Series on Science for Sustainable Development No. 3

INTERNATIONAL COUNCIL FOR SCIENCE

... strengthening international science for the benefit of society...



Resilience and Sustainable Development

Science Background Paper commissioned by the Environmental Advisory Council of the Swedish Government in preparation for WSSD

ICSU Series on Science for Sustainable Development

The ICSU Series on Science for Sustainable Development is produced by the International Council for Science in connection with preparations for the 2002 World Summit on Sustainable Development (WSSD). The aim of WSSD is to bring together governments, United Nations agencies and other key stakeholders, including representatives of civil society and the Scientific and Technological Community, to build upon the 1992 United Nations Conference on Environment and Development (UNCED) and to enhance efforts toward the future of sustainable development. The Series includes a set of inter-disciplinary reports focusing on major issues that are relevant to science for sustainable development. The Series is meant to serve as a link between the scientific community and decision-makers, but the reports should also be useful to all others interested in the contribution of science to sustainable development. The Series highlights the fundamental role science has played and will play in finding solutions to the challenges of sustainable development. It examines experiences since UNCED and looks towards the future. It provides up-to-date knowledge, examines lessons learned, successes achieved, and difficulties encountered, while also outlining future research agendas and actions to enhance problem solving and good practices in sustainable development. The Series was made possible due to a generous grant provided by the David and Lucile Packard Foundation.

ICSU

The International Council for Science (ICSU) is a non- governmental organisation representing the international science community. The membership includes both national science academies (98 members) and international scientific unions (26 members). The combined expertise from these two groups of scientific organisations provides a wide spectrum of scientific expertise enabling ICSU to address major international, interdisciplinary issues, beyond the scope of the individual organisations. ICSU builds upon this scientific expertise in a number of ways. It initiates, designs and co-ordinates major international, interdisciplinary research programmes, particularly in the areas of global environmental change. It also establishes policy and advisory committees to address important matters of common concern to scientists, such as education and capacity building in science, access to data, or science in developing countries. ICSU acts as a focus for the exchange of ideas, communication of scientific information and development of scientific standards and networks. Because ICSU is in contact with hundreds of thousands of scientists worldwide, it is often called upon to represent the world scientific community.

ICSU Series on Science for Sustainable Development No. 3

Resilience and Sustainable Development: Building Adaptive Capacity in a World of Transformations

by
Carl Folke, Steve Carpenter, Thomas Elmqvist, Lance Gunderson, CS Holling, Brian Walker, Jan Bengtsson, Fikret Berkes, Johan Colding, Kjell Danell, Malin Falkenmark, Line Gordon, Roger Kasperson, Nils Kautsky, Ann Kinzig, Simon Levin, Karl-Göran Mäler, Fredrik Moberg, Leif Ohlsson, Per Olsson, Elinor Ostrom, Walter Reid, Johan Rockström, Hubert Savenije and Uno Svedin

Scientific Background Paper commissioned by the Environmental Advisory Council of the Swedish Government in preparation for WSSD

Suggested Citation:
International Council for Science. 2002. ICSU Series on Science for Sustainable Development: Resilience and Sustainable Development No. 3. 37 pp.

ISSN 1683-3686

Cover Images:
Each of the photographs on the cover represents one of the three pillars of sustainable development. (from left to right):
• Environment: © CNRS Photothèque / P. Dollfuss
View of Lake Yamdrok, a field of Mustard crops in southern Tibet.
• Social: © IRD / E. Katz
Mixtec woman washing coffee grains, Oaxaca, Mexico.
• Economic: © IRD / E. Deliry-Antheaume
View of the Newton, Johannesburg, Gauteng Province, South Africa.

Graphics and layout:
Atelier Marc Rosenstiehl, France

Printed by Stipa

Printed on recycled paper

Preface

Policy makers need information from many sources for their decision making. For issues related to sustainable development, the Scientific and Technological Community will provide essential background information. Research has in the past provided knowledge necessary for the development on international agreements on issues such as long-range transport of air pollutants, climate change and biodiversity. Without research and assessments of best available knowledge, it would have been very difficult to come to international agreements and policy commitments.

However, the research community has in the past primarily focussed on the natural sciences and the environmental pillar of sustainable development. Today, as we prepare for the World Summit on Sustainable Development (WSSD) in Johannesburg, the Scientific and Technological Community must address all three pillars: Social, Economic and Environmental. To do this, it is necessary to develop new methodologies to integrate information from natural and social sciences as well as economic research.

The research community has started to address the linkage between the ecological and the social systems. The present report argues the case for research aimed at developing management strategies that support the resilience of ecosystems, which are vital for the social systems through their production of goods and services. Policy makers as well as scientists, must take note of the necessity to understand the interdependence of these coupled systems. A paradigm shift will be necessary. The future is not what it has been, and the problems of tomorrow cannot be addressed using the concepts and methodologies of yesterday.

The WSSD process is focussed on the development of new partnerships for the implementation of Agenda 21. This report provides one example of such partnerships. This report was commissioned by the Swedish Environmental Advisory Council, chaired by the Minister for the Environment, as part of the Swedish preparations for WSSD. The report was written by a group of internationally renowned scientists and is published by ICSU as one example of the types of approaches needed to address science and technology for sustainable development. ICSU has been requested by the UN to take the lead in providing input from the Scientific and Technological Community to WSSD, and it has been decided to publish this report in the ICSU series to ensure that it becomes widely circulated to all the various groups involved in the WSSD process and to serve as an example of science and policy collaboration.

KJELL LARSSON
Minister for the Environment
Government of Sweden

THOMAS ROSSWALL
Executive Director
ICSU

Table of Content

Executive Summary

The goal of sustainable development is to create and maintain prosperous social, economic, and ecological systems. These systems are intimately linked: humanity depends on services of ecosystems for its wealth and security. Moreover, humans can transform ecosystems into more or less desirable conditions. Humanity receives many ecosystem services (such as clean water and air, food production, fuel, and others). Yet human action can render ecosystems unable to provide these services, with consequences for human livelihoods, vulnerability, and security. Such negative shifts represent loss of resilience.

New insights have been gained during the last ten years about the essential role of resilience for a prosperous development of society. A growing number of case studies have revealed the tight connection between resilience, diversity and sustainability of social-ecological systems. In this report we provide an up-to-date synthesis of these case studies and recent insights, in the context of emerging theories of complex systems characterized by uncertainty and surprise.

Resilience, for social-ecological systems, is related to (a) the magnitude of shock that the system can absorb and remain within a given state, (b) the degree to which the system is capable of self-organization, and (c) the degree to which the system can build capacity for learning and adaptation. Management can destroy or build resilience, depending on how the social-ecological system organizes itself in response to management actions.

More resilient social-ecological systems are able to absorb larger shocks without changing in fundamental ways. When massive transformation is inevitable, resilient systems contain the components needed for renewal and reorganization. In other words, they can cope, adapt, or reorganize without sacrificing the provision of ecosystem services. Resilience is often associated with diversity – of species, of human opportunity, and of economic options – that maintains and encourages both adaptation and learning. In general, resilience derives from things that can be restored only slowly, such as reservoirs of soil nutrients, heterogeneity of ecosystems on a landscape, or variety of genotypes and species.

Social-ecological systems are constantly changing. Usually one assumes that ecosystems respond to gradual change in a smooth way, but sometimes there are drastic shifts. Regime shifts are known for many ecosystems and these shifts can be difficult, expensive, or sometimes impossible to reverse. Although we understand ecological regime shifts retrospectively, it is difficult to predict them in advance. Measurements or predictions of thresholds typically have low precision, and often ecological thresholds move over time. It is difficult to design assessment programs that learn as fast as thresholds change.

One approach to the ongoing change of social-ecological systems has been the attempt to control or canalize change. Paradoxically, management that uses rigid control mechanisms to harden the condition of social-ecological systems can erode resilience and promote collapse. There are many examples of management that suppressed natural disturbance regimes or altered slowly-changing ecological variables, leading to disastrous changes in soils, waters, landscape configurations or biodiversity that did not appear until long after the ecosystems were first managed. Similarly, governance can disrupt social memory or remove mechanisms for creative, adaptive response by people, in ways that lead to breakdown of social-ecological systems.

In contrast, management that builds resilience can sustain social-ecological systems in the face of surprise, unpredictability, and complexity. Resilience-building management is flexible and open to learning. It attends to slowly-changing, fundamental variables that create memory, legacy, diversity, and the capacity to innovate in both social and ecological components of the system. It also conserves and nurtures the diverse elements that are necessary to reorganize and adapt to novel, unexpected, and transformative circumstances. Thus, it increases the range of surprises with which a socio-economic system can cope.

Building social-ecological resilience requires understanding of ecosystems that incorporates the knowledge of local users. Thus the ecological ignorance of some contemporary societies undermines resilience. The outdated perception of humanity as decoupled from, and in control of, nature is an underlying cause of society's vulnerability. Technological developments and economic activities based on this perception further contribute to the erosion of resilience. It can be counteracted by understanding the complex connections between people and nature, which create opportunity for technological innovations and economic policies aimed at building resilience.

Two useful tools for resilience-building in social-ecological systems are structured scenarios and active adaptive management. People use scenarios to envision alternative futures and the pathways by which they might be reached. By envisioning multiple alternative futures and actions that might attain or avoid particular outcomes, we can identify and choose resilience-building policies. Active adaptive management views policy as a set of experiments designed to reveal processes that build or sustain resilience. It requires, and facilitates, a social context with flexible and open institutions and multi-level governance systems that allow for learning and increase adaptive capacity without foreclosing future development options.

At least three general policy recommendations can be drawn from the synthesis of resilience in the context of sustainable development. The first level emphasizes the importance of policy that highlights interrelationships between the biosphere and the prosperous development of society. The second stresses the necessity of policy to create space for flexible and innovative collaboration towards sustainability, and the third suggests a few policy directions for how to operationalize sustainability in the context of social-ecological resilience.

1. Although most people appreciate that development is ultimately dependent on the processes of the biosphere, we have tended to take the support capacity of ecosystems for granted. This report illustrates that erosion of nature's support capacity leads to vulnerability. Policy should strengthen the perception of humanity and nature as interdependent and interacting and stimulate development that enhances resilience in social-ecological systems, recognizing the existence of ecological threshold, uncertainty and surprise.

2. Policy should stimulate the creation of arenas for flexible collaboration and management of social-ecological systems, with open institutions that allow for learning and build adaptive capacity. Policy frameworks with clear directions for action towards social-ecological resilience are required in this context (the EU watershed management directive is one example). They create action platforms for adaptive management processes and flexible multi-level governance that can learn, generate knowledge and cope with change. Such systems create a diversity of management options of significance for responding to uncertainty and surprise.

3. Policy should stimulate the development of indicators of gradual change and early warning signals of loss of ecological resilience and possible threshold effects. Policy should encourage monitoring of key ecosystem variables and aim to manage diversity for insurance to cope with uncertainty. Policy should stimulate ecosystem friendly technology and the use of economic incentives to enhance resilience and adaptive capacity. The development of monocultures should be avoided. Policy should provide incentives that encourage learning and build ecological knowledge into institutional structures in multi-level governance. Policy should invite participation by resources users and other interest groups and their ecological knowledge. Structured scenarios and active adaptive management processes should be implemented.

Managing for resilience enhances the likelihood of sustaining development in a changing world where surprise is likely. Resilience-building increases the capacity of a social-ecological system to cope with surprise. A changing, uncertain world in transformation demands action to build the resilience of the social-ecological systems which embrace all of humanity.

The need to account for resilience in a world of transformations is a perspective that should become embedded in strategies and policy of the World Summit on Sustainable Development and recognized in the next phases for implementation of Agenda 21.

