to predict the dynamics of any of these sectors. But they may prove useful in learning about the implications of interactions within and across sectors. How networks evolve through establishment and culling of relationships, how networks of different sizes and structures might variably impact elements of the economic and biophysical sectors. These are some of the many potential questions such models can usefully explore.

How can resilience theory contribute to this "modeling for learning" framework in CAVES? The exact details of the specific questions modeled in each case study are the ultimate determinants for how resilience theory might be applied. This report offers a general introduction to resilience theory and application to stimulate further questions and ideas about how each modeling team may apply it. What follows are some preliminary suggestions to facilitate the next round of discussion of modeling applications.

5.3 Resilience theory invoked as a series of questions

The primary focus on the dynamics of human networks suggests that initial consideration be given to how testing resilience theory might illuminate those dynamics. To that end this report stresses models of SES with human actors at the center. That is, resilience is invoked to examine the dynamics of regime change, where a regime is a set of actors, networks, and processes that tend to persit in time because they cluster and reinforce one another in their interactions and which contribute to the dominant controlling actions in the SES. This raises a series of questions as to whether one can identify:

Q 5.1 A regime that dominated the direction of the SES in the past or present?
Q 5.2 Potential regimes in the future that might emerge to take control of the SES?
Q 5.3 Pairs of regimes that link the present to the future?
Q 5.4 Pathways that map out possible routes along those links between present and future regimes?
Q 5.5 Over what scales do these regimes operate in time and space, especially over time frame do we measure?

If such questions prove a useful framework to imagine change in the SES of concern, then one might follow by trying to identify in more detail the regime that currently dominates one's case study SES, defining it with an eye toward the structure of one's model (i.e. how do the details of my question map onto the way I describe the SES and the network within the SES in the model?).

This raises a second round of questions:

Q 5.6 What factors in the regime are of crucial interest to its dynamics (what may be vulnerable and how might that vulnerability influence transition?) (resilience *of* what)?
Q 5.7 What factors might prove to be crucial stressors or shocks (resilience *to* what) to the factors identified in Q 5.5?
Q 5.8 What factors might influence the vulnerable factors (Q5.5) or their stressors (Q 5.6)?

Pursuant to Q 5.8 I list below (Table 5.1) five factors proposed by Olsson et al. (2006) as key determinants of transformability along with some suggestions as to factors that might represent examples of these determinants that can be varied in a model.

Table 5.1 Determinants of Transformability as proposed by Olsson et al. 2006.

No.	Determinant of Transformability	Associated Factor(s)
1	Incentives	Institutional changes
2	Awareness	Critical thresholds of awareness
3	Experimentation	Fraction of risk takers in population
4	Reserves	
5	Governance	New governance configurations

In addition to these determinants, other factors might be associated with regime change. For example, in a way analogous to the way that increased variance in water concentrations of phosphorus indicated impending shift from clear to turbid, perhaps increasing variability in links between actors in a network and/or between networks would suggest a potential shift to a new set of links defining a new network? More basic and clear evidence of regime shift might be the emergence of a new network that remains stable for some appreciable length of time. This suggestion reinforces the importance of Q 5.5. That is to say, over what time scales do we measure such that specific durations constitute an "appreciable length of time" and what not? Other evidence of regime shift might be the emergence and persistence of a function of a new regime that heretofore had not been present. For example, water storage or water flow in canals that are properly maintained might signal the emergence of a new regime reinforced by better collaboration between actors in the Odra river case study.

Finally, these and other factors can be examined not by looking for evidence of successful transition to a new regime but from the reverse perspective: failure. Networks may form but only ephemerally, failing to coalesce into a self-reinforcing pattern. This might be a consequence of trust eroding for any of a number of reasons: more actors pursue their own interests rather than collaborate, no sharing of information, no emergence or sustained commitment of leaders to facilitate risk-taking in trying a new way of operating (cooperation, for example) and at working at the scale of the problem. An example of the latter case, along the Odra river local farmer networks cannot address regional groundwater declines created by lock construction unless local actors and networks align and cooperate to function at the regional level.

