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A Systems Model Approach to Determining Resilience Surrogates for Case Studies

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Abstract

Resilience theory offers a framework for understanding the dynamics of complex systems. However, operationalizing resilience theory to develop and test empirical hypotheses can be difficult. We present a method in which simple systems models are used as a framework to identify resilience surrogates for case studies. The process of constructing a systems model for a particular case offers a path for identifying important variables related to system resilience, including the slowly-changing variables and thresholds that often are keys to understanding the resilience of a system. We develop a four-step process for identifying resilience surrogates through development of systems models. Because systems model development is often a difficult step, we summarize four basic existing systems models and give examples of how each may be used to identify resilience surrogates. The construction and analysis of simple systems models provides a useful basis for guiding and directing the selection of surrogate variables that will offer appropriate empirical measures of resilience.

Key words: resilience; thresholds; archetypes; complex systems; social-ecological systems; ecosystem management; vulnerability; system models.

Introduction

Many of the management and policy problems that society currently faces arise from causes that are both social and ecological. Linked social–ecological systems are often difficult to manage and understand due to their non-linear and multi-scale dynamics, the potential for rapid change in system drivers, their sensitivity to external perturbations, and the reflexivity of human action. Further, many of the most important changes in social–ecological systems are extremely difficult to predict. Attempts at managing social–ecological systems using an optimization-based or ''command and control'' approach have often met with failure (Holling and Meffe 1996). Rather than using ecological prediction or forecasting to decide upon a singular optimal management strategy, an alternative approach is to manage in such a way that the resilience of desirable system attributes is maintained or increased (Walker and others 2002).

Ecological resilience is a measure of the amount of change or disruption that is required to transform a system from being maintained by one set of mutually reinforcing processes and structures to a different set of processes and structures (Holling 1973; Peterson and others 1998; Carpenter and

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others 2001). Although the theory relating to ecological resilience is becoming increasingly more refined (Holling and Gunderson 2002), there are few practical methods for applying this body of theory in real world situations (Carpenter and others, this issue). A practical approach to understanding and assessing resilience in social–ecological systems is needed (Kinzig 2001; Walker and others 2002). Yet resilience has proven difficult to measure. An alternative to estimating resilience directly is to monitor attributes of systems that are related to the resilience of the system and are measurable. These measurable attributes can be used to select resilience surrogates, defined in this Special Feature as proxies that are derived directly from theory for use in assessing resilience in a social–ecological system.

Ecological resilience theory assumes that an ecosystem can exist in alternative self-organized or ''stable states'' (Holling 1973). Measures of resilience focus on estimating the potential of existing drivers and perturbations to move the ecosystem from being organized around one set of mutually reinforcing structures and processes to another (Scheffer and others 2001). Resilience theory thus suggests that the key places to look for resilience surrogates are system attributes that separate sets of mutually reinforcing processes (Peterson 2002b). In this context, mutual reinforcement implies a cause and effect relationship in which cause and effect facilitate one another. Analysis of resilience therefore aims to identify alternative sets of mutually reinforcing processes. Changes from one set of processes to another are usually triggered either by the action of slowly changing drivers that force the system over a threshold, or by relatively discrete shocks to the system (Scheffer and others 2001). For example, the state change of a shallow lake from clear to turbid may be driven by a gradual increase in phosphorus loads, or by a large storm that alters its turbidity, or by both of these changes acting in concert (Carpenter 2003).

In this paper, we present a step-by-step approach for selecting resilience surrogates in the context of a new case study where little is already known about system resilience. The main steps are (1) problem definition, (2) feedback loop discovery, (3) systems model design, and (4) determining resilience surrogates. Because systems model design is one of the most difficult aspects of this process, we discuss the utility of some existing qualitative, conceptual systems models that help to fill the gap between unstructured and structured formalizations of system function. In so doing, we outline a set of archetypical systems models that can provide templates for the analysis of social–ecological systems for which minimal data or understanding exists.

Developing parsimonious models of complex systems is not easy. Good systems models will capture essentials while ignoring unnecessary details – they should be, as Albert Einstein said, ''as simple as possible, but no simpler''. For researchers with little formal background in systems theory, formulation of systems models may be a major stumbling block in the development of quantitative approaches for assessing resilience in complex systems. Once a formal qualitative systems model has been developed, quantifying relationships and developing causal hypotheses becomes considerably easier (Shipley 2002). Systems models are particularly useful for organizing the key elements of a case into a structure that can be used to appreciate the connections and interactions among the elements. In this way, they can be used to identify the factors – such as slowly-changing variables, stabilizing and destabilizing forces, and important thresholds – that determine the resilience of a system.

