Kinzig, Ann P., William C. Clark, Ottmar Edenhofer, Gilberto C. Gallopín, Wolfgang Lucht, Ronald B. Mitchell, P. Romero Lankao, S. Sreekesh, Crispin Tickell and Oran R. Young. 2004. Group report: Sustainability. Chapter 20 in Earth System Analysis for Sustainability, edited by Hans Joachim Schellnhuber, Paul J. Crutzen, William C. Clark, Martin Claussen, and Hermann Held. Cambridge, MA: MIT Press.

Report of the 91st Dahlem Workshop on
Earth System Analysis for Sustainability
Berlin, May 25–30, 2003

Held and published on behalf of the
President, Freie Universität Berlin: D. Lenzen

Funded by:
Deutsche Forschungsgemeinschaft
Deutscher Akademischer Austausch Dienst
Andrea von Braun Stiftung

Earth System Analysis for Sustainability

Edited by

Hans Joachim Schellnhuber, Paul J. Crutzen,
William C. Clark, Martin Claussen, and
Hermann Held

Program Advisory Committee:

Hans Joachim Schellnhuber, Paul J. Crutzen, and
William C. Clark, Chairpersons
Martin Claussen, Hermann Held, Tim M. Lenton, and
Will Steffen

The MIT Press
Cambridge, Massachusetts
London, U.K.

in cooperation with Dahlem University Press

Back: Wolfgang Lucht, Bill Clark, Oran Young, and Ron Mitchell
Front: Alison Jolly, Gilberto Gallopin, Patricia Romero Lankao, S. Sreekesh, Ann Kinzig, and Crispin Tickell (not shown: Ottmar Edenhofer)

20

Group Report: Sustainability

A. P. KINZIG, RAPPORTEUR
W. C. CLARK, O. EDENHOFER, G. C. GALLOPÍN, W. LUCHT, R. B. MITCHELL, P. ROMERO LANKAO, S. SREEKESH, C. TICKELL, and O. R. YOUNG

INTRODUCTION

How can science, technology, and knowledge be harnessed more generally to advance the goals of global sustainability? We approached this ambitious question in two ways: by addressing how a better understanding of Earth system science could help society meet the sustainability challenge, and how a better understanding of the sustainability challenge could help Earth system scientists produce more useful research and development. We emphasize that Earth system science must stress both the biogeophysical and socioeconomic aspects of our world as well as the interactions between them (Steffen et al. 2003; Sahagian and Schellnhuber 2002). As such, science and technology must also be taken to include the full sweep of scholarly activities devoted to understanding this integrated Earth system, from the natural sciences to social sciences, humanities, and engineering.

We based our discussions on the modern view of the Earth system, explored more thoroughly in the other working groups, which views nature and society as a tightly coupled, dynamical system. This tight coupling between nature and society has characterized all of human history, although in the past it was evident predominantly at local or regional scales. We assume that most ancient societies did not wish their own demise, and thus posit a certain level of "self-awareness" or self-direction toward environmental stewardship. Nonetheless, history has seen the decline of many earlier civilizations (Redman 1999). These declines were not always directly related to environmental degradation, but the interplay among environmental, social, and political dynamics often led to their undoing.

Scholars have developed a substantial body of analytically derived and empirically grounded knowledge regarding the determinants of robustness or sustainability in human–environment relationships (Allen et al. 2003; Folke et al. 2002; Gunderson and Holling 2001; Redman and Kinzig 2003; Tainter 1988). Much of this knowledge has arisen from a widely shared sense among many researchers that the "tragedy of the commons" (Hardin 1968) is by no means a universal phenomenon and that many small-scale societies have invented successful methods for "governing the commons" (Berkes and Folke 1998; Ostrom 1990). Major contributions on the part of anthropologists, economists, ecologists, and political scientists have produced important insights regarding the conditions governing the occurrence of the tragedy, and of successful management of common resources as well (Bromley 1992; Burger et al. 2001; McCay and Acheson 1987; for a critical review of the literature, see Ostrom et al. 2002).

Today's situation is more daunting. Humanity is now a global environmental force, altering biological communities, biogeochemical cycles, landforms, and climate on unprecedented spatial scales, with unprecedented rates of change (NRC 1999; Turner et al. 1990; Vitousek et al. 1997). This raises two major scientific challenges. The first centers on the problem of scale: To what extent can we "scale up" findings derived from the study of small-scale systems to shed light on what might occur at larger, even global, scales (Folke et al. 2002; Kates et al. 2001; Ostrom et al. 1999; Young 2002)? Second, humanity operates today in an interdependent world in which global processes affect outcomes at the local level, and many small-scale processes can have global consequences, making the consideration of cross-scale interactions essential (Clark 2000; Gunderson and Holling 2001; Young et al. 1999). Past experience suggests that the world will not fall into sustainability by accident; a certain active reflection on the impacts of our behavior and actions as well as purposeful avoidance or amelioration of threatening consequences are required. This "self-awareness" must now come at a global level, commensurate with the scale of impacts.

One cannot glibly discuss a "global self-awareness" as if the means of achieving it were self-evident or simple. Humans have always fostered group identities that to some extent rested on the notion of "an other" or an enemy. Paralleling the unprecedented changes in the Earth's biogeophysical cycles are equally unprecedented changes in the scope and quality of human social organization. In the last century, for the first time, the world organized under an international banner — first as the League of Nations and now as the United Nations — that lends some precedent to global self-reflection and organization, and provides some insights for which strategies to follow and which to avoid. In the environmental and social realms, this global will contributed to the eradication of smallpox and other diseases, the incipient establishment of a global ethics that includes recognition of universal human rights, international technologies and policies to address the problems of ozone depletion and climate change, and hundreds of treaties protecting endangered species and reducing freshwater and marine pollutants.

What kind of world is humanity trying to create with this "global self-awareness"? Answers to this involve values that properly differ across times and places. Nonetheless, as a point of departure for our discussion, we found useful the goal of "sustainable development," originally crafted by the Brundtland Commission and subsequently adopted by world leaders in Rio de Janeiro at the UN Conference on Environment and Development. In this view, society wants development "that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987). To emphasize the dynamic, open-ended character of nature–society interactions, we followed the broad consensus set forth by the world's scientific community at the 2002 Johannesburg World Summit on Sustainable Development: the goals of sustainability "should be to foster a *transition* toward development paths that meet human needs while preserving the Earth's life-support systems and alleviating hunger and poverty" (ICSU et al. 2002). A simpler formulation we particularly liked was "treating the Earth system as if we intended to stay."

