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Young, O. R., E. F. Lambin, F. Alcock, H. Haberl, S. I. Karlsson, W. J. McConnell, T. Myint, C. Pahl-Wostl, C. Polsky, P. Ramakrishnan, H. Schroeder, M. Scouvart, and P. H. Verburg. 2006. A portfolio approach to analyzing complex human-environment interactions: institutions and land change. *Ecology and Society* **11**(2): 31. [online] URL: http://www.ecologyandsociety.org/vol11/iss2/art31/

Insight

A Portfolio Approach to Analyzing Complex Human-Environment Interactions: Institutions and Land Change

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ABSTRACT. The challenge confronting those seeking to understand the institutional dimensions of global environmental change and patterns of land-use and land-cover change is to find effective methods for analyzing the dynamics of socio-ecological systems. Such systems exhibit a number of characteristics that pose problems for the most commonly used statistical techniques and may require additional and innovative analytic tools. This article explores options available to researchers working in this field and recommends a strategy for achieving scientific progress. Statistical procedures developed in other fields of study are often helpful in addressing challenges arising in research into global change. Accordingly, we start with an assessment of some of the enhanced statistical techniques that are available for the study of socio-ecological systems. By themselves, however, even the most advanced statistical models cannot solve all the problems that arise in efforts to explain institutional effectiveness and patterns of land-use and land-cover change. We therefore proceed to an exploration of additional analytic techniques, including configurational comparisons and meta-analyses; case studies, counterfactuals, and narratives; and systems analysis and simulations. Our goal is to create a portfolio of complementary methods or, in other words, a tool kit for understanding complex human-environment interactions. When the results obtained through the use of two or more techniques converge, confidence in the robustness of key findings rises. Contradictory results, on the other hand, signal a need for additional analysis.

Key Words: *land change; institutions; methodology; analysis; socio-ecological systems; statistical techniques;*

INTRODUCTION

Efforts to understand human-environment interactions relevant to global environmental change often encounter analytic and methodological problems that are difficult to solve using familiar scientific procedures (Turner et al. 2003, Schröter et al. 2005). Scientists seeking to explain patterns of land-use change, for instance, must wrestle with disparate operationalizations of the dependent variable and sort out the relative importance of an array of interactive anthropogenic and biophysical factors (Verburg and Chen 2003, Rindfuss et al. 2004). Similarly, scientists exploring the roles institutions play in causing and addressing large-scale environmental problems must find ways to separate the signal of institutional impacts from the noise of numerous other factors and cope with substantial heterogeneity among the set of institutions they are examining (Young 1999*a*). How can we come to terms with these analytic and methodological issues and produce results concerning human-environment interactions that meet high scientific standards?

This article explores a number of strategies that scientists associated with research projects investigating global change as part of the Institutional Dimensions of Global Environmental Change and Land-Use and Land-Cover Change projects have developed to overcome or circumvent the obstacles facing efforts to build knowledge in this realm. These two streams of research have

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received large amounts of attention over the past decade, and the community of researchers recognizes substantial links between institutions and land dynamics. The strategies we discuss represent the most successful methods that this integrated science community has developed to date.

We begin by identifying and commenting on the nature of the analytical challenges arising in this integrative effort. Often developed in other fields of study, several advances in statistical procedures can help to alleviate the difficulties noted. By themselves, however, statistical models cannot produce fully satisfactory explanations of many forms of human-environment interactions. Thus, complementary approaches and methods are required. We identify and critically examine several of the most promising options (Underdal and Young 2004), including those addressing causal links between independent and dependent variables as well as systems approaches that adopt holistic perspectives in which efforts to pin down the role of individual variables are less prominent. In the end, we argue, integrated environmental science of the kind discussed here requires a portfolio approach. Researchers using this approach begin by creating a tool kit of individual methods suitable for analyzing human-environment interactions. They then proceed to develop a research strategy that combines two or more methods to maximize our understanding of the dynamics of the complex systems that lie at the center of our field of study.

CHALLENGES: LIMITS TO CONVENTIONAL SCIENTIFIC PROCEDURES

Studies of human-environment interactions occurring in socio-ecological systems are necessarily interdisciplinary in character, often using multidisciplinary research teams with specific members drawing on methods originating in their respective sciences. Although this approach is necessary, it runs the risk of producing results that are poorly integrated and not sufficiently rigorous in methodological terms (Rindfuss et al. 2004). Such problems have been recurrent among those addressing institutions and land change. They can be clustered into four main categories involving: (1) dependent variables, (2) independent variables, (3) universes of cases, and (4) spurious relationships.

