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ECOSYSTEMS

An Exploratory Framework for the Empirical Measurement of Resilience

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ABSTRACT

Deliberate progress towards the goal of long-term sustainability depends on understanding the dynamics of linked social and ecological systems. The concept of social-ecological resilience holds promise for interdisciplinary syntheses. Resilience is a multifaceted concept that as yet has not been directly operationalized, particularly in systems for which our ignorance is such that detailed, parameter-rich simulation models are difficult to develop. We present an exploratory framework as a step towards the operationalization of resilience for empirical studies. We equate resilience with the ability of a system to maintain its identity, where system identity is defined as a property of key components and relationships (networks) and their continuity through space and time. Innovation and memory are also fundamental to understanding identity and resilience. By parsing our systems into the elements that we subjectively consider essential to identity, we obtain a small set of specific focal variables that reflect changes in identity. By assessing the potential for changes in identity under specified drivers and perturbations, in combination with a scenario-based approach to considering alternative futures, we obtain a surrogate measure of the current resilience of our study system as the likelihood of a change in system identity under clearly specified conditions, assumptions, drivers and perturbations. Although the details of individual case studies differ, the concept of identity provides a level of generality that can be used to compare measure of resilience across cases. Our approach will also yield insights into the mechanisms of change and the potential consequences of different policy and management decisions, providing a level of decision support for each case study area.

Key words: resilience; infrastructure; connectivity; networks; identity; social-ecological system; interdisciplinary; scenario.

INTRODUCTION

Resilience theory offers insights into the behavior of complex systems and the importance of such system attributes as diversity, ability to self-organize, system memory, hierarchical structure, feedbacks, and non-linear processes (for example, Carpenter and others 1999; Holling 2001). Resilience has been defined as (1) the amount of change that a system can undergo while still maintaining the same controls on structure and function; (2) the system's ability to self-organize; and (3) the degree to which the system is capable of learning and adaptation (Carpenter and others 2001). Depending on the nature of the system properties that we are inter-

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ested in, resilience can be desirable (for example, in ensuring continuous provision of clean water) or undesirable (for example, in the difficulty of removing a corrupt dictator). One of the aims of applying resilience theory to empirical case studies is to assess the current state of a social-ecological system and make predictions about whether or not properties of interest are resilient. Such an assessment can be used by managers and policy makers to either (1) identify actions that alter system resilience, or (2) identify strategies that focus on enhancing or reducing particular priorities, such as human health or invasive species, as system changes occur.

The abstract, multidimensional nature of the concept of resilience makes it difficult to operationalize. It is by no means obvious what leads to resilience in a complex system, or which variables should be measured in a given study of resilience. In this paper we present a framework for operationalizing resilience concepts. Our motivation derives from collaborative research interests in the conservation of natural resources and human well-being in forested regions of Latin America. Our study systems are experiencing infrastructure developments (roads and bridges) that will increase their socioeconomic connectivity. Although connections allow for exchanges of information, capital, and products, they may also suppress diversity, innovation, and the development of local capacity. We predict that resilience will be highest when endogenous and exogenous controls are balanced, giving a parabolic form to the relationship; that is, the resilience of social-ecological systems will be highest at intermediate levels of infrastructure connectivity. An alternative hypothesis is that increasing infrastructure will monotonically degrade the resilience of local systems. Ultimately we seek to test the hypothesis that changes in connectivity associated with infrastructure development cause predictable changes in the resilience of our social-ecological systems, with the hope that our work will suggest some clear management and policy priorities for these and other, similar systems.

The Relationship Between Identity and Resilience

Current definitions of resilience can lead to distorted or limited interpretations in empirical studies. The heart of the problem lies in the fact that when doing field work, we need to measure variables in the present that will determine system resilience at some point in the future. If we define a priori the variables that lead to system resilience, then our conclusions will be largely driven by our initial selection of variables.

To avoid this problem, we adopt a novel view of resilience as *the ability of the system to maintain its identity in the face of internal change and external shocks and disturbances*. This definition does not conflict with alternative views (for example, resilience defined as the width of a stable attractor; Carpenter and others 1999), but by changing the emphasis of the problem to focus on *identity* makes it a little easier to grasp. System identity is largely dependent on (1) the components that make up the system; (2) the relationships between components; and (3) the ability of both components and relationships to maintain themselves continuously through space and time (Wiggins 1967; Cumming and Collier 2005). The maintenance of identity is also related to (4) innovation and self-organization; resilient systems will typically be capable of adjusting to a variety of exogenous conditions, although innovation can also reduce resilience (for example, cultural evolution may be destabilizing). Depending on the question, the performance of a particular function or set of functions may also be used to guide the choice of identity criteria (see Table 1, and discussion below).