Introduction

Sustainable development is about creating and maintaining our options for prosperous social and economic development. Sustaining this capacity requires understanding and managing feedbacks and interrelations among ecological, social and economic components of systems across temporal and spatial scales (Gunderson and Holling 2002, Kates et al. 2001). Human society is part of the biosphere and societies are embedded in ecological systems. The diversity of biotic systems across scales, from genes to landscapes, and the ecosystem services they generate, provides the basic foundation on which social and economic development depends.

Despite tremendous improvements in technological, economic and material well being in some parts of the world, development of human society still relies on ecosystems services and support, and will continue to do so. Therefore, a major challenge is to manage our interconnected environmental assets in a fashion that secures their capacity to support societal development for a long time into the future (Costanza et al. 2000).

Development challenges now evident in both rich and poor nations, with millions of people in scores of regions caught up in enormous ecological and social changes, are full of surprises and uncertainties (Holling 1986, Kates and Clark 1996). We are facing "permanent white-waters" which demands strategies for adaptation to uncertainty in contrast to the conventional emphasis on optimisation based on prediction (Malhotra 1999). To quote a decision-maker in a large multinational firm; "The future is moving so quickly that you can't anticipate it... We have put a tremendous emphasis on quick response instead of planning. We will continue to be surprised, but we won't be surprised that we are surprised. We will anticipate the surprise." (Malhotra 1999).

When surprise and the unexpected loom so large, partial economic, social or environmental solutions exclude the benefit of integration between social, ecological and economic processes and ignore the returns from resilient solutions. A foundation for sustainable policies and investments must integrate ecological with economic with institutional with evolutionary understanding – an understanding, grounded in empirical studies, that combines disconnected nodes of academic and managerial perspectives into a coherent, plausible and useful whole, one capable of guiding society to more productive, unfolding encounters with nature over uncertain and contested futures (Gunderson and Holling 2002).

A minimal integrated solution would involve selected social, economic and ecological actions at the appropriate scales. Because surprise is certain, the integration should be loose and adaptive, based not only on information and knowledge but also on understanding and wisdom (Gunderson and Holling 2002). Diversity is conserved to maintain and encourage adaptive and learning capabilities. Diversity of species performing critical functions, diversity of knowledge, institutions and human opportunity and diversity of economic supports all have the potential to contribute to sustainability and adaptive opportunity (Berkes et al. 2002).

Linked systems of people and nature, especially with the extent and interconnections of today's populations, technologies, and human activities, behave as complex adaptive systems (Levin 1999). Forward-looking analyses of these systems (Hammond 1998, Raskin et al. 1998, Nakicenovic and Swart 2000, GEO-3 Scenarios http://www1.unep.org/) suggest that the transition to sustainability derives from fundamental change in the way people think about the complex systems upon which they depend. Thus a fundamental challenge is to change perceptions and mind-sets, among actors and across all sectors of society, from the over-riding goal of increasing productive capacity to one of increasing adaptive capacity, from the view of humanity as independent of nature to one of humanity and nature as co-evolving in a dynamic fashion within the biosphere.

The Concept of Resilience

This paper will address the challenge using recent work related to the concept of resilience in complex adaptive systems (Holling 1986, 1996, 2001). Resilience provides the capacity to absorb shocks while maintaining function. When change occurs, resilience provides the components for renewal and reorganisation (Gunderson and Holling 2002, Berkes et al. 2002). Vulnerability is the flip side of resilience: when a social or ecological system loses resilience it becomes vulnerable to change that previously could be absorbed (Kasperson and Kasperson 2001a). In a resilient system, change has the potential to create opportunity for development, novelty and innovation. In a vulnerable system even small changes may be devastating. The concept of resilience shifts policies from those that aspire to control change in systems assumed to be stable, to managing the capacity of social-ecological systems to cope with, adapt to, and shape change. Managing for resilience enhances the likelihood of sustaining development in changing environments where the future is unpredictable and surprise is likely (Levin et al. 1998, Holling 2001).

The Resilience Alliance (www.resalliance.org) defines resilience as applied to integrated systems of people and nature as (a) the amount of disturbance a system can absorb and still remain within the same state or domain of attraction (b) the degree to which the system is capable of self-organization (versus lack of organization, or organization forced by external factors) and c) the degree to which the system can build and increase the capacity for learning and adaptation (Carpenter et al. 2001a).

The antonym of resilience is often denoted vulnerability. Vulnerability refers to the propensity of social and ecological system to suffer harm from exposure to external stresses and shocks. It involves exposure to events and stresses, sensitivity to such exposures (which may result in adverse effects and consequences), and resilience owing to adaptive measures to anticipate and reduce future harm (Kasperson et al. 1995). Coping capacity is important, at all stages, to alter these major dimensions. The less resilient the system, the lower is the capacity of institutions and societies to adapt to and shape change. Managing for resilience is therefore not only an issue of sustaining capacity and options for development, now and in the future, but also an issue of environmental, social and economic security (Germany Advisory Council on Global Change 2000, Adger et al. 2001).

A Road Map to the Paper

This paper, a synthesis of the rapidly-changing field of resilience research, was written as a scientific background document to the process of the World Summit on Sustainable Development. Because the paper attempts to cover a broad and diverse set of topics, we develop a guide to the remainder of this paper. We begin with a section that provides context by describing the linked systems of humans and nature as complex adaptive systems. The dynamic nature of these systems poses a challenge for those who seek sustainability–what should be sustained and why? The next section starts to address this paradox by providing examples that illustrate societies' dependence on ecosystem services and the tight coupling between societal development and ecosystem dynamics, as well as the role of key properties for sustainability–resilience and adaptive capacity. The next section exemplifies essential processes and mechanisms of resilience. These include descriptions of how humans erode resilience, how that erosion increases social and economic vulnerability, and how diversity in social-ecological systems can enhance resilience. These threads are gathered together in a section on managing for social-ecological resilience and sustainability. This sections starts by illustrating how vulnerability is created by efforts to rigidly control processes of change in landscapes simplified by humans in an attempt to stabilize ecosystem outputs and sustain consumption patterns (Holling and Meffe 1996, Carpenter and Gunderson 2001). Such well-intentioned, but ultimately disastrous, management contrasts with adaptive approaches and flexible institutions that attempt to build social-ecological resilience in the face of complexity, uncertainty and surprise (Lee 1993). We end the paper with a few recommendations for implementation of sustainable development in the context of social-ecological resilience.

The Context and the Challenge

The Context – Complex Adaptive Systems

All ecosystems are exposed to gradual changes in climate, nutrient loading, habitat fragmentation or biotic exploitation. Nature has usually been assumed to respond to gradual change in a smooth way. However, sudden drastic switches to a contrasting state can interrupt smooth change, with serious social and economic consequences. Although stochastic events like storms or fire can trigger such shifts, recent studies of rangelands, coral reefs, forests, lakes and oceans show that loss of resilience usually paves the way for a shift to an alternate state (Scheffer et al. 2001). Shifts between states are one characteristic of complex adaptive systems.

Complex systems theory (Holland 1995, Kauffman 1993) is in contrast to the perspective of a world in steady state or near-equilibrium that has dominated resource and environmental science and policy (Gunderson et al. 1995a). To understand and address the challenges facing humanity, new perspectives, concepts and tools about the dynamics of complex systems and their implications for sustainability are now developing in parallel, influencing not only the natural sciences but also the social sciences and humanities, through the work of many people and groups. Complex systems thinking is used to bridge social and biophysical sciences to understand, for example, climate, history and human action (McIntosh et al. 2000), assessments of regions at risk (Kasperson et al. 1995), syndromes of global change and how to link social and ecological systems for sustainability (Berkes and Folke 1998, Scoones 1999, Gunderson and Holling 2001, Berkes et al. 2002). It underpins many of the new integrative approaches, such as ecological economics (Costanza et al. 1993, Constanza et al. 2001, Arrow et al. 1995) and sustainability science (Kates et al. 2001). It is embedded in the foundation for the Resilience Alliance, a consortium of institutes and research groups focusing on sustainability, and publishing the web based scientific journal Conservation Ecology (www.consecol.org).

Assessing and evaluating sustainability in the context of complex systems requires a shift in thinking and perspective (Ludwig et al. 2001). The earlier world-view of nature and society as systems near equilibrium is being replaced by a dynamic view, which emphasizes complex non-linear relations between entities under continuous change and facing discontinuities and uncertainty from complexes or suites of synergistic stresses and shocks. Complex systems are self-organizing. Self-organization is when the macroscopic system properties and patterns that emerge from the interactions among components feedback to influence the subsequent development of those interactions. Self-organization creates systems far from equilibrium, characterized by multiple possible outcomes of management (Levin 1999). A long-term perspective suggests that stability in the management of complex systems is an illusion that disappears when one chooses a scale of perception commensurate with the phenomena under investigation (van der Leeuw 2000). A long view also highlights the importance of scale interactions across time and space in relation to adaptive renewal cycles of exploitation, conservation, release and reorganization in social and ecological systems (Gunderson and Holling 2002).

A fundamental challenge in this context is to raise awareness of the long view. We should build knowledge, incentives, and learning capabilities into institutions and organisations for managing the capacity of local, regional and global ecosystems to sustain human well-being in the face of complexity and change. Such management should involve diverse interest groups in new and imaginative roles, for example through adaptive co-management as will be illustrated later in this document.

The dynamic view of nature and society also has major implications for economic valuation and policy. Most approaches to valuation attempt to capture the value of marginal change under assumptions of stability near a local equilibrium (Daily et al. 2000). They seldom take into account the inherent complexities and resulting uncertainties associated with ecosystem management and natural capital assets in general (Brock et al. 2002). They ignore the slowly-changing probability distributions of critical ecosystem thresholds (Carpenter 2002). New approaches to valuing the environment, such as portfolio management, are required to capture the significance and value of resilience and the capacity of the environment to sustain well being (Costanza et al. 2000). Sudden and abrupt change has major implications for policies on production, consumption and international trade. It has also major implications for economic policy, like taxes on resource use or emissions. Because of the complex dynamics, optimal management will be difficult if not impossible to implement (Mäler 2000).

Attempts to manage social and economic capacity to adapt to and shape change cannot easily be done by dividing the world into economic sectors. That approach misses too many interactions. Instead, capacity needs to be managed in an integrated and flexible manner at appropriate spatial and time scales. For example, freshwater should not be viewed simply as an economic good to be consumed in households, industry or through irrigation of cropland but rather should be assessed and managed at catchment or landscape levels. Freshwater connects terrestrial and aquatic environments and its diverse functional roles in sustaining resilience and supporting ecosystem production must be taken into account to secure societal development and to avoid vulnerability (Rockström et al. 1999). Consequently, water management is not a sectoral issue. Focusing on economic growth to eradicate poverty, disconnected or decoupled from the environmental resource base on which it ultimately depends, is also a wrong approach (Arrow et al. 1995). Focusing on technical solutions to make societal development independent of nature will not lead to sustainable solutions (Holling and Meffe 1996). Instead efforts should be made to tune and create synergies between economic development, technological change and the dynamic capacity of the natural resource base to support social and economic development.

ADAPTIVE CAPACITY

Adaptive capacity is the ability of a social-ecological system to cope with novel situations without losing options for the future, and resilience is key to enhancing adaptive capacity. Adaptive capacity in ecological systems is related to genetic diversity, biological diversity, and the heterogeneity of landscape mosaics (Carpenter et al. 2001a, Peterson et al. 1998, Bengtsson et al. 2002). In social systems, the existence of institutions and networks that learn and store knowledge and experience, create flexibility in problem solving and balance power among interest groups play an important role in adaptive capacity (Scheffer et al. 2000, Berkes et al. 2002).

Systems with high adaptive capacity are able to re-configure themselves without significant declines in crucial functions in relation to primary productivity, hydrological cycles, social relations and economic prosperity. A consequence of a loss of resilience, and therefore of adaptive capacity, is loss of opportunity, constrained options during periods of reorganisation and renewal, an inability of the system to do different things. And the effect of this is for the social-ecological system to emerge from such a period along an undesirable trajectory.

