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Regional analysis of social-ecological systems

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Introduction

The process of regional analysis of socio-ecological systems (RASE) has evolved in the last 20 years to provide a comprehensive description of the ecosystem patterns, processes and functions, including relevant social and political factors, needed to synthesize our knowledge of coupled natural-human systems, or social-ecological systems (SES; Berkes *et al.*, 2003) and the interactions among their component[1]. RASE techniques are rooted in the integration of the natural and social sciences. Such a synthesis is the cornerstone upon which environmental monitoring schemes are designed.

In the last two decades, as sustainable development (World Commission on Environment and Development, 1987) has become a priority, a chief objective of RASE is to define the management scenarios under which SES sustainability (*e.g.* Kates *et al.*, 2001; Parris and Kates, 2003; Asah, 2008) and resilience (Walker and Salt, 2006; Guzy *et al.*, 2008) might be achieved. RASE is typically a component of integrated systems of environmental regulation that include strategic planning, objective setting, performance standards, monitoring, and review of the entire process (*e.g.* Treweek, 1999; Jensen and Bourgeron, 2001; Jensen *et al.*; 2001). Recent applications of RASE (see case studies in Johnson *et al.*, 1998; Dale and Haeuber, 2001; Jensen and Bourgeron, 2001) integrate approaches developed in response to specific problems, social and political contexts, national legislation, and international accords (see review in Treweek, 1999; see also English *et al.*, 1999; Lyndon, 1999). In particular, RASE includes the ecological assessment methodologies that were initially developed during the early twentieth century to evaluate the capacity of the land to sustain various human activities in the context of land-use planning (*e.g.* Klingebiel and Montgomery, 1961; Beek and Bannema, 1972; Olson, 1974; FAO, 1976, 1993; Zonneveld, 1988). RASE informs decisions for ecosystem management (*e.g.* Jensen *et al.*, 1996; Jensen and Bourgeron, 2001). Various terms have been used under different circumstances to describe part or all of the process of assessing and monitoring the state of the environment and its relationship to economic development.

In the United States (US), the US National Environmental Policy Act (NEPA) provided a national legal background for conducting RASE. In 1969, the US Congress established NEPA as the first legislative requirement for the use of some type of environmental assessment as a prerequisite for effective environmental planning and management (Robinson, 1992; Treweek, 1999), and also established the Endangered Species Act (first enacted in 1973), among other pieces of legislation. The specific methodology used in an environmental assessment varies with the category of impact considered, such as human health or economic development. Ecological risk assessment (US EPA, 1992, 1998; NRC, 1994) is a category of environmental assessment designed to meet specific regulatory mandates, which focuses on the relationship between one or more stressors and ecological effects in a way that is useful for environmental decision-making. Environmental assessment legislation currently exists in over 40 countries (Robinson, 1992), and legislative tools

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have been developed for international assessments and monitoring of problems that have multiple causes (*e.g.* Convention on Biological Diversity, Burhenne-Guilmin and Glowka, 1994). To inform international and national policies, international research programs such as the Land-Use and Land-Cover Change (LUCC) project and its successor the Global Land Project (GLP) were established to emphasize the study of changes in coupled human-environmental systems at local to regional scales. An international example of strategic integrated assessment is the Millennium Ecosystem Assessment (MEA, 2005) that was carried out to establish the scientific basis for management decisions to sustain the use of ecosystems and their contributions to human well-being.

The purpose of this paper is to discuss the implementation of RASE at multiple spatial scales which are relevant to achieving sustainable patterns of ecosystem services (*sensu* MEA, 2005; Guzy *et al.*, 2008). The following aspects of RASE are emphasized: (1) general properties, (2) implementation, (3) data issues, and (4) strategic scenario planning. A US example of RASE is presented.

