SCENARIOS AND DECISIONMAKING FOR COMPLEX ENVIRONMENTAL SYSTEMS

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Abstract. Scenarios are used for expanding the scope of imaginable outcomes considered by assessments, planning exercises, or research projects on social-ecological systems. We discuss a global case study, the Millennium Ecosystem Assessment, and a regional project for an urbanizing agricultural watershed. Qualitative and quantitative aspects of scenarios are complementary. Scenarios can help address several of the currently recognized challenges of sustainability science.

INTRODUCTION

Society faces unprecedented challenges due to the pace and magnitude of environmental change (Millennium Ecosystem Assessment 2005). Human actions are important drivers of environmental changes through effects on land use, biogeochemical cycles, species invasions, disease emergence, and climate. These actions have large and long-lasting consequences for provision of food and fresh water; regulation of floods, pests and diseases; and the other benefits that people receive from nature, which collectively are called ecosystem services. Changes in ecosystem services affect human food security, health, and access to resources for both current and future generations.

Future changes in systems of people and nature (social-ecological systems) are deeply uncertain. The high velocity and vast extent of current changes in Earth's systems have not occurred before in the history of our species. We cannot rely on historical analogs for guidance. Social-ecological dynamics are unpredictable for many reasons, including nonlinear processes, the propagation of shocks in an increasingly connected world, and the role of human volition. Controllability of social-ecological systems is equally uncertain. Our ability to predict the consequences of policy instruments and management interventions is limited. Actions intended to mitigate environmental problems often have unintended consequences, including the emergence of new and unexpected problems. Collectively, these uncertainties make it impossible to predict futures of social-ecological systems, or even compute probability distributions for social-ecological futures.

Despite these difficulties, the need to think about the future of social-ecological systems cannot be avoided. The definition of sustainability includes the notion of non-decreasing wealth: sustainable policies meet the needs of the present without undermining future generations' ability to meet their needs (Arrow et al. 2004). Inevitably, environmental actions affect future generations as well as the present. Therefore, present-day decisionmakers must think about long-term consequences of environmental actions.

In view of profound uncertainty, how can environmental decisions best be guided to meet current and future human needs? Tools are needed to organize vast amounts of information, and portray uncertainties that cannot be computed using the usual tools of decision theory. Decisions can at least use all of the information available when the decision is made, even if that information is incomplete. Scenarios are one of the tools for supporting decisions in this setting. Here we provide a brief summary of scenarios for complex environmental decisions.

WHEN ARE SCENARIOS USEFUL?

The set of plausible and possible future trajectories for a social-ecological system occupies a vast and mostly unknown space (Fig. 1). Most of the space is in the realm of unasked questions—outcomes that are not imagined and therefore not subject to inquiry. Imaginable but non-computable outcomes occupy a smaller part of the total space. These are outcomes that are plausible, are potentially important, and should be considered in decisionmaking even though they are difficult to analyze. A still smaller space is occupied by the recognized uncertainties, unknowns which are subject to formal analysis with computable probabilities. What we know for certain occupies the smallest region of all.

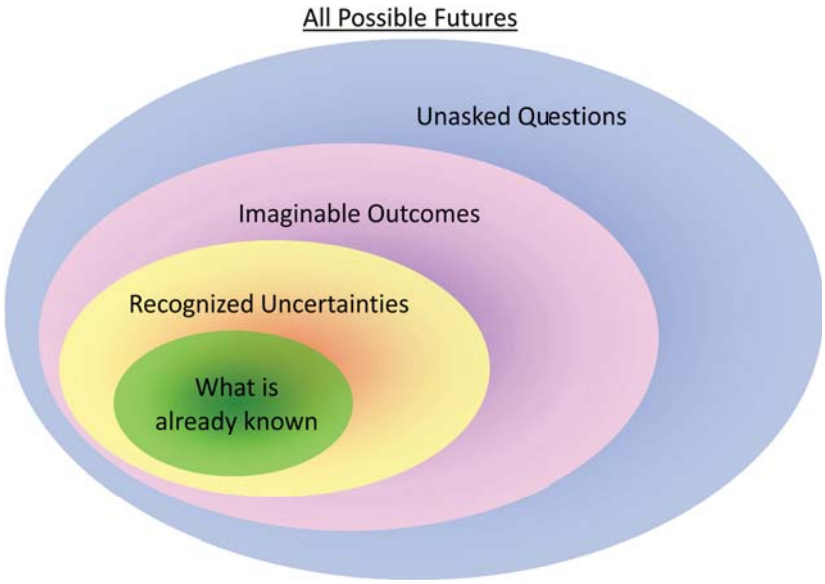

Figure 1.—The space of all possible future trajectories for a social-ecological system. Modified from Carpenter et al. (2006).