Are there elements that sustain adaptive capacity of social-ecological systems in a world that is constantly changing? Addressing how people respond to periods of change, how society reorganizes following change, is the most neglected and the least understood aspect in conventional resource management and science (Gunderson and Holling 2002). Folke et al. (2002) identify and expand on four critical factors that interact across temporal and spatial scales and that seem to be required for dealing with natural resource dynamics during periods of change and reorganization:

- learning to live with change and uncertainty;
- nurturing diversity for resilience;
- combining different types of knowledge for learning; and
- creating opportunity for self-organization towards social-ecological sustainability.

Each of these points is discussed in the following paragraphs.

Learning to live with change and uncertainty

Robust, adaptive strategies of social-ecological systems accept uncertainty and change. They take advantage of change and turn it into opportunities for development. For example, management actions can be structured to generate a disturbance, which in turn entrains ecosystem development and is followed by monitoring and testing of ecological understanding of ecosystem condition that are embedded in social institutions. Many traditional societies and local communities have long recognized the necessity of the coexistence of gradual and rapid change. These groups have developed institutions that have accumulated a knowledge base for how to relate to and respond to environmental feedback, and allow for disturbance to enter at smaller scales instead of accumulating to larger scales, thereby precluding large-scale collapse (Holling et al. 1998). Such management practices seem to have developed as a result of selection through experience with change and crisis, realizing that not all possible outcomes can be anticipated, planned or predicted (Berkes and Folke 1998). In modern societies some of the same mechanisms have evolved from slow cultural adaptation. Addition of a 3-5 year election cycle in democratic societies, for example, adds a new scale of opportunity for evaluation and change (Holling 2001).

Nurturing diversity for resilience

Diversity is not just insurance against uncertainty and surprise. It also provides a mix of components whose history and accumulated experience helps cope with change, and facilitates redevelopment and innovation following disturbance and crisis (Folke et al. 2002). Social and institutional learning (Lee 1993) based on such experience of crises and surprises may help avoid shifts in ecosystems to less valuable states (Scheffer et al. 2001). In this sense, institutions emerge as a response to crisis and are reshaped by crisis (Olsson and Folke 2001). Diversity and an apparent redundancy of institutions (in the sense of overlapping functions) appears to play a central role in absorbing disturbances, spreading risks, creating novelty and reorganizing following disturbances (Low et al. 2002). This is analogous to the functional diversity and apparent redundancy (or response diversity) of species and their functions, that will be described in the later section on ecosystem capacity and biological diversity.

Combining knowledge systems

Peoples' knowledge and experience of ecosystem management embed lessons for how to respond to change and how to nurture diversity (Gadil et al. 1993, Berkes and Folke 2002). This third factor addresses the significance of such knowledge, its inclusion in management institutions, and its complementarity to conventional resource management and science (Gadgil et al. 2002). Scientific understandings of complex adaptive systems can be enriched by insights from local communities and traditional societies with an experience and historical continuity in ecosystem management (Colding and Folke 2001). There is also a need to expand knowledge from structures of nature to functioning of nature and its role in resilience. Combining different ways of knowing and learning will permit different social actors to work in concert, even with much uncertainty and limited information (Kates et al. 2001).

Creating opportunity for self-organization

The fourth factor brings together the first three in the context of self-organization. Sustaining the capacity for a dynamic interplay between diversity and disturbance is an essential part of self-organization (Folke et al. 2002). The learning process is of central importance for social-ecological capacity to build resilience. Learning includes the use of monitoring to generate and refine ecological knowledge and understanding into management institutions and future action. Such learning approaches are present in adaptive co-management, a process by which institutional arrangements and ecological knowledge are tested and revised in a dynamic, ongoing, self-organized process of trial-and-error (Pinkerton 1989, Pomeroy 1995, Hanna 1998).

The Challenge – What to Sustain and Why?

A social-ecological system can be resilient at one time scale because of technological innovations. Iron axes, for example, helped agricultural societies to persist over a particular time span because they enabled their owners to clear more forests and grow more food. But at a longer time scale, once some threshold of forest cover had been crossed, fallowing could no longer maintain soil fertility and the resilience of the systems eroded. Social-ecological resilience in one time period was gained at the expense of the succeeding period (Carpenter et al. 2001a). Similarly, resilience at one spatial extent can be subsidized from a broader scale, a common pattern in human cultural evolution (Redman 1999). Through the use and dependence on fossil fuels and freshwater reservoirs, current social-ecological systems are subsidized by resources from a past era and from distant places.

Hence, to judge whether or not social-ecological resilience is sustained or erodes it is necessary to address and understand transfers across spatial scales and time periods. To build resilience for social-ecological sustainability we need first to clarify the human-nature relation, and identify what to sustain and why.

NATURE AND HUMANITY AS ONE SYSTEM

Throughout history humanity has shaped nature and nature has shaped the development of human society (Tainter 1988, Turner et al., 1990). For example, the North American landscape at the time of Columbian contact in late 1400 had already been transformed through land clearing, hunting, farming and fire management practices. Indeed, the tropical rainforests of the Americas reached their current form under the selective pressures of human groups (Gomez-pompa and Kaus 1992, Redman 1999). Hence, these are neither natural or pristine systems, nor are there social systems without nature. Instead humanity and nature have been co-evolving, for good or ill, in a dynamic fashion (Norgaard 1994, Berkes and Folke 1998, Raskin et al. 2001, Kasperson and Kasperson 2001b) and will continue to do so. Human actions are a major structuring factor in the dynamics of ecological systems.

The human footprint has expanded at an accelerating rate, from local to global scales, during the last half of the 20th century. Land-use and land-cover changes by humans now significantly affect key aspects of Earth System functioning including climate change (Falkowski et al. 2000). Chemical pollution is no longer only a local problem. The sheer magnitude of the production and application of chemicals has reached global dimensions. Human activities dramatically accelerate evolutionary change in other species This is apparent in microbial antibiotic resistance to drugs, plant and insect resistance to pesticides, life-history changes in commercial fish stocks, rapid changes in invasive species, pest adaptation to biological engineering products, and emergence of new diseases (Palumbi 2001, McMichael et al. 1999, Epstein 1999). A large fraction of the world's available freshwater, nitrogen budget, CO_2 balance, fisheries production, and biotic turnover are driven by human activities (Vitousek et al. 1997). The same is true of the global phosphorus budget that drives freshwater and coastal eutrophication (Bennett et al. 2001). During the 20th century the human population increased by a factor 4, the urban population by a factor of 13, water use by a factor 9, sulphur dioxide emissions 13, carbon dioxide emissions 17, marine fish catch 35 and industrial output 40 times (McNeill 2000).

Consequently, most aspects of the structure and functioning of Earth's ecosystems cannot be understood without accounting for the strong, often dominant influence of humanity. Humanity is a keystone species and may even be the world's dominant evolutionary force (O'Neill and Kahn 2000, Palumbi 2001). In the present era of a human dominated biosphere, co-evolution now takes place also at the planetary level and at a much more rapid and unpredictable pace than previously in human history and many ecosystems require human intervention to be sustained.

However, despite tremendous improvements in technological, economic and material well being, in some parts of the world, development of human society in all parts of the world still relies on ecosystems services and support, from local levels to global scales.

HUMAN DEPENDENCE ON ECOSYSTEM SERVICES AND SUPPORT

Societal development depends on the generation of ecosystem goods such as food, timber, genetic resources, and medicines, and services such as water purification, flood control, carbon sequestration, pollination, seed dispersal, soil formation, disease regulation, nutrient assimilation and the provision of aesthetic and cultural benefits (Baskin 1996, Daily 1997). Carbon sequestering is a debated ecosystem service in the context of the Kyoto Protocol. In Costa Rica forested conservation areas are credited with income for the services that they provide both as carbon sinks and watersheds (Chichilnisky and Heal 1998). Coral reefs provide seafood, shoreline protection and recreational services of high economic significance as well as many services difficult to capture in monetary terms (Moberg and Folke 1999). Mangrove ecosystems serve as essential breeding, nursery and feeding grounds for numerous shellfish and fish, protect the coast from floods, hurricanes and tidal waves, and sustain the livelihood of coastal communities (Rönnbäck 1999). Natural and restored wetlands of the large-scale Baltic Sea drainage basin of Northern Europe annually retain an amount of nitrogen that corresponds to about 10-20% of the total emissions entering the Baltic Sea thereby counteracting eutrophication (Jansson et al. 1998).

Investments in wetland functioning to gain one ecosystem service like nitrogen cleansing often generate several other valuable services like fodder for animals, bird watching, sport fishing and other recreational and tourism values, due to the multifunctional nature of ecosystems. This makes the total value of investments in Swedish wetlands at least twice as high as alternative investments (Gren European Economic Review). In China, the remaining forests in the upper Yangtzee river catchment have a value for flood control that is estimated to be ten times higher than the timber value (WRI 2001). In 1996, New York City invested between $1billion and $1.5 billion in restoration of a watershed in the Catskill mountains to provide freshwater to the city. The alternative capital cost of building a filtration plant would have been about 5-6 times larger, plus annual operational costs of about $300 million (Chichilnisky and Heal 1998). Often, however ecosystem goods and services cannot be translated into economic values, an issue of ongoing and continuous debate (Costanza et al. 1997, Daily et al. 2000).

However, the value of ecosystem services is not only an issue of economic and technical trade off. Societal development depends on ecosystem support irrespective of whether or not this is recognized in human preferences. For example, roughly two-thirds of the food crops in the world require visits by a diversity of animal pollinators (bees, flies, bats, wasps, beetles, birds, moths, butterflies and thrips) to set fruit and seed (Nabhan and Buchman 1997). Such diversity plays a significant role in sustaining ecosystem services and support (see below).

Freshwater is required to sustain the capacity of, for example, forests, wetlands, agricultural land, and savannas to uphold the flow of ecosystem goods and services to humans. The annual amount of freshwater flow for providing terrestrial ecosystem support to the urban people in the Baltic countries is 50 times larger than the freshwater consumed directly in household and industry (Jansson et al. 1999). Another example of whole catchment-management is South Africa's Working for Water programme that maximizes an ecosystem service (delivery of water), enhances sustainability by eliminating invading alien plants, and promotes social equity through jobs and training for economically marginalized people. Without removal, the alien plants convert species-rich vegetation to single-species stands of trees with increasing biomass and water consumption by the trees, thereby diminishing the water supply to densely populated areas downstream. Removal of water-demanding alien trees is a more cost-effective way of delivering water than building new dams while at the same time improving the quality of life amongst previously disadvantaged people (van Wilgen et al. 1998).

As a specific example of human dependence on ecosystem support, the city of Hong Kong requires ecosystem work over an area that is 2200 times its built-up land to support its inhabitants with essential ecosystem goods and services. Thirty percent of this support is derived from Chinese ecosystems, and 95% of its seafood supply is obtained from marine waters of other nations (Warren-Rhodes and Koenig 2001). The 29 largest cities in the Baltic Sea drainage basin cover only 0.1% of the area of the drainage basin, but their inhabitants appropriate an ecosystem area about 1000 times the city area (Folke et al. 1997). This 'ecological footprint' is used for production of food (including seafood) and timber consumed inside the city, and for assimilation of waste emitted from the city (nutrients and carbon dioxide). Each city inhabitant depends on ecosystem work over an area of about 220,000-225,000 m^2, drawing on the work of nature from all over the planet. It is in the self-interest of the city inhabitants to sustain the capacity of ecosystems to supply this support, and not only within national boundaries but also in regions from where this support is derived.

Focusing on the production of ecosystem goods or valuation of ecosystem services will not lead to sustainable use by itself, because it does not address the dynamic capacity of ecosystems to uphold the supply of these goods and services. The challenge is to sustain the capacity, here referred to as resilience, through active management in order to secure prosperous social and economic development. In the next section we will exemplify essential premises of resilience and human use and abuse of ecosystem capacity.