System components can be thought of as the pieces of the system, the 'nodes' of graph theory. In a simple system diagram they would be represented as the contents of a box. Components include such things as human actors of various kinds (for example, institutions, companies, leaders, ethnic groups); particular ecosystem types or habitat types (for example, forest, grassland, coral reefs); resources, goods and materials (for example, wood, fruit, water, bushmeat; many of these will be marketable); and abiotic variables (for example, water, heat, elevation, and geomorphology). The details of system specification (for example, how 'many' components to consider) depend upon both the knowledge base, and the questions of interest. In specifying components, it is important to be clear about system and component boundaries (either implicitly, or explicitly).

Relationships describe the ways in which system components interact or fit together. In a system diagram they would be the causal or logical arrows that link boxes ('edges' in graph theory). Relationships of interest in most study systems include such things as nutrient cycles, food webs and trophic interactions (relating different organisms to one another and to the abiotic environment, as in the dependency of people on fresh water), economic and ecological competition, land tenure

Table 1. Identity Criteria and the Selection of Identity Measures

Aspect of identity	Ecosystem example	Social example	MAP ecosystem example	MAP social example	Identity threshold examples
Components Objects, agents, entities that make up the system	Amount of focal habitat	Cultural groups	Percentage humid tropical forest cover	Resource user groups (indigenous groups, forest extractors, colonists, ranchers, loggers, urban population)	Deforestation of >25% forest; forest product extraction <50% 1990 levels
Relationships Process or interaction variables that link components	Food webs, predator-prey interactions	Land tenure (*de jure*)	Plant pollination by insects; seed dispersal by mammals	Tenure regimes (logging concessions, large ranches, small farms, extractive reserves, etc.)	Hardwood seedling recruitment falls >30%; land use violates tenure rules in >30% of extractive reserves
Innovation Variables that relate to the development of novel solutions and responses to change	Biodiversity	Cultural and livelihood diversity	Plant and insect diversity	New state forest policies, tri-national meetings, new enviro. ed. curricula, marketing of new forest products	>25% reduction in >25% of woody plant species; >30% decline in rural incomes from forest products
Continuity Variables that maintain identity through space and time	Seed banks, biotic legacies post-disturbance	Institutional memory, oral history	Vegetation, esp. structure, seed banks, seedling recruitment	Extractive reserves, income from traditional extractivism	Old growth forest reduced <20%; 10% net population loss in extractive reserves in 5 years due to migration

Identity depends on the maintenance of components, relationships, innovation and continuity. Adding or losing components or relationships, or decreasing the ability of the system to innovate or persist, will alter the system's resilience. We give an example of a quantifiable measure of identity in each instance, a specific example for the MAP region in Amazonia, and an example of a threshold value that could be used to define when identity changes. Selection of these measures is highly subjective and will depend on the location of the case study and the questions of interest to the researcher and the community. If the overall system identity (as a multivariate measure) is projected to change beyond a pre-defined level under the influence of specified drivers and perturbations, we can claim that the current system is not resilient to these future conditions. Note that this approach does not exclude functional definitions of identity; if the identity criterion of greatest interest is functional (for example, provision of water), components and relationships will be selected that relate directly to the function of interest.

systems, and interactions between human actors (for example, Daily et al. 1997, Ostrom 1990, Harris De Renzio 1997).

The sources of innovation are those subsets of the system that generate change or novelty. They may include or be closely related to such things as diversity (both ecological and social), migration, levels of education, and the ways in which new technologies are developed and/or adopted.

Continuity describes the ability of the system to maintain itself as a cohesive entity through space and time. Systems that are incapable of spatio-temporal continuity will frequently change their identity, providing a moving target for resilience studies. In social-ecological systems the key issue is often whether identity can be maintained through times of flux. Continuity is facilitated by system memory, which may take the form of elderly people, seed banks, social and biological legacies that remain after disturbances, customs and taboos, laws, or formal archives and libraries that become repositories of knowledge and also of identity.

Although specific components and relationships within a complex system will change over time, the essential attributes that define its identity must be maintained if the system is to be considered resilient. For example, in a ranching system such as that discussed by Carpenter and others (2001) we might base the notion of identity on the presence of ranchers, livestock, and a harvesting relationship between them. Loss of ranchers, livestock or the harvesting relationship would constitute a loss of identity. By contrast, and depending on the context, replacement of sheep in the system by goats might be seen as a system innovation that entails a degree of reorganization but no loss of identity. Sometimes, a change in identity may involve qualitative changes (for example, a species' extinction), whereas in others, identity change is more gradual and may be best demarcated by quantitative thresholds.