The factors associated with resilience and regime change mentioned in this report, and especially in this concluding section, probably represent only a fraction of the potential factors that might be examined in dynamic models of networks of human agents. Hopefully, this preliminary set will provide the nucleus for discussion that fully elaborates the model structures and specific variables that allow exploration of resilience in the dynamics of case study regimes.

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APPENDIX ONE - DEFINITIONS OF RESILIENCE

The following are a sampling of different definitions and descriptions of Resilience.

Resilience related to Biodiversity (Walker 1992)
- the key structure of biodiversity resides in the balance between *driver* and *passenger* species, where the former drive (control or steer toward the future) and the latter ride (do not significantly influence the system's trajectory). Based on this definition, *Resilience* is a product of the diversity of *drivers* and in the number of *passengers* that can become *drivers* in emergency.

Resilience related to Viability Theory (Martin, S. 2004)
The concept of resilience depends on six characteristics: (i) the *state of the system*, (ii) the *objectives* (the property to be maintained. in the case of a lake, the resilience of the oligotrophic property or the eutrophic one may be studied; in the case of a farmer population, the resilience of the profitability of their activities may be studied and, in the case of a lake surrounded by a farmer population, the resilience of both oligotrophic property and profitability may be studied), (iii) the *anticipated types of disturbances* (the stronger the disturbance is, the less resilient any state of the system will be whatever the property under consideration), (iv) the *cost* associated with the effort that is necessary *to restore this property* (this cost may be either economic the amount of money needed to restore the property; or ecological the length of the period during which the population has to put up with the sight of turbid water in the lake; or both), (v) the *control measures* that are available, and (vi) the *time scale of interest* (Carpenter et al. 2001).

"Resilience measures the strength of mutual reinforcement between processes [operating at different scales], incorporating the ability of the system to persist despite disruptions and the ability to regenerate and maintain existing organization…" (1 *p.6*) Gunderson and Pritchard 2004

"…the extent to which a system can absorb recurrent natural and human perturbations and continue to regenerate without slowly degrading or even unexpectedly flipping into less desirable states. Resilience in this context is defined as 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. " - Folke et al. 2005, Walker et al. 2004

From Redman and Kinzig 2003

Four key features of ecosystems provide the underlying assumptions of resilience theory (Holling and Gunderson 2002:25-27). First, change is neither continuous and gradual nor consistently chaotic. Rather, it is episodic, with periods of slow accumulation of "natural capital" punctuated by sudden releases and reorganizations of those legacies. This episodic behavior is caused by interactions between fast and slow variables. Second, spatial and temporal attributes are neither uniform nor scale-invariant; rather, patterns and processes are patchy and discontinuous at all scales. Therefore, scaling up from small to large cannot be a process of simple aggregation. Third, ecosystems do not have a single equilibrium with homeostatic controls to remain near it; instead, multiple equilibria commonly define functionally different states. Destabilizing forces are important in maintaining diversity, flexibility, and opportunity, whereas stabilizing forces are important in maintaining productivity, fixed capital, and social memory. Fourth, and finally, policies and management that apply fixed rules for achieving constant yields, independent of scale and changing context, lead to systems that increasingly lose resilience, i.e., to systems that suddenly break down in the face of disturbances that previously could be absorbed. Because ecosystems are moving targets, management has to be flexible and work at scales that are compatible with the scales of critical ecosystem and social functions. These critical scales may themselves change over time. The key to enhancing system resilience is for individuals, their institutions, and society at large to develop ways to learn from past experiences, and to accept that some uncertainties must inevitably be faced.

Peters (1991) defines resilience as the ability of a system to restore structure after perturbation and argues that it is composed out of five factors

1. *Inertia* or resistance to perturbation
2. *Elasticity* or time to recover
3. *Amplitude and brittleness* identifying the extend of departure from which recovery is possible.
4. *Hysteresis* the degree to which the pattern of recovery divers from the initial pattern.
5. *Malleability* the ease of alteration.

Dovers and Handmer (1992) distinguish between reactive (strengthening structures, building resistance) and proactive resilience (accepting change and learn to live with it).