Processes and Mechanisms behind Resilience and Vulnerability

Structural Premises – Biological Diversity and Ecosystem Adaptive Capacity

Biological diversity and ecosystem functioning

Diversity plays a significant role in sustaining the resilience of ecosystems (Perrings et al. 1995, Peterson et al. 1998, Chapin et al. 2000, Loreau et al. 2001, Diaz and Cabido 2001, Kinzig et al. 2002). This role is related to the diversity of *functional groups* of species in a system, like organisms that pollinate, graze, predate, fix nitrogen, spread seeds, decompose, generate soils, modify water flows, open up patches for reorganization and contribute to the colonization of such patches. Vertebrates that eat fruit, like flying foxes, play a key role in the regeneration of tropical forests hit by disturbance such as hurricanes and fire by bringing in seeds from surrounding ecosystems for renewal and reorganization (Cox et al. 1992, Elmqvist et al. 2001). In these examples the loss of the functional groups will severely affect the capacity of ecosystems to reorganize after disturbance. Conversely, in systems that lack a specific functional group, the addition of just one species may dramatically change the structure and functioning of ecosystems (e.g. Diaz and Cabido 2001). In Hawaii, the introduced nitrogen-fixing tree *Myrica faya* has in a dramatic way changed the structure and functioning in many ecosystems where no native nitrogen fixing species had been present. Once established, M. faya, can increase nitrogen inputs up to five-times, thereby facilitating establishment of other exotic species (Vitousek and Walker 1989).

Diversity as insurance

Resilience does not only depend on the diversity of functional groups in ecosystems. It is also related to the number of species within a functional group and the overlapping functions among groups (a species may perform several functions, like birds that both spread seeds and pollinate plants) (Peterson et al. 1998). Species within the same functional group appear to respond differently to environmental change, a property we call *response diversity* (Walker 1989, Walker 1997, Ives et al. 1999). In semi-arid rangelands, for example, resilience of production to grazing pressure is achieved by maintaining a high number of apparently less important and less common, or apparently 'redundant', species from the perspective of those who want to maximize production, each with different capacities to respond to different combinations of rainfall and grazing pressures. They replace each other over time, ensuring maintenance of rangeland function over a range of environmental conditions (Walker et al. 1999). (Figure 1).

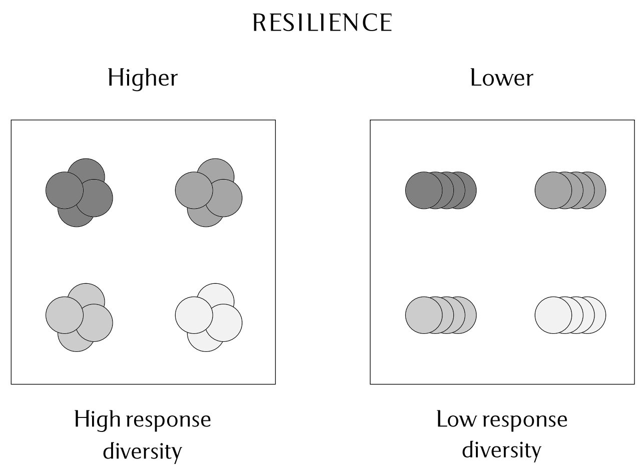

Figure 1. *Four different functional groups of species are represented (e.g. pollinators, predators, grazers, nitrogen fixing plants). All four species in each group perform the same function. In the left figure species differ in their response to environmental change (response diversity). In the right, the four species within each functional group respond in a similar way to environmental change. Their capacity to absorb disturbance and sustain ecosystem functioning is lower.*

Hence, a resilient ecosystem contains functional groups with several species that perform a similar function, but respond in different ways to environmental changes. In lake systems, animal plankton species with higher tolerance to low pH sustain the grazing function on phytoplankton during acid conditions (Frost et al. 1995). In areas where humans reduce response diversity by decreasing biodiversity and favoring monocultures, the capacity of ecosystems to sustain society with goods and services becomes more vulnerable to disturbances and environmental, social or political change. For example, in several Pacific Islands flying fox populations have been severely reduced through over hunting and trade to a market in Guam (Bräutigam and Elmqvist 1989). Hence, human demand for a certain resource on a regional market decreases the seed dispersal capacity and thereby diminishes the capacity of forest ecosystems on many islands to reorganize after hurricanes and other disturbances (Elmqvist et al. 2001).

Lawton (2000) and Loreau et al. (2001) synthesized the evidence from many experiments and affirmed that the diversity of functionally different kinds of species affected the rates of recovery and increased the reliability of ecosystem processes. Furthermore, a number of observations suggest that biodiversity at larger spatial scales, i.e. landscapes and regions, ensures that appropriate key species for ecosystem functioning are recruited to local systems after disturbance or when environmental conditions change (Peterson et al. 1998, Nyström and Folke 2001, Bengtsson et al. in press). In this sense biological diversity provides insurance, flexibility and risk spreading across scales (Barbier et al. 1994, Folke et al. 1996).

Reserves have been the cornerstone of biodiversity conservation and though they will continue to be important for species conservation, their role as sources for renewal and reorganization of ecosystem functioning in managed landscapes and seascapes needs to be recognized. They contribute to ecosystem resilience, but they need to be complemented with biodiversity management in human-dominated landscapes (Bengtsson et al. in press). In some cultures, taboo systems such as sacred groves perform the same function as reserves in the developed world (Colding and Folke 2001). They are effective because they are embedded in local institutions and value systems (Gadgil et al. 1993, Colding and Folke 2000).

The role of biodiversity in ecosystem resilience needs to be explicitly accounted for in management and policy (Perrings et al. 1992). Hence, in addition to the conservation of biological diversity for aesthetic, ethical or psychological reasons (eg, biophilia, Wilson 1984), there is a more pragmatic reason for conservation. Erosion of functional diversity and response diversity may lead to vulnerability, alterations in nature's capacity to supply society with essential ecosystem services and support, and degraded social-ecological regimes (Homer-Dixon and Blitt 1998).

The Dynamics – Shifts between Ecosystem States

There is increasing evidence that ecosystems often do not respond to gradual change in a smooth way. Studies of rangelands, coral reefs, forests, lakes and oceans show that human induced loss of resilience can lead to sudden switches to alternative states, triggered by stochastic events like storms or fire (Table 1. p.18).

In lakes, water clarity often seems to be hardly affected by increased human-induced nutrient concentrations until a critical threshold is passed at which point the lake shifts abruptly from clear to turbid, eutrophied waters (Scheffer et al. 1993, Carpenter et al. 1999). With this increase in turbidity, submerged plants disappear. Associated loss of animal diversity and reduction of the high algal biomass makes this state undesired. Substantially lower nutrient levels than those at which the collapse of the vegetation occurred are required to restore the system. The economic and social intervention involved in such a restoration will be complex and expensive (Mäler 2000, Brock et al. 2002).

Resilience of rangelands depends on the ability of the landscape to maintain water infiltration, water storage capacity, nutrient cycles and vegetation structures. Rangeland shifts between grass dominance and woody plants (small trees and shrubs) dominance. The shifts are driven by fire and grazing pressure under highly variable rainfall (Walker 1993). Persistent high grazing pressure precludes fire and above some density of woody plants, even if grazing animals are removed, there is insufficient grass fuel to permit a fire and the rangeland shifts to the less productive (from a human use perspective) woody plant state. It can take decades for the woody plant community to re-structure and open up sufficiently to allow fire back into the system (Carpenter et al. 2001b).

Ecosystem Type	Alternative State 1	Alternative State 2	References
Freshwater Systems	Clear Water	Turbid Water	*Carpenter 2001*
	Benthic Vegetation	Blue-green algae	*Scheffer et al. 2001*
	Oligotrophic macrophytes and algae	Cattails and blue green algae	*Gunderson 2001*
Marine Systems	Hard coral	Fleshy Algae	*Nyström et al. 2000*
	Kelp forests	Urchin dominance	*Estes and Duggins 1993*
	Seagrass beds	Algae and muddy water	*Gunderson 2001*
Rangelands	Grass structure	Shrub structure	*Walker 1993*
Forests	Pest outbreak	No pest	*Holling 1986*
	Pine Trees dominate	Hardwood plants dominate	*Peterson et al. 2002*
	Birch-Spruce succession	Pine dominance	*Danell et al. in review*
Arctic Systems	Grass dominated	Moss dominated	*Zimov et al. 1995*

Table 1. *Examples of documented shifts in states in different kinds of ecosystems.*

In other cases regime shifts may be largely irreversible. Loss of trees in cloud forests is one example. In some areas the forests were established under a wetter rainfall regime thousands of years previously. Condensation of water from clouds intercepted by the canopy supplies necessary moisture. If the trees are cut, this water input stops and the resulting conditions can be too dry for recovery of the forest (Wilson and Agnew 1992). A continental scale example of an irreversible shift seems to have occurred in Australia, where overhunting and use of fire by humans, some thirty to forty thousand years ago, removed large marsupial herbivores and accumulated nutrients. Without large herbivores to prevent and fragment vegetation, an ecosystem of fire and fire-dominated plants could expand, irreversibly switching the system from a more productive state, dependent on rapid nutrient cycling, to a less productive state, with slower nutrient cycling maintained by fire (Flannery 1994).

Sensitivity of keystone species to environmental change and human exploitation can cause major shifts in ecosystem composition. One well known example is the role of sea otters in northern Pacific rocky, -near-shore kelp ecosystems. The otters prey upon sea urchins, controlling their grazing of the kelp thereby sustaining a state that is dominated by the submerged kelp forests. In the absence of the sea otters, urchin populations can increase to a density that prevents the kelp forests from establishing, creating an alternate state of urchin dominance (Estes and Duggins 1995).

In a similar way, in the boreal forest foraging by ungulates can change the relative distribution of tree species, with cascading consequences for the development of the forest ecosystem. In the mountain range of Scandinavia birches dominate young stands with Norway spruce following in the natural succession. If the birches are heavily browsed by ungulates, spruce does not get shelter andfails. Instead, pines may establish and later become dominant, causing long-term changes in soil fertility as a consequence. The direction and magnitude of responses of plant communities depend on the ungulate species involved, their population densities, site productivity, successional stage (early or late), and whether or not the herbivores have been present in the ecosystem for extended (evolutionary) time (Danell et al. in review).

An interesting "experiment" was created in Venezuela, where a set of islands was created by a hydroelectric impoundment. The islands were free of top predators and populations of seed predators and herbivores subsequently increased by a factor 10 to 100 compared to nearby mainland sites, with severe reductions in densities of seedlings and saplings of canopy tree species as a result. This study suggests that removal of predators may result in trophic cascades in the terrestrial ecosystem, affecting the densities and species composition of both herbivores and plants and significantly changing the structure and functioning of the ecosystem (Terborgh et al. 2001). The same trophic cascade phenomenon occurs in lake ecosystems (Carpenter and Kitchell 1993).

In Florida Bay, the system has flipped from a clear-water, seagrass-dominated state to one with murky water, comprised of algae blooms and recurrently stirred-up sediments. Several hypotheses have been proposed to explain this shift, including change in hurricane frequency, reduced freshwater flow entering the Bay, higher nutrient concentrations, removal of large grazers like sea turtles and manatees, sea level rise, and construction activities restricting circulation in the Bay (Gunderson 2001). In the Everglades the freshwater marshes have shifted from clear water wetlands dominated by sawgrass to cattail marshes, due to nutrient enrichment. The soil phosphorous content defines the alternative states and a number of disturbances (fires, drought, freezes) can trigger a switch between these states (Gunderson 2001).