Dependent variables in studies of human-environment interactions are often hard to define in a manner that is analytically valid and measurable and that can produce agreement within relevant communities of researchers. Even straightforward variables, like patterns of deforestation, are problematic. Should we approach deforestation as a matter of density of standing trees per hectare, volume of live wood per hectare, or rate of regeneration in the wake of fire or commercial harvesting? None of these measures is objectively (in)correct. However, different choices give rise to challenges when we try to combine the results from separate studies in meta-analyses of land use (Geist and Lambin 2002). These concerns are even more severe when it comes to the role of institutions. Participants in institutions often adopt divergent views regarding the problems these arrangements are created to solve or the objectives they are designed to fulfill. We lack a common metric for evaluating and comparing the contributions of a variety of institutions in solving substantive problems such as ozone depletion, biodiversity loss, and climate change. Measuring the effectiveness or success of institutions as problem solvers requires implicit, if not explicit, causal judgments.

Challenges with regard to independent variables are equally important. Multiple factors influence the course of human-environment interactions. It is often difficult to separate proximate drivers from underlying causal forces (Young 2002, Lambin et al. 2003). Individual variables regularly figure as members of interactive causal clusters. Although structures of property rights often loom large in processes of land-use change, for example, their effects commonly depend on the roles of other factors, such as the ability of the state to ensure respect for property rights and the roles that markets play in influencing the incentives of property owners. Similarly, the effectiveness of environmental regimes generally involves a host of factors ranging from the compatibility of institutional attributes and ecosystem properties to interactions between distinct regimes and conditions prevailing in overarching biophysical and socioeconomic settings. In systems that have co-evolved, interactive forces are the norm, so that the distinction between dependent and independent variables becomes fuzzy and may become irrelevant.

Many research projects dealing with these issues are plagued by small and heterogeneous universes of cases that limit the usefulness of familiar statistical procedures and may preclude the use of statistical inference altogether. When data sets do not cover enough cases that deviate from the dominant pattern of correlation, analysts may find two or more variables so confounded that they cannot disentangle them empirically. In other cases, researchers find themselves working with only a handful of cases; the number of candidate explanatory variables may even exceed the number of cases. Studies of environmental regimes or governance systems regularly run into this problem. As a result, it is difficult to subdivide the universe of cases to control for the impact of some variables to determine the effects of others. Sometimes there are ways to expand the universe of cases, such as splitting environmental regimes into separate components and treating the individual component rather than the regime itself as the basic unit of analysis (Breitmeier et al. 2006). There are also good reasons to adhere as much as possible to the logic of statistical inference even when the universe of cases is too small to satisfy normal statistical requirements (King et al. 1994). It will come as no surprise, then, that analysts working in this area must not only make an effort to maximize the number of cases that can be grouped credibly into single universes but also search for rigorous modes of analysis usable even in small-*N* situations.

It follows that the dangers of ending up with spurious relationships are especially serious in research on human-environment interactions (Rindfuss et al. 2004). Statistical inference never establishes causal connections in any definitive sense. Nevertheless, strong interdependence between variables increases the risk of circular reasoning. Efforts to sort out the relative importance of anthropogenic forces, e.g., human harvesting of living resources or intentional use of chemical fertilizers, and biophysical drivers, e.g. interannual variability in stream flows or temperature, often fall prey to this problem. When theories are too complex to be tested by means of systematic empirical analysis, no amount of data can resolve these identification problems.

As a result, those working to develop the science of human-environment interactions need to consider the advantages and disadvantages of a range of methods. In this spirit, we turn first to enhanced statistical techniques. Our conclusion here is straightforward. Sophisticated statistical techniques, often developed in other disciplines, have much to offer those studying complex human-environment interactions. We need to proceed vigorously to apply these techniques when addressing issues of global environmental change. However, by themselves, such techniques cannot overcome all the challenges described in this section. Following an account of the uses of sophisticated statistical tools, therefore, we broaden our horizon to include other analytic methods that are available to researchers working in this field.

ADVANCED STATISTICAL PROCEDURES

In many cases, the effect of one independent variable depends on its interaction(s) with one or more other variables, e.g., the impact of population pressure on natural resources depends on interactions among population, consumption patterns, and regulatory arrangements, among other factors. For such synergistic factor combinations, a common solution is the specification of “interaction terms” in regression models; two or more drivers are combined to represent a single effect. The difficulty with this solution is that all the variables specified as part of an interaction term, e.g., population and consumption per capita, should also be specified as individual terms. This leads to an explosion of necessarily similar terms, and multicollinearity becomes a potentially serious problem that can lead models to treat variables as statistically insignificant when they are actually significant (Rindfuss et al. 2004). This difficulty is particularly important for research on institutions and land change because of the large number of potentially important explanatory variables and insufficient theory to guide model specification toward a workable balance between parsimony and comprehensiveness. In many cases, the theory is not sufficiently defined to support the specification of the equations required to assess theoretical links in empirical terms.