Determining Resilience Surrogates

How can systems models be used to identify resilience surrogates in a practical manner? Our approach features four steps. We begin by identifying the problem or the criteria for analysis. In the second step, these criteria are then used to define the system of interest and search for key feedback processes. Following this scoping process, the system is mapped using a systems model. Finally, the model is used to identify resilience surrogates.

Step 1: Assessment and Problem Definition

Searching for the sets of mutually reinforcing processes that lead to alternate states first requires defining the problem or reason why the system is being analyzed. For example, the central problem may be to maintain a particular group of species in a forest ecosystem. The definition of the problem determines the focal variables, identifying the conditions that are of interest and removing from consideration those that are not.

Problem definition can be accomplished by answering the questions (Table 1):

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

The answers to these questions define the problem by identifying the system of interest, the

Table 1. Questions that can be Used in Steps to Identifying Resilience Surrogates

			Case Study Examples		
Step	Question	Answer Defines	Limits to Growth with a Threshold	Tipping Point	Tipping Point with a Threshold
1	What aspect of the system should be resilient?	System boundaries, criteria for building system model	Water quality	Longleaf pine forest	Availability of food for elephants
1	What kind(s) of change would we like the system to be resilient to?	External drivers, disturbances, desired state of the system	Land use, land management, weather	Hardwood invasion, changes in fire, changes in climate	Changes in elephant population, climate fluctuations
2	What variables are changing?	System elements	Algae populations, [P] in water	Forest composition	Elephant populations, mix of woody species and grasses
2	What processes and drivers are producing theses changes?	System drivers	Increases P in runoff from agricultural land	Fire suppression	Fire, elephant grazing, tree growth
2	What forces control the processes that are generating change?	Connection among processes and elements	P recycling in the lake, extreme rain events, agricultural land management practices	Understory flammability, light penetration of canopy, leaf type	Elephant population size, rainfall, anthropogenic and wild fire
3	What are the key elements and how are they connected?	Editing and refining connections among elements and processes	P runoff, P in lake, P recycling, P outflow, [See Figure 2]	Longleaf and hardwood density, fire frequency, fuels. [See Figure 3]	Elephant population, woodland, grassland See [Figure 4]
4	What positive and negative feedback loops exist and which variables do they connect?	Identifying loops in model	+ Algae Populations, P recycling − Algae limited by P availability	+ Populations of both tree species + Longleaf increase fuels increasing fire which kills hardwood, − Hardwood leaves inhibit fire allowing hardwood to reproduce − Both species limited by space	+ Woodland growth, grass growth, elephant growth, fire increases grass − Limiting interaction between grass and wood, fire inhibits wood, elephants regulate wood
4	What (if anything) moves the system from being controlled by one feedback loop to another?	Identifying threshold and leverage points in loops	[P] in lake determines the rate of P recycling from sediments, P runoff is a major determinant of [P] in lake.	Changes in hardwood density in longleaf pine forest	Hunting, climate, logging

(Continued)

Table 1. Continued

Step	Question	Answer Defines	Case Study Examples: Limits to Growth with a Threshold	Tipping Point	Tipping Point with a Threshold
5	As indicated by the feedback loops, what is the threshold value of the state variable?	Threshold conditions	The P concentration when P recycling starts to become significant	The understory condition when it can be considered to contain easily burnable fuels	Threshold changes based on fire and elephant population
5	How far is the state variable from the threshold value?	Compare current state to threshold level	Compare lake [P] to the concentration when P recycling becomes	Compare amount of easily burnable fuels to that needed for regular fires	Compare woodland area is there relative to needs of elephant population
5	How fast is the variable moving toward or away from the threshold?	Whether system is becoming more vulnerable or more resilient	Measure rate of P recycling, Measure P load to lake from watershed	Growth rate of hardwoods	Rate of destruction of woodland
5	How do external controls and shocks affect the state variable and how likely are those shocks and controls?	Whether system is resilient is the system to external shocks	Extreme weather conditions can suddenly change P runoff and P load to the lake	Dry or wet period change spread of fires, prescribed fire and fire suppression change fire frequency	''Dry periods following wet Years encourage fire,'' extreme drought can kill elephants, hunting reduces elephant populations
5	How are slow variables changing in ways that affect the threshold location?	Whether slow changes in the organization of the system decreasing or increasing the resilience of the system	Accumulation of P in the watershed soils increases the potential P runoff to the lake	Fragmentation of landscape, invasive species that change fire mix	Elimination of woodland
5	What factors control the changing of these slow variables?	Controls of the resilience of the system	Agricultural practices	Road policy, human activities	Agricultural expansion