It has long been clear that progress in promoting a transition toward sustainability will require substantial reforms in both the political and economic realms of human activity. Many have argued that it may also require fundamental changes in human values. What has less frequently been recognized is that successful navigation of a transition toward sustainability will necessarily be a knowledge-intensive activity as well. Science and technology have contributed significantly to the vigorous growth of human civilization and associated pressures on the environment that have put at risk "the freedom of future generations to sustain their lives on this planet" (Annan 2002). The question before us now is how the science and technology that unconsciously helped to get us into our present predicament can, through a program of purposeful, self-conscious research and development, best support society's larger effort to sustain our common future. In our discussions we came to three major conclusions:

1. The scientific community should place more emphasis on areas of research that are critical to the prospects for achieving sustainability. These include identification of "safe" and "benign" domains of operation for the Earth system; integrated assessment of production–distribution–consumption systems that provide the basis for a better quality of life; and research on the types of institutions, and institutional change, that will foster a transition to sustainability.
2. We recognize that the scientific community is not adequately organized to contribute its appropriate voice to the global dialogue on the world's future. The scientific community needs to consult regularly with, and learn from, stakeholders in setting the questions and determining priorities for science devoted to sustainability; it needs to use more appropriate techniques in constructing scenarios and analyzing uncertainties; and it must clearly communicate what is and is not known to the users of scientific information.
3. The above conclusions place additional organizational demands on the scientific community. This includes developing a global observation network (with both centralized and distributed elements) to assess the state of key components of the coupled society–environment system and

creating a process with the authority and stature of the Intergovernmental Panel on Climate Change (IPCC), but devoted to scientific assessment of sustainable development and environment on a wider basis. Finally, and perhaps most importantly, we strongly endorse a global effort to develop scientific capacity in the regions of the world where it is currently lacking or weak. Without this capacity, global scientific efforts to inform policy making will be irrelevant at best, and wrong at worst.

CARING FOR THE EARTH SYSTEM

Before turning to our major conclusions, we wish first to review briefly two approaches often put forth as effective ways of coping with human-made hazards in a complex, dynamic, but uncertain Earth system: adaptive management and participatory decision making. We note that there is no hope for humanity to control all of the infinite complexities of the Earth system. However, humans can aspire to manage effectively some of their activities, in ways that enhance social well-being while imposing progressively lower stresses on the Earth system, and correct or mitigate some of the ill effects of their own activities.

Adaptive Management

Adaptive management approaches emerged in the 1970s from a recognition that the complexity and scale of human–environment interactions makes it impossible to predict accurately the ultimate impact of candidate management strategies (Holling 1978; Walters 1986, 1997). Rather than futilely striving for such predictions or hoping to avoid entirely inevitable surprise, "adaptive" approaches sought to treat management and policy as system-scale experiments rather than one-off solutions. Monitoring and evaluation of systems response to management, and institutions capable of learning from error, are central to adaptive management strategies. Because adaptive management requires society's support for its policy experiments, the practitioners of adaptive management also became early advocates of the involvement of stakeholders, alongside scientists and policy makers, in the management process. These participants are brought into an on-going process of scientific and policy experimentation with related feedback systems intended to reduce uncertainties and improve knowledge about the operation of the environmental system, the human social system, and the interaction between the two. In the adaptive management model, the process allows for responses to be frequently evaluated and altered so that managers can be responsive to new information about how these systems work, but also to new information about or changes in the fundamental goals of those most directly affected by and involved in the human–environment system.

Adaptive management approaches have been applied to a wide range of local- and regional-scale environmental problems (Lee 1993; Gunderson et al. 1995; NRC 1996; Dovers and Mobbs 1997). A review of this experience suggests that much good has come from the struggle to implement adaptive approaches to environmental management. The approach nonetheless has yet to fulfill its promise in practice. As scholars have shown, the abilities of managers and other individuals to process information and/or respond to it are modest in comparison with the complexity of the problems and environments confronted (Bourdieu et al. 1983; Simon 1977). In addition, the difficulties encountered, even in relatively small-scale, self-contained settings, will surely be greatly exacerbated in the case of the Earth system transformations that concern us here. We review several of the challenges below, drawing in part on findings of other working groups at this Dahlem Workshop.

- *Uncertainty*: Adaptive management was explicitly developed to deal with uncertainty. The combination of integrated modeling and focused, large-scale management experiments have had some success in addressing uncertainty. However, these approaches have worked best where the uncertainty in question can be formulated in terms of specific probabilities or competing hypotheses. Uncertainties encountered in analysis of the Earth system have generally not been "tamed" to this level, leaving the likelihood that adaptive management approaches can usefully respond to them open to question.
- *Non-decomposability*: Elements that cannot be decomposed are unable to be analyzed piecemeal, one factor at a time, because of functional interlinkages. This is a common feature of ecological systems and has been a fact of life in all adaptive management experiences. Classical factor-isolation experiments are inadequate for analyzing such systems. When integrated models can be constructed for guidance, large-scale management experiments have been useful in addressing non-decomposability. In the case of the Earth system, non-decomposability characterizes the coupled social–ecological system. This presents a challenge for adaptive management, since fully integrated models of the social–ecological system at the level of the Earth system are only beginning to be developed.
- *Nonlinearities*: Nonlinearities are characteristic properties of complex systems, contributing to their unpredictability. Nonlinearities take many forms, such as thresholds, lack of proportion between causes and effects, and chaotic behavior. Some events may be so "nasty," rapid, and irreversible (see below) that they make adaptive management's process of policy formulation–implementation–feedback–assessment–reformulation less effective or impossible.
- *Timescales and response times*: In theory, adaptive management can address processes that occur on a variety of timescales. Two particular types of cases, however, challenge the effectiveness of an adaptive management framework: (a) when changes occur abruptly relative to the capacity of the management system to perceive and respond to the change; and (b) when

processes unfold very slowly or exhibit long time lags between a pressure and response. In both cases, management through experimentation tends to become less effective, as necessary feedback is received long after actions can be taken to avert those consequences. This calls into question the very "adaptive" nature of adaptive management, and this set of problems has not yet been satisfactorily addressed.

- *Singularity*: When the system is unique, standard statistical techniques based on comparisons across a number of replicates cannot be applied. This is common in a number of cases of managed ecosystems or natural resources and is obviously the case for the Earth system.
- *"Nasty" irreversibilities*: Irreversibility in itself is not necessarily a problem for adaptive management. The Earth system could, after all, move into a domain from which there is no return (in practice or principle), but which is generally more attractive than the previous one. Irreversibility is only threatening if the domain that cannot be escaped is a "nasty" one, that is, inhospitable for life and unsustainable for human society. Unfortunately, as detailed elsewhere in this volume, nasty irreversibilities seem to be lurking in many Earth system dynamics. In such cases, large-scale experiments might push the system into a trajectory of nonrecovery, the information thus gained would be irrelevant, and the system would irreparably deteriorate.

An additional challenge is the need to perform management experiments, and the institutional capacity to learn from those experiments. When experimentation risks causing harm to people's livelihoods or well-being, it is likely to be politically difficult and certain to be ethically inappropriate. Unfortunately, such issues are at the heart of sustainable development, calling into question the extent to which managers can experiment under an adaptive management framework. One possibility is to use passive adaptive strategies, which involve making use of information as it becomes available through "natural" experiments as they occur in the policy-making process. Decisions are not intentionally modified for the purpose of probing the system and gathering information on its dynamics.

Adaptive management has been offered by some as a panacea for dealing with uncertainty, obviating the need to invoke precautionary principles. The attributes of the Earth system, including (a) the long timescales involved in some processes, (b) the possibility of abrupt change, (c) the potential of nasty irreversibilities, and (d) the singularity of the Earth system, call this proposition into question. It seems almost certain that a "bright line" does not exist between those cases in which large-scale management experiments offer the best approach and those cases in which the precautionary principle should prevail.

The combination of high uncertainties and high stakes present in the Earth system makes it necessary to apply the best science-based management available, but one bounded by the degree of societal acceptance of the risks involved. Therefore, the participation of members of society in management is essential for determining what constitutes socially acceptable risk.