Overfishing – illustrating the shift

Coral reefs in the Caribbean region have undergone dramatic changes over the past two to three decades, often from a state dominated by hard coral to one dominated by fleshy algae. The changes have been brought about through a combination of natural (hurricanes and disease) and human (overfishing and nutrient increase) processes. The grazing function of algae that fish species and other grazers perform contributes to the resilience of the coral reef, by keeping the substrate open for recolonization of coral larvae and thereby reorganizing the reef into a coral dominated state following disturbances such as hurricanes (Nystrom and Folke, 2001). Continuous overfishing of reef fish grazers has led to increased abundance of sea urchins. The sea urchin became a keystone grazer and could, despite high levels of nutrients in the water, continue to keep the density of invading algae low after disturbance, thereby maintaining the coral dominated state. However, the sea urchin populations were hit by a species-specific pathogen and were reduced by 99% in some areas. Since all major grazers were now in very low numbers they were not able to prevent algae invading. Brown fleshy algae became overwhelmingly abundant and prevented coral larvae settlement and the reef changed to a state of algae dominance.

The coral reef example demonstrates how loss of diversity through overfishing of the functional group of grazers resulted in eroded resilience and increased vulnerability. A disturbance event – the species specific pathogen - that previously could have been absorbed by a diverse functional group of herbivores with different capacities to respond to change (response diversity), became the trigger that caused the ecosystem to shift from a coral-dominated state to one dominated by algae. To what extent this phase shift is irreversible is unclear (Nyström et al. 2000).

It is becoming increasingly clear that complex biotic interactions are much more important in driving oceanic community dynamics than previously thought, and that biological diversity plays a significant role in this context (Jackson et al. 2001). Human fishing pressure can affect the entire food-web, causing profound shifts in species abundance at various trophic levels. The best evidence of food web effects comes from lakes where other important causal factors, such as nutrients and invasive species, can be measured independently (Carpenter and Kitchell 1993, Carpenter et al. 2001b). Nevertheless it is clear that large changes in marine ecosystems follow from biotic interactions (Shiomoto et al. 1997, Steele 1998, Walters and Kitchell 2001, Daskalov 2002). In the Black Sea, for example, overfishing has contributed to the collapse of valuable fin fisheries, population explosions of jellyfish, blooms of algae and collapse of benthic communities (Daskalov 2002). Overfishing has contributed to the collapse of northern cod populations in northern Atlantic and the Baltic Sea and similar declines are known from lake sport fisheries (Post et al. 2002).

Global fisheries impacts are reflected in the industrial fishing down of marine food webs in a transition from long-lived, high trophic level fish to short-lived, low trophic level invertebrates and small plankton eating pelagic fish (Pauly et al. 1998). Historical overfishing by humans of coastal ecosystems has led to a sequential reduction of functional groups of species (mammals, turtles, fish) and removal of entire trophic levels, thereby creating more vulnerable and fragile coastal ecosystems. The loss of functional diversity and response diversity through fishing over human history, with escalating exploitation during the last half century, has paved the way for impacts such as eutrophication, algal blooms, disease outbreaks, and species introductions in coastal areas (Jackson et al. 2001).

Creating Vulnerability through Loss of Resilience

Intensive fertilizer use, high densities of animals and poor tillage practices in catchments decrease the resilience of freshwater systems, and increase their vulnerability to flood events or toxic algal blooms (Carpenter et al. 1998). Intensive conventional tillage often results in long term reduction in infiltration capacity of soils and lowered water holding capacities, and therefore a larger proportion of rainfall flowing as rapid surface runoff instead of slow subsurface water recharging rivers downstream. This changes the hydrological pattern of aquatic habitats, and increases the vulnerability of key populations that are sensitive to fluctuations in water flow.

In North America, climate warming combined with agricultural runoff is leading to spread of a subtropical cyanobacterium, *Cylindrospermopsis raciborskii*, through the Great Lakes and Upper Mississippi basins. Unlike other species of cyanobacterium, *C. raciborskii* appears to release neurotoxins all the time (Chorus et al. 2000), so that losses of water supplies that used to be sporadic may now become continuous.

This example highlights one important reason why individual regions, and the world as a whole, need to increase attention to resilience: To provide a buffering against effects of climate change. All the evidence from climate change research suggests that the frequency of major climate events (perturbations) will increase, as expressed in changes in the current variation in climate regimes (Carter et al 2000). The IPCC 2001 Working Group I report concludes that, in addition to projected warming scenarios for various regions, there will be changes in the variability of climate and in the frequencies and intensities of some climate phenomena. Examples include extreme events of drought, rainfall and major floods and spread and emergence of diseases (Epstein 1999, Palmer and Räisanen 2002, Milly et al. 2002, Lindgren and Gustafson 2001). The Working Group II report on impacts and adaptation concludes that these changes will have very significant impacts on many of the world's ecosystems, including agro-ecosystems. In the face of these projections it will require big increases in resilience to enable social-ecological systems to cope with future climate events. If resilience continues to decrease in response to efforts to increase production efficiencies, the frequency of regional catastrophes will escalate accordingly.

These trends illustrate the pervasive uncertainty, variability and vulnerability of resource flows and ecosystem support that social and economic development on a human dominated planet is currently facing (Kasperson and Kasperson 2001a,b). "Catastrophes" - the undesirable sudden changes in social-ecological systems - are due to the combination of the magnitudes of external forces and the internal resilience of the system. As resilience declines it takes a progressively smaller external event to cause a catastrophe (Alexander 2000, Quarantelli 1998).

Hence, ecosystems with low resilience may still maintain function and generate resources and ecosystem services - i.e. may seem to be in good shape - but when subject to disturbances and stochastic events, they may exceed a critical threshold and change to a less desirable state. These shifts are sometimes irreversible and in other cases the costs (in time and resources) of reversal are so large that reversal is impractical. Such shifts may significantly constrain options for social and economic development, reduce options for livelihoods, and create environmental refugees as a consequence of the impact on ecosystem life-support.

Erosion of resilience causing vulnerability in livelihoods

Reducing resilience increases vulnerability. Increasing vulnerability places a region on a trajectory of greater risk to the panoply of stresses and shocks that occur over time. And the process is a cumulative one, in which sequences of shocks and stresses punctuate the trends, and the inability to replenish coping resources propels a region and its people to increasing criticality (Kasperson et al. 1995, 1996).

For example, in the Argolid valley of Greece, people speak of an environmental crisis because there is not enough water to continue irrigating the citrus crops that were planted in the valley about 40 years ago. As a consequence of citrus irrigation, the water table in some parts of the valley has dropped up to seven meters a year, and now water is pumped at the valley's edge from depths as great as 400 meters. Hence, the environmental crisis is caused by the intensive cultivation system itself, driven by an industrial perspective of agriculture. The people who brought this agro-industrial perspective to bear on the exploitation of the fertile lands of the valley came from outside the local farming communities and were not familiar with the local ecological context. They could claim large economic subsidies by declaring themselves as farmers for more than 50% of their time, enabling them to make the investment in the citrus cultivation that drove the region towards vulnerability. Originally these subsidies, derived from policies of the Greek government and the European Union, were aimed at the young generation of existing farming communities (van der Leeuw 2000).

Throughout history people have transported their cultural landscapes to new areas. Just as the Polynesians brought their pigs and breadfruit for migration to New Zealand and other islands, so did later the British settlers with their wheat fields, sheep and green lawns. Sometimes these transported landscapes were suited to the new climate and thrived in their new setting, but sometimes they generated major problems (Redman 1999).

A current major problem in this context is the large-scale salinization of land and rivers in Australia. Extensive land clearing during the last two hundred years has changed ecosystem structure and processes and altered the hydrological-ecological dynamics of the Australian continent. In particular, European introduced agriculture removed native woody vegetation for annual crops and grasses that transpire much less water. Thereby, more water is leaching down through the soils causing water tables to rise (McMahon et al. 1992, McFarlane et al. 1993). The Australian soils are saline. The increased water movement through the soils mobilizes salts. This causes problems with salinity both in rivers and at, or close to, the soil surface severely reducing the capacity for growth of most plants (MDBC 1999).

About 5.7 million hectares are currently at risk of dryland salinity and this could rise to over 17 million hectares by 2050 (NLWRA 2001). The costs of salinization are manifested as production loss due to saline river water, health hazards, production loss in agricultural lands and destruction of infrastructure in rural and urban areas. Added to these are the less well-known costs due to loss of biodiversity and ecosystem services in both terrestrial and aquatic environments (MDBC1999). Hence, the terrestrial support capacity for societal development in Australia has been reduced through unexpected changes in ecosystem processes, as a consequence of management. Successful restoration requires ecological as well as hydrological knowledge, an understanding that actively manages the interplay of freshwater flows and ecosystem processes in both terrestrial and aquatic ecosystems, and appropriate incentives and institutional arrangements.

Ancient villages in southern Jordan seem to have become more vulnerable due to a self-generated loss of resilience of their productive natural resource base. The ever-present need for fuel wood and the grazing of goats put pressure on vegetative ground cover over a wider and wider area. As the fuel and grazing needs pushed the boundary of native vegetation further from the villages, less timber was available for home construction and fuel and wild resources became less available. Consequently, the villagers narrowed their food sources by relying more and more on domestic fields and herds. The villagers presumably invented ways to adapt to the narrowed options of the developing agricultural system, thereby mentally masking the land degradation and vulnerability. It is likely that a slight change in climate led to a series of dry years that were too much for the agricultural villages to absorb leading to abandonment (Redman 1999).

It may be that we at present are witnessing similar effects, predominantly in arid and semi-arid regions, where human settlements appear to have lost ecological and social resilience to cope with years of drought, resulting in an agrarian crisis (Rockström and Tilander 1997). The capacity of the land to support human societies has been reduced. In the savannas and steppe belts in Africa, there have been significant land-use changes. Where there originally was shifting cultivation and livestock movements with a high degree of natural vegetation, permanent settlements have become dominant and the vegetation cover has been reduced (Hudak 1999, Niamir-Fuller 1999). This land-use change reduces the evapotranspiration during the rainy season, reduces the feedback of moisture to the atmosphere, reduces the recycling of moisture, and hence reduces the rainfall further inland, until it reaches a threshold below which there is no longer any significant rainfall (De Groen and Savenije 1996).

Water vapour from terrestrial ecosystems is the engine that recycles moisture to the atmosphere, which replenishes the atmospheric moisture content, and in this way sustains rainfall (Savenije 1996a, 1996b, 1997). In the Sahel belt 90% of the rainfall stems from continental water vapour. A sequence of dry years, as was experienced during the 1980s, accelerates the process of desertification; during dry years, people expand their forest clearing activities even more, which exacerbates the loss of moisture recycling. As a consequence of reduced moisture recycling the drought period is prolonged. Hence, land degradation led to the persistence of drought.

There are substantial local benefits to be gained from improved soil and water management. Conservation farming practices, where conventional tillage is abandoned in favour of minimum or zero tillage practices that maximize crop nutrient and water availability, are examples of affordable and appropriate technologies that can contribute to both reduced poverty and increased resilience (Rockström et al. 2001). Rainwater harvesting systems, where surface runoff flow is used for productive purposes for dry spell mitigation, can be used to improve crop productivity while conserving soil and water. Dry spell mitigation in semi-arid and dry sub-humid tropics is an important adaptation that increases social resilience (Rockström, 2000) and which in arid and semi-arid regions of North Africa and the Middle East has formed the basis for the establishment of sedentary societies (Evanari et al. 1971).

Loss of livelihood and increased conflict

The increase in social and economic vulnerability as a consequence of reduced resilience may cause losses of livelihood and trigger tension and conflict over critical resources such as freshwater or food (Homer-Dixon and Blitt 1998). Empirically, it has been difficult to establish whether poverty or environmental factors are determinants of such conflict. Losses of livelihood constitute an often-missing link in explanations of current conflict patterns. A common denominator for many, if not most, of the internal wars and conflicts plaguing Africa, South Asia, and Latin America during the last decade, is poverty as a result of loss of livelihoods, in turn often caused or exacerbated by environmental degradation (de Soysa et al. 1999, Messer et al. 2001). While poverty may be a near-endemic condition in certain societies, loss of livelihood marks a rapid transition from a previously stable condition of relative welfare into a condition of poverty or destitution (Dasgupta 1993). It is this rapid process of change, resulting in a sudden and unexpected fall into poverty, more than the endemic condition of poverty, which creates the potential for what rightly may be termed livelihood conflicts (Ohlsson 2002).