A special problem of interaction arises when independent variables cluster in geographic space or are hierarchically organized. The role of an institution, such as a pollution abatement program that has municipal, provincial, and national levels of implementation, should be evaluated using a model that specifies which municipalities are clustered within what provinces to differentiate the average municipality effect of the abatement program from the general municipality effect in specific types of provinces (Snijders and Bosker

1990). Hierarchical structures are common in human-environment relations, and hierarchical or multilevel modeling frameworks are increasingly common tools used to address these structures. Multilevel models can sometimes account for variability at different levels (Hoshino 2001, Polsky and Easterling 2001).

Another common problem is that dependent variables may also act as independent variables, leading to problems of endogeneity. Do roads cause deforestation, or does deforestation lead to the construction of roads (Pfaff 1999)? Do institutions introduce conservation measures, or does damage to the resource lead to the (re)formation of institutions? How can we proceed when the causal arrows run in both directions? Methods for diagnosing and mitigating certain consequences of endogeneity have been available for decades (Cliff and Ord 1973). In structural equation modeling, for instance, the analyst specifies a set of regression models in which the dependent variable in one model serves as an independent variable in a parallel model. However, these methods have gained traction in the literature on human-environment interactions only in recent years (Polsky 2004).

The problem of endogeneity is especially important when all the relevant variables are not included in a model, whether, as is often the case in human-environment studies, because of ignorance, insufficient data, or both. To analyze these cases, spatio-temporal regression can be a helpful technique. For example, a farmer's decision to modify land-use practices in response to a change in climate may depend not only on that farmer's personal situation but also on whether neighboring farmers or other agents provide information on superior land-use alternatives. In this case, the mechanism of knowledge networks and local communication makes specific decisions about land use partially a function of nearby land use or external knowledge (Overmars et al. 2003, Polsky 2004). Unable to specify variables that reflect such networks, the second-best option is to specify proxy endogeneity terms. These "placeholders," which capture the variation associated with effects that exhibit spatial or temporal dependencies, can improve the explanatory power of the model significantly (Anselin 2001). An important limitation of this approach, however, is that the proxy terms representing endogeneity do not directly contribute to substantive explanations because the details of the causal mechanism remain unspecified (Anselin 2001, Polsky 2004).

In short, advances in statistical techniques can play an important role in addressing the challenges identified in the preceding section, although there are still numerous cases in which even advanced or enhanced techniques will not suffice. When questions remain regarding what variables to specify, what form the model should take, or even what data are available, it is essential to supplement or even replace statistical models. Accordingly, we turn next to three clusters of methods that deserve consideration in this context.

CONFIGURATIONAL COMPARISONS AND META-ANALYSES

Several appealing methods adopt a comparative perspective and seek to identify causal mechanisms, either by looking for distinct patterns that are common to many cases or by applying tools that focus on conjunctures or combinations of factors that together can explain outcomes of interest. These techniques search for explanations derived from empirical evidence based on distinct but comparable case studies using rigorous analytic procedures.

The simplest technique features pattern recognition in case studies that cover distinct regions or issues and seek answers to similar questions without specifying in advance the driving forces to be examined, much less a model of their interactions (Haas et al. 1993, Kasperson et al. 1995, Indian National Science Academy et al. 2001). The advantages arising from the limited effort required to study individual cases in such analyses is offset by the inability to go beyond qualitative comparisons. A prominent example drawn from the literature on international environmental regimes emphasizes the role of the level of concern, the character of the contractual environment, and the capacity of the participants, i.e., the three Cs, as determinants of institutional effectiveness (Haas et al. 1993). Requiring case studies to use a common structure and address a preset collection of factors or hypothesized causal mechanisms imposes a higher level of effort but allows more systematic comparisons (Turner et al. 1993, Young 1999*b*). To study whether population growth in rural Africa has led to agricultural intensification, for instance, the authors of 10 case studies were requested to provide information on a common core of items at comparable spatial and temporal scales (Turner et al. 1993). Surprisingly, this approach has not been applied in a large number of studies to date and tends to be confined to an examination of a few cases in each comparative effort. The most powerful study of international regimes using this approach, for example, includes evidence pertaining to 15 cases (Miles et al. 2002).