Participatory Decision Making

Participatory decision making has been promoted as being capable of resolving many global and regional environmental problems. There are many benefits of such participation — not the least of which is securing people's rights in industrialized societies. However, can we presuppose that such inclusive systems automatically, or even usually, achieve outcomes consistent with fostering the long-term sustainability of the Earth system? There are many reasons to believe, in fact, that such processes are inherently ill-equipped to grapple with the complex dynamics that span large spatial and temporal scales. There may be a tension between "rightness of procedure" and "goodness of outcome" (Sen 1995).

Despite the difficulties, for reasons outlined below, we support participatory decision making whenever possible, without supposing that those processes would usually be democratic in the strictest sense of the word. Participants will assume different roles, assets, strategies, and opportunities for participation. Negotiation of the values society holds or will hold is legitimately within the purview of every stakeholder or citizen. Scientists ought not to have a stronger voice in that negotiation than any other citizen. Scientists can, and should, however, have a stronger voice concerning the likelihood of various future scenarios and their courses and impacts (both beneficial and harmful). Similarly, others with specialized knowledge (lawyers, historians, economists) will have particular roles to play. Final decisions that weigh scientific, economic, political, social, and cultural considerations are ultimately in the hands of legitimately recognized representatives or leaders, when they exist. Many countries, unfortunately, lack such legitimate leadership.

A number of factors are relevant to a consideration of the role of participatory decision making in addressing Earth system issues:

1. *Rationale*: Wide participation on the part of the interested parties may be advocated for normative or instrumental reasons. Normatively, participation may simply be regarded as good in itself. Instrumentally, participation may generate creative input into decision-making processes or increase the willingness of affected parties to implement or comply with commitments made during decision-making processes.
2. *Types of participation*: Different types of participation may be more or less relevant to decision making on Earth system issues. For example, interested or affected parties may be allowed (a) to vote or merely to comment, (b) to participate in agenda setting or final choices among options, or (c) to have equal weight or differential weight in making choices.
3. *Types of decisions*: Participation on the part of interested or affected parties may be more important for some types of decisions than others. For

example, participation is highly important in making basic value decisions (e.g., choices regarding social justice versus economic growth) but relatively less important in making highly technical decisions (e.g., how to measure concentrations of greenhouse gases in the Earth's atmosphere). In practice, most decisions or choices are likely to fall somewhere between these extremes. It would be helpful to place different types of choices on this spectrum and to make decisions about appropriate levels and types of participation accordingly.

A number of additional challenges emerge when applying participatory decision making to problems of sustainable development. First, it is difficult to include all interested or affected groups, not the least of which are those members of future generations who will be irrevocably affected by our actions, but whose voices cannot be strongly or accurately represented. In addition, even for present-day stakeholders, identifying those who should be involved, and enlisting them, can be daunting, since potential participants extend from individuals to entire nations. Second, it proves challenging to convey the complex science involved to both those who must negotiate what values should prevail (all citizens) and those who must make decisions. We return to these points below, but there are no simple answers to this challenge, and it must be recognized that many, if not most, of the participants making decisions about our complex world do so with a limited scientific understanding as well as with diverse perceptions, opinions, and interests regarding what should be done. Third, participatory processes may favor "consensus" solutions that reflect the need for political compromise and incrementalism, rather than reflecting environmental exigencies that make such compromises environmentally and socially intolerable, even when the majority of participants wish to avoid such an outcome. Finally, the inherent disparity among interested parties ultimately tends to favor the rich and powerful, both within a society and between societies. Participatory processes devoted to questions of sustainable development will have to find a way to strengthen, and perhaps (given the forces orienting us toward the rich and powerful) favor, the poor and disenfranchised.

Participatory processes can broaden the legitimacy accorded to environmental decision making and thereby increase the concern and commitment of a range of actors in society to the goal of sustainability. At the Earth system level, however, the processes must be designed in ways that ensure that the political exigencies of participation do not override the environmental exigencies of the problem being addressed.

WHAT IS NEEDED FROM SCIENCE AND TECHNOLOGY?

Recent efforts have begun to outline the core questions that a mature science of the Earth system would strive to answer (Carley and Shapens 1998; Kates et al. 2001; Sahagian and Schellnhuber 2002). In our discussions, we focused on three groups of questions directly tied to the reconceptualization of sustainability goals quoted earlier: (a) meeting human needs while putting less pressure on the Earth's life-support systems, (b) identifying relatively "safe" or "benign" domains of operation for the Earth system, and (c) assessing the efficacy of institutions and institutional change.

Meeting Human Needs: Integrated Systems of Production, Consumption, and Distribution

The post-industrialization period witnessed large-scale commodification of natural resources, in many cases without an appropriate consideration of the resultant environmental stresses (Carley and Christie 2000). Emphasis was on overall production and consumption, with little attention paid to equitable distribution. An essential need is to explore how alternative systems of production, consumption, and distribution can be configured to provide greater levels of human prosperity while producing significantly lower levels of environmental stress, and while simultaneously accounting for regional and sectoral differences in such systems. Work has already been conducted on the production side, with efficiency improvements, "green design" principles, and pollution recovery or sequestration measures proposed to reduce environmental pressures per unit of goods produced. In addition, the science community has begun to understand the sources of variance of human consumption patterns beyond mere income and opportunity (Princen et al. 2000; Heap and Kent 2000). As part of the research agenda on economic globalization, attention has begun to focus on ways in which the increasing physical separation of production and consumption activities can lead to substantial additional environmental burdens because of extensions to distribution systems (Chisholm 1990). Nonetheless, only in the areas of energy needs and global product chains does the scientific community have even the beginnings of an integrated understanding of the environmental pressures imposed by alternative production–consumption–distribution systems (ICSU et al. 2002; von Moltke et al. 1998). Such integrated analyses of full "systems" options for advancing human well-being are badly needed as management tools to avoid the technical pitfalls inherent in focusing policy on only one or another dimension of the production–consumption–distribution chain. There are also political and equity imperatives for developing such integrated views due to the increasing tendency for rich regions' consumption to be produced in poor regions, which thereby incurs a disproportionate share of the resultant environmental burden (Gwinne 1999). Without an objective and verifiable understanding of such inevitable asymmetries, the prospects for rational management of a sustainability transition will be severely constrained. Investigation of alternative integrated systems of production, consumption, and distribution are needed in at least each of the basic needs identified by the UN Secretary General in his "WEHAB" agenda (i.e., water, energy, health, agriculture, and conservation of biodiversity; Annan 2002). A good case can be made for such analyses in the area of human habitation as well.

Protecting Lifestyles and Livelihood: Delineating "Safe" Regions, Trajectories, and Their Boundaries

One of the major challenges in achieving a transition to sustainability is the capacity of the Earth system (or parts of it) to experience sudden and irreversible shifts to undesirable or even catastrophic domains (e.g., global collapse of fisheries, cessation of thermohaline circulation, inundation of low-lying areas by sea-level rise). These "precipices" can be particularly difficult to avoid when early-warning signals of impending disaster are weak, unnoticed, or tardy relative to the time when mitigative or remedial action must be taken. Unfortunately, science has progressed very little in its capacity to identify relatively "safe" or "benign" domains in which the Earth system can operate, or safe trajectories that provide a reasonable expectation of remaining in these domains. Part of the difficulty lies in the definitions of safe and benign. At their most conservative, the words might be taken to mean that excursions across "nasty and irreversible" state changes have little chance of occurring, or can be avoided. The words as applied to the socioeconomic system may be more problematic. The history of complex civilizations suggests that life is rarely safe or benign for those at the lower levels of society. Defining safe and benign domains appropriately may require identifying "minimal" criteria that avoid increasing the share of society currently at risk due to environmental degradation, more desirable criteria in which environmental risk is actually decreased, and a minimum acceptable quality of life for all people. Whether this latter state would be considered benign by those in the lowest social strata is a matter of speculation.