Classical resilience definitions (Holling 1986; Holling and Gunderson 2002) have relied heavily on the idea that complex system behaviours in multivariate space will typically fall within a stability domain around an attractor. System resilience is lost when the system enters a new domain. In similar fashion, identity can be quantitatively defined in relation to boundaries within a state space of the variables of interest. Many aspects of system identity will relate closely to the location of a system within a particular region of its state space, providing the conceptual link between attractor-based definitions of resilience and those that focus on identity.

One advantage of using the notion of identity is that it provides a clear separation of drivers from system attributes. For example, in the analysis of a shallow lake ecosystem, phosphorus levels may serve to define the system's location in relation to alternative attractors (clear or turbid states) but would probably not be considered a part of system identity. The use of an identity definition also forces us to be explicit about the system attributes that we are most interested in, creating a focal point for the analyses that follow and facilitating the operational step of selecting scales of analysis.

Another idea that we add to the standard notions of resilience is that if resilience is to be assessed operationally, it must be in relation to a potential and specific change in the system. Simply stated, if system identity is maintained over the time horizon of interest under specified conditions and perturbations, we can term the system resilient. If the identity of the system is lost or modified, the aspects of the system in which we are interested may lack resilience to different degrees. To assess whether identity is likely to be maintained we propose the formulation of an a priori notion of identity and an a priori set of alternative future system states that would indicate a loss of identity. For example, we might state a priori (and based as far as possible on reliable science) that the identity of an ecosystem will change if 40% of the primary consumer species in it are lost. This level of change then becomes a fixed point against which we can quantify changes in resilience. Obviously, identity will usually be a multivariate entity. Although there will be times when changes in system domain (that is, shifting to a new attractor) will change identity, there will also be times when they will not; although resilience and identity are closely related, they do not map directly onto one another.

An issue that must be confronted directly in developing surrogate measures of resilience based on identity is that definitions of identity will necessarily be based on human decisions and values. Given the impossibility of studying *all* aspects of any real-world system, some level of subjectivity in determining which system properties to study seems inevitable in any applied study of resilience. Ideally, subjective decisions about elements of system identity will be made through stakeholder workshops; the people who constitute the social part of the social-ecological system should select what they regard as key system attributes. The resilience of the system will then be assessed in relation to the properties of interest to the stakeholder community. This does not exclude the consideration of other drivers that may have strong effects on variables of interest. For example, if a community is particularly interested in the long-term resilience of its water supply, analysis of climate change could enter the assessment (for example, Caudro Dias De Paiva and Clarke 1995, Marengo and Hastenrah 1993). even though the community may have little awareness of its relevance at the start of the exercise. Moreover, in some cases stakeholders may be impossible to identify, or no longer extant; one could nonetheless carry out an analysis of resilience, for instance in a study of classic Mayan society.

We anticipate that the results of our research should be more generally applicable than our case studies, because so many social-ecological systems world-wide are currently experiencing rapid infrastructural development. However, because the ontogenetic stage of resilience theory is between the ‘consolidating’ and ‘empirical-interactive’ stages defined by Pickett and others (1994), due to lack of well-defined theory framework, translation modes, confirmed generalizations and stable definitions, neither measurement of resilience nor research designs for questions like ours have canonical standards. We stress that our own work on the application of these ideas is at an early stage, and present this framework in the hope that it will be useful to other researchers who are grappling with similar issues; we have not yet had the opportunity to test it rigorously. The remainder of the paper develops an approach to operationalizing resilience theory in the context of our research question of how changes in infrastructure connectivity could affect social-ecological resilience.

Roads and Resilience

Many developing countries have prioritized the development of roads, bridges, and communications, often in regions with fragile ecosystems and complex, resource-dependent societies (CEPEI 2001). Advocates of regional development and global market integration emphasize the positive impacts of infrastructure, such as greater competitiveness for local producers via improved access to resources and reduced transportation costs (Vance 1986; Owen 1987). In part this reflects the experience of advanced post-industrial countries (Friedman and Stuckey 1973). Contemporary frontier expansion in tropical environments in Latin America has historical, environmental and economic differences from earlier experiences (Goodland and Irwin 1975; Laurance and others 1997). The negative ecological impacts of new roads in tropical ecosystems include forest fragmentation, carbon emissions, increases in fire frequency, and species extinctions (Forman and Alexander 1998; Trombulak and Frissell 2000). Social scientists have documented negative impacts of infrastructure-induced perturbations on indigenous peoples (Davis 1977; Treece 1987), and increased conflict, violence, inequality and poverty in tropical regions (Hall 1989; Schmink and Wood 1992). The concept of resilience offers one way in which it is possible to address these concerns in an integrated, interdisciplinary manner.