Decisionmaking under uncertainty is a lively discipline with many tools that are useful for environmental decisions (Polasky et al. 2011). Some established and effective tools, such as optimization of expected utility or related alternatives, are designed for the realm of recognized uncertainties (Polasky et al. 2011). In this realm, scenarios are not as effective as the more established tools. Scenarios are not especially useful if the set of potential outcomes is known, probabilities are computable for the outcomes, desirability (utility) of the outcomes is computable (or at least rankable), and the controllability of the social-ecological system is understood.

Scenarios are uniquely valuable for expanding the space of imaginable outcomes by prompting questions that have not yet been asked. Scenarios also organize and condense complex information in ways that improve communication and understanding. Thus, scenarios evoke broad conversations about the future while providing a framework to integrate diverse points of view about the future. Simulation modeling is not essential for scenarios, but in many cases scenarios and simulation models have been used in complementary ways within a single project. Examples of scenario projects are presented in the next two sections of the paper.

MILLENNIUM ECOSYSTEM ASSESSMENT

The Millennium Ecosystem Assessment (MA) was conducted from 2000 to 2005 to assess the status and future of the world's ecosystem services and the implications for human well-being. Scenarios for global ecosystem services from 2000 to 2050 were developed as a part of the MA. The creators of the MA scenarios were able to learn from earlier efforts to build global environmental scenarios, notably the Global Scenarios Group of the Stockholm Environment Institute (Raskin 2005) and the Special Report on Emissions Scenarios of the Intergovernmental Panel on Climate Change (Nakicenovic and Swart 2000). Yet ecosystem services and their links to human well-being had never before been addressed by a global scenarios program (Bennett et al. 2003). The MA scenarios team had to consider nonlinear ecological feedbacks (Cumming et al. 2005) as well as relationships of ecosystem conditions to diverse aspects of human well-being (Butler et al. 2005). The challenges of addressing ecosystem services in the context of global change were reviewed in depth by the MA scenarios team in the early stages of the project (Chapters 2, 3, and 4 of Millennium Ecosystem Assessment 2005).

The overarching question for the MA Scenarios Working Group was: What will be the condition of the world's

ecosystem services in 2050, and what changes will occur along the way? The process of building the MA scenarios began with a workshop to review the status of global scenarios and the particular challenges posed by ecosystem services. Shortly after this workshop, MA staff conducted a telephone survey of about 60 global thinkers to gather ideas about the vulnerability and resilience of the Earth's systems (Bennett et al. 2005). At about the same time, pilot projects were launched to "learn by doing" scenarios for several regions around the world.

Four storylines emerged from broad discussions following the synthesis of previous global scenarios and the interviews of global thinkers (Carpenter et al. 2006). In Global Orchestration, economic development and globalization accelerate. Environmental management is reactive, responding to crises as they arise. In Order From Strength, nations emphasize their own security, leading to a divided world with slower economic growth. Environmental management is reactive. Adapting Mosaic also envisions a less globalized world, in response to movement toward local and regional management of ecosystem services. Environmental management is proactive, emphasizing local knowledge, engagement of local people, and property rights to create incentives for more resilient stewardship of natural resources. In TechnoGarden, economies are globalized and technological innovation is booming. Environmental management is proactive due to implementation of large-scale innovative technological approaches for maintaining flows of ecosystem services. The four scenarios portray very different combinations of opportunities, risks, benefits, and costs. Outcomes are quite different across regions. Daily life for people would be very different in the four worlds of the scenarios.