Making progress in this area first requires that scientists be able to identify the principal "state variables," both socioeconomic and biogeophysical, that describe the Earth system. These state variables could then be used to identify the existence, nature, and location (in time and space) of thresholds and the more desirable domains of attraction. Since nasty and irreversible thresholds should be avoided both on regional and global scales, a more sophisticated understanding of cross-scale interactions and dynamics is warranted. Early-warning signals of change should be identified whenever possible and used to develop indicators of sustainability that can be updated and checked on a regular basis.

This will not be easy. Addressing the issue of thresholds and domains of attraction alone may take the better part of a generation. However, it must be done.

Improving the Capacity to Cope with Environmental Change: Institutions and Institutional Change

It is widely recognized that scientific information is not the only, and may not even be the primary, limitation to achieving a transition to sustainability. Lack of knowledge is frequently not the impediment to action. Global and national institutions will therefore have to evolve in many ways if humanity is to cope more effectively with global environmental problems. These changes will include, among other things: (a) recognition that Earth system maintenance is a necessary step in the pursuit of social good; (b) more effective means of handling long time horizons, including construction and negotiation of future scenarios; (c) recognition that the global marketplace can only provide some of the desired social goods (primarily those associated with the allocation of resources); and (d) capacity to recognize the possibilities and limitations of extending regionally tested institutions (e.g., emissions trading or participatory processes) to global scales. These changes must ultimately be driven by the public and governmental sectors; however, science has a role to play in analyzing and distilling past successes and failures, and providing guidelines for future institution-building efforts. We briefly elaborate on some of these research challenges below.

Scenario Building

Model development and scenario building involve the social components of the Earth system. At the simplest (although by no means simple) level, social drivers must be included in various models of the system. This, in turn, requires collecting, analyzing, and including certain social variables that have frequently been ignored in such exercises. Scenarios are not predictions, but rather explorations of the future. Strictly speaking they are not science, but careful exercises of imagination informed by science and other sources (Schwartz 1991). Scenarios can, however, be useful in understanding the choices that may face humanity in elucidating the long-term consequences of our actions and in providing a focus for science–policy dialogues. As such, they can provide useful perspectives for defining scientific priorities and exploring the implications of scientific findings in terms of sustainable development (Gallopín 2002). Scenario building, in general, needs to incorporate more quantitative elements, criteria of plausibility, and new understandings generated by Earth system science.

Effective scenario building also requires identifying the indicators or parameters of interest to the stakeholders whom the scenario-building exercise is hoping to inform. Success at such efforts requires involving stakeholders in defining the output parameters of the models or scenarios that are most relevant to the decisions they will need to be making. This process will most likely be an iterative one in which stakeholders identify initial parameters of interest, but then those parameters are revised in response and reaction to the scenario-building exercises undertaken. As with initial efforts in the natural sciences, first efforts from the social sciences are likely to be simplistic and unsophisticated, even to those creating them. However, over time, efforts in this direction are likely to pay large dividends in terms of the ability to develop models that more accurately reflect likely scenarios for the future of the Earth system than are currently being constructed.

Investments

Technological change is driven by a suite of drivers, but among them are investments. The determinants of investment decisions are, however, poorly understood by economists. Many models used in climate economics (e.g., the Ramsey model) implicitly assume that there is a complete set of future markets that guarantees intertemporal efficiency. However, recent developments have shown that capital markets are by no means intertemporally efficient. If this is true, the formation of expectations of investors as a process of social learning becomes an important issue. This formation could be influenced by global environmental management: quotas for renewable energy, tradeable permits, or carbon sequestration bonds can help to enforce investments that have a long time horizon. Until now, this insight has been widely neglected by global environmental policy. A challenging research area would be to assess institutional designs that have the potential to stabilize expectations and redirect capital flows to make an economy more sustainable.

Time Horizons and Discount Rates

Solving environmental problems frequently requires a long time horizon in decision making. Therefore, the discounting of damages of environmental change and the costs of mitigation are a highly debated issue, not least because policy advice depends heavily on the assumed discount rate. Many economists argue for the use of a discount rate that can be observed in capital markets. This argument becomes less convincing, however, in light of the increasing discount rate in many OECD countries over the last three decades, which suggests that the time horizon of investors and politicians has been reduced. Little is known about the determinants of discount-rate variation. Some social scientists have argued that both capital markets and democratic institutions tend to reduce time horizons and increase discount rates. If discount rates are susceptible to such influences, we may want to investigate how institutions can use policies to self-consciously lengthen the time horizons and decrease the discount rate, of politicians and investors, since that can increase attention to long-term environmental effects.

Extending Successful Institutions to Larger Scales

In many cases, there are local institutions that work quite effectively at resolving tragedies of the commons and other forms of environmental problems (Kaul 1996; Keohane and Ostrom 1995; Ostrom 1990; Ostrom et al. 1999). Currently an important question is whether and how lessons from these local institutions can be generalized to other localities and "scaled up" to national, regional, or global scales. Efforts in this direction require research into not only why particular local institutions were effective, but also into identifying both analogues to the sources of success in the case analyzed as well as factors in the local context that might facilitate or inhibit such strategies from working in other local settings or at higher levels of social aggregation. There is considerable room for research in identifying how lessons from useful but non-analogous situations have been and could be applied to institutions at other levels and other contexts.

Institutional Renewal

Organizations tend to grow toward large and inflexible bureaucracies aimed more toward their self-perpetuation and enhancement of power than toward the original goals they were designed to pursue. This is particularly true for organizations and agencies working outside the marketplace (where such inflexibility tends to be self-correcting). This hazard faces many natural-resource management agencies and organizations.

There is a healthy and growing literature on the kinds of institutional structures and rules that allow continued "renewal" (flexibility, adaptation) and avoid excessive, and ultimately crippling, bureaucratization. These include a fostering of small-scale "creative destruction" cycles that allow contained questioning of current conditions and creation of new strategies and approaches that can come to permeate the larger organization. More work is needed in understanding how the continued renewal and adaptation is best achieved.

A SCIENCE–POLICY DIALOGUE

If scientists are to realize their full potential in helping to pilot a transition to sustainability, they need to understand the hybrid character of a science that serves policy (Jasanoff and Wynne 1998) and the context-specific character of the interface. In particular, both scientists and policy makers must be constantly aware that they are different actors bound by diverse sets of goals and tools, with different abilities to perceive and digest uncertainty (Weiss 1978). Moreover, there are constraints to the use of scientific decision makers by policy makers, and to the use of public information by scientists, that arise from the beliefs, paradigms, and cultures surrounding the various participants in the dialogue (March and Olsen 1989). We elaborate on some of this below.