A more ambitious approach involves the development of relational databases in which experts encode a much larger number of cases by responding to a standard questionnaire encompassing many variables under the supervision of project managers to maximize intercoder reliability. The most ambitious example involving institutions or land change may be the International Regimes Database, which contains information on some 200 variables and allows analysts to obtain answers to queries based on several hundred records (Breitmeier et al. 2006). Databases of this type are difficult to construct, costly to maintain, and hard to adjust to address new issues arising in the relevant fields of study. Although most analyses using such databases have relied on descriptive statistics, a range of other forms of analysis, including both qualitative studies and regression analyses, is often feasible in such settings.

An alternative procedure focuses on extracting and analyzing information included in pre-existing case studies to identify patterns and to develop generalizations about human-environment interactions. Land-Use and Land-Cover Change (LUCC) studies of land use involving tropical forests and dryland or intensive agricultural settings offer prominent examples of this type of analysis (Geist and Lambin 2002, 2004, Keys and McConnell 2005). Such meta-analyses are able to evaluate more than a hundred cases, tracking dozens of variables associated with their respective outcomes. They discern patterns in combinations of variables through the use of descriptive statistics, revealing clusters of factors, e.g., property rights, markets for agricultural products, government policies, that appear in different geographic regions or time periods.

A more sophisticated comparative approach uses Boolean logic, analyzing configurations of factors to reduce complexity and reveal a limited number of conjunctures that can account for outcomes. Developed to bridge the gap between more traditional qualitative and quantitative approaches, Qualitative Comparative Analysis or QCA combines some of the advantages of both strategies (Ragin 1987). QCA assumes diversity as a middle ground between irreducible complexity and simplistic or superficial generalization. It takes a holistic view of the phenomena under consideration, avoiding the simplifying assumptions of the most commonly used quantitative approaches such as linear or additive causality or causal homogeneity. QCA examines each case and each causal path. It deals explicitly with complex causal relationships, considering cases as configurations and allowing for what Ragin characterizes as limited historical generalizations (Ragin 1987). Recent developments in QCA feature the introduction of fuzzy sets to permit application to larger groups of cases in a more probabilistic manner (Ragin 2000). Prominent efforts to bring this mode of analysis to bear on human-environment interactions include Rudel's studies of interacting factors leading to tropical deforestation (Rudel 2005) and Stokke's work on the role of shaming as a determinant of the effectiveness of fisheries regimes (Stokke 2004).

QCA simplifies complexity by identifying causal patterns. This requires a parsimonious approach to the selection of drivers, because the number of logically possible configurations grows exponentially with the number of factors included (Hellström 1998, Stokke 2004, Rudel 2005). Moreover, the causal configurations that QCA identifies are seldom finished products; they serve to group like cases together as a prelude to in-depth exploration of the ways in which causal conditions combine in different cases to produce similar outcomes. A phase of interpretive analysis typically follows.

Overall, comparative methods hold a number of attractions for analysts seeking to understand issues related to institutions and land change. It is fair to say that some of the best work currently emanating from the Institutional Dimensions of Global Environmental Change and LUCC communities makes use of this cluster of methods. Nevertheless, the limits of such work, such as a tendency to rely on descriptive statistics or to limit sharply the number of drivers considered, are also apparent. This has led us to broaden our horizons to encompass additional methodological options.

CASE STUDIES, COUNTERFACTUALS, AND NARRATIVES

Many analysts working in the area of institutions and land change use qualitative techniques of analysis. These techniques fall into two principal categories: (1) those that endeavor to conform to the logic of inference through careful case selection, use of natural experiments, and investigation of rival hypotheses (King et al. 1994), and (2) those that seek to achieve understanding through interpretive procedures that are rigorous but less concerned with inferential logic (Geertz 1973). Although the use of these techniques is not confined to discrete case studies (Kasperson et al. 1995) or to nonquantitative analyses, they do come to the fore in studies of this sort (Mitchell and Bernauer 1998).

As with other approaches, these methods typically seek to specify causal mechanisms and validate causal claims. Conditions that make these procedures appropriate include highly restricted universes of cases, opportunities to probe critical cases in depth (Eckstein 1975, George and Bennett 2005), and acute problems with fundamental assumptions embedded in mainstream statistical procedures. Rigorous study of a small number of cases allows for sustained exploration of the observable implications of posited causal relationships. The work of the International Institute for Applied Systems Analysis project emphasizing the role of monitoring along with what have become known as Systems of Implementation Reviews as determinants of the effectiveness of international environmental regimes exemplifies this approach (Victor et al. 1998). Such work is often helpful in theory development and in inductively informed, iterative specification of causal mechanisms.