Logical consequences of the four storylines were developed in both qualitative and quantitative form. Narratives emphasized the coherent and logical features of the storylines while attempting to explain what it would be like to live in each of the four worlds, in rich countries as well as poor ones (Cork et al. 2006). Quantitative analyses grounded in the logical structures of the storylines generated computable outcomes. This process required an analysis of drivers of change and their implications for ecosystem services (Nelson et al. 2006). Global models for macroeconomics, human demography, demand for food and fresh water, nitrogen emissions, climate, and biodiversity were run in parallel to compute changes in global land cover and land use, freshwater flows, freshwater quality, species diversity, and other outputs (Alcamo et al. 2005, van Vuuren et al. 2006). Harmonizing the qualitative and quantitative analyses, as well as the linkages among the various global models, was a major task for the Scenarios Working Group (Carpenter et al. 2006).

The MA exposed, and in some cases illuminated, several challenges of global scenarios for ecosystem services. These challenges include the problems of dealing with many different response variables (in contrast to climate-change scenarios that focus on only one response, greenhouse gas emission to the atmosphere), the challenges of harmonizing qualitative and quantitative scenarios, and the difficulty of integrating multiple global models. The MA also focused attention on the difficulty of analyzing and understanding the interactions of local- and global-scale processes (Biggs et al. 2007). Research on the integration of global and local scenarios has become an important frontier of scenarios research. We address one recently initiated case in the next section of this paper.

WATER SUSTAINABILITY AND CLIMATE IN THE YAHARA WATERSHED, WISCONSIN

The Yahara Watershed includes the five lakes of Madison, WI. It drains 996 km^2 and is home to about 400,000 people. The watershed has been substantially altered by agricultural land use, urbanization, and climate change (Carpenter et al. 2007, Kucharik et al. 2010). Climate change, population growth, land-use change, and competing goals for the region place growing pressure on freshwater resources. Groups with competing water management goals include farmers, urban and suburban residents, developers, realtors, recreational lake users, neighborhood associations, environmental organizations, business organizations, and policy makers.

Water management in the region confronts many changes. Groundwater levels are declining in the deep

aquifer that supplies drinking water, while runoff from road salt is increasing the salinity of surface water and shallow groundwater. Lake levels are becoming more variable over time, due to the increasing area of impermeable surface and more variable precipitation. Fluctuating lake levels trigger conflict over management of the locks that regulate discharge from the lakes. Some of the changes have come as surprises. In the late 1960s, Eurasian watermilfoil invaded the lakes and severely disrupted boating until the weed densities declined by about 1990. Diversion of sewage by 1971 did not cause the expected improvements in lake water quality. Instead, poor water quality and algae blooms were maintained by heavy runoff of nutrients from agricultural lands and construction sites (Carpenter et al. 2007). The recent invasion of spiny water flea is harming the native grazers in the lakes, and is likely to lead to more severe algae blooms. The lakes are vulnerable to invasion by zebra mussels in the future, which will litter beaches with sharp shells while promoting thick mats of decomposing algae along shorelines. Meanwhile climate change, urbanization, and intensive agriculture are likely to drive further changes in the hydrology and biogeochemistry of the lakes.

Scenarios of social-ecological change in the watershed from 2010 to 2060 will be developed as part of a new project that the authors have initiated with co-investigators Chris Kucharik, Steve Loheide, and Monica Turner. The overarching questions for the scenarios exercise are: (1) What will be the future condition of the natural capital and ecosystem services of the region between the present and 2060? and (2) What human actions will make the region more resilient (or vulnerable) to climate change?

The principal goal of the scenarios is to expand basic knowledge about sustainability and change in social-ecological systems (Table 1). Scenarios can be used to address many of the pressing questions of sustainability science (Kates et al. 2001, Swart et al. 2004). Qualitative narratives will be developed, based on in-person interviews and participatory workshops. Quantitative implications for land use, land cover, hydrology, and water quality will be modeled. The primary goal of this National Science Foundation-funded project is research, but outreach and public education are also important objectives. The scenarios will provide an arena for conversation about the future. Because the time horizon is significantly longer than the time frame of local politics, discussions can encourage a context of collaborative learning rather than conflict. Broad collaborative thinking may reveal new ways of improving the resilience of the region that are not known at present. In the long run, collaborative learning may help change the ways that people think about the region.