A second integrating concept is that of political ecology, which addresses the political, economic, and cultural factors underlying human use of natural resources and the complex interrelations among people and groups at different scales (Blaikie and Brookfield 1987; Schmink and Wood 1987; Peterson 2000). It focuses first on local land users and their social relations, tracing these relations to higher scales of decision-making power (Blaikie 1985; Schmink and Wood 1992). Management and decision-making depend on addressing the needs of multiple stakeholders through socio-political structures that have varying degrees of influence, knowledge, and material resources. Consideration of political ecology suggests that resilience may be highest at intermediate levels of connectivity that break social isolation, without imposing outside interests on local groups.

Research Design

To fully test the hypothesis that resilience is predictably related to connectivity, we have developed a research design that accommodates several of the biggest challenges for the application of resilience theory. These challenges include defining the system, measuring drivers of change and the conditions under which system resilience will be assessed, and explicitly recognising the subjectivity of our own goals in undertaking the study. We illustrate our argument using examples from the MAP case study (Box 1). Our approach has five central elements, described below.

Define Current System

Our starting point for the analysis of resilience in our case studies is a clear definition of the *identity* of the system. The characterization of identity includes a clear statement of components, interactions, continuity, and innovation (as described above). Part of the process of initial definition is to ascertain boundaries (for example, spatial and temporal scales of investigation). Having specified

Box 1: Description of the MAP case study

Our example case study focuses on the 'MAP' region of the southwestern Amazon, the tri-national frontier where Bolivia, Brazil and Peru meet in the states of Madre de Dios (Peru), Acre (Brazil), and Pando (Bolivia). The MAP region provides a fascinating study case because it contains extremely high ecological and cultural diversity, while entering a period of rapid change triggered by the paving of the Transoceanic highway. The regional economy is based on traditional forest product extractivism, which occurs together with more recent forest clearing for agriculture in a complicated spatial patchwork of distinct tenure types. The MAP social system is greatly dependent on the region's humid tropical forests, which yield a wide array of products ranging from hardwoods to various oils and food crops, while providing ecological services such as the maintenance of water quality and quantity. Some of the key variables in the MAP case study are relative market prices for forest and non-forest products (adjusted for state policies), the spatial distribution of tenure types and forest resources within different tenure categories, land cover change, transport time and costs to regional markets, innovations and technologies relating to the economics of forest products, effective rules for land and resource use, and water availability per capita in urban areas.Paving of the Transoceanic highway (that is, going west from Brazil to ports on the Pacific) will increase the MAP region's connectivity to other regions, opening MAP to the impacts of external processes and facilitating perturbations brought by the increase in unpaved roads in recent decades (CEPEI 2001). In Brazil, where road paving has been completed to the Peruvian and Bolivian borders, land values have risen and forest extractivism has declined, while forest clearing has increased (even in extractive forest reserves; Wadt and others 2005), and rural-urban migration has increased urban water demand even as water availability declines. New legislation for logging concessions in Peru and Bolivia has fostered increased logging, raising concerns about sustainability. At the same time, Acre's 'Forest Government' has created numerous innovative policy programs to support forest-based development strategies; and universities, NGOs and local communities have engaged in intensive collaborations to identify, process and market non-timber forest products (Kainer and others 2003

the elements of system identity, we then specify which subsets of system constituents are of greatest interest (Table 1). Each of our case study systems is an integrated social-ecological system that is affected by exogenous and endogenous drivers and perturbations (Figure 1). The drivers that we choose to investigate are selected according to their relevance to our research question (see section on Roads and Resilience). We explicitly characterize the identity of each of our study systems in a two-stage process, first (a) conceptualizing the four essential system attributes (structural components, functional relationships, innovation, and continuity) most relevant to our research hypothesis; and then (b) for each of these, selecting specific variables that are most likely to change in response to changes in the intensity or extent of the drivers we selected (some examples are given in Table 1 and below).

System visualization and the determination of system identity are both informed by workshops (Chambers 1992, Walker and others 2002; Peterson and others 2003) involving people that live in or influence the study systems through their roles in institutions and/or research activities. Workshop findings are supplemented by data collection to quantify the variables that define identity (system attributes) and the variables that cause change (system drivers).

In the MAP region (Box 1), the existence and uses of humid tropical forest products, as by indigenous groups, rubber tappers and other traditional extractivists, are system components that are central to identity. A part of MAP's identity also resides with small-scale forest clearing for agriculture and agroforestry, as well as regional urban markets for local forest and agricultural products. The high cultural diversity of MAP occurs within a highly biodiverse, almost entirely forested region. Some key components of the MAP system's identity (Table 1) are the region's extensive primary and secondary forest cover and dense river network, alongside the various social actors (such as indigenous groups, forest extractors, logging firms and colonists) who make direct use of those resources.