The use of natural experiments requires the identification of real-world situations that approximate experimental conditions. The resultant comparisons control for as many potential causal factors as possible while looking for variation in one key factor that distinguishes the cases from one another. In such cases, variations in dependent variables such as patterns of land use lend credence to claims regarding the causal significance of the key driver (Repetto 2001). A study of the long-term outcomes of policies for conservation and community development in Africa, for instance, used a natural experiment involving the Serengeti-Mara ecosystem: similar ecological, microeconomic, and ethnic conditions made it possible to control for many confounding variables, whereas the Kenya/Tanzania border bisecting the ecosystem permitted a comparative analysis of the implications of contrasting systems of land tenure (Homewood et al. 2001). Although these studies do not attempt to differentiate random noise from patterned relationships in a systematic way, the strength of this technique lies in its ability to reduce the risks associated with unit heterogeneity (Campbell and Fiske 1959).

Studying a small number of cases can yield particularly useful results when rival hypotheses are examined systematically. Although normal tests of rival hypotheses involve large data sets, critical cases can provide considerable leverage when they focus on causal mechanisms that are understood to be mutually exclusive. A good example involves the effort to sort out the relative significance of the regime governing marine pollution and broader economic considerations as forces affecting intentional oil pollution at sea (Mitchell et al. 1999). A more recent example explores the extent to which uncertainty in contrast to other forces enhances cooperative behavior in bargaining over property rights in fisheries (Alcock 2002).

Counterfactuals are thought experiments used to explore how a sequence of events would have unfolded if some specific element in the actual sequence had not occurred or had taken a different form (Fearon 1991, Tetlock and Belkin 1996). Counterfactual analysis seeks to compare systematically actual outcomes with those that would have occurred under slightly altered conditions. Used frequently in historical studies, this approach has recently entered new research areas. One recent effort to understand the effectiveness of international environmental regimes, for example, seeks to determine what would have happened with regard to sulfur dioxide emissions in the absence of the 1979 Geneva Convention and its protocols on sulfur dioxide (Munton et al. 1999). The usefulness of counterfactual analysis depends on identifying the right causal sequence. In many cases, it helps to combine counterfactual analysis with other methods. For instance, researchers may start with a counterfactual analysis to identify potentially important variables and then move on to statistical work to pin down the relative importance of individual variables.

Many streams of research, especially in history and in the social sciences, rely on narrative techniques, including procedures known as thick description and process tracing. These are useful tools to unpack “black boxes” and uncover both the institutional and ecological drivers that influence human-environment interactions. Such methods can be particularly illuminating in efforts to explain or account for the choice of specific policies in corporate or political settings in which many actors are active participants (Sabatier 1999). Recent studies of the outcomes resulting from the transfer of authority from the national government to regional and local governments in a number of countries (Agrawal and Gibson 2001) and the performance of transnational river basin regimes (Myint 2003) illustrate the use of these procedures to shed light on human-environment interactions.

Case studies, counterfactuals, and narratives have obvious limitations as methods for producing scientific knowledge about institutions and land change in the domain of global environmental change. They can contribute important insights, especially when used as elements in a portfolio of analytic techniques. However, there is no justification for stopping here in our examination of analytic techniques that can provide insights regarding the sources and consequences of human-environment interactions. In the next section, we turn to a cluster of methods inspired explicitly by the challenges facing those seeking to understand the dynamics of complex systems.

SYSTEMS ANALYSIS AND SIMULATIONS

It is always hard to establish clear-cut assessments of the causal roles that individual drivers play in human-environment interactions. What is more, conventional procedures designed to highlight the role of specific variables can deflect attention from important features of socio-ecological systems such as nonlinear events and emergent properties. As a result, many have turned to various forms of systems analysis and to the use of simulations to explore the behavior of complex systems. The resultant approaches assume that it makes sense to view human-environment interactions as collections of elements that are organized around some function or purpose and that can be considered apart from the larger contexts in which they operate.

Studies of ecosystems are the focus of the discipline of ecology; research on economic and political systems figures prominently in the disciplines of economics and political science (Scoones 1999). When it comes to the understanding of human-environment interactions, what is critical is a focus on socio-ecological systems. As human actions have become larger and sometimes dominant forces in determining patterns of land cover, concentrations of greenhouse gases in the atmosphere, and allocations of fresh water, studies of socio-ecological systems have taken center stage. We have moved from analyses of the carbon cycle couched in biophysical terms, for instance, to studies of the carbon-climate-human system (Field and Raupach 2004). Similar remarks are in order regarding the hydrological and nitrogen cycles as well as other large socio-ecological systems.