General

RASE includes characterization and integration of the biological, physical, and human dimensions of socio-ecological systems, their status, functions, interactions, and limits at spatial and temporal scales appropriate to the objectives of the assessment (Slocombe, 1993a, 2001; Lessard *et al.*, 1999; Bourgeron *et al.*, 2001a, Jensen and Bourgeron, 2001; Jensen *et al.*, 2001; Holling, 2001; Gunderson and Holling, 2001; Walker and Salt, 2006; US LTER, 2007). Past, present, and future states of components as well as all assumptions and estimates of uncertainty must be documented to provide a decision space for managing for sustainability (*e.g.* Folke *et al.*, 2004). Therefore, RASE is intended to provide the data and interpretive tools needed to address planning objectives and place land-use planning decisions for specific areas in the appropriate context (Haynes *et al.*, 1996; Jensen *et al.*, 2001). RASE information provides the context for decisions made by managers and for the implementation of these decisions, and should be the template for future planning and the iterative process of adaptive management (*e.g.* Slocombe, 1993b) through monitoring. Information from RASE can be used to link local to regional planning levels.

There are several specific circumstances that may trigger a RASE:

- Making new decisions and assessing previous decisions.
- Changes in institutional priorities.
- Occurrence of significant external (*e.g.* climate) or internal (*e.g.* land use) change in an SES.
- Changes in understanding of SES due to new information.

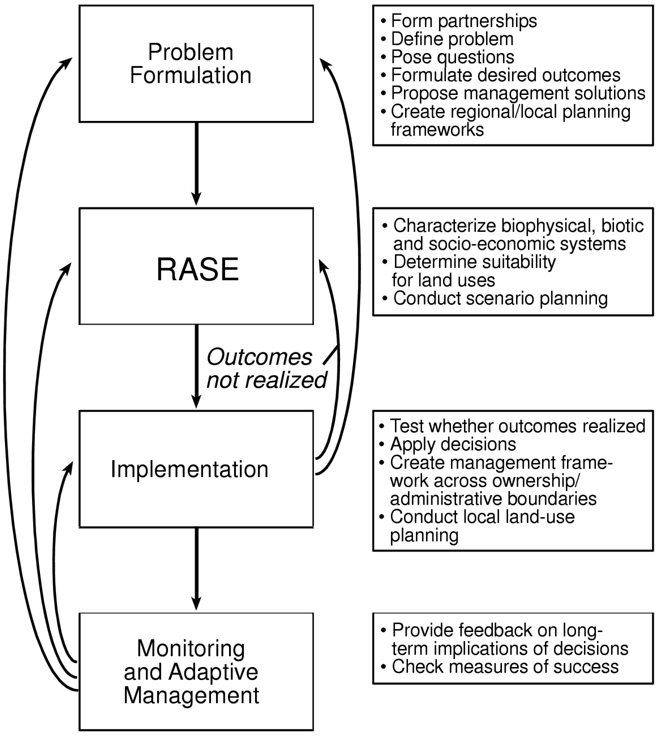

Fig. 1. Planning process for RASE (after Bourgeron *et al.*, 2001a).

A considerable body of work exists concerning the planning process and the role of environmental impact assessments and RASE (Margerum, 1999; Morrison-Saunders and Bailey, 1999). The choice of a flexible, adaptive-management-oriented planning process is a critical step in RASE (Shea *et al.*, 1998; Johnson, 1999; Morrison-Saunders and Bailey, 1999; Haeuber, 2001; Walker *et al.*, 2002). A prototype of such a planning process for RASE (adapted from Lessard, 1995; Haynes *et al.*, 1996; Bourgeron *et al.*, 2001a, Jensen *et al.*, 2001; see Yaffee *et al.*, 1996 and Walker *et al.*, 2002 for alternative models) is presented in figure 1. Part of the process includes the exploration of alternative scenarios that allow all participants, including stakeholders, to think in broad terms about possible futures (Walker *et al.*, 2002; Guzy *et al.*, 2008). Regardless of the specific model selected, previous work indicates that problems, questions, and alternatives should be clearly formulated as hypotheses; RASE should be designed to test the explicit outcomes predicted by the hypotheses (Underwood, 1995). Should the predicted outcomes not be realized, an evaluation should be conducted of how the process led to failure. If the predicted outcomes are realized, RASE results could be implemented and monitoring schemes designed at local to regional scales to determine whether the desired outcomes are maintained over time. Monitoring results are then incorporated back into the planning process.