The losses of livelihood resulting from scarcities of arable land and water are of increasing concern and importance. Water for irrigation and competition for scarce water resources have been portrayed as a source of international conflict. Nations, however, and the international system have learned to manage this threat. There is now a growing consensus that water scarcity is not likely to create wars between nations - but there is also a growing certitude that water scarcity may work in a direction to exacerbate the basic conditions that fuel livelihood conflicts (Postel 1999).

Other types of conflict arise in rich countries, where partial solutions generate new classes of problems with consequences greater than the original problems they were intended to solve. The Everglades in southern Florida is a classic example where four stages of partial and short-term solutions each ended with a larger set of problems at larger scales, involving more people (Gunderson et al. 1995a,b). Initially the solutions were local, then watershed-wide, and then at the scale of the regional sugar trade. Now the approvals are in place for the largest, most expensive process of regional transformation anywhere in the world. With enough money, the problems generated by earlier partial solutions can be dealt with, but the cost and difficulty grow due to loss of resilience at each successive scale (Gunderson et al. 1995a,b).

van der Leeuw (2000) characterizes land degradation and loss of ecosystem resilience as a socio-natural process that has occurred throughout history. This process highlights the importance of the underlying perception behind the management systems. Human drivers of ecosystem change are deeply embedded in cultural values and underlying perceptions (Thompson et al. 1990), and economic production systems and lifestyles, mediated by institutional factors (Lambin et al. 2001, Raskin et al. 2001). Urbanization and many aspects of globalization tend to distance people from their relation to ecosystem support by disconnecting production from consumption and production of knowledge from its application (Folke et al. 1998). People become alienated from their dependence on access to resources and ecosystem functions outside the boundaries of their own jurisdiction (Folke et al. 1997).

Managing for Social-Ecological Resilience and Sustainability

Wrong Focus of Management

Human simplification of landscapes and seascapes for production of particular target resources to be traded on markets has stabilized resource flows in the short term. But it has done so at the expense of reduced diversity and it has eroded resilience (Gunderson and Holling 2002). Far too often managers seek to command and control processes of change in simplified landscapes in an attempt to stabilize ecosystem outputs and sustain consumption patterns (Holling and Meffe 1996, Carpenter and Gunderson 2001). Humans control agricultural pests through herbicides and pesticides; convert multi-species variable-aged forests into monocultures of single-aged plantations; hunt and kill predators to produce a larger, more reliable supply of game species; suppress fires and pest outbreaks in forests to ensure a steady lumber supply; clear forests for pasture development to achieve constantly high cattle production

Fire management provides a good example. Suppression of fire in ecosystems that have evolved with fire as an integral part of their environments is successful in the short-term, but the consequence is an accumulation of fuel, over large areas, which eventually generates large fires that may fundamentally change the state of the ecosystem (Holling and Meffe 1996). Intense management in many temperate and boreal forests during the last 100 years has reduced resilience and fire-tolerance of forests. After several decades of fire and grazing exclusion and logging, formerly open forests or savannas now have very high tree densities. Surface fuel loads are higher, ladders of fuel (tall shrubs and small trees) connect the ground surface with the crowns and the biggest trees, with the thickest bark, have been selectively removed. As a result fire severity has increased and fire tolerance has decreased (Agee 2002).

Putatively "optimal" management of systems assumed to be stable and predictable has reduced options and compromised the capacity of life-support ecosystems to buffer change (Ludwig et al. 1993) by suppressing disturbance and by reducing the diversity of the environment. Conventional resource management has taken for granted the capacity of ecosystems to sustain production and to sustain the flow of ecosystem services. Contemporary fish farming, or aquaculture, is a recent example. The spread of monocultures of (e.g.) shrimp and salmon in coastal waters worldwide has degraded coastal areas and marine food webs under the assumption that production can be controlled (Folke and Kautsky 1989, Naylor et al. 1998, 2000).

Short-term success of increasing yield in homogenized environments reinforces mental models of human development as being superior and largely independent of nature's services. Short-term successes allow managers to shift their attention from the original purpose to efforts to increase organizational or economic efficiency and to control variation in nature. The perception, or belief system, of humanity as independent of nature is reinforced. According to this thinking, nature can indeed be conquered, controlled and ruled (Thompson et al. 1990). Technology, based on this perspective, further masks the feedback from the environment, contributing to an accumulation of the feedback at larger spatial scales and longer temporal scales. Short-term success makes navigating nature's dynamics appear to be a non-issue and as a consequence knowledge, incentives and institutions for monitoring and responding to environmental feedback erode (Holling et al. 1998). Societies become vulnerable without recognizing it.

Cases such as those discussed earlier in this report show that management of resources often fails to achieve its goals. Management increases vulnerability and may cause social disruption and a decline in the resource base it was attempting to manage. An important reason is that many approaches to development are partial and short term. They represent application of good economics or good engineering or good environmental protection to large problems and

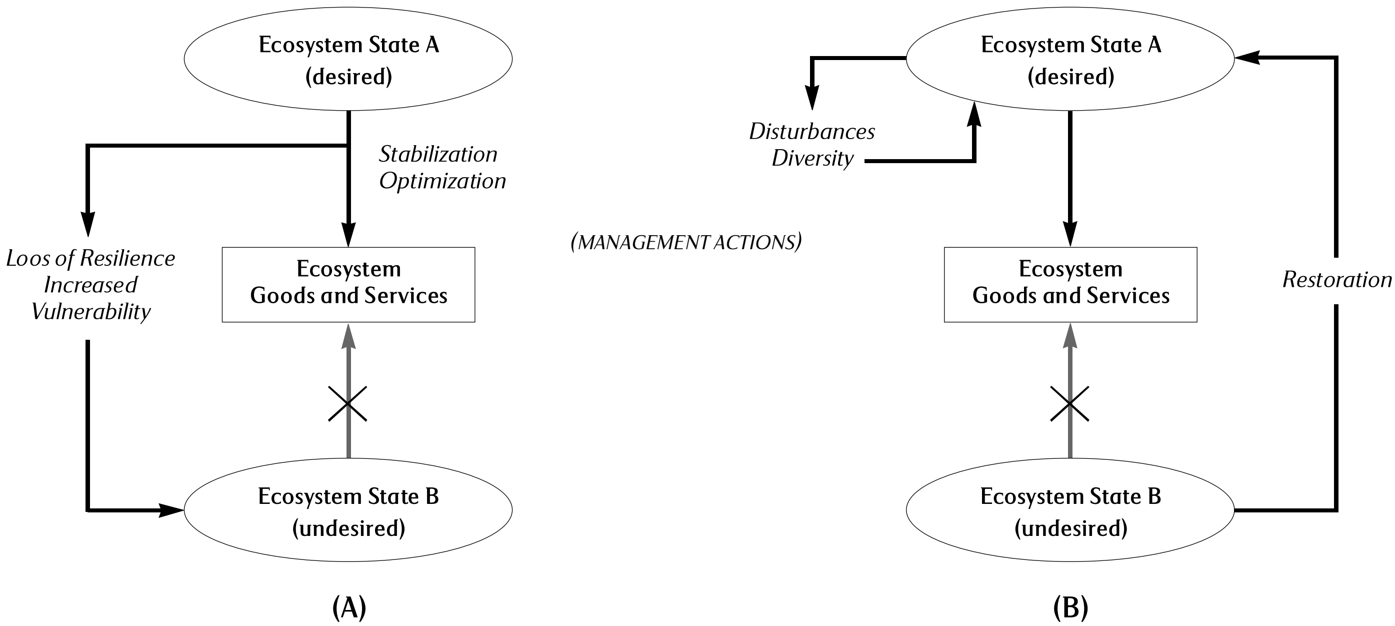

Figure 2. *(A) The pathology of command-and-control management that erodes ecosystem resilience. Optimization and stabilization of key ecosystem variables reduce resilience and make the system more vulnerable to shifting to an alternative (and usually socially undesirable) state.*

(B) Adaptive management approach to restore and maintain resilience and adaptive capacity. Resilience management manages for variability in components and processes. Often, adaptive management seeks to restore a desired ecosystem state.

opportunities that have high uncertainties. That approach can provide short-term benefit but ultimately leads to long-term loss (Gunderson and Holling 1995a, Kasperson and Kasperson 2001a).

How can the trap of successful short-term management at the expense of long-term loss be counteracted? The likelihood that a social-ecological system will remain within a desirable state is related to slowly changing variables that determine the boundaries beyond which disturbances may push the system into another state. Consequently, efforts to reduce the risk of undesired shifts between ecosystem states should address the gradual changes that affect resilience rather than trying to control disturbance and fluctuations (Holling and Meffe 1996, Carpenter et al. 2001a). The slowly changing variables include such things as land use, nutrient stocks, soil properties and biomass of long-lived organisms (Gunderson and Pritchard 2002). For example, economic and institutional constraints limit the ability of agriculturalists of the lake districts in the US and of rangelands in Australia to organize management of slow variables (Carpenter et al. 2001a). Also, differences in land tenure, agricultural policy and market conditions are more significant drivers of long-term changes in semi-arid African savannas than are agro-pastoral population growth, cattle numbers, or smallholder land use (Homewood et al. 2001).

Resilience measures differ from most existing sustainability indicators. Resilience focuses on variables that underlie the capacity of social-ecological systems to provide ecosystem services, whereas other indicators tend to concentrate on the current state of the system or service. Management that monitors, clarifies, and redirects underlying, fundamental variables may succeed in building resilience, and thereby adaptive capacity. Stochastic events (hurricanes, droughts, etc) that trigger shifts between states cannot be predicted with much certainty. Therefore, building resilience of desired ecosystem states is the most pragmatic and effective way to manage ecosystems in the face of increasing environmental change (Scheffer et al. 2001).

Key attributes of resilience in complex adaptive systems include:

- Ecological resilience can be assessed by the amount of variability that can be accepted without patterns changing and controls shifting to another set of keystone processes.
- In an ecosystem keystone processes interact in an overlapping, apparently redundant manner. They should not be evaluated by the efficiency with which any one process functions.
- Resilience within a system is generated through major changes and renewal of systems at smaller, faster scales.
- Essential sources of resilience lie in the variety of functional groups and the accumulated experience and memory that provides for reorganization following disturbances.

Successful ecosystem management requires monitoring and ecological understanding and institutional capacity to respond to environmental feedback (Hanna et al. 1996, Berkes and Folke 1998, Danter et al. 2000) and the political will and perception to make such management possible. By responding to and managing feedbacks from complex adaptive ecosystem, instead of blocking them out, adaptive management has the potential to avoid the pathology of natural resource management that threatens the existence of many social and economic activities (Holling and Meffe 1996).

Adaptive Management and Flexible Institutions

Adaptive capacity is closely related to learning, and learning is central to the notion of adaptive management (Holling 1978, Lee 1993, Gunderson and Holling 2002). Adaptive management proceeds by a design that simultaneously allows for tests of different management policies and emphasizes learning as we use and manage resources, monitoring and accumulating knowledge on the way, and constantly adjusting the rules that shape our behavior to match the dynamics and uncertainty inherent in the system. The adaptive management approach treats policies as hypotheses, and management as experiments from which managers can learn, accepting uncertainty and expecting surprises (Walters 1986, Cook et al. 1990, Gunderson et al. 1995a, Ostrom 1999). Ecological resilience maintains the capacity for institutional learning in a dynamic environment by providing a buffer that protects the system from the failure of management actions that are based upon incomplete understanding. It thereby allows managers to learn and to actively adapt their resource management policies. In other words, those participating in adaptive management expect to continually monitor the system they are managing, and in doing so they expand and enrich their understanding of the dynamics of the system. Management decisions are regularly revisited and changed as knowledge advances.