Systems analyses direct attention to macro-level considerations including feedback mechanisms that can amplify changes and result in large or sudden shifts in the relevant systems, e.g., forest transitions that occur when declines in forest cover cease at a national scale and a recovery of forest cover begins. Such analyses improve our understanding of how specific attributes of systems, such as species diversity, influence systemic properties like resilience or vulnerability. So far, analyses of socio-ecological systems have emphasized questions pertaining to resilience, vulnerability, and adaptability (Peterson 2000, Walker et al. 2002, Turner et al. 2003, Janssen et al. 2006, Young et al. 2006), giving rise to broad integrative ideas like the proposition that we can identify adaptive cycles featuring well-defined stages observable in one form or another in a wide range of systems (Holling 2001, Gunderson and Holling 2002). They deemphasize traditional distinctions between dependent and independent variables.

Systems analysis promotes the examination of processes at different spatial, temporal, or jurisdictional scales and encourages studies of the interplay among them. This is increasingly important in a context that features both socioeconomic globalization and global environmental changes in which outcomes on one level become drivers on other levels. There are many cases in which regulatory arrangements created to solve or mitigate a problem at one jurisdictional level, such as local air pollution resulting from industrial production, generate unforeseen but potent effects that cause problems at other levels, e.g., long-range air pollution resulting from the introduction of tall smokestacks to mitigate local pollution. Similarly, the rise in sea level attributable to global climate change can have an adverse effect on individual coastal communities. A systems approach can facilitate cross-level analyses either by starting at one level and examining how drivers originating at that level impact other levels and vice versa or by focusing on studies of the dynamics of several levels in parallel (O’Neill 1988, Karlsson 2000, Easterling and Polsky 2004).

Socioeconomic metabolism is an approach to the study of socio-ecological systems that focuses on stocks and flows of energy or materials between ecosystems and societal systems (Ayres and Simonis 1994). Using energy, materials, or a substance such as carbon as a common currency, this approach probes interactions between socioeconomic systems and ecosystems, allowing analysis of the interplay of biophysical and social factors as determinants of system behavior (Haberl et al. 2004). Analysts have used the metabolism approach, for instance, to understand characteristic transitions from agrarian to industrial societies within individual countries or at a regional scale as in the case of central Europe (Krausmann and Haberl 2002).

Another systems approach emphasizes the cultural landscapes emerging in contingent historical processes through interactions between ecosystems, including their geomorphological and climatic components, and social systems (Antrop 2005). Cultural landscapes are shaped simultaneously by natural and social factors that interact in many ways, as is also revealed by studies in historical ecology (Foster and Motzkin 1998, Crumley 2001, Foster and Abers 2003). Although analyses of materials or energy flows contribute to understanding these interactions, studies of cultural landscapes also address perceptions of spatial patterns of landscapes and their cultural representation (Ramakrishnan et al. 1998, Farina 2000). Both “traditional” and “scientific” knowledge systems constitute connecting links for analyzing socio-ecological systems and (re)developing them in ways that take into account connections between biological diversity and cultural diversity (Ramakrishnan et al. 2003). Soft systems approaches or, in other words, nonquantitative studies of systems can take into account the fact that subjective perceptions and socially constructed realities determine the behavior of actors and stabilize patterns of behavior in systems (Checkland 1993, Pahl-Wostl 2002). One result is a better understanding of the barriers to introducing more sustainable management regimes.

The behavior of complex systems is difficult to analyze, explain, or forecast reliably (Axelrod and Cohen 2000). Many analysts have turned to simulation as a method to synthesize models and observations in a consistent framework, a process that has great potential to add to our understanding of human-environment interactions from a systems perspective (Holling 1978). Simulation features the use of artificial representations of interactions to explore the dynamics of complex systems, test the sensitivity of interactive relationships to discrete changes in key variables, and generate new puzzles for systematic empirical investigation. Formalized, computer-aided simulation models, in particular, can provide coherent representations of situations that incorporate insights from different scientific disciplines, thus fostering interdisciplinary cooperation and generating results that can be compared against empirical observations (Holling 1978, van der Leeuw 2004). These models are also useful in exploring the resilience and vulnerability of socio-ecological systems, a process that can help in developing scenarios in contrast to testable predictions (Holling 1978, Walters 1986, Carpenter and Brock 2004).