APPENDIX TWO – Comparison of Resilience with Similar Terms

Term	*Definition*	*Ref.*
Ecological Resilience	"…the magnitude of disturbance that can be absorbed before the system redefines its structure by changing the variables and processes that control behavior." Implication – multiple equilibria potentially exist for the system	(4 p.426
Engineering Resilience	"…the time required for a system to return to an equilibrium or steady-state…" Implication – system exists near a single, global equilibrium Often used in engineering to optimize designs, attractive because maths are tractable	
Robustness	- Not as efficient as a system that is tuned for maximum performance, but performance will not drop off as rapidly as its non-robust counterpart when confronted with external disturbance or internal stresses. - A model is robust if it is true under assumptions different from those used in construction of the model - Robustness is the persistence of specified system features in the face of a specified assembly of insults.	1 5
Stability	"…persistence of a system near or close to an equilibrium state" whereas Ecological Resilience indicates dynamic behavior of systems far from an equilibrium state.	2
Viability	"…deals with dynamic systems under state constraints. This method analyzes the compatibility between the (possibly nondeterministic) dynamics and state constraints. It also determines the set of controls that would prevent the system from violating the state constraints.	3
Resistance	Resistance: the ease or difficulty of changing the system; how "resistant" it is to being changed. the extent of response after a disturbance., corresponding to negative feedbacks between system constituents that dampen reaction to perturbation	6
Persistence		

References:

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2- Carpenter, S.R. (2002). "Ecological futures: building an ecology of the long now." *Ecology* **83** (8): pp. 2069-83.

3- Martin, S. 2004. The cost of restoration as a way of defining resilience: a viability approach applied to a model of lake eutrophication. *Ecology and Society* **9**(2): 8. [online] URL: http://www.ecologyandsociety.org/vol9/iss2/art8

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5 - Allen, C. R. 2001. Ecosystems and immune systems: hierarchical response provides resilience against invasions. Conservation Ecology **5**(1): 15. [online] URL: http://www.consecol.org/vol5/iss1/art15/

6 - 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

APPENDIX THREE - PARADOXES OF RESILIENCE

1. Flexibility vs Control

   "…more resilient system implies more flexibility and hence less tight controls, but resilient systems are also defined as those able to maintain their controls and structure." - From Redman and Kinzig 2003

2. Changes in Resilience over Time – Initially high R → Long-term Lo R

   - Tainter 2000

"…the long-term history of human-environment interactions contained in the archaeological record reveals that many human responses and strategies that apparently helped to increase resilience in the short term, or even over a few generations, nonetheless led to a serious erosion of resilience in the long term, resulting in the collapse of both environmental and social systems (McGovern et al. 1988, van Andel et al. 1990, Kirch et al. 1992, Kohler 1992, Rollefson and Köhler-Rollefson 1992, Redman 1999)."

"…some social adaptations or cultural traditions may appear inefficient or "illogical" when viewed in the short term, but reduce risk and increase resilience in the long term (Butzer 1996)."

- From Redman and Kinzig 2003

Take, for instance, the case of social memory and system connectivity. Resilience theory recognizes these features as key adaptive elements that allow a system to retain its heterogeneity while remaining flexible enough to react to changing environmental and social contexts. This approach is similar to one advocated some time ago by anthropologists Marshall Sahlins and Elman Service (1960) when describing the "law of evolutionary potential." Adaptive capacity is enhanced by a rich social memory of alternative situations and responses, and by the accumulation of social capital in the form of the networks of trust, shared knowledge, and actual materials needed to facilitate those responses. At the same time, societies cannot always be buffeted by alternative responses; true resilience will lie in knowing when to change course and when to forge ahead. There is a cost to continually revisiting this question. Although system connectivity may be crucial in formulating a shared response in a timely fashion, too many connections may constrain response and lead to a "hypercoherent" situation in which excessive connections tend to make the system "brittle" or less resilient in the face of perturbations (Flannery 1972, Rappaport 1978). The key is in filtering information and fostering connectivity in times of stability, increasing exchange of information and fostering flexibility in times of change, and recognizing when a shift from one strategy to the other is necessary. Hence, we assert that there is no single optimal form of system connectivity or networking that will foster resilience, and that the most favorable level of connectivity will vary across the systems, and within a particular system across time.