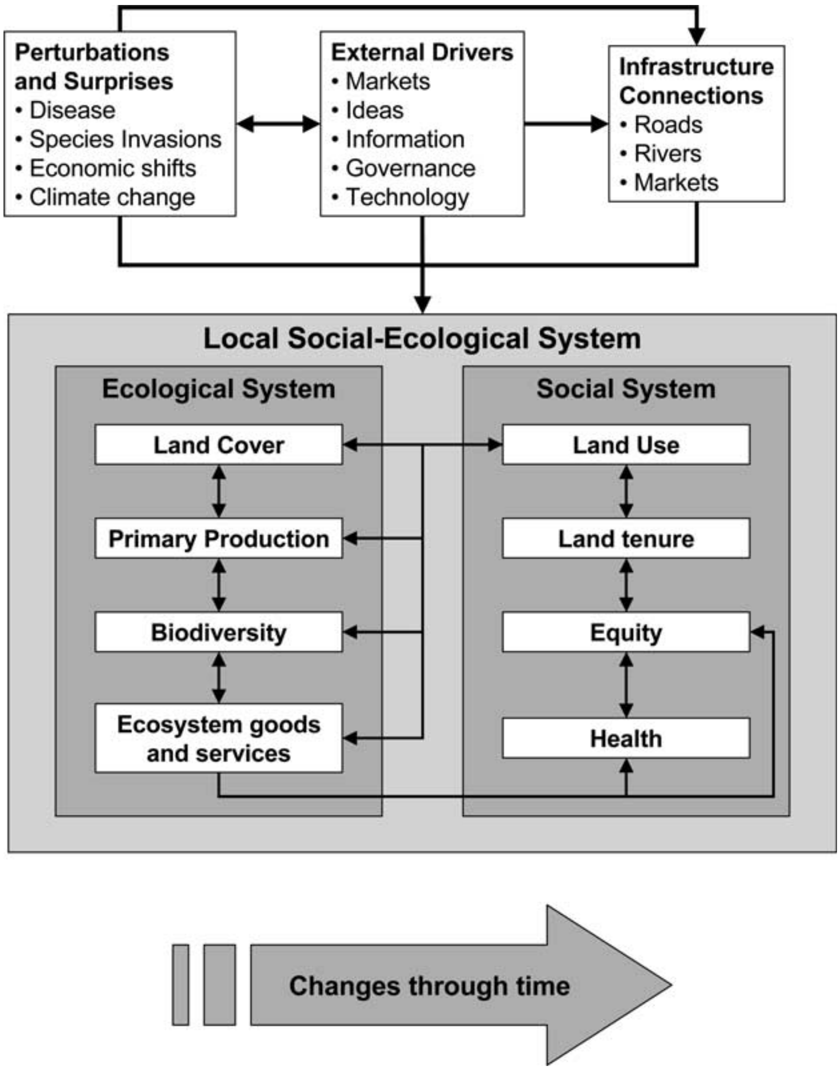

Figure 1. Simple visualization of key components (*in boxes*) and relationships (*in arrows*) within each of our study systems. External drivers and surprises may affect the local social-ecological system directly, or via connections; increasing the number of connections increases the coupling between the external and internal components. The regulation of land use by the social system has a large effect on the ecosystem; the provision of goods and services by the ecosystem has a large effect on the social system.

MAP regional identity incorporates numerous ecological and social relationships. For example, animal-plant interactions are central to pollination and seed dispersal for many of the Amazon's forest species (Wunderle 1997; Vulinec 2000). Brazil-nut trees are bee-pollinated and rely on ground-dwelling forest mammals to break open the thick husks of the nuts. Socially, MAP is defined by a wide range of tenure institutions which structure relationships between governments and landholders, and between social groups (Schmink and Wood 1987). Tenure types in MAP include indigenous lands, extractive reserves, biological preserves, and private landholdings. Each has specific rules for resource use, and the rules differ between Bolivia, Brazil and Peru. As a result, MAP is a patchwork of different tenure types with distinct land use regimes. In this system, ecological and social systems interact strongly; for example, the ecological process of pollination influences the economically important Brazil-nut crop, and socially-governed extractive reserves ensure that forests remain intact enough to support the persistence and movements of bees to pollinate Brazil-nut trees.

Innovation is also crucial to MAP regional identity. The region's extremely high biodiversity, especially in terms of insects and flowering plants, reflects past speciation and the potential for continued evolution in the future. Socially, the high cultural diversity of the area suggests a substantial capacity for innovation and has contributed to the formation of social movements in recent years. Such movements have created pressures for new state policies for sustainable forest management, environmental education, and other initiatives designed to address forest loss and reduced incomes from forest products. A key link between social and ecological innovation in MAP will be the identification of new forest products that can be sustainably extracted and marketed, yielding additional income sources for rural populations and constituting incentives for forest conservation.