Setting Priorities for Science and Technology

Traditionally, scientists have viewed themselves as the best arbiters of appropriate questions and areas of inquiry. Negotiation with non-scientists concerning these questions is often viewed with skepticism because the resulting science is perceived as being tainted. More recently there have been calls for a "new contract" of science with society, formalizing the responsibility of scientists to be responsive to society's articulated needs (Lubchenco 1998). Similar relationships already exist in the areas of health and industrial and corporate development. There is therefore nothing fundamentally new about the notion that certain branches of science should be devoted to meeting human needs and can operate most effectively when listening to societal expressions of which outcomes are and are not desirable. This sort of social contract has not, however, been strongly present in the area of the environment. Its time has come. The science community must facilitate communication with the public and policy makers in ways that allow legitimate participation by a wide variety of stakeholders in determining the types of questions that will be asked by the scientific community and the appropriate level of resources devoted to these questions. Such advances will not be easy; in politically charged policy-making environments, for instance, scientific information is often used to insulate policy making from public accountability (Lemos et al. 2002).

Scientists need not merely wait for non-scientists to cast their votes. They can and should have strong input into the process in two ways. First, they can expand the agenda considered by the public by revealing hazards or compelling areas of inquiry of which the public may be unaware. Second, they can help in ordering the priorities, from those that are most pressing or most ripe, to those where achievement may rest on other advances, and thus be more distant.

Finally, a note of caution. It should not be assumed that humanity will have "smooth sailing" if only it could get past the current environmental problems. Were the world to solve these, others would appear. Society cannot begin to anticipate the kinds of knowledge or information we might need to solve these (unknowable) future challenges. There will always be a place for curiosity-driven science to expand the body of knowledge from which the world can make use. This pushing of intellectual frontiers is also what ultimately makes us human. We are thus not suggesting that all science be subjected to public negotiations concerning immediate needs. However, the challenges today are pressing enough that a greater proportion of our efforts need to be placed in a responsive science devoted to questions of sustainable development.

Scientific Analysis and Inquiry

The modes of objective analysis developed and refined as part of the scientific process have served the community well, and there is little room for negotiation with the public and policy makers concerning these approaches. Nonetheless, we highlight three areas in which it is critical for scientists to make advances in analysis and inquiry.

Lay Knowledge

Several studies have noted the tremendous benefits that can be derived by tapping the sophisticated understanding of coupled human–environment interactions held by many in society who have no formal advanced scientific training but do have extensive firsthand experience with the consequences of those

interactions, sometimes referred to as the "lay public." These benefits include the capacity to gain access to and even test predictions immediately against data about the past already available in the minds and memories of the lay public, without having to wait for additional long-term experimentation or observation; the ability to use several different independent information sources in analysis; and an increased transparency and legitimacy of the scientific process in the eyes of the ultimate users of scientific information.

In spite of these benefits, the use of lay knowledge is limited both by the abilities of scientists to identify and sift such knowledge, and by a scientific culture that places a high value on data derived in standard scientific fashion. The scientific community must overcome both, which will place certain demands on our training program. How is lay knowledge effectively and respectfully elicited? Who are the holders of lay knowledge, and how does one know when one has enough? How are data of several different types — from narratives to lists of numbers — to be reconciled and compared?

The scientific community currently engaged in gathering lay knowledge has, however, developed certain guidelines for its incorporation. For example:

1. Make no judgments about the adequacy of conceptual models or methods.
2. Apply the same broad evidentiary principles to all sources of knowledge:
   (a) Traceability: The source of knowledge must be known and shared.
   (b) Repeatability/testability: There must be sufficient internal consistency in the knowledge system that different practitioners within that system provide compatible information and the same practitioner provides compatible information at different times (allowing for learning).
   (c) (Un)certainty: A statement of confidence should accompany key findings, along with an explicit statement about the limits of knowledge (e.g., under which circumstances is it valid, and for which period and area).

Evidentiary Standards

The scientific process is built on the goal of advancing knowledge — penetrating and reducing the reaches of what is not known. Each advance is built on knowledge acquired earlier. The cost of incorrect knowledge is therefore quite high, affecting not only that building block in the foundation, but those that follow. Science has thus evolved procedures whose primary goals are to protect against incorrect generalizations. This includes the use of relatively strict evidentiary standards designed to assure the generalizability of results.

This emphasis on strict evidentiary standards selects for fairly reductionist approaches to studying phenomena whose drivers can be tightly controlled and manipulated. Until recently, this meant largely avoiding study of precisely the kinds of environmental systems that society is influencing most profoundly: global climate systems, entire ecosystems, or landscapes. Scientists must also advance their capacity to convey what is known and what is unknown in these (sometimes highly) uncertain systems. Scientists will have to enhance their capacity to perform synthesis and assessment (drawing in large part on the past experiences with such efforts), to use Bayesian and other approaches for revising our measures of uncertainty in the light of new knowledge, and employ alternative forms of conveying uncertainty (confidence limits, consensus statements on what is and is not known). This places many demands on the training of graduate students, and an overhaul of graduate curriculums may be necessary.

Communicating the Results of Science

Much has been written about the need to improve communication among scientists, the public, and policy makers. This dialogue is crucial not only for introducing needed scientific information into decision-making processes, but for defining the appropriate areas for scientific inquiry, as we have already noted. The scientific community could improve this dialogue in several ways.

The first is to recognize that policy makers are not the only, and may not even be the most important, recipients of scientific information. Changes in policy frequently come as the result of a rising awareness in civil society about a class of problems that are inadequately addressed in the policy arena. Such dynamics characterize, at least in part, the politics of climate change; civil society also played a crucial role in spawning the environmental movement of the 1960s, which led to many new national and international environmental policies. Scientists must spend more time distilling scientific information for the public, thus enhancing their ability to understand science. This means more public lectures, more articles for magazines, and greater efforts at web-based or video-based lectures.

Perhaps the thing that most hampers effective scientific communication, however, is the arrogance that scientists often bring to the table. Scientists have been trained to hone their analytic abilities and frequently believe, or at least behave as if they believe, that their abilities are superior to those of anyone else. This is revealed in their assumptions that policy makers are unable to deal with complexity or uncertainty, and that the scientists themselves know best about how to choose among alternative courses, even when choosing among these courses ultimately involves a (subjective) choice among competing values. Scientists have a unique role to play in society, but it is by no means a role superior to others being taken.

"Communication" must therefore be a conversation, not a lecture. Scientists must expend more effort listening to and conversing with multiple publics in an effort to understand better the concerns and questions as well as models and evidence that drive broader social views of human–environment interactions.

WHAT DOES THIS MEAN FOR THE ORGANIZATION OF SCIENCE AND TECHNOLOGY?

Achieving the above, in terms of extending science to new areas of inquiry and facilitating a dialogue between the scientific community, civil society, and policy-making bodies, will mean introducing some new structures and organizing principles to the scientific community. Here we focus on three new endeavors: (a) building a global observation network for sustainability, (b) implementing global-level institutions for sustainability assessment, and (c) enhancing scientific capacity in all regions of the world.

Observation Networks: A "Macroscope"

Management that seeks to span scales in space ("think locally, act globally"), time ("take care of our grandchildren"), and topical categories ("combine human welfare with environmental stability") requires observational data to support analysis, argument, and action across these scales. Given that the departure point of experience and observation is almost completely local, creating generalized views on coarser scales is the main challenge. To build such "macroscopes" (instruments that do not view the far, such as telescopes, or the small, such as microscopes, but rather bring into view interconnections of first order between major subsystems of a complex world; see Lucht and Pachauri, this volume) requires a close coevolution of observation and corresponding formalization.