Three principles underpin RASE :

- SES are hierarchical. Hierarchy theory provides a framework for characterizing SES components and the linkages between different scales of social-ecological organization (O'Neill and King, 1998; Holling, 2001). In hierarchical systems, higher levels provide the context or environment within which lower levels evolve (Allen and Starr, 1982; Holling, 2001; Gunderson and Holling, 2001).
- SES are dynamic. Although the assumption of equilibrium at a given scale may be required by some scientific exercises (*e.g.* modeling) and planning, it should be recognized that the dynamics of SES may include multiple pathways, discontinuities, unexpected changes (called surprise events by Holling, 1978), and tracking constantly changing environmental conditions (*e.g.* Holling, 1986; Kay, 1991; Costanza *et al.*, 1993; Scheffer *et al.*, 2001a). Decision-makers should acknowledge that SES have limits (*e.g.* productivity, accumulation of biomass).
- There are limits to SES predictability. The existence of complex dynamics, hierarchical structuring, and multiple optimum operating points in SES, most far from equilibrium, raises important questions about the predictability of ecosystem behavior (Costanza *et al.*, 1993; Scheffer at al., 2001b). Predictability varies over spatial and temporal scales. Characteristics of some events are predictable but others may not be. In some cases, a small fluctuation in a system component can lead to a large change in the functioning of the system as a whole (May, 1976).

These three principles form the basis for the recent developments in the theory and study of SES (Levin, 1999; Holling, 2000; Van der Leeuw and Aschan-Leygonie, 2005; Carpenter, 2001; Carpenter and Gunderson, 2001; Carpenter *et al.*, 2001a, Gunderson and Holling, 2001; Holling, 2001; Holling *et al.*, 2001; Scheffer *et al.*, 2001a, 2001b). Nonlinear processes organize the shift from one range of scales to another (Holling, 1992). SES have multiple equilibria or attractors (states into which the system settles) that commonly define functionally different states. Interactions between stabilizing and destabilizing forces maintain structure, diversity, and resilience (Carpenter, 2001). Resilience is defined here as the amount of change an SES can undergo and remain within the same state (Holling, 2001; Carpenter *et al.*, 2001a, 2001b, Walker and Salt, 2006). They are moving targets with multiple potential futures that exhibit uncertainty and unpredictability (Walters, 1986; Gunderson *et al.*, 1995).

Decades of ecosystem research and management have shown that most systems cycle through successional phases, driven by a combination of interacting biotic, biophysical, and social processes which include what is termed disturbances. The process of dynamics through which SES grow and change can be described using an adaptive cycle as a heuristic model (Holling, 1986, 2001). SES dynamics are cast in terms of the four phases of adaptive cycles that function at each of the emerging levels (Fig. 2): α (reorganization), r (exploitation), K (conservation), and Ω (release) (Holling, 1986, 2001). For the purpose of simplicity, a stylized representation of adaptive cycles in two dimensions (potential and connectedness) is shown in figure 2 for two stable states. When proceeding through an adaptive cycle, an SES experiences routine changes within a stable state (stable state A in Fig. 2). As long as the system remains within a given state, it is considered to be resilient. When radical change occurs, a threshold may be crossed as resilience decreases. The SES then shifts to a new stable state (stable state B in Fig. 2; Scheffer *et al.*, 2001b) through which the system cycles. For example, using a simple fire-spread model, a recent study of fire dynamics in the US wildland-urban interface (WUI) showed that fire size can be strongly modified by the density and flammability of houses (Spyratos *et al.*, 2007). A sharp transition zone from historically small to potentially large fires occurred in a parameter space of vegetation flammability and house density. Under current socio-economic conditions including projected housing increases in the WUI, the presence of flammable buildings will maintain the system at the higher level of fire sizes, even with a reduction in natural fuel loading. Therefore, the system has at present two alternative stable states, one of which is a novel ecosystem resulting from weakly regulated development in the WUI.

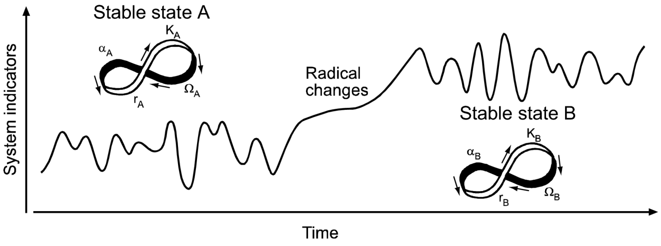

Fig. 2. The adaptive cycle: crossing a threshold from one stable state to another.