The column ''Answer defines'' indicates what aspect of the system is defined by the answer to the question posed. The last three columns provide the answer to the question for each of the three example systems described in the paper. + indicates a positive feedback loop and − indicates a negative feedback loop.

desired state of that system, and potential impediments or aids to maintaining the system in that state. For example, consider a case study where the area of interest is a longleaf pine forest and the problem is retaining sets of species such as red cockaded woodpeckers, which prefer longleaf pine to hardwood forest habitat. In this case the aspect of the system that should be resilient is the longleaf pine forest, and one of the most important kinds of change to which it should be resilient is invasion by hardwood tree species.

Step 2: Identifying Feedback Processes

Once the problem is defined, the next step is to begin to identify the sets of mutually reinforcing processes that maintain a condition, or offer the potential for an alternative condition. For example, long leaf pine forest is maintained by fire, whereas hardwood species that can invade longleaf pine forests suppress fire (Heyward 1939; Glitzenstein and others 1995).

Feedback processes are an important component of the resilience of a system because they determine the nature of the interactions among key variables. A feedback loop occurs when the output of a process influences the input of the same process. Feedback that amplifies the process is termed positive feedback. Feedback that dampens the process, pushing it towards an equilibrium, is termed negative feedback. Positive feedback tends to be destabilizing, whereas negative feedback tends to be stabilizing. Competing positive feedbacks can limit each other and result in alternate states. Many systems combine both positive and negative feedbacks (DeAngelis and others 1980; Peterson 2002b).

Feedback loops can be identified by asking the following set of questions (Table 1):

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

The answers to these questions will define, respectively, the variables of the system that should be examined, the processes internal and external to the system that are producing important changes, and the connections among these processes. Answering these questions should result in a rough understanding of the key processes that define a system and the likely locations of feedback loops.

In the longleaf pine forest example, the key changes are changes in the amount of longleaf pine and hardwood forest. The drivers that produce changes in the amount of longleaf pine and hardwood forest are fire and climate. Fire is controlled by local forest managers, who can start fires or put them out, as well as by the relative mix of forest types present. Hardwood forest tends to suppress fire, whereas longleaf pine is prone to fires (Peterson 2002a). Climate is not controllable by local managers.

Step 3: Designing a Systems Model

The preceding steps provide a basis for mapping the system by defining its analytical boundaries. A good system model will include all the key elements of the system and the feedback processes and linkages among the elements. Therefore, the mapping process includes identifying the system components and processes that are important to resilience dynamics. The researcher should also identify recent and long-term changes in the key system elements. This process is iterative by necessity; as processes and interactions are mapped out, it may become clear that what initially appeared to be a central process is subsumed in some more general process or dynamic.

Designing a good, simple system model is a key step in the process of identifying resilience surrogates because it formalizes and provides structure for the answers to the questions you have now answered about your system. System formalization is often best done in small but diverse research teams that can discuss the existing data about the system and integrate it with general social–ecological understanding. Such a team can productively map social–ecological systems and establish which processes are well understood, uncertain, or important.

The development of a system model is facilitated by asking the following questions (Table 1):

- 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?

In the longleaf pine example, the key elements are hardwood forest and longleaf pine forest, which are connected through competition for space and through fire. Fire regulates competition for space, suppressing hardwood species and promoting longleaf pine. We therefore can identify a negative feedback loop between hardwood species and longleaf pine habitat. This feedback loop is regulated by fire, which has a negative feedback loop in relation to the abundance of hardwood species and a positive feedback loop in relation to the abundance of longleaf pine (Peterson 2002b).

Key elements and connections, including feedback loops can be drawn as a systems diagram. The model designed for the longleaf pine system can be seen in Figure 3. We provide system archetypes for a few basic systems models. Elements and connections can be added to or subtracted from these basic starting points as needed to fit other cases.

Step 4: Using the Systems Model to Identify Resilience Surrogates

Once the systems model is established, resilience surrogates can be identified. As explained in Table 2, there are five main places to look for resilience surrogates. The first three relate to the distance of the system from a threshold (the first three columns of Table 2). These three surrogates are the distance of the state variable from the threshold, the rate at which the state variable is moving toward or away from that threshold, and the outside controls or shocks that may change the direction or rate of change of this state variable. The final two places to look for resilience surrogates relate to movement of the threshold itself (the last two columns of Table 2). For these two resilience surrogates, we suggest examining changes in the slow variables that control the location of the thresholds.