In the face of rapid change, elements of continuity have been vital for maintenance of the identity of MAP. Ecosystem continuity in MAP has been contingent on the presence of seed banks and seedling recruitment of forest species, as well as genetically viable populations of key insects and animal species that pollinate or disperse seeds. Social continuity in MAP is fostered by forest extractivism, its attendant cultural practices and oral histories, and support for viable livelihoods. As MAP becomes more integrated into the global economy, institutional support for forest extractivism (such as that practised in extractive reserves) and successful commercialization of forest products, especially value-added or new products, will be important contributors to social continuity in MAP.

Having defined what we mean when we talk about MAP regional identity, it is important to give some indication of critical thresholds beyond which MAP would lose its identity. As noted earlier, identity is multivariate, so many or all of the thresholds that follow would have to be violated for the region to completely lose its identity. Ecologically, one key threshold for forest sustainability is approximately 25% forest clearing. Acre's Forest Government has vowed to limit deforestation to 14–18%. Another ecological threshold would be a decline of approximately 30% in hardwood seedling recruitment, which would reflect perturbations in key interspecific relationships crucial to forest structure reproduction and maintenance. Socially, a key threshold concerns the level of traditional forest extractivism in the region. Although rural households in MAP have long exhibited diversified livelihoods, forest products have been crucial, especially for cash incomes. One critical threshold is therefore a 50% decline in rubber production or Brazil nut collection from their 1990 levels, when extractive reserves were established to support them. Such a decline would relegate these forest products to a minor status while removing the current justification for extractive reserves. In addition, an approximately 30% decline in cash incomes from these activities relative to a baseline defined for the early 1990s would represent an important shift in rural household incomes that would force inhabitants to seek alternative income sources. In terms of social relationships, we can define thresholds such as the frequency of violations in tenure rules. A key case concerns extractive reserves, which mandate a cap of 10% deforestation. There are indications that in some places, forest clearing is nearing the cap. If 30% of households violate this rule, it would indicate a broad shift toward non-forest land use precisely where forested land use is mandated, thus constituting a critical threshold. Concerning social continuity, a critical threshold could involve migration to and from forest reserves. If, over a 5-year period an extractive reserve experiences a 10% net loss of population due to migration, this rapid decline would indicate that such reserves are incapable of retaining their populations. Because migration strategies for many rural households increasingly involve sending children to school, a net decline would likely be due to younger generations staying in towns rather than returning, thus undermining the capacity of rural communities to reproduce themselves over time, threatening a key social aspect of MAP regional identity.

As these examples illustrate, our proposed approach to the measurement of resilience derives from a clear definition of identity, together with the selection of measurable variables across the four main attributes of identity. The specific variables that collectively quantify the identity of the MAP system are unlikely to be the same as those that would be selected for other case studies, because the resilience of the system is strongly dependent on its local context. However, we could still use this approach to compare across our cases because each case study would have representative variables measured in each of the four categories of system identity. The degree of identity change that occurs in multivariate space (and in particular, whether the system crosses any key identity thresholds) then becomes the response variable of interest that best represents whether or not the systems are resilient to the changes brought about by increased connectivity.

Define Possible Future Systems – Same and Different Identities

The second element of our research design is to define a small number of plausible future identities for each study system, using a scenario building approach (Peterson and others 2003). We attempt to define a set of systems that our system might conceivably become, including entirely new systems as well as systems that retain the same identity while having experienced growth and reorganization. If we see no scope for the maintenance of system identity, the system clearly lacks resilience; the focus of the exercise then shifts to the management of change, both to mitigate negative outcomes and enhance positive outcomes. An important objective is to specify quantitatively the amount of change in the key variables comprising identity that would constitute a new system.

Paving of the Transoceanic highway raises prospects of land use/land cover change, which in turn will potentially catalyze all manner of social and ecological alterations in the MAP region. For example, if prices for agricultural products such as beef and milk remain high relative to prices for traditional forest products such as rubber and Brazil nuts, deforestation is likely to spread. Such changes are likely to occur most rapidly in areas near the highway, and it is possible that tenure regimes that mandate restricted forest clearing could develop. As highway paving improves access to regional markets and ports, timber extraction (including illegal logging) may expand if international prices for wood remain at current levels, given reduced transport costs. These prospective changes would together reduce the importance of forest products for rural livelihoods while also fragmenting forest cover, interrupting key interspecific relationships, and hindering seed production and tree recruitment. In this scenario, the MAP region would lose its identity in many respects. On the other hand, innovative state policies to support forest extractivism and social movements seeking to commercialize new forest-based products may hinder anthropogenic perturbations of forest ecosystems while also sustaining rural livelihoods. In this scenario, the MAP region would retain its identity.