Although simulations often feature the use of computer models, they can involve real actors engaged in role-playing exercises (Barreteau et al. 2001, Pahl-Wostl 2002, Bouissau and Castella 2003, Pahl-Wostl and Hare 2004). In addition, there is a useful distinction between simulations that emphasize systems dynamics and rely on differential equations together with aggregated process-based descriptions and simulations that rely on agent-based approaches involving interactions among individual agents in specified settings to illuminate processes of collective action. A number of system-based models exist for land-use change simulation (Verburg et al. 2004) and institutional analysis (Luterbacher 2001). Agent-based modeling has garnered increasing attention in recent years because it can represent interactions between humans, individually or collectively, and the environment in a spatially explicit and interactive fashion (Kohler and Gumerman 2000, Janssen 2002, Parker et al. 2003). Such simulations can generate insights about the outcomes that arise when multiple, interactive forces influence the dynamics of land-use changes, urban development, or management regimes for common-pool resources.

Simulation models are particularly helpful when used to explore scenarios dealing with the potential trajectories of complex systems. They generate insights regarding the dynamics of these systems and identify emergent properties arising from interactions among actors that studies of agents in isolation commonly miss. Relative simplicity, which makes it possible to relate outcomes to the effects of specific assumptions, helps to produce insights. Gaps in knowledge become obvious during the model-building process. The value of each model depends not only on the purposes for which it is constructed but also on the potential for improvements with real-world parametrization.

All simulations abstract from reality and produce results in artificial settings. Links back to the relevant real-world context are essential to assess the usefulness and validity of these models. Simulations are often helpful in probing the effects on collective outcomes of different assumptions, e.g., assumptions about discount rates decision makers use. Good simulation modeling requires clear communication about all the assumptions entering the model-building process. Ideally, models should deal with uncertainties, e.g., future concentrations of carbon dioxide in the Earth's atmosphere, by including alternative structures that are compatible with theoretical expectations and empirical observations. Validity involves internal consistency and the match between model results and empirical observations, including both temporal and spatial outcomes (Pontius 2002). Numerical validation alone cannot determine the usefulness of a simulation; consideration of intended uses, contexts, and stakeholder interests is necessary as well (Oreskes et al. 1994). When decision makers use simulations to inform the policy process, the validity of the relevant models is a matter of their ability to structure debate and integrate different kinds of knowledge pertinent to the issue at hand (Pahl-Wostl 2002; Pahl-Wostl, *in press*).

Many simulation models are used in scenario planning approaches that integrate quantitative data, computer models, and qualitative understanding (van der Heijden 1996, Waltner-Toews et al. 2003; Alcamo and Rothmans, *in press*). Combining these techniques can help in dealing with uncertainties in complex systems and make the best use of the capacity of computer models to explore the responses of complex systems to a wide range of possible disturbances (Peterson 2003, Carpenter et al. 2005). By combining participant observations, qualitative analyses, and quantitative modeling techniques, scenario planning can become a supple tool that can enrich the efforts of decision makers to identify additional options and to examine the likely consequences of specific options in a systematic manner (van der Heijden 2000; Pahl-Wostl, *in press*).

As with the methods examined in previous sections, we conclude that there is a place for systems analysis and simulation in studies of environmental institutions and land-use and land-cover change. These procedures are particularly helpful in analyzing dynamic systems in which interactions among clusters of driving forces produce nonlinear changes and emergent properties that are difficult to anticipate, much less to explain, through the use of more conventional methods. However, there is no basis for concluding that systems analysis can replace mainstream methods that seek to separate the effects of individual variables and focus attention explicitly on causal connections.

TOWARD A PORTFOLIO APPROACH TO UNDERSTANDING SOCIO-ECOLOGICAL SYSTEMS

The range of approaches and methods examined here reflects the array of procedures that analysts have devised to overcome the challenges confronting efforts to understand complex systems that involve the performance of institutions and patterns of land change. None offers a comprehensive mode of analysis that can solve all the problems we identified in the first substantive section of this article. In our view, there is little prospect of developing a single, unified mode of analysis in this field of study, at least during the foreseeable future. Specific procedures are useful under certain conditions and can provide insights regarding some aspects of human-environment interactions. Multidisciplinary teams increasingly recognize this and make use of multiple procedures to avoid the excesses and limitations of any one (e.g., Turner et al. 2004). Our challenge, then, is to develop and select appropriate analytic strategies to address particular puzzles.