Selection of resilience surrogates is initiated by asking the following questions (Table 1):

- 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?

In the longleaf pine example, the threshold value would be the pine density threshold at which fire is maintained in the system at an appropriate frequency and extent to allow longleaf pine to outcompete hardwood species. The first set of resilience surrogates, those based on the distance of the system from the threshold, is measured as the difference between the current density of longleaf pine and the threshold density and the rate of change in longleaf pine density. The rate of change in the threshold, the second type of resilience surrogate, is measured as the relative sensitivities of fire frequency and fire extent to changes in the amount of longleaf pine and the relatively mortality of oaks to fire. In this example, outside shocks in the form of slowly-changing variables include climate, which influences fire frequency and extent, and the actions of humans.

Archetypal Systems Models

In our experience, one of the most difficult steps in this process is moving from an informal or partial understanding of the system to a more integrative, formalized system model. In this context, there are a number of existing systems models that can help to fill the gap between informal and formal descriptions of system function. Following Senge (1990), we call these simple and general models ''system archetypes''.

System archetypes are representations of patterns that appear repeatedly in many different systems. These archetypal systems models are general, formal, flexible, simple, and largely qualitative. They can be used as templates for the development of specific models suited to particular cases. System archetypes are particularly helpful in identifying rapidly- and slowly-changing variables and stabilizing and destabilizing forces. Applying system archetypes to a social–ecological system can suggest potential surrogates of resilience for a particular social–ecological system. Here, we focus on four archetypal systems models that contain different combinations of rapidly- and slowly-changing variables and limits, and show how they can be adapted to fit a series of particular circumstances.

We present three archetypal types of systems that can exhibit alternative stables states, and (for comparison) one system that does not. The archetypal systems models presented here are generic structures that often occur in social–ecological systems. We start with a simple ''limits to growth'' archetype that does not have alternative stable states. The following three models, ''limits to growth with a threshold'', ''tipping point'' and ''shifting tipping point'', all exhibit alternative stable states. The models are constructed by adding feedback processes and thresholds to make each

Table 2. A Comparison of Useful Surrogates of Resilience as found in the Examples of the Archetypal Models

	Resilience Surrogates				
Generic Description of Surrogates →	*The state of the system relative to the location of the threshold*	*The sensitivity of the system to further movement*	*The rate at which the system is moving toward thresholds*	*The location of the threshold*	*The rate of change in the movement of the threshold*
Archetypical Models ↓	*Dominated by fast variables*	*Dominated by feedback strength, internal to the system*	*Dominated by shocks or controls imposed from outside the system*	*Dominated by changes in the slow variables*	*Dominated by changes in the slow variables*
Limits to growth	N/a	N/a	N/a	N/a	N/a
Limits to growth with a threshold (for example, eutrophic lakes)	P concentration of lake relative to P concentration at which the rate of P recycling increases	Amount of P recycling relative to lake P dynamics	Rate of terrestrial input of P and factors that influence that rate, such as fertilizer use	N/a	N/a
Tipping point (for example, Longleaf pine habitat in Florida)	Longleaf pine density relative to threshold at which fire and longleaf savanna out competes hardwood regeneration	Relative sensitivity of fire frequency and spread to changes in longleaf pine density Relative mortality of oaks to fire	Management control of fires by fire control and prescribed fire Climate variation, dry and wet periods	N/a	N/a
Shifting tipping point (for example, elephant populations in Southern Africa)	Density of woodland relative to threshold density at which fire and grassland out competes woodland regeneration	Relative sensitivity of fire frequency and spread to changes in grassland density, Relative mortality of woodlands to fire	Amount of prescribed fire Climate variation: wet and dry periods Killing of elephants by people	Relative balance between woodland growth versus fire and elephant woodland elimination	Intensity of elephant elimination of woodlands, Rate of change in elephant population

The first three columns are determined by the fast variables in the system and relate to the state of the system relative to the location of the threshold. In these columns, the threshold itself is not changing. The last two columns are related to changes in the location of the threshold itself and are dominated by changes in slowly-changing variables. N/a indicates that this type of surrogate is not applicable for this system model. There are no resilience surrogates for the Limits to Growth system because this system does not exhibit alternate states.

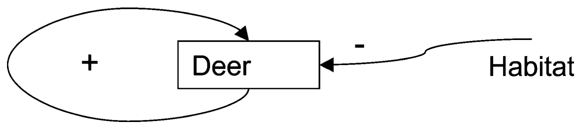

Figure 1. Limits to growth. Growth of a variable is inhibited by a limit. In this case the exponential growth of a deer population is limited by the availability of habitat.