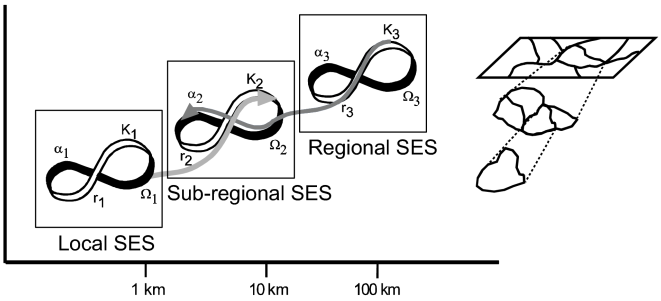

Fig. 3. A hierarchy of nested SES and adaptive cycles.

As an example, application of these principles to the SES in the US Colorado Front Range has led to the following characterization. Decades of studies of regional montane forest ecosystems show that the interactions between subsets of biotic, biophysical, and social processes establish and regulate the key features of these Rocky Mountain ecosystems (*e.g.* Everett *et al.*, 1994; Knight, 1994; Veblen *et al.*, 2000; Baron, 2002). The entities produced by these interactions form hierarchies (Fig. 3) that interact with each other to constitute self-organized processes over specific spatial scale ranges on a physical template. The boxes in figure 3 represent three levels in the Front Range that emerge based on the patterns and processes of interest, and correspond roughly to a fine-scale catchment (local), subwatershed (6th-field hydrologic unit code, HUC; subregional), and subbasin (4th-field HUC) or larger area (regional). Within each level, SES components exhibit dynamic behavior. The Front Range SES functions as a nested set of adaptive cycles (Holling, 2001; Gunderson and Holling, 2001; Walker and Salt, 2006). Nested sets of adaptive cycles transform hierarchies from fixed static structures into dynamic, adaptive entities whose levels are sensitive to small disturbances at transitions from K to Ω, and from α to r. This representation permits multiple connections of a phase at one level to higher or lower phases, *e.g.* the arrows in figure 3 connecting the Ω phase of lower levels to the K phase of higher levels, representing a cascade of changes associated with release to the next highest level.

Implementation of RASE

The implementation of RASE can be very complicated, with a variety of issues, factors, scales, and analyses that need to be considered. Three major steps should be clearly articulated at the onset of an assessment and/or the design of an environmental monitoring scheme:

- Integration of biological, physical, land-use, and socio-economic data. This step (Herring, 1998; Haeuber, 2001; Slocombe, 2001; Venter *et al.*, 2008) requires formulating clear relationships among ecosystem components (Berry *et al.*, 1996).
- Recognition of the scaled relationships between the different activities of RASE. RASE activities progress from data acquisition to strategic scenario planning (Haber, 1994; Bourgeron *et al.*, 2001a); accordingly, the degree of abstraction increases and validation of results is achieved by comparisons between levels.
- Delineation of spatial scales and boundaries for different aspects of RASE. There are six types of boundaries to consider: assessment area, characterization area, analysis area, cumulative impact area, reporting unit, and basic characterization unit (Bourgeron *et al.*, 2001a).

Although these three steps are described separately, in practice, they are usually considered together during an assessment.

Data Issues

Knowledge about SES in a region is needed in five areas to conduct RASE (Bourgeron *et al.*, 1994; 2001a): (1) characterization of biological component(s); (2) characterization of physical components; (3) characterization of biological-physical interactions; (4) characterization of social components; and (5) characterization of SES as a whole, including coupling of components and system properties, such as disturbances and resilience. This knowledge is acquired via the analysis and interpretation of hierarchical databases and maps that describe biophysical environments and the current and historical status of biological and human ecosystem components (*e.g.* individual species, vegetation, road density, etc.; Bourgeron *et al.*, 2001a, 2001b, 2001c, 2001d).