The question of setting out a priori futures for a given system is discussed extensively in the scenario literature (for example, Peterson and others 2003; Bennett and others 2003). Our approach builds on both scenario analysis and the resilience analysis proposed by Walker and others (2002). The operational aspects of defining a range of alternate futures against which to assess current resilience are difficult, but not impossible. Two of the hardest requirements to meet in systems that are not already well-studied are that drivers should be appropriately specified and that the impacts of a range of potential future perturbations are considered. Operationalization demands that the roles of specific drivers and specific perturbations are considered, making the validity of the assessment to some degree contingent on the plausibility and rigour with which the problem is posed. Despite these issues, we argue that it should ultimately be possible to assign some level of probability to each alternative future. These probabilities, together with an assessment of uncertainty and the degree to which the identity of the system is maintained in each future (step 4), would provide an operational guide to the resilience of the current system.

Clarify Change Trajectories

This step is undertaken interactively with the second step. It involves defining the main causes of change in the system, with particular relevance to their impacts on properties of interest. At this stage we also identify the kinds of perturbation and disturbance against which resilience will be assessed. In our case studies, the construction or improvement of infrastructure (particularly roads and bridges) is the single perturbation of greatest interest. To assess the influences of infrastructural change in a rigorous causal framework, however, it is also necessary to establish what kinds of change are ongoing in the absence of changes in infrastructure.

A key aim of this step is to determine a suite of mechanistic sub-hypotheses that explain how connectivity affects resilience, via alteration of the balance between endogenous (local, small-scale, mainly internal) and exogenous (regional or national, larger-scale, mainly external) forces (drivers and perturbations) acting on the system. Given that we will quantify resilience by determining the effects of key drivers and perturbations on system identity, we predict that resilience will be highest when endogenous and exogenous controls are balanced, giving a parabolic form to the relationship; that is, the resilience of social-ecological systems will be highest at intermediate levels of infrastructure connectivity. By tracking changes in individual variables in relation to our aggregate summary of system identity, we argue that it will be possible to derive quantitative empirical measures of resilience that can be compared to changes in infrastructure connectivity between our case studies.

Holling's adaptive cycle (Holling 1986, 1987, 2001; Holling and Gunderson 2002) offers a metaphor for the dynamics of change in complex systems. In the adaptive cycle, periods of growth and rigidification are followed by shorter bursts of system collapse and reorganization. The study of reorganization is important in understanding the overall dynamics of the system and the role that is played by innovation. We do not expect that all of the important variables in a study will change all of the time, or even most of the time. A goal of our framework is to identify key variables that may be important at any one phase of the adaptive cycle, but will not necessarily be important throughout it.

Road paving in MAP is likely to catalyze social and ecological changes linked to land use/land cover change, but it remains to be seen whether it will change the identity of the system. To clarify whether the 'agriculture-identity change' scenario or the 'new forest products-resilient identity' scenario comes about requires monitoring of key indicators consistent with these distinct change trajectories. Market prices for key products, the number of ''head'' of cattle, new forest-based products, and the mix of income sources in rural livelihoods are all key social indicators, because they can indicate whether change is following one scenario or another. Some crucial ecological indicators that could play the same role include forest clearing (especially within specific types of reserves), and periodic vegetation surveys (especially for seeds and seedling recruitment). If beef prices remain high, the number of cattle expands, rubber tappers clear forest for cattle, and seedling recruitment declines, we would have evidence for the identity change trajectory.

Assess Likelihoods of Alternate Futures

Based on our assessment of current conditions, potential futures, and the roles of different drivers and perturbations in the system, we next consider the alternative futures that may occur. This step is at the core of the analysis; are we likely to lose the system properties of interest, or not? If system identity is likely to be lost, our system is not very resilient. By contrast, if our system is likely to maintain its identity across a broad range of scenarios, it is resilient. If both identity and the likelihood of identity change in alternate scenarios are rigorously and quantitatively determined, the likelihood of a change in identity (and its magnitude) will provide a quantitative measure of resilience.

Two relatively recent trends in the environmental sciences are attempts to quantify uncertainty (for example, Bradshaw and Borchers 2000; Regan and others 2002, 2003) and the application of more sophisticated forecasting and prediction techniques (Clark and others 2001; Carpenter 2002; Rose and Cowan 2003). Although some of these approaches are relatively new and untested, we believe that they will prove to be essential for quantitative assessments of resilience. The idea of resilience is inevitably forward-looking; developing resilience measures will depend on our being able to assess the likelihood of plausible future changes in our study systems using models that are based on current conditions and trends, known drivers, specified perturbations, and a finite and specified range of alternative future trajectories. As part of the forecasting process we will need to assess the uncertainties that are inherent in our models and scenarios, acknowledging that some uncertainties (such as those that relate to human reflexivity, for example) may be irreducible. It is difficult, but not impossible, to assign likelihoods to different scenarios; or at least, to assess the likelihoods of some of the more important changes that occur in each storyline and to quantify some of the main uncertainties associated with different events. We have not yet been through this process for our case studies, and so cannot provide a detailed example. However, enough on this topic has been published to suggest that this step of our proposed approach is at least feasible.