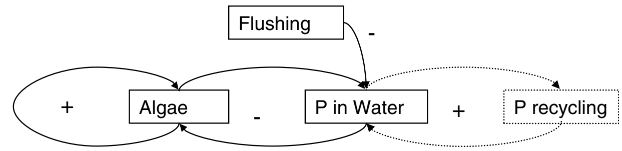

Figure 2. Limits to growth with a threshold. Algal growth is limited by the amount of P in the water, but at high levels of P in water a new positive feedback increases the P recycling to create a higher equilibrium for algae.

archetype slightly more complex than the one before. Other archetypal systems models can be found in Senge (1990) and other ecosystem modeling texts (Odum 1983; Hilborn and Mangel 1997; Petschel-Held and others 1999; Gunderson and Holling 2002).

Generic Archetypes

Here, we provide a generic description of the archetypes and show how potential resilience surrogates can be extracted from these system models. In the next section, we provide examples of each archetype and discuss how the steps and system model can be used together to determine resilience surrogates.

Limits to Growth. In limits to growth, a population enters a growth phase that eventually slows as a consequence of an increasing constraint imposed by a limit (Figure 1). The limit is sometimes caused by secondary effects of the growth itself. For example, deer populations may increase until habitat becomes limiting due to high deer density, which slows, and then eventually stops, the growth of the population. The processes that drive the limits to growth archetype are generally stabilizing in the sense that they tend to push the system towards a steady state. The positive feedback of growth is limited by the negative feedback of decreasing opportunities for growth. ''Limits to growth'' is dominated by fast dynamics and does not have alternate states in the primary variables of interest, though it can lead to alternate states in other components of the system. Population dynamics can often be explained using the ''limits to growth'' archetype with growth limited by such variables as habitat, food supply, nesting and roosting sites, disease, and predation.

In its basic form, ''Limits to growth'' can be considered highly resilient, because the system's potential for a shift to an alternate state is nonexistent. In reality, however, few systems are this resilient. We next consider some more complex cases in which limits to growth occur together with the potential for alternate states.

Limits to Growth with a Threshold. In limits to growth with a threshold, the system tends toward a limit; however, the limit can shift if the system exceeds some threshold (Figure 2). A threshold exists if the processes that regulate the behavior of the system change as the state of the system changes. That is, as the system crosses a threshold, new processes suddenly regulate system dynamics, changing the state of the system. In the cases of depensation in fisheries (Walters and Kitchell 2001) or the Allee effect in populations (Stephens and Sutherland 1999), the processes that control population growth rates differ depending on whether the population is below or above a given population size. Such a threshold can, in some cases, cause a system to exhibit alternative stable states. Alternate states arise as the quickly-changing variable crosses the threshold, and then is pushed in a new direction by the newly dominant dynamics.

The key to measuring resilience in this system is to understand the limits and the threshold that causes the system to exhibit alternate states. Resilience can be quantified by measuring how far the state variables are from the threshold which will cause the system to enter an alternate state and the rate at which it is moving toward or away from that threshold.

Tipping Point. In the tipping point model, there are two potential limits and the one in effect at any given time depends on the condition of the system (Figure 3). The system can be organized by either of two alternative sets of processes, which are each constrained. A tipping point exists when the system is in a condition when neither set of processes dominates. The condition of the system at a tipping point is unstable as the alternative positive feedback processes move the system away from the tipping point. In the case of the longleaf pine forest, below a certain density of hardwood trees, fire encourages the creation of a savannah forest that encourages fire. At hardwood densities above this tipping point, the growth of hardwood tree species suppresses fire encouraging the further growth of hardwood species.

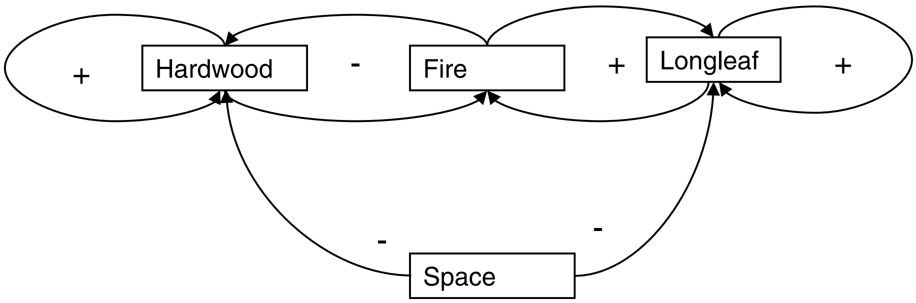

Figure 3. Tipping point. Growth of two variables is each inhibited by one another. In this case longleaf pine and hardwood both exist in positive feedback loops, however each limits the growth of the other. Fire mediates this relationship.