Observational data are necessary to ground thinking about the Earth system in the reality of what that system actually does, rather than in guesses about, or metaphors of, what it might do. Today, and with respect to a science of sustainability, the world lacks adequate global-scale systems for the selected observation of ecosphere–biosphere interactions. Such macroscope systems of observation and reporting, built to complement the existing systems of environmental, economic, and social measurement and accounting, are required to provide an empirical foundation, a system of empirical reference, for sustainability science.

Building macroscopic observation and reporting systems that span the whole of the Earth system, particularly the coupling of the physical, biological, and human components, is a central challenge to Earth system analysis. Properly executed, such systems would facilitate bidirectional switching — between local realities and macroscopic views of the planet — that is a prerequisite for the occurrence of a collective (though spatially and temporally heterogeneous) global intent and action. It would also support the communication between different actors at different scales that will be necessary for the emergence of a democratic and participatory form of global will. The knowledge generated through such macroscope systems cannot be the privileged possession of only some actors in the global system, but will have to be widely distributed and accessible to all.

Global Organizations for Earth System Analysis

Taking care of the Earth system and ensuring ultimate sustainability require arrangements that far transcend the scope of local communities, regions, and sovereign states. Without the full support and participation of greater entities, little can be realistically achieved.

There are a few broad methods for achieving such support. The first is to make better use of existing institutions. For the United Nations, there exists a multiplicity of topical programs ranging from the UN Environmental Program to the UN Development Program, plus such decision-making and operational groups as the General Assembly, the Economic and Social Council, and the Commission on Sustainable Development. On the scientific side, there is the International Council for Science, with its existing international research programs and its new commitment to sustainability science (ICSU 2003); the International Social Science Council (ISSC); and the Third World Academy of Science and new Inter-Academy Council, which are bringing together the world's main scientific academies on sustainability issues. There is also a range of ongoing international scientific assessments (ICSU et al. 2002). On the development side, there are countless organizations at all levels involved in sustainability issues (see, e.g., the web site of the International Institute for Sustainable Development at www.iisd.org). These groups have produced a variety of ongoing management programs as well as several hundred multilateral environmental agreements with different degrees of status and authority (Mitchell 2003).

There are some advantages to having the diverse set of approaches and perspectives represented in these organizations, not the least of which is the development of knowledge and expertise relevant to particular local or regional problems as well as a breadth of "natural experimentation" in trying to find compelling solutions to environmental problems. Nonetheless, their sheer multiplicity can mean that, collectively, they lack coherence and may undermine one another's effectiveness. No doubt more could and should be done to avoid overlap and make the work of existing programs more accountable and better coordinated. However, as things are, lack of coordination can blur the messages. Governments and business corporations can usually find means to ignore or sidestep their recommendations. Groups that want quality scientific information may not know where to turn. Moreover there is the constant danger that conflicts of interest and obligation will arise, particularly with the World Trade Organization.

A second method of proceeding is to create a new international organization that would coordinate existing institutions and devote itself to building bridges between science, technology, and the environment, on one hand, and their practical application for sustainability, on the other. The idea of a World Environment Organization has been promoted by a wide range of actors — including the German Chancellor, the French President, and the outgoing Director General of the World Trade Organization — as a way of achieving a balance between scientific, environmental, and trade considerations on a basis of broad equality, with the necessary arrangements for judging and settling any disputes or conflicts between them. Proponents have argued that such an organization would give sustainability, in all its complexity, a single and powerful focus at a global level. Opponents cite the dubious track record of "super" organizations trying to encompass environment and development at the international or national level. In our discussions, the desirability of a single world *environmental* organization to address issues of global *sustainability* remained very much a subject of debate.

A proposition favored by some, but not all, in our group is the creation of an international process for environment and sustainability assessments that would have a stature, authority, and scientific integrity at least the equivalent of the IPCC. There would be a single international coordinating body, but with regional forums on all the populated continents of the world. These regional forums would be devoted to *assessment* of the scientific knowledge base for sustainable development; the international coordinating body would facilitate dialogue among the regional forums, as well as serve as a clearinghouse for information from other ongoing regional and global assessments. As in the IPCC, the scientific analysis itself would not be subject to revision by policy makers, although the decisions concerning which areas of analysis are most useful and how they should be reported would be subject to negotiation. Other ongoing assessments should be studied to determine what does and does not work in fostering dialogue between scientists, politicians, and stakeholders, while still maintaining scientific independence and integrity in assessing the state of the world. Work done to date suggests that regional forums would need to play a much larger role in such sustainability efforts than they do currently in most international efforts (Clark et al. 2002; Farrell et al. 2001). These regional forums are of critical importance in ascertaining the different challenges that visit the major regions of the world, particularly the different sustainability challenges faced by the richer and poorer nations. To maximize learning, a fluid exchange of practitioners and information among these regional forums is necessary. Regional forums could also coordinate the crucial acquisition of lay knowledge and public priorities for assessment. Coordination in a single body holds the promise of raising the international profile of sustainable development, which is certainly as deserving of attention as global climate change.

Increasing Regional Scientific Capacity

There is an immense need to increase the capacity for research and development in many of the low- and middle-income regions of the world. Without this increased capacity, the world has little hope of solving the challenges of sustainable development: our knowledge of regional- and place-based dynamics would be incomplete, and our understanding of how cultural persuasion and social history influence perceptions of futures and efficacy of policies would be inadequate. Substantial new resources, far beyond those currently available for such capacity building, will be needed. The richer countries of the world need to see both the ethical and practical mandates for supplying such resources.

At the same time, it needs to be recognized that there are many developing countries that already have significant scientific capacity. The scientific community needs to draw on this capacity whenever possible. Human–environment interactions likely have different dynamics in different regions of the world; failure to test the insights gained in one region against another means both risking the opportunity to identify valid generalizations and missing the opportunity to probe local findings with relevant perspectives from elsewhere.

Individual

The capacity to train individual scientists from nations currently lacking in adequate scientific capacity must be increased. For many of these students, the best graduate education and training can still be found in the richer nations of the world; however, these programs need to encourage students to return to their home regions for dissertation research. It is also crucial that training and support not end with completion of a graduate degree. Modest postgraduate resources should be provided, including small "start-up" funds to begin in-country research, funds for a few return trips to the graduate institution and/or for travel to scientific meetings, as well as funds for journal subscriptions and crucial textbooks. It is essential that university programs come to consider this an indispensible part of the degree-granting process. Otherwise, individual scientists, returning to countries with weak support for science, risk failure or isolation, which seriously reduces the value of the degree.

Collaborative Research Teams

North–South and South–South research collaborations, and their equivalents, are a valuable way to enhance regional scientific capacity. The focus of much sustainability research should be place-based, either comparatively across sites located in several countries or at sites in less-developed nations. It is essential that these collaborative efforts be built on the assumption and practice of equity among all the participants, even though the funding contributions will rarely be equal. The design meetings for the research projects must, whenever possible, be held in the less-developed country to enhance the visibility of local scientific participants and to emphasize the local importance of the research being conducted. Similarly, outreach programs in which all scientific members participate, including "open days" and policy briefings, are crucial for visibility and future enhancement of capacity building. These outreach programs also provide a forum for obtaining societal feedback concerning the appropriateness of the research and the applicability of the findings. Data archives and networks must be maintained locally or regionally, in recognition of the "digital divide" that prevents many developing country scientists and citizens from accessing large data files stored in other locations. Information technology, therefore, needs to be an additional target of capacity building. All scientific findings should be made available locally and in local languages, either through direct translation of papers appearing in professional journals or through the production of reports containing the critical findings.