As it proceeds in a stepwise fashion, responding to changes and guided by feedback from resource dynamics, adaptive management allows for institutional and social learning (Lee 1993), developing a collective memory of experiences. This memory provides context for social responses to ecosystem change, increases the likelihood of flexible and adaptive responses, particularly during periods of crisis and reorganization. Adaptive management therefore draws on experience but allows for novelty and innovation. It provides a repertoire of general design principles that can be drawn on by resource users at multiple levels to aid in the crafting of new institutions to cope with changing situations (Ostrom et al. 2002, Berger et al. 2001).

There are indigenous and traditional ecological knowledge-based systems that parallel adaptive management in their reliance on learning-by-doing, and the use of feedback from the environment to provide corrections for management practice (Berkes et al. 2000). They rely on the accumulation of knowledge over many generations. This knowledge is transmitted culturally. Such systems differ from technically-based systems in that they do not rest solely, or even primarily, on testable hypotheses and generalizable theories. Instead, they integrate moral and religious belief systems with management, though in many cases such belief systems have "co-evolved" to be sensitive to the attributes of the ecological system upon which the people are relying (Gadgil et al. 1993). For example, people of Hudson Bay, Canada, have knowledge about changes in slow variables in relation to climate and link this knowledge to the long history of close interaction with nature (Riedlinger and Berkes 2001).

Local users can provide early information about ecosystem change and complement scientific monitoring. In the Newfoundland cod fisheries, coastal fishers registered changes in the ecosystem long before the collapse of the fishery happened. The signals of change were not perceived either by large-scale offshore fisheries or governmental decision-makers (Finlayson and McCay 1998). Olsson and Folke (2001) describe how members of a local fishing association in Sweden use indicators at various scales that are critical in detecting fundamental changes in ecosystem dynamics. Management decisions are guided by monitoring of these indicators to keep track of environmental change. With the careful design of research that carefully records both social and ecological system characteristics and their interactions over time, it will be possible to develop shared knowledge systems about the factors that enable some people to sustain ecological systems for long periods of time while others destroy them rapidly (Gibson et al. 2000).

Multi-level Governance and Institutional Change

The parallels between adaptive management and local and indigenous management systems that respond to environmental feedback are not accidental (Berkes et al. 2000). Flexible social networks and organizations that proceed through learning-by-doing are better adapted for long-term survival than are rigid social systems that have set prescriptions for resource use. Such flexible institutional arrangements have been judged as inefficient since they look messy and are non-hierarchical in structure. A growing literature on polycentric institutions (McGinnis 1999, 2000) is demonstrating that dynamic efficiency is frequently thwarted by creating centralized institutions and enhanced by systems of governance that exist at multiple levels with some degree of autonomy complemented by modest overlaps in authority and capability. A diversified decision-making structure allows for testing of rules at different scales and contributes to the creation of an institutional dynamics important in adaptive management.

The challenge for management is to develop institutional structures that match ecological and social processes operating at different spatial and temporal scales and addressing linkages between those scales (Ludwig et al. 1993, Holling and Meffe 1996, Folke et al. 1998). Therefore, an important part of adaptive management is to encourage local organizations to interact with each other and with organizations at other levels. Adaptive management would be enhanced by linking institutions both horizontally (across space) and vertically (across levels of organization) (Svedin et al. 2001, Ostrom et al. 2002). Multi-level governance of complex ecosystems needs constant adjustment, which requires innovation and experimentation (Shannon and Antypas 1997, Imperial 1999, Danter and others 2000, Ludwig and others 2001). Olsson and Folke (2001) describe the development of watershed management by a local fishing association in a multi level governance system faced with internal and external ecological and social change. The social change included devolution of management rights which provided an arena for local users to self-organize and developed, refine, and implement rules for ecosystem management. Not only do these people respond to change but by doing so they build adaptive capacity to deal with future change in the multi-level governance system.

Two large-scale resource systems in the United States provide compelling examples of how adaptive capacity can be built in industrialized developed areas. The Everglades of Florida and the Grand Canyon ecosystem are both complex social-ecological systems, where unwanted ecosystem state shifts (eutrophication, species endangerment, loss of habitat and biodiversity) have resulted from large scale water management projects (Gunderson et al. 1995a). In both cases, the restoration of resilience has been a social objective, involving millions to billions of dollars.

Uncertainty has been confronted in both areas through the articulation of a set of competing hypotheses about what led to the loss of resilience, and what is needed to restore those lost ecosystem functions and services. Those hypotheses are tested through a structured set of management actions designed to sort among the alternative explanations and a comprehensive monitoring plan established through decades of research. The slowly-changing variables–nutrients in sediments, and decadal hydrologic cycles - are the critical objects of monitoring, as they are the key indicators of ecosystem resilience. In larger, more complex systems than the Everglades and Grand Canyon, structured management experiments may be impossible, yet it is still necessary for people to assess the fundamental variables and branch points that lead to alternative futures. In these situations, scenario exercises are a useful mechanism for building understanding and flexibility toward adaptive change (Raskin et al. 1998, Carpenter 2001, Peterson et al. 2002, Millennium Ecosystem Assessment www.millenniumassessment.org).

The Everglades and the Grand Canyon diverge with respect to their ability to cultivate institutional learning. The Everglades process has been trapped by special interest groups (agriculture and environmentalists) who seek to avoid learning, thus undermining the possibilities for enhancing resilience. The Grand Canyon group, on the other hand, has developed an 'Adaptive Management Work Group' which uses planned management actions and subsequent monitoring data to test hypotheses, and build understanding of ecosystem dynamics. Such understanding is one necessary ingredient of adaptive capacity.

Working with such 'open institutions' is essential for dealing with ambiguity of multiple objectives, uncertainty and the possibility of surprising outcomes (Shannon and Antypas 1997, Kasperson and Kasperson 2001b). Such emergent governance (Shannon, SUNY Buffalo Law School, pers.comm.) that creates new institutional platforms for adaptive management is evolving in many places. For example, adaptive co-management systems, i.e. flexible community-based systems of resource management tailored to specific situations and supported by and working in collaboration with concerned governmental agencies, educational institutions and where appropriate NGOs, is part of the sub-global assessments of the *Millennium Ecosystem Assessment* (www.millenniumassessment.org) (Ayensu et al. 1999). Adaptive co-management draws on accumulated social-ecological experience and is informed by both practice and theory. It relies on the participation of a diverse set of interest groups operating at different scales, from local users, to municipalities, to regional and national organizations, and occasionally also international networks and bodies. Adaptive co-management takes place, for example, in the context of the Biodiversity Register program in India (Gadgil et al. 2000) and through the involvement of several local steward associations in the management of semi-urban and urban landscapes in Sweden.

Diversity in functions and in response among local level resource management systems, from the individual level to organizational and institutional levels (Pinkerton 1998, Olsson and Folke 2001, Burger et al. 2001, Westley 2002, Folke et al. 2002), enhances performance so long as there are overlapping units of government that can resolve conflicts, aggregate knowledge across scale, and insure that when problems occur in smaller units, a larger unit can temporarily step in (Low et al. 2002). Cash and Moser (2000) propose that governance for linking global and local scales should utilize boundary organizations, utilize scale-dependent comparative advantages, and employ adaptive assessment and management strategies. Such cross-scale governance should focus on nurturing ecosystem states that generate essential support to society.

Building adaptive capacity in linked social-ecological systems to respond to change now and in the future is a prerequisite for sustainability in a world of rapid transformations (Gunderson and Holling 2002, Raskin et al. 2002). In addition to scientific information, it requires the involvement of resource users, decision-makers and other interest groups in resource management (Ostrom et al. 1999, Berkes et al. 2002). Ecological knowledge and understanding of resource and ecosystem dynamics among resource users and other interest groups, its incorporation into resource-use practices and institutions, its temporal and spatial transmission and transformation, and its re-creation through cycles of crises and re-organization needs to be nurtured to counteract the creation of social-ecological vulnerability.

Concluding Remarks and Policy Implications

Humanity has powerful interactions with biogeochemical, hydrological and ecological processes, from local to global scales. The complexity of social-ecological systems makes it necessary to abandon the perception of a global steady state. Instead, managing complex, coevolving social-ecological systems for sustainability requires the ability to cope with, adapt to and shape change without losing options for future development. It requires resilience - the capacity to buffer perturbations, self-organize, learn and adapt. When massive transformation occurs, resilient systems contain the experience and the diversity of options needed for renewal and redevelopment. Sustainable systems need to be resilient.

Management can diminish or build resilience. Rigid control mechanisms that seek stability tend to erode resilience and facilitate breakdown of socio-economic systems. There are many examples where management has altered slowly-changing ecological variables, such as soils or biodiversity, with disastrous social consequences that did not appear until long after the ecosystems were first affected. An extensive literature documents human-induced regime shifts into less productive and less desirable ecosystem states, which are difficult, expensive, or sometimes impossible to reverse. Similarly, management can disrupt flexible social institutions and experience or remove mechanisms for creative, adaptive response by people. Erosion of the sources of resilience leads to fragile social-ecological systems, with consequences for human livelihoods, vulnerability, security and conflicts.

Although we may understand the mechanisms behind shifts in ecosystems, it will be difficult to predict such shifts. Measurements and predictions of ecological thresholds have broad-tailed and changeable probability distributions. Often, passive monitoring-and-control systems are unable to learn as fast as the thresholds move. In such situations, prediction and optimization have little use, and will have to be replaced by risk spreading and insurance strategies to maintain options and sustain social-ecological systems in the face of surprise, unpredictability, and complexity.

Resilience-building management needs to be flexible and open to learning. It attends to slowly-changing, fundamental variables such as experience, memory, and diversity in both social and ecological systems. The crucial slow variables that determine the underlying dynamic properties of the system, and that govern the supply of essential ecosystem services, need to be identified and assessed. The processes and drivers that determine the dynamics of this set of crucial variables need to be identified and assessed. The role of biological diversity in ecosystem functioning and response to change should be explicitly accounted for in this context and acknowledged in resilience building policies.

Two useful tools for resilience-building in complex, unpredictable systems are structured scenarios and active adaptive management. Structured scenarios attempt to envision alternative futures in ways that expose fundamental variables and branch points that may be collectively manipulated to evoke change. Active adaptive management seeks a set of structured management experiments designed to reveal fundamental variables and system potential. These techniques should be encouraged and expanded to help increase capacity to build resilience. They require, and facilitate, a social context with flexible and open institutions and multi-level governance systems that allow for learning and that build adaptive capacity without constraining future development options.

Managing for social-ecological resilience requires understanding of ecosystem dynamics, incorporating also the knowledge and wisdom of local users and interest groups. Consequently, the spread of ecological illiteracy in contemporary society needs to be counteracted. Outdated perceptions of humanity as decoupled from, and in control of, the processes of the biosphere will foster vulnerability and large-scale surprise and counteract sustainability. Instead, technological development and economic policies need to contribute to building resilience, founded on a perception of coevolving social-ecological systems from local to global scales.

At least three general policy recommendations can be drawn from the synthesis of resilience in the context of sustainable development. The first level emphasizes the importance of policy that highlights interrelationships between the biosphere and the prosperous development of society. The second stresses the necessity of policy to create space for flexible and innovative collaboration towards sustainability, and the third suggests a few policy directions for how to operationalize sustainability in the context of social-ecological resilience.

1. Although most people appreciate that development is ultimately dependent on the processes of the biosphere, we have tended to take the support capacity of ecosystems for granted. This report illustrates that erosion of nature's support capacity leads to vulnerability. Policy should strengthen the perception of humanity and nature as interdependent and interacting and stimulate development that enhances resilience in social-ecological systems, recognizing the existence of ecological threshold, uncertainty and surprise.