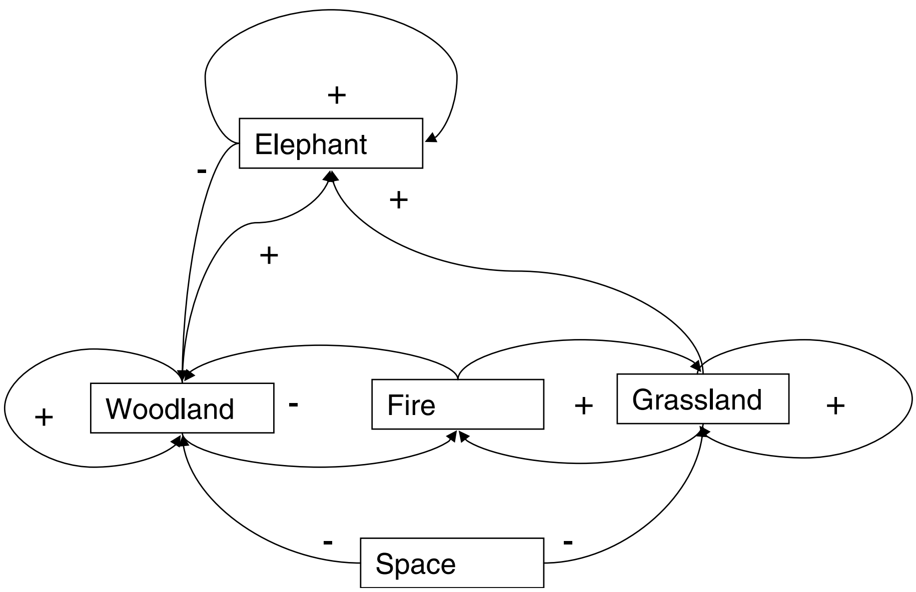

Figure 4. Shifting tipping point. Growth of two variables is each inhibited by one another. In this case woodland and grassland both exist in positive feedback loops, however each limits the growth of the other. Fire and elephant woodland destruction mediate this relationship. Elephant numbers depend upon availability of woodland allowing the system to exist in different configurations that can be long-lasting, but are not sustainable.

Quantifying the resilience of this system depends on understanding how the limits interact with one another and what causes the system to remain in a given state or flip into another state. Resilience surrogates can be identified by looking for system attributes that change as the system changes from being dominated by one set of positive feedback processes to another. In other words, what are systems attributes that change in detectable ways as a system is approaching a tipping point? Other resilience surrogates include how far the system is from the tipping point, and how fast it is moving towards or away from the tipping point.

Shifting Tipping Point. The addition of a third set of processes to two competing limits can produce complex dynamics, as in the case of the shifting tipping point model. A third process can control the relative balance between the two competing limits, causing the tipping point between them to shift over time. For example, a shifting tipping point would exist if climate change were causing the longleaf pine density required for a fire-regulated forest to shift over time. Because the third process is often linked to the other processes in the model, the interaction of these dynamics can produce a variety of complex dynamics (Figure 4).

For this archetype, the important features of the model are similar to those in the previous archetypes. Although resilience can be quantified by measuring how far the system is from the threshold that will cause it to enter an alternate state, in this system the threshold can move and disappear. Therefore, the additional resilience surrogates that exist for this archetype (and not for the archetypes explained earlier) are the rate and direction in which the threshold is moving. These variables determine the ability of an existing state to persist.

Relating Systems Models to Resilience Surrogates: Examples

Each of these archetypal systems models may be used to identify resilience surrogates by working through the questions outlined earlier and found in

Table 1. The following examples, which come from systems that have been analyzed in detail, are presented as an aid for researchers who are attempting to identify resilience surrogates in a system about which less is known.

Limits to Growth with a Threshold: an Example

In shallow lakes, there is often a threshold between a set of ecological interactions that maintain a clear oligotrophic lake with low nutrient levels, and a set of ecological interactions that maintain a turbid eutrophic lake with high nutrient levels (Scheffer and others 1993). Eutrophication is usually caused by the flow of nutrients, primarily phosphorus (P) to a lake (Schindler 1977). Many human activities cause nutrients to flow into lakes, but agricultural fertilizer is a primary source (Carpenter and others 1998b). P in fertilizer builds up in soil that, in turn, erodes into water bodies (Bennett and others 2001). P recycling within a lake can maintain a eutrophic state. Recycling exhibits threshold behavior that is related to the accumulation of P in sediments, wind mixing, and the oxygen content of deep water (Carpenter and others 1998a). In eutrophic lakes, the flow of recycled P from lake sediments can exceed annual inputs (Soranno and others 1997). Some eutrophic lakes quickly return to an oligotrophic state following the cessation of nutrient addition, while others do not (Scheffer and others 1993; Carpenter and others 1998a).