Institutions and Networks

The establishment of regional synthesis centers devoted to sustainability–environment issues can promote in-region scientific capability, both by supplying employment opportunities for local scientists and through networking with other institutions that can leverage resources and information. Regional synthesis centers should be established with clear connections to existing centers and organizations and, when possible, close physical proximity to some or all of those partner agencies. South–South networking is as crucial as North–South networking, and partner organizations in other countries in the region should be identified whenever possible. These regional synthesis centers could also serve as crucial links in the global to regional to local science–policy–public dialogue that we envision as a crucial component of the transition to sustainability. These centers could also facilitate South–South networking of individual scientists or research teams through workshops, short courses, and annual meetings.

The scientific community must make a particular effort to build capacity in regions that are isolated, or isolate themselves, from the global community as a result of political disagreements or dynamics. Long-term isolation from the global community has often resulted in serious environmental degradation, crushing economic problems, and tragic social dislocation. Recovery from this state of affairs will require scientific and technical capacity, and having even a modest foundation from which to start can alleviate significant human suffering.

CONCLUSIONS

We emerged from this Dahlem Workshop with recommendations in three areas: scientific inquiry, scientific communication, and organization of the science community (see Box 20.1). These recommendations necessitate changes in the culture of science (what scientists see as important and how they view their role in the environmental dialogue), in scientific training (producing students with a grasp of synthesis, improved abilities for broad dialogues, and the tools to analyze and convey complexity and uncertainty), and the resources devoted to science (new research programs, establishment of an international assessment body, and regional capacity building).

Box 20.1 Recommendations emerging from the 91[st] Dahlem Workshop.

1. Promote new Earth system sustainability research in the areas of:
   - Meeting human needs by designing integrated systems of production, consumption, and distribution that radically reduce environmental impact.
   - Protecting life and livelihood support systems by delineating relatively "safe" or "benign" domains in the Earth system, including with it the identification of the principal biogeophysical and socioeconomic variables that define the state of the Earth system.
   - Improving human capacity to cope with environmental problems by improving the efficacy of institutions in linking the global and the local.
2. Improve scientific communication by:
   - Including the public and policy makers in identifying key questions and priority research areas in Earth system studies.
   - Incorporating lay knowledge in scientific analysis and assessments.
   - Employing a broader suite of tools for analyzing and conveying complexity and uncertainty.
3. Enhance the capacity of the science and technology community to provide scientific information on sustainability by:
   - Developing global observing networks for sustainability with an integrative regional focus.
   - Promoting internationally coordinated scientific assessment on the implications of different development paths for sustainability.

Given the plethora of books, reports, and articles written on sustainability, sustainable development, and the need for reform in the scientific community, we suspect there is little in this document that is new. Nonetheless, there is ample evidence that progress is made not only by saying something new, but by saying something, old and true, repeatedly. Thus, we say it again. The current state of affairs — including the extant approaches to scientific research and the capacity to sustain a reasonable dialogue among scientists, policymakers, and the public — is simply incommensurate with the challenges the world faces.

History has shown that humanity will not discover a pathway toward sustainability by accident. A conscious awareness of civilization's present and possible future trajectories as well as a conscious effort toward continuous learning and course correction is necessary. Moreover, humanity must improve upon the abilities of previous, and now absent, complex civilizations for such self-reflection. Technological, scientific, economic, and political advances give rise to an optimism that we may develop an adequate "global will" for sustainable development. The immensity of the challenge — including its global nature, potential for irreversible excursions into undesirable or catastrophic states, and long time dynamics — is more sobering.

A FINAL NOTE

There was a broad sweep of topics at the 91[st] Dahlem Workshop on Earth System Analysis for Sustainability: from a retrospective assessment of the emergence of life over the 4-billion-year history of the planet (see Chapter 6, this volume) to a forward-looking assessment of the prospects for a transition toward sustainability in our group. What connects these dialogues in a single conference? A guiding principle for some, but not all, of the participants is Gaia — a notion that life creates the conditions for its own persistence. If humanity is to achieve a transition to sustainability, it will likely require a fundamental shift in the prevailing view of the world: from linear, compartmentalizable, mechanical to complex, interconnected, living. In this, Gaia may provide some hope and some answers. We resist, however, the suggestions of some that Gaia may also provide a blueprint for humanity's transition to sustainability. A principle that may explain the emergence and persistence of life broadly over an ancient and archaic sweep of time seems to have little in common with the efforts of a single species to not just maintain life in general but to enhance it for all its members in the space of a century or so. Humans are a unique species, with language, foresight, memory, and dreams. Those dreams tell us that the goal of humanity is not merely to persist, but to thrive.

ACKNOWLEDGMENTS

We have benefited from fruitful conversations with all of the participants at this Dahlem Workshop. We wish to thank particularly Bert Bolin, Alison Jolly, Bob Scholes, Will Steffen, Nebojsa Nakicenovic, and Liana Talaue-McManus for thoughtful comments that contributed directly to the discussions and conclusions contained in this report.

REFERENCES

Allen, T.F.H., J.A. Tainter, and T.W. Hoekstra. 2003. Supply-side Sustainability. New York: Columbia Univ. Press.

Annan, K. 2002. Toward a sustainable future. *Environment* 44:10–15.

Berkes, F., and C. Folke, eds. 1998. Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience. Cambridge: Cambridge Univ. Press.

Bourdieu, P., J.-C. Passeron, and C. Chamboredon, eds. 1983 (1968). Le métier de sociologue: Préalables épistémologiques. Paris: Mouton.

Bromley, D., ed. 1992. Making the Commons Work: Theory, Practice, and Policy. San Francisco: ICS Press.

Burger, J., E. Ostrom, R.B. Norgaard, D. Policansky, and B.D. Goldstein, eds. 2001. Protecting the Commons: A Framework for Resource Management in the Americas. Washington, D.C.: Island Press.

Carley, M., and I. Christie. 2000. Managing Sustainable Development. London: Earthscan Publ.