A paradox, however, is that many human systems organize toward efficiency, which can reduce flexibility. What then happens to resilience? Efficient behaviors, such as specialization, reduction of redundancy, and streamlining of connectivity, allow a system to produce more at a lower cost of labor, materials, and energy and hence may bestow an advantage in a competitive context. Efficiency may allow a system to create and accumulate a surplus beyond its direct consumption needs and hence enable the concentration of power or the storage of capital. Stored capital may increase the resources available for adaptive behaviors, thus increasing adaptive capacity. It is this ability to accumulate a productive surplus that is a necessary, although not always sufficient, condition for the emergence of complex society. The growth of socially complex, hierarchical societies is a widespread, although not universal, process that has characterized much of human history. Individual cities, societies, and civilizations may have disappeared, but the longevity of the human experiment with efficiency, complexification, and stratification suggests that this is a strategy with significant staying power."

3. Paradoxes arising from Development of Complexity over Time

From Tainter 2000

In a large, complex system, constraints internal to the organization are as crucial as those external, and often more immediate. R. H. Coase (1937) argued that business firms exist to reduce transaction costs by internalizing diverse services. Hierarchy always simplifies, and within a firm internalizing services reduces the cost of establishing their prices. Yet as firms become larger there are diminishing returns to scale. Transaction costs increase as information channels become congested (Rosen, 1991, p. 82), waste increases, and the cost of organizing further internal transactions grows. Until recently, hierarchies proliferated in the business sector as easily as they did in government (Bendix, 1956, p. 216). Ancient states also experienced transaction costs. The early Roman Empire, for example, externalized parts of its own defense by allowing client states to buffer its periphery (Luttwak, 1976). Those states were in time absorbed, internalizing defense and administration, until the costs of continued expansion grew too high relative to the benefits of further internalization (Tainter, 1994).

From Scheffer and Jansson 2003
"…Tainter proposed an economic explanation of collapse. During development, societies increase in complexity. That is, they comprise more parts and more kinds of parts, and they develop greater integration of parts. At a certain level of complexity, the costs of increasing complexity surpass the benefits, leading to a collapse (Tainter 1988).

APPENDIX FOUR – Step-Wise Methodology for Defining Resilience Surrogates

From: Bennett, E.M., Cumming, G.S., Peterson, G.D. (2005). "A Systems Model Approach to Determining Resilience Surrogates for Case Studies." *Ecosystems* **8**:pp. 945–957.

Step 1: Assessment and Problem Definition

Key Questions:

- What aspect of the system should be resilient?
- What kind(s)of change would we like the system to be resilient to?

Step 2: Identifying Feedback Processes

Key Questions:

- What variables are changing?
- What processes and drivers are producing these changes?
- What forces control the processes that are generating change?

Step 3: Designing a Systems Model

Key Questions:

- What are the key elements and how are they connected?
- What positive and negative feedback loops exist in the model and which variables do they connect
- What, if any, are the intervening factors that influence or control these feedback loops?
- What (if anything) moves the system from being controlled by one feedback loop to another?

Step 4: Using the Systems Model to Identify Resilience Surrogates

Key Questions:

- As indicated by the feedback loops, what is the threshold value of the state variable?
- How far is the state variable from the threshold value?
- How fast is the state variable moving toward or away from the threshold?
- How do outside shocks and controls affect the state variable and how likely are those shocks and controls?
- How are slow variables changing in ways that affect the threshold location?
- What factors control the changing of these slow variables?