Walking through the questions for defining resilience surrogates, we begin with problem identification (Table 1). The focal problem identified in this example is to maintain high water quality in a lake by managing P concentrations. P recycling, which happens at low rates when P concentration in the lake is low and at high rates when P concentration is high, is a key positive feedback. The threshold is set by the concentration of P in the lake at which the amount of recycling changes. The slow variables that affect how close the P concentration in the lake is to the threshold are P in lake sediments and P in watershed soils.

In the ''Limits with a threshold'' system model, resilience is measured in three ways: *the state of the system relative to the location of the threshold, the sensitivity of the system to movement toward the threshold, and the rate at which the system is moving toward the threshold* (Table 2). In the example of shallow lakes, the first measure of resilience is the amount of change in the P concentration in lake water required to move the state of a lake into a state of high P recycling from lake sediments. Therefore, the first measurable resilience surrogate we identify in this system is the P recycling rate in a lake. We must also consider the importance of that feedback cycle relative to the other processes. Therefore, the second important measure of resilience is the importance of P recycling relative to other rates of P input to the lake, such as input from point and non-point sources of P. The third important way to measure resilience is to think about the slowly-changing variables that affect the feedback cycles and the rate at which the system is moving toward the thresholds. In the case of eutrophic lakes, the slow variable is phosphorus in watershed soils. Therefore, we look for a third surrogate in the amount of P stored in the watershed that could move downhill into the lake, which can be considered by measuring soil P concentrations in the watershed and fertilizer use in the watershed.

Tipping Point: an Example

An example of competing limits comes from the forests of northeast Florida that can exist in two alternative states: pyrogenic longleaf pine (*Pinus palustris*) savanna or mesic oak (*Quercus* spp.) forest (Peterson 2002a, b). The transition between these alternative states is regulated by fire. The ground vegetation in these forests burns frequently, and because longleaf pine and oak have quite different responses to and effects on fire, fire mediates the competitive relationships between these two vegetation types (Heyward 1939; Rebertus and others 1989). Both young and mature longleaf pines can survive ground fires. Additionally, mature longleaf pines also shed needles that provide easily combustible fuel for ground fires. By contrast, young oaks are intolerant of fire, and the leaves shed by mature oaks suppress the build-up of fine fuel that can spread ground fires. Fire suppression in oak stands thus enables the further growth of young oaks. Without fire, oaks grow up beneath longleaf pine and eventually replace it. Regular fires suppress oak growth and allow longleaf pine to thrive, which in turn permits more fuel to accumulate in stands of pine and encourages more fires, thus further suppressing hardwoods and encouraging the growth of pine (Glitzenstein and others 1995).

Again, walking through the steps for defining resilience surrogates, we identify maintaining longleaf pine forest to be the key problem. Invasion by hardwood species must be managed through fire, which is in turn partly determined by forest composition. The important feedback loops to consider are the positive feedback loops of both tree species wherein longleaf pine leads to more longleaf pine and hardwood leads to more hardwood; the positive relationship between longleaf pine and fire; and the negative relationship between hardwood species and fire.

In this system model, resilience is again measured in three ways: *the state of the system relative to the location of the threshold, the sensitivity of the system to movement toward the threshold, and the rate at which the system is moving toward the threshold* (Table 2). The threshold is measured as the amount of change required to move the state of the forest from longleaf pine to hardwood forest. Fire mediates the competition of hardwoods and longleaf pine for space, and the amount of fire is largely determined by the relative proportion of longleaf pine and hardwood species in the area, as well as by human management practices. Appropriate resilience surrogates would include the proportion of both types of forest, the rate of change in these proportions, the fire history, and details of fire management.

Shifting Tipping Point: an Example

A steady increase in the populations of both humans and elephants in Southern Africa has resulted in increased conflict between elephants and humans (Hoare and Du Topit 1999; Osborn and Parker 2003). Elephants are long-lived and ecologically engineer the ecosystems in which they live (Jones 1994). At densities of over approximately 0.5 per square kilometer, the activities of elephants and the linked interactions between woodlands and fire can convert savanna woodlands to shrub lands or grasslands (Starfield and others 1993; Cumming and others 1997). In recent decades, growth in elephant populations in Southern Africa, together with habitat contraction, has lead to increasing conversion of woodlands in many protected areas.