Information integration involves a threefold challenge (Slocombe, 2001): (1) integrating information about different kinds of attributes, *i.e.* across domains (*e.g.* integrating geomorphology and human values concerning the environment); (2) integrating information across different sources (*e.g.* scientific surveys and administrative records); and (3) integrating information across different formats (*e.g.* qualitative and quantitative surveys). Efforts to address these challenges have been initiated by the US LTER network (Redman *et al.*, 2004), the International Geosphere-Biosphere Programme, and the Global Land Project (Haberl *et al.*, 2006). The Human-Environment Regional Observatory (HERO) project is developing methods for handling the heterogeneous quantitative and qualitative biophysical and socio-economic data generated to study human-environment interactions, through the web-based HERO Internet Network Environment (http://hero.geog.psu.edu/). The HERO project also includes development of techniques to analyze and visualize data from heterogeneous sources.

Issues in the spatial analysis of RASE data are both analytical and practical. Analytical issues fall into three broad categories (Bourgeron *et al.*, 2001c): (1) sampling, (2) numerical summary and characterization of the spatial properties of the data, and (3) analysis of multivariate data sets. Spatial sampling schemes must be designed to fit the goals of RASE (Jensen *et al.*, 2001), whether with existing or de novo data (Bourgeron *et al.*, 2001b), including accuracy assessment of remotely sensed data (Lachowski and Johnson, 2001). Numerical descriptions of the spatial properties of mapped data include the study of the spatial arrangements of map values and summary measures that characterize spatial patterns and their properties at different scales (*e.g.* Burrough, 1995; Bourgeron *et al.*, 2001c). The third analytical issue stems from the fact that the issues addressed in RASE (Jensen *et al.*, 2001) generally require the analysis of data describing multiple variables in a region. Multivariate analysis of spatial data includes multivariate geostatistics (Wackernagel, 1995), latent variable analysis of multivariate spatial data (Christensen and Ameniya, 2002), measures of association between variables, and regression models such as geographically weighted regression, and higher-order trend surface analysis (Casetti and Jones, 1987; Anselin, 1988; Haining, 1990).

Three broad categories of practical issues exist in the spatial analysis of RASE data (Bourgeron *et al.*, 2001c): (1) choosing conceptual models and inference frameworks, (2) modeling spatial variation as a function of attribute properties, and (3) analyzing spatially referenced point and area data. The choice of an inference framework for the analysis of spatial data is a fundamental issue because the assumptions of classical inference theory (*i.e.* that the data are the outcome of some well-defined experiment), and its implications (*e.g.* the stationarity assumption), may not apply to RASE spatial data. The choice of a model of spatial variation is influenced by the geographic attributes of the data and the study region, which constrain data analysis. It is important to note that whereas temporal and spatial data share a number of similarities, they also differ in significant ways, which may preclude the use of the same models for both types of data. Consideration should be given to the spatial attributes of the data and study region prior to data analysis. Among the most important considerations are boundary conditions (*e.g.* type of boundary, its geometry), discontinuities (*e.g.* geological fault lines, administrative boundaries), and areal characteristics (*e.g.* scale relations). The latter are dependent upon the nature of the objectives addressed by the analysis. The third practical issue to address in the analysis of spatial data for RASE is related to the statistical modeling of spatial data.

Strategic scenario planning

Scenario planning is a strategic activity which is conducted during the last stages of RASE. It is a tool which incorporates all aspects of RASE (data, analyses, and products) to determine the implications and tradeoffs of various possible environmental and land use scenarios (Lessard, 1995; Haynes *et al.*, 1996; Walker *et al.*, 2002; Guzy *et al.*, 2008). Each scenario describes a set of possible outcomes given a particular land use approach and/or environmental change. Uncertainty is explicitly included, with an emphasis on what might happen, including the potential merits and pitfalls of an approach. Scenario planning can be applied at many different scales to resolve specific issues. Scenarios are also tool to engage all stakeholders, including local residents, in thinking about many aspects of managing for resilience (Carpenter *et al.*, 2001b; Walker *et al.*, 2002), including weighting the short-term cost of possible loss of profits associated with maintaining resilience versus the long-term benefit of not shifting to an undesirable new stable state due to loss of resilience (Walker and Salt, 2006).