APPENDIX FIVE – Stability Landscapes as heuristics for resilience

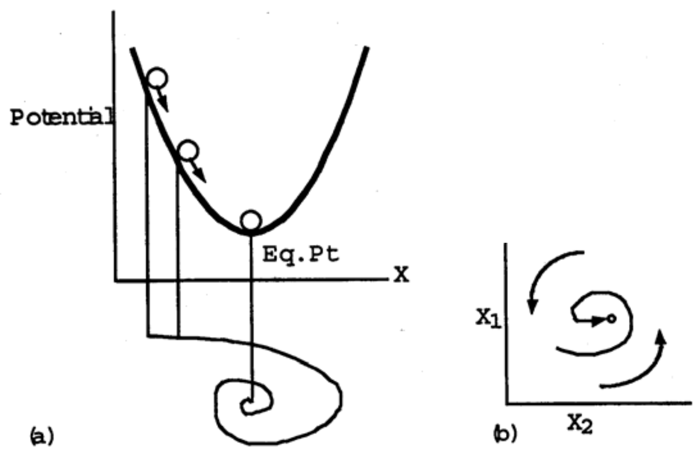

Figure 15 – A stable equilibrium as seen in a) stability landscape, b) state space.

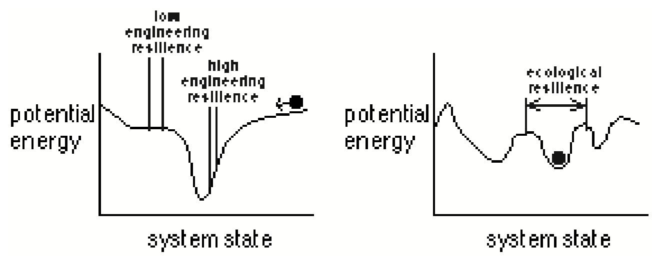

Figure 16. Stability landscapes can be used to represent the dynamics of a system. A system's 'state' is represented the position of a ball that minimizes its potential energy. The shape of the landscape represents the forces acting upon a system. In this model, the stability of a state increases with the depth of a pit. Zones of the stability surface that have low slopes have less engineering resilience than areas that have steep slopes. A system may be locally stable in a number of different states. Disturbance which moves the system across the landscape, or slow systemic changes which alter the shape of the landscape both drive the movement of a system between states. Engineering resilience of a system is a local measure. It is determined by the slope of the landscape at its present position. The ecological resilience of a system is a large scale measure, as it corresponds to the width of the pit of the system that the system is currently within. (taken from Gunderson et al. 2002).

The Text and graphics below are taken directly from the following publication
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

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).

The *latitude* is the whole set of system states (configurations) within the same stability domain. The larger the domain the higher the resilience is. *Resistance* refers to the extent of response after a disturbance., corresponding to negative feedbacks between system constituents. Strong resistance means that larger perturbations are needed to change the systems configuration. *Precariousness* refers to the distance to threshold. It is suggested that if the threshold is far away a relative strong perturbation is needed to push the system into a state that exceeds a threshold, if it is near it only requires a small additional push.

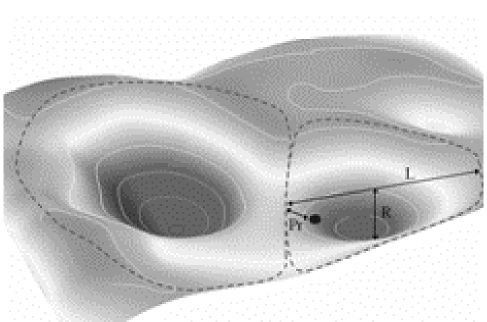

Fig. 1a. Three-dimensional stability landscape with two basins of attraction showing, in one basin, the current position of the system and three aspects of resilience, L = latitude, R = resistance, Pr = precariousness.

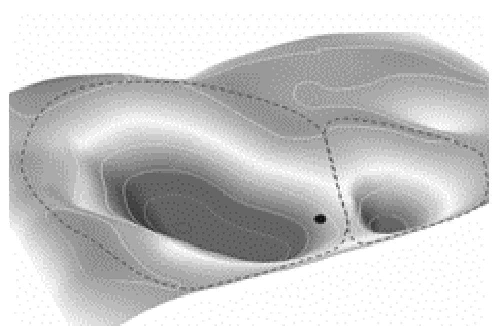

Fig. 1b. Changes in the stability landscape have resulted in a contraction of the basin the system was in and an expansion of the alternate basin. Without itself changing, the system has changed basins.