Carley, M., and P. Shapens. 1998. Sharing the World: Sustainable Living and Global Equity in the 21st Century. London: Earthscan Publ.
Chisholm, M. 1990. The increasing separation of production and consumption. In: The Earth as Transformed by Human Action: Global and Regional Changes in the Biosphere over the Past 300 Years, ed. B.L. Turner II, W.C. Clark, R.W. Kates et al., pp. 87–101. Cambridge: Cambridge Univ. Press.
Clark, W.C. 2000. Environmental globalization. In: Governance in a Globalizing World, ed. J.J. Nye and J. Donahue, pp. 86–108. Washington, D.C.: Brookings Press.
Clark, W.C., R. Mitchell, D.W. Cash, and F. Alcock. 2002. Information as influence: How institutions mediate the impact of scientific assessment on global environmental affairs. Working Paper RWP02–04. Cambridge, MA: Kennedy School of Govt.
Dovers, S., and C. Mobbs. 1997. An alluring prospect? Ecology and the requirements of adaptive management. In: Frontiers in Ecology: Building the Links, ed. N. Klomp and I. Lunt, pp. 39–52. London: Elsevier.
Farrell, A., J. Jäger, and S. VanDeveer. 2001. Environmental assessments: Four under-appreciated elements of design. *Global Env. Change* **11**:311–333.
Folke, C., S. Carpenter, T. Elmqvist et al. 2002. Resilience and Sustainable Development: Building Adaptive Capacity in a World of Transformations. Series on Science for Sustainable Development, No. 3. Paris: ICSU (Intl. Council of Sci. Unions).
Gallopín, G.C. 2002. Planning for resilience: Scenarios, surprises, and branch points. In: Panarchy: Understanding Transformations in Human and Natural Systems, ed. L. Gunderson and C.S. Holling, pp. 361–392. Washington, D.C.: Island Press.
Gunderson, L., and C.S. Holling, eds. 2001. Panarchy: Understanding Transformations in Human and Natural Systems. Washington, D.C.: Island Press.
Gunderson, L., C.S. Holling and S.S. Light, eds. 1995. Bridges and Barriers to the Renewal of Ecosystems and Institutions. New York: Columbia Univ. Press.
Gwinne, R. 1999. Globalization, commodity chains, and fruit exporting regions in Chile. *Tidschrift voor Economische en Sociale* **90**:211–226.
Hardin, G. 1968. The tragedy of the commons. *Science* **162**:1343–1348.
Heap, B., and J. Kent, eds. 2000. Towards Sustainable Consumption: A European Perspective. London: The Royal Society.
Holling, C.S., ed. 1978. Adaptive Environmental Assessment and Management. London: Wiley.
ICSU, ISTS and TWAS. 2002. Science and Technology for Sustainable Development: Consensus Report and Background Document for the Mexico City Synthesis Conf., 20-23 May 2003. Series on Science for Sustainable Development, No. 9. Paris: ICSU.
ICSU. 2003. Report of the CSPR Assessment Panel on Environment and its Relation to Sustainable Development, ed. R. Watson, A. Buttimer, A. Cropper et al. Paris: ICSU.
Jasanoff, S., and B. Wynne. 1998. Science and decision-making. In: Human Choice and Climate Change: The Societal Framework, ed. S. Rayner and E. Malone. Columbus: Battelle Press.
Kates, R.W., W.C. Clark, R. Corell et al. 2001. Sustainability science. *Science* **292**:641–642.
Kaul, M.C. 1996. Common Lands and Customary Law: Institutional Change in North India over the past Two Centuries. Delhi: Oxford Univ. Press.
Keohane, R.O., and E. Ostrom, eds. 1995. Local Commons and Global Interdependence. Thousand Oaks, CA: Sage Publ.
Lee, K. 1993. Compass and Gyroscope: Integrating Science and Politics for the Environment. Washington, D.C.: Island Press.

Lemos, M.C., T.J. Finan, R.W. Fox, D.R. Nelson, and J. Tucker. 2002. The use of seasonal climate forecasting in policymaking: Lessons from Northeast Brazil. *Climatic Change* **55**:479–507.
Lubchenco, J. 1998. Entering the century of the environment: A new social contract for science. *Science* **279**:491–497.
March, J.G., and J.P. Olsen. 1989. Rediscovering Institutions. New York: Free Press.
McCay, B.M., and J.M. Acheson, eds. 1987. The Question of the Commons: The Culture and Ecology of Communal Resources. Tucson: Univ. Arizona Press.
Mitchell, R.B. 2003. International environmental agreements: A survey of their features, formation, and effects. *Ann. Rev. Env. Resour.* **28**: 429–461.
NRC (National Research Council). 1996. Upstream: Salmon and Society in the Pacific Northwest, ed. Board on Environmental Studies and Toxicology, Committee on Protection and Management of Pacific Northwest Anadromous Salmonids, p. 472 ff. Washington, D.C.: Natl. Acad. Press.
NRC 1999. Our Common Journey: A Transition Toward Sustainability. Washington, D.C.: Natl. Acad. Press.
Ostrom, E. 1990. Governing the Commons: The Evolution of Institutions for Collective Action. Cambridge: Cambridge Univ. Press.
Ostrom, E., J. Burger, C.B. Field, R.B. Norgaard, and D. Policansky. 1999. Revisiting the commons: Local lessons, global challenges. *Science* **284**:278–284.
Ostrom, E., T. Dietz, N. Dolsak et al., eds. 2002. The Drama of the Commons. Washington, D.C.: Natl. Acad. Press.
Princen, T., M. Maniates, and K. Conca, eds. 2000. Confronting Consumption. Cambridge, MA: MIT Press.
Redman, C.L. 1999. Human Impact on Ancient Environments. Tucson: Univ. Arizona Press.
Redman, C.L., and A.P. Kinzig. 2003. Resilience of past landscapes: Resilience theory, society, and the longue durée. *Conserv. Ecol.* **7**:14[online]. http://www.consecol.org/vol7/iss1/art14/index.html
Sahagian, D., and H.-J. Schellnhuber. 2002. GAIM in 2002 and beyond: A benchmark in the continuing evolution of global change research. *IGBP Newsl.* **50**:7–10.
Schwartz, P. 1991. The Art of the Long View. New York: Doubleday.
Simon, H. 1977. Models of Discovery and Other Topics in the Methods of Science. Boston: Reidel Publ. Co.
Steffen, W., J. Jäger, D.J. Carson, and C. Bradshaw, eds. 2003. Challenge of a Changing Earth: Proc. Global Change Open Science Conference, Amsterdam, The Netherlands, July 10–13, 2001. Newbury: CPL Press.
Tainter, J.A. 1988. The Collapse of Complex Societies. Cambridge: Cambridge Univ. Press.
Turner, B.L. II, W.C. Clark, R.W. Kates et al., eds. 1990. The Earth as Transformed by Human Action: Global and Regional Changes in the Biosphere over the Past 300 Years. Amsterdam: Cambridge Univ. Press.
Vitousek, P.M., H.A. Mooney, J. Lubchenco, and J.M. Melillo. 1997. Human domination of the Earth's ecosystems. *Science* **277**:494–499.
von Moltke, K., O.J. Kuik, N.M. van der Grijp et al. 1998. Global Product Chains: Northern Consumers, Southern Producers, and Sustainability. UNEP Environment and Trade Series 15. Geneva: UNEP.
Walters, C. 1986. Adaptive Management of Renewable Resources. New York: MacMillan.

Walters, C. 1997. Conservation ecology: Challenges in adaptive management of riparian and coastal ecosystems. *Conserv. Ecol.* 1:1 [online] http://www.consecol.org/vol1/iss2/art1/

WCED (World Commission on Environment and Development). 1987. Our Common Future. Oxford: Oxford Univ. Press.

Weiss, C.H. 1978. Improving the linkage between social research and public policy. In: Knowledge and Policy: The Uncertain Connection, ed. L.E. Lynn, pp. 23–81. Washington, D.C.: Natl. Acad. Press.

Young, O.R. 2002. The Institutional Dimensions of Environmental Change: Fit, Interplay, and Scale. Cambridge, MA: MIT Press.

Young, O.R., A. Agrawal, L.A. King et al. 1999. Institutional Dimensions of Global Environmental Change (IDGEC) Science Plan. Hanover, NH: IDGEC Intl. Project Office. [online] http://fiesta.bren.ucsb.edu/~idgec/html/publications/publications.html