Multi-agent systems (also called agent-based modeling) have features especially suited to integrating social and ecological components under different forms of organization (spatial, networks, hierarchical) and interactions among different organization levels (Bousquet and LePage, 2004). Such multi-agent based models represent a promising approach to strategic scenario planning (Carpenter *et al.*, 1999). For example, a model incorporating a representation of decision-making to control lake pollution is designed as a set of three modules: ecosystem, assessment and forecast, and human behavior (Carpenter *et al.*, 1999). The model runs as a stand-alone economic optimization or as a game in which participants can initiate the year-by-year actions of various experts or stakeholders. An important characteristic of the model is its integration of an appropriate level of ecosystem reality with economic optimization and decision processes. The behavior of key actors (stakeholders, scientific and economic advisors, managers, and decision-makers) is represented either through model simulation, or alternatively, through explicit interventions made by an individual or group who take control of one or more of the actor's decisions. In the latter form, the model becomes a learning game in which the limits of the ecosystem and opportunities to manage resilience are discovered.

Further model development should explore the conditions in which cooperation emerges between the main actors, that is, the conditions under which they accept paying a certain cost for a shared benefit derived from the ecosystem. The use of these models as learning games could contribute to building such cooperation and to better understanding the process at stake. Recent developments in theoretical biology have shown that sharing "information" is a necessary step for living systems to induce cooperation between individual actors and thereby manage their environment.

Example of the Interior Columbia Basin Ecosystem Management Project

The Interior Columbia Basin Ecosystem Management Project (ICBEMP) represents an example of RASE prompted by potential natural resource conflicts and changes in institutional priorities (i.e. shift to ecosystem management by US land management agencies)

(Quigley and Arbelbide, 1997a; Haynes et al., 2001). To date, the ICBEMP is the largest regional effort undertaken in the US, implemented in an area totaling 30.9 million hectares of US Forest Service (USFS) and Bureau of Land Management (BLM) land. This USFS and BLM land comprises 53 percent of the 58-million-hectare interior Columbia River basin (covering approximately 8 percent of US land area), a region which consists of mosaics of terrestrial and aquatic ecosystems, as well as a variety of land-use and ecological conditions (Quigley and Arbelbide, 1997a, 1997b, 1997c, 1997d; Haynes and Quigley, 2001).

Under a directive from President Clinton, the project was intended to address three major policy questions, three major policy question implications, and three process questions (Quigley *et al.*, 2001). The ICBEMP comprised an executive steering committee, a RASE scientific team, and two environmental impact assessment teams. Products included a scientific assessment and two environmental impact assessments. RASE provided the information needed by the environmental impact assessment teams, including scenario planning, to address the policy and process questions. All RASE documents received anonymous peer review under the supervision of an independent science review board.

Through scenario planning, seven management strategies were examined and three were retained for possible implementation. ICBEMP results currently are being used as templates for local land-use planning. For example, individual National Forests are using data and results as a context for their Forest plan revisions. All data (more than 20 databases and 300 GIS data layers) and documentation have been made available to the public through the internet (http://www.icbemp.gov/). Finally, the ICBEMP contributed to the advancement of knowledge in a variety of fields through the publication of over 100 peer-reviewed publications.

Conclusions

This paper described a framework for conducting RASE for land-use planning and as a pre-requisite for monitoring the environment at local to regional scales. RASE is the process by which the natural and social components of regional SES are characterized at all spatial and ecological scales that are relevant to assessment and monitoring objectives. RASE is a strategic component of the planning process, and as such should be imbedded within it. Methods should be chosen that strengthen the on-the-ground implementation of land-use goals. Many of the RASE steps are the focus of active research and development. RASE projects are being conducted and incorporated into the planning system increasingly often, as a number of national and international regulations and new management orientations trigger their implementation.

Finally, when designing a RASE, it is important to keep in mind the following:

- Information from different disciplines shares many analytical and practical characteristics.
- Match issues with approaches and tools: information should be appropriate for the objectives.
- Identify information characteristics, including representativeness of regional patterns or processes.
- Interdisciplinary assessments need to synthesize data, analyses, and interpretations in policy-relevant form.

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