Identify Mechanisms and Levers for Change

Based on the previous analyses, we then derive a deeper understanding of the key mechanisms that determine resilience in our study system. These mechanisms are used to suggest manipulation points, or levers, at which changes in the system trajectory could be brought about. Ultimately, if we (that is, the community of stakeholders) are working with an agenda in which we desire to facilitate or prevent certain kinds of system change, this step will identify some of the key issues that would need to be addressed by planners and policy makers.

Although MAP is experiencing rapid change due to road paving, it is also the focus of innovative state policies as well as new forms of collaborative learning among various social actors. New policies and collaborative learning both represent potential approaches to resource management in MAP. State agencies, universities, NGOs and communities in the region regularly hold workshops with diverse goals, for example, coordination of tri-national vegetation surveys and urban health research, organization of community-private sector ventures in new forest-based products, and new school curricula in environmental education. Increasingly, lending agencies, elected representatives, and international NGOs have become interested in supporting and funding these initiatives, virtually all of which focus on retaining the MAP region's identity in one aspect or another.

Discussion and Conclusions

Rigorous development of both the theoretical and empirical components of this framework will allow us to measure resilience in our case studies. These measurements will allow us to test the hypothesis that resilience and connectivity relate to one another in a predictable manner. By linking a broad but somewhat superficial overview of our study systems with the deliberately subjective notion of social-ecological identity, we can make a clear and unambiguous statement about the system properties in which we are most interested. Having established which attributes we are interested in, we then proceed to establishing the relevant causes of change in these attributes and the ways in which they might respond to both gradual and abrupt kinds of change. This process in turn leads to the elaboration of a small number of plausible futures, designed to cover a range of uncertainty rather than produce any single 'correct' prediction. By assessing the likelihood that the system will change in certain specified ways in the future, we obtain a surrogate measure of resilience that will tell us how likely it is that the system properties that we are interested in will be maintained at a specified time interval in the future.

Our scheme for visualizing system structure and identity is novel and holds promise for applying resilience theory. Our approach is transitive, because people can apply the identity framework in Table 1 in other systems to guide the selection of measures that, collectively, should capture system identity and allow quantitative tracking of identity change. It is also important to stress that much of the value of this process comes from the insights and understanding that are developed along the way. We perceive the ultimate aims of the empirical application of resilience theory as twofold: (1) to test resilience concepts and develop a broader and more robust body of theory, for example through our explicit hypothesis about resilience and connectivity; and (2) to contribute in a relevant way to policy and management by exploring mechanisms and alternatives for change, for example by evaluating the potential consequences of manipulations by policy makers and managers.

We have focused on systems for which there is little prior synthesis of interdisciplinary knowledge. The same caveats apply to this framework as to any other reductionist methodology. In particular, certain system properties will only be evident at higher scales or levels of analysis, making them difficult to measure directly. We also anticipate difficulties in applying some aspects of this framework, particularly in determining the likelihoods of alternative futures in a rigorous manner when long-term data sets are unavailable. Nonetheless, we are optimistic that solutions to these problems are possible.

Resilience-based approaches to the development of management solutions offer an important alternative to 'command and control' (Holling and Meffe 1996) and even adaptive management for understanding how to generate and protect social-ecological well-being. Although complex systems can behave in a bewildering variety of ways, as sentient beings living in a complex, uncertain and variable world we often have a feel for change that goes beyond the kinds of analysis that most of us are capable of undertaking quantitatively in a formal scientific context. Balanced against this subjective understanding is the need for refutability of our hypotheses and for rigorous, quantitative tests of our cherished beliefs Bernard 2002. The framework that we have presented has aspects of both the qualitative and the quantitative embedded within it. By stating clearly the inevitable role of subjectivity and values in the analysis of resilience, we hope to bring our subjective decisions about the importance of different variables into a more testable domain while still acknowledging and allowing their important contribution to the scientific process. More than virtually any other approach, resilience thinking starts with the premise that the social and ecological aspects of the study system are not identifiably separate. As innovative components of our social-ecological system, we hope that the conceptual framework that we have sketched will help to further integrate the social and ecological sciences through the unifying concept of resilience.

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