The archetypal model framework of ''limits to growth'' suggests that elephant populations should stabilize at some equilibrium level; however as they approach this limit, elephants began to change the habitat by removing woody vegetation (Starfield and others 1993). By altering the ratio of woodland to grass and shrub, elephants shift the fire-maintained balance between woodland and grassland. Trees in Miombo woodlands are not particularly fire-resistant when young. By contrast, most grass species in savannas accumulate moribund material that can lead to hot fires that increase the area of grassland. Consequently, as elephant populations increase they undercut the ability of the ecosystem to support large elephant populations. Without external management of the elephant population, this dynamic is thought to create a boom and bust population cycle in which elephant numbers increase to unsustainable levels over several decades and then plummet. Such population crashes are highly undesirable in most protected areas.

In this example, an important consideration for developing resilience surrogates for elephant management lies in the different speeds at which fire, grass, elephants, and trees change. The slow regeneration time of many savanna tree species, and the relatively fast dynamics of grasses and fire, mean that the sustained pressure exerted by elephants on the slower variable (tree cover) can allow the faster variables (grasses and fire) to capture the system. In the shallow, nutrient-limited soils and drought-prone conditions of southern Africa, grasslands have a lower long-term carrying capacity for elephants than do mature woodlands. This means that elephants can lower the carrying capacity of their habitat.

Resilience in the ''Shifting tipping point'' example can be quantified by measuring *how far the system is from the threshold that will cause it to enter an alternate state* and *the rate and direction in which the threshold is moving* (Table 2). Possible resilience surrogates include quantifying how far the elephant density is from the threshold at which elephants will start to degrade their own habitat; the relative proportions of mature trees, shrubs and grasses in the system; and the relationship of both elephants and vegetation to the number and extent of fires. Because the threshold moves in response to climate and its interaction with fire, with drier years having lower carrying capacities for elephants, measuring rainfall can also provide a useful resilience surrogate.

From Systems Models to Surrogates of Resilience

Resilience, an important indicator of the current state and potential future of social–ecological systems, can be difficult to measure. A practical approach towards quantifying system resilience may be identification and measurement of resilience surrogates, quantifiable proxies derived from theory for use in assessing the resilience of social–ecological systems. In this paper, we identified five key types of resilience surrogates (Table 2). Three relate to the state of the system relative to some threshold, and two relate to change in the threshold itself. Although these five types of resilience surrogates are not appropriate for all cases, being aware of all of them will help researchers understand and identify appropriate resilience surrogates for their study system. We provide a set of steps that can be used to determine resilience surrogates for a system about which little is known. We also indicate questions that can help someone complete each step for their case study. The four systems model archetypes we present will help researchers through the most difficult step of building a simple systems model.

Systems archetypes provide a set of basic systems models that encapsulate typical problems encountered in natural resource management. Although developing system archetypes can be difficult, the simple approach that we have presented has the virtues of being transparent and easily replicated. It also compels researchers to refine ideas and to reduce the number of variables that are possible contenders for resilience surrogates. It is possible to add extra complexity to the systems archetypes when necessary, although in many cases, the addition of detail adds little to the insights into the system function that the model generates. Models of complex systems that include too many variables or try too hard to incorporate all aspects of system dynamics tend to be unwieldy, and may be virtually impossible for casual users to understand.

Archetypal models offer valuable insights into resilience because they are highly focused templates that particular actors and interactions can be mapped onto. Most ecosystem management situations will fit into one or more archetypal systems model, but some models will illuminate the central questions better than others. Our archetypal models, and the process we propose for developing archetypal models, are designed to aid researchers in identifying resilience surrogates. They will help researchers identify and map key elements, processes, feedbacks, and thresholds that play a role in determining the resilience of a system.

In addition to aiding in analysis of the current state of the system, archetypal systems models offer a way of thinking about the future. System resilience may ultimately be dependent on future disturbances or environmental extremes that are not usually considered in traditional management frameworks. In combination with forward-looking planning frameworks, such as the development of scenarios (Van der Heijden 1996; Peterson and others 2003a, 2003b), archetypal systems models highlight a small set of actors and interactions that can be considered essential to system function. When thinking about future disturbances, it is useful to consider how this minimal set is affected. Simple systems models offer a straightforward, qualitative method for identifying key system components and understanding their role in system resilience.

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