EVALUATING SCENARIO PLANNING

Scenarios have been widely used by businesses, nonprofit organizations, researchers, and policy-makers, but relatively few evaluations of scenario planning have been conducted (Chermack et al. 2001). Improved understanding of the value of scenario planning could enhance its application in diverse contexts. Scenario planning engages groups to imagine plausible future alternatives, articulate previously unasked questions, and consider trajectories of change with unknowable outcomes. Evaluations may examine whether the theoretical advantages of scenario planning were realized, such as creating plausible alternative futures, encouraging creativity and collaboration, enhancing causal and story-based thinking, and changing mental models (Harries 2003). In addition, evaluations could address outcomes in terms of improved decisionmaking, changed behavior, or enhanced performance (Bartholomew and Ewing 2009). Since scenarios are not forecasts, it would be unreasonable to evaluate scenarios on the basis of whether they accurately predict future conditions. Yet some organizations highlight the success of scenarios in helping decisionmakers anticipate future changes in an increasingly interlinked world, although these self-reported success stories are not representative (Harries 2003).

Scenario planning for social-ecological change in the Yahara Watershed in Wisconsin will incorporate an evaluative component. The evaluation process will examine the role of scenario planning in enhancing participants' understanding of complex and dynamic social-ecological relationships, perceptions of utopian and dystopian futures, and perceived mechanisms and

Table 1.—Research challenges to be addressed using scenarios in the Yahara Watershed project. Research challenges of sustainability science are based on Kates et al. (2001) and Swart et al. (2004).

Research Challenge	Key Aspects of the Challenge	Contribution of Scenarios
Spanning spatial scales	Local, regional, and global processes interact.	Identifying cross-scale feedbacks and their potential consequences
Spanning response times	Societal decisions about long-term change must be made in the short term.	Linking long-term goals to short-term decisions
Recognizing wide range of outlooks	Values and preferences for the future differ among people.	Accounting for perspectives that are recognized through outreach activities, surveys, etc.
Reflecting critical thresholds, surprise, and uncertainties	Unprecedented changes cannot be calibrated in models, and nonlinear thresholds are hard to measure.	Creative "what if" scenarios suggesting novel analyses and model simulations
Accounting for human volition	Human behaviors have strong effects yet are hard to forecast.	Normatively distinct viewpoints of desired or undesired futures being cast as scenarios for analysis and model simulation
Combining qualitative and quantitative thinking	Values, culture, and institutions have as much impact on sustainability as do quantifiable aspects of social, economic, and biophysical change.	Combining narrative scenarios with quantitative model simulations
Engaging stakeholders	Stakeholders have deep local knowledge of the system. Engaging them widens the knowledge base, helps address normative aspects of sustainability, and increases learning by all participants.	Providing a framework for synthesis and communication among researchers and stakeholders

pathways of change. It will also examine the role of scenarios in changing the discourse in regional media and policy-making contexts on adaptive strategies for increasing resilience and decreasing vulnerability in the face of climatic, water resource, and human population change.

CONCLUSIONS

Scenarios can increase the scope of environmental assessments by asking new questions and expanding the domain of uncertainties to be considered. Both qualitative and quantitative scenarios are useful. Qualitative narratives can be accessible to non-technical participants and thereby expand the diversity of people who participate in the scenario process (Carpenter et al. 2009). Qualitative scenarios are also useful for thinking about rare unpredictable events that are difficult to compute. Qualitative scenarios can help frame the social-ecological context for quantitative scenarios. Quantitative analyses enrich scenarios by providing details about computable aspects of environmental change, including important ecosystem services such as provision of food and fresh water. In addition, quantitative analyses provide a useful check on the plausibility of assumptions that are made when constructing qualitative scenarios.

Beyond playing a role in assessment, scenarios can help address basic research challenges in sustainability science (Table 1). Scenarios have also been used as a teaching device in university courses dealing with social-ecological systems (Biggs et al. 2010).

Use of scenarios in environmental assessment, management, and research seems to be expanding rapidly, based on the number of citations apparent in Google Scholar and Web of Knowledge. This brief article has only scratched the surface of an extensive and growing literature. We hope, at least, to have exposed some of the opportunities and challenges of scenarios for addressing change in social-ecological systems.

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