These choices depend not only on the purpose of the study but also on the size of the universe of cases, the extent of interaction between individual variables (including feedback loops), the number of variables that display a wide range of values, and the dangers of spurious relationships. Advanced statistical procedures, for instance, can identify patterns of association between variables when large data sets are available and causal relationships are expected to be relatively uncomplicated. Studies of the links between political decentralization and policies regarding the use of public lands lend themselves to such an approach. Other analytical approaches are appropriate for problems with more complex, systemlike relationships among variables. Simulation is particularly powerful in exploratory efforts to detect emergent properties arising from interactions in complex systems. Qualitative Comparative Analysis (QCA) is most useful in analyzing causal patterns in situations with small numbers of cases, limited sets of drivers, and relatively clear-cut outcomes. Natural experiments provide an attractive means for testing causal claims in situations in which two or more cases are more or less identical except for variation related to a factor of particular interest. When the purpose is an in-depth understanding of the causal mechanisms at work in a single case, narrative techniques are the privileged tools. Overall, the rewards will go to those who have the versatility to use a variety of analytic procedures and the judgment to make good choices about which procedures to use in specific situations.

In more complex research endeavors, it makes sense to combine several modes of analysis to develop an effective strategy for studying human-environment interactions (Roe 1998, Holling and Allen 2002). Sometimes it is helpful to use two or more analytic techniques sequentially. Statistical analyses, for instance, can help to specify the forms of relationships included in simulation models. Narratives can play a role in interpreting the results of (semi)quantitative analyses. Agent-based simulations can pinpoint key agents whose behavior deserves deeper exploration in studies that go beyond the confines of rational choice. Meta-analyses of discrete case studies featuring statistical procedures or narrative techniques can produce a higher level of generalization.

Still other situations lend themselves to a true portfolio approach featuring the use of two or more modes of analysis in parallel. Suppose, for example, that we want to understand variance in the performance of a collection of multilateral environments agreements (MEAs) and that we are seeking to sort out arguments pointing to power, knowledge, and the character of the rules themselves as critical factors. Traditional work in this realm has emphasized the use of rigorous but qualitative case studies (Haas et al. 1993, Young 1999*b*). Recently, opportunities have emerged to add analyses based on QCA (Stokke 2004) and, with the development of the International Regimes Database, on quantitative measures using a relatively large universe of cases (Breitmeier et al. 2006). These additional methods are not substitutes for case studies. Rather, taken together, they constitute a portfolio of methods whose results can be expected to be more powerful than those flowing from any single method.

Similarly, suppose we want to account for major changes in land cover, and we are endeavoring to understand interactions among factors such as ecological features, physical phenomena like rainfall, demographic patterns, market forces, and systems of land tenure. Here, too, case studies have an important role to play. However, recent work in this field has demonstrated the value of making use of advanced statistical procedures such as multilevel regression analysis and especially meta-analysis (Angelsen and Kaimowitz 1999, Geist and Lambin 2002, Verburg et al. 2004, Moran and Ostrom 2005, Rudel 2005). As in the preceding example, the point is not to identify the single best method for enhancing our understanding. Rather, we are convinced of the value of a portfolio approach. When the results generated by different methods converge, confidence in the strength of our conclusions rises. On the other hand, divergent results are also helpful in the sense that they provide evidence of the need to engage in more extensive investigations regarding the issues at hand.

Can we expect the use of such a portfolio approach to understanding institutions and land change to generate solutions to the methodological problems we have emphasized in this article and to produce results that pass muster in scientific terms? There is no question that complex causality is pervasive in these settings and that the resultant methodological challenges often restrict the use of familiar scientific methods. However, this does not warrant the conclusion that we will be unable to arrive at scientifically valid conclusions about human-environment interactions. Researchers seeking to understand the dynamics of the Earth's climate system are not deterred by the difficulties they encounter in using standard scientific procedures. Research on human-environment interactions and the socio-ecological systems from which they emerge and to which they give rise is today an infant field of study. Neverthless, there is nothing in the issues we have discussed in this article that should dampen our aspiration to develop a growing body of scientific knowledge about such matters.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/vol11/iss2/art31/responses/

Acknowledgments:

This article is the product of a workshop organized jointly by the project on the Institutional Dimensions of Global Environmental Change (IDGEC) and the project on Land-Use and Land-Cover Change (LUCC) and held in November 2004 in Bonn, Germany. We are grateful for financial support from IDGEC and LUCC as well as from the International Human Dimensions Programme on Global Environmental Change. Several anonymous reviewers helped us to clarify and enhance the logic of our argument. Maria Gordon suggested ways to make the presentation as clear as possible.

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