APPENDIX SIX – Equations for models of Carpenter and Brock (2006)

$$\frac{dU}{dt} = F - cUH, \quad (1)$$

$$\frac{dX}{dt} = cUH - (s+h)X + rMR(X) + \sigma MR(X)\frac{dW}{dt}, \quad (2)$$

$$\frac{dM}{dt} = sX - bM - rMR(X) - \sigma MR(X)\frac{dW}{dt}, \quad (3)$$

where F is the input rate of phosphorus to soil (e.g. from fertilizer use, dust deposition or weathering), c is a coefficient for transfer of soil phosphorus to the lake, H is noise for input to the lake (see below), s is sedimentation loss, h is hydrologic loss (outflow), r is a recycling coefficient, σ is the SD of recycling noise and b is the permanent burial rate of phosphorus in sediments; dW is a white noise process with mean zero and variance dt. The recycling function $R(X)$ is

$$R(X) = \frac{X^q}{m^q + X^q}, \quad (4)$$

where m is the value of X at which recycling is half the maximum rate and the exponent q determines the slope of $R(X)$ near m (Carpenter *et al.* 1999). The annual load disturbance H is calculated within each year as the solution of the Ito SDE

$$\frac{dH}{H} = \lambda dZ \quad (5)$$

with initial condition $H_0 = 1$; dZ is a white noise process with mean zero and variance dt (independent of dW). Using standard methods for Ito SDEs (Malliaris & Brock 1982), the solution of eqn 5 is obtained as

$$H_t = \exp\left[\lambda Z_t - \frac{t\lambda^2}{2}\right]. \quad (6)$$

$$\frac{dX}{dt} = a_0 + L - a_1 X, \quad (7)$$

where a_0 and a_1 are functions of the actual but unknown parameters of the true but unknown ecosystem processes, and the time series of input L and water phosphorus X are measured. Equation 7 is a minimal empirical representation of phosphorus dynamics that depend on input (L), losses (a_1) and recycling (a_0) in a situation where X is the only state variable that is monitored. L is assumed constant over one annual time step. This situation is similar to many lake monitoring programmes that estimate annual values for L and X, where the annual mean estimate of X is based on many observations in the course of the year.

Over one time step the solution of eqn 7 from initial condition $X = X_0$ at $t = 0$ is

$$X_1 = X_0 e^{-a_1} + \frac{1 - e^{-a_1}}{a_1} L + \frac{a_0(1 - e^{-a_1})}{a_1}. \qquad (8)$$

Dynamic linear models (DLMs) are among the statistical methods available for analysing time-series processes such as eqn 8 (Pole *et al.* 1994). In DLMs, the parameters can change slowly over time as new data are observed. Thus DLMs can adapt to gradual changes in the underlying ecosystem dynamics. In this situation, where ecosystem dynamics depend on slow change in unobserved variables (soil and sediment phosphorus), the DLM approach is reasonable (Pole *et al.* 1994; Cottingham *et al.* 2000; Carpenter 2003). Equation 8 converts to the following DLM:

$$X_t = \begin{bmatrix} b_0 & b_P & b_L \end{bmatrix}_t \begin{bmatrix} 1 \\ X_{t-1} \\ L_t \end{bmatrix} + \omega_t, \qquad (9)$$

$$\begin{bmatrix} b_0 & b_P & b_L \end{bmatrix}_t = \begin{bmatrix} b_0 & b_P & b_L \end{bmatrix}_{t-1} + v_t. \qquad (10)$$

In eqns 9 and 10, ω and v are independent normally distributed observation and process errors respectively. The parameters b_0, b_P and b_L correspond to $a_0(1 - \exp(-a_1))/a_1$, $\exp(-a_1)$ and $(1 - \exp(-a_1))/a_1$ respectively. At each time step, parameter estimates are updated using measurements of L and X (Pole *et al.* 1994). Because of the regular updating driven by data, the parameters do not follow a random walk but instead move with trends in the data. The updating equations are well known (Pole *et al.* 1994) and will not be repeated here.