2. Policy should stimulate the creation of arenas for flexible collaboration and management of social-ecological systems, with open institutions that allow for learning and build adaptive capacity. Policy frameworks with clear directions for action towards social-ecological resilience are required in this context (the EU watershed management directive is one example). They create action platforms for adaptive management processes and flexible multi-level governance that can learn, generate knowledge and cope with change. Such systems create a diversity of management options of significance for responding to uncertainty and surprise.

3. Policy should stimulate the development of indicators of gradual change and early warning signals of loss of ecological resilience and possible threshold effects. Policy should encourage monitoring of key ecosystem variables and aim to manage diversity for insurance to cope with uncertainty. Policy should stimulate ecosystem friendly technology and the use of economic incentives to enhance resilience and adaptive capacity. The development of monocultures should be avoided. Policy should provide incentives that encourage learning and build ecological knowledge into institutional structures in multi-level governance. Policy should invite participation by resources users and other interest groups and their ecological knowledge. Structured scenarios and active adaptive management processes should be implemented.

We have emphasized that managing for resilience enhances the likelihood of sustaining development in changing environments where the future is unpredictable. More resilient social-ecological systems are able to absorb larger shocks without changing in fundamental ways. Resilience-building policy attempts to increase the range of surprises with which a socio-economic system can cope. It also conserves and nurtures the diversity – of species, of human opportunity, of learning institutions and of economic options – that is necessary to renew, reorganize and adapt to unexpected and transformative circumstances. The need to account for resilience in a world of transformations is a perspective that should become embedded in strategies and policy of the World Summit on Sustainable Development and recognized in the next phases for implementation of Agenda 21.

References

Adger W. 2000. Social and ecological resilience: are they related? *Progress in Human Geography* 24: 347-364.

Adger W, Neil P. Kelly M and Huu Ninh N. 2001. *Living with Environmental Change: Social Vulnerability, Adaptation, and Resilience in Vietnam.* Rutledge, London.

Agee, J.K. 2002. The fallacy of passive management. Conservation Biology in Practice. Vol 3: 18-25.

Alexander D. 2000. *Confronting Catastrophe: New Perspectives on Natural Disasters.* Terra Publishing, Harpenden, England.

Arrow K, Bolin B, Costanza R, Dasgupta P, Folke C, Holling CS, Jansson B-O, Levin S, Mäler K-G, Perrings C and Pimentel D. 1995. Economic growth, carrying capacity and the environment. *Science* 268: 520-521.

Ayensu E, van Claasen DR, Collins M, Dearing A, Fresco L, Gadgil M, Gitay H, Glaser G, Calestous Juma C, Krebs J, Roberto Lenton R, Lubchenco J, McNeely JA, Mooney HA, Pinstrup-Andersen P, Ramos M, Raven P, Reid WV, Samper C, Sarukhán J, Schei P, Galízia Tundisi J, Watson RT, Xu G and Zakri AH. 1999. International Ecosystem Assessment. *Science* 286:685-686

Barbier E, Burgess J and Folke C. 1994. *Paradise Lost? The Ecological Economics of Biodiversity.* Earthscan Publications, London.

Baskin Y. 1997. *The Work of Nature: How the Diversity of Life Sustains Us.* Island Press, Washington DC.

Bengtsson J, Angelstam P, Elmqvist T, Emanuelsson U, Folke C, Ihse M, Moberg F and Nyström M. In press. Reserves, Resilience, and Dynamic Landscapes. *Ambio.*

Bennett EM, Carpenter SR and Caraco NF. 2001. Human impact on erodable phosphorus and eutrophication: a global perspective. *BioScience* 51:227-234.

Berkes F and Folke, C. 2002. Back to the future: Ecosystem dynamics and local knowledge. In: Gunderson, LH and Holling CS (eds.) *Panarchy: Understanding Transformations in Human and Natural Systems.* Island Press, Washington DC.

Berkes F and Folke C, editors. 1998. *Linking Social and Ecological Systems. Management Practices and Social Mechanisms for Building Resilience.* Cambridge University Press, Cambridge.

Berkes F, Colding J and Folke C. 2000. Rediscovery of traditional ecological knowledge as adaptive management. *Ecological Applications* 10: 1251-1262.

Berkes F, Colding J and Folke C, editors. 2002. *Navigating Social-Ecological Systems: Building Resilience for Complexity and Change.* Cambridge University Press, Cambridge.

Bräutigam A and Elmqvist T. 1990 Conserving Pacific island flying foxes. *Oryx* 24:81-89.

Brock WA, Mäler K-G and Perrings C. 2002. Resilience and sustainability; The economic analysis of nonlinear systems. In: Gunderson LH and Holling CS. editors. 2002. *Panarchy: Understanding Transformations in Human and Natural Systems.* Island Press, Washington, DC.

Burger J, Ostrom E, Norgaard RB, Policansky D and Goldstein BD. 2001. *Protecting the Commons. A Framework for Resource Management in the Americas.* Island Press, Washington, DC.

Carpenter SR. 2001. Alternate states of ecosystems: Evidence and its implications. Pages 357-383 in Press MC, Huntly N and Levin S. (eds). *Ecology: Achievement and Challenge.* Blackwell, London.

Carpenter SR. 2002. Ecological futures: building an ecology of the long now. *Ecology*: in press. Available on the Internet – URL: http://www.limnology.wisc.edu/macarthur/ecofutures.pdf

Carpenter SR and Gunderson LH. 2001. Coping with collapse: Ecological and social dynamics in ecosystem management. *BioScience* 51:451-457.

Carpenter SR and Kitchell JF. (editors). 1993. *The Trophic Cascade in Lakes.* Cambridge University Press, Cambridge.

Carpenter SR, Ludwig D and Brock WA. 1999. Management of eutrophication for lakes subject to potentially irreversible change. *Ecological Applications* 9:751-771.

Carpenter SR, Cole JJ, Hodgson JR, Kitchell JF, Pace ML, Bade D, Cottingham KL, Essington TE, Houser JN and Schindler DE. 2001. Trophic cascades, nutrients and lake productivity: whole-lake experiments. *Ecological Monographs* 71:163-186.

Carpenter SR, Caraco NF, Correll DL, Howarth RW, Sharpley AN and Smith VH. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications* 8:559-568.

Carpenter SR, Walker B, Anderies JM and Abel N. 2001. From metaphor to measurement: Resilience of what to what? *Ecosystems* 4:765-781.

Carter TR, Hulme M, Crossley JF, Malyshev S, New MG, Schelsinger ME and Tuomenvirta H. 2000. Climate Change in the 21st Century - Interim characterizations based on the new IPCC emissions scenarios. Paper 433. The Finnish Environment, Helsinki.

Cash DW and Moser SC. 2000. Linking global and local scales: Designing dynamic assessment and management processes. *Global Environmental Change* 10:109-120.

Chapin FS, Zavaleta ES, Eviner VT, Naylor RL, Vitousek PM, Reynolds HL, Hooper DU, Lavorel S, Sala OE, Hobbie SE, Mack MC, and Diaz S. 2000. Consequences of changing biodiversity. *Nature* 405:234-242.

Chichilnisky G and Heal G. 1998. Economic returns from the biosphere. *Nature* 391:629-630.

Chorus I, Falconer IR, Salas HJ, and Bartram J. 2000. Health risks caused by freshwater cyanobacteria in recreational waters. *Journal of Toxicology and Environmental Health*-Part B-Critical Reviews 3:323-347.

Colding J and Folke C. 2001. Social taboos: 'invisible' systems of local resource management and biological conservation. *Ecological Applications* 11: 584-600.

Colding J and Folke C. 2000. The taboo system: Lessons about informal institutions for nature management. *The Georgetown International Environmental Review* XII: 413-445.

Cook B, Emel JL and Kasperson RE. 1990. Organizing and managing radioactive wastes as an experiment. *Journal of Policy Analysis and Management.* 9:339-366.

Costanza R, Daly H, Folke C, Hawken P, Holling CS, McMichael AJ, Pimentel D, and Rapport D. 2000. Managing our environmental portfolio. *BioScience* 50:149-155.

Costanza R, Low BS, Ostrom E and Wilson J. 2001. *Institutions, Ecosystems, and Sustainability.* Boca Raton: Lewis Publishers.

Costanza R, d'Arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill RV, Paruelo J, Raskin RG, Sutton P and van den Belt M. 1997. The value of the World's ecosystem services and natural capital. *Nature* 387:253-260.

Costanza R, Waigner L, Folke C and Mäler K-G. 1993. Modeling complex ecological economic systems: towards an evolutionary dynamic understanding of people and nature. *BioScience* 43: 545-555.

Cox PA, Elmqvist T., Rainey EE and Pierson ED. 1991. Flying foxes as strong interactors in South Pacific Island ecosystems: A conservation Hypothesis. *Conservation Biology* 5:448-454.

Daily G. editor. 1997. *Nature's Services: Societal Dependence on Natural Ecosystems.* Island Press, Washington DC.

Daily G, Söderqvist T, Aniyar S, Arrow K, Dasgupta P, Ehrlich PR, Folke C, Jansson AM, Jansson B-O, Kautsky N, Levin S, Lubchenco J, Mäler K-G, Simpson D, Starrett D, Tilman D and Walker B. 2000. The value of nature and the nature of value? *Science* 289:395-396.

Danell K, Bergström R, Edenius L and Ericsson G. in review. Ungulates as drivers of tree population dynamics. *Forest Ecology and Management.*

Danter KJ, Griest DL, Mullins GW and Norland E. 2000. Organizational change as a component of ecosystem management. *Society and Natural Resource* 13: 537-547.

Dasgupta P. 1993. *An Inquiry into Well-Being and Destitution.* Clarendon Press, Oxford.

Daskalov GM. 2002. Overfishing drives a trophic cascade in the Black Sea. *Marine Ecology Progress Series* 225: 53-63.

De Groen MM and Savenije HHG. 1996. Do land use induced changes of evaporation affect rainfall in Southeastern Africa? *Physics and Chemistry of the Earth* 20: 515-519.

de Soysa I and Gleditsch NP (with Gibson M and Sollenberg M). 1999. To cultivate peace: Agriculture in a world of conflict. The Woodrow Wilson Center Environmental Change & Security Project Report, Issue 5 (Summer 1999), pp. 15-25. [http://ecsp.si.edu/pdf/Report5-Sect1.pdf]

Diaz S and Cabido M. 2001. Vive la difference: plant functional diversity matters to ecosystem processes. *Trends in Ecology and Evolution* 16:646-655

Elmqvist T, Wall M, Berggren AL, Blix L, Fritioff S and Rinman U. 2001. Tropical forest reorganization after cyclone and fire disturbance in Samoa: remnant trees as biological legacies. *Conservation Ecology* 5(2): 10. [online] URL: http://www.consecol.org/vol5/iss2/art10

Epstein PR.1999. Climate and health. *Science* 285:347-348.

Estes JA and Duggins DO. 1995. Sea otters and kelp forests in Alaska: Generality and variation in a community ecological paradigm. *Ecological Monographs* 65: 75-100.

Evanari M, Shanan L and Tadmor N. 1971. *The Negev – The challenge of a desert.* Harvard University Press, Cambridge.

Falkowski P, Scholes RJ, Boyle E, Canadell J, Canfield D, Elser J, Gruber N, Hibbard K, Hogberg P, Linder S, Mackenzie FT, Moore B, Pedersen T, Rosenthal Y, Seitzinger S, Smetacek V, Steffen W. 2000. The global carbon cycle: A test of our knowledge of earth as a system. *Science* 290: 291-296.

Finlayson AC and McCay BJ. 1998. Crossing the threshold of ecosystem resilience: the commercial extinction of Northern cod, pp 311-337 in Berkes F, Folke C (eds.). *Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience.* Cambridge University Press, Cambridge.

Flannery T. 1994. *The Future Eaters: An ecological history of the Australasian lands and people.* Reed New Holland, Sydney.

Folke C, Colding J and Berkes F. 2002. Building resilience for adaptive capacity in social-ecological systems. In: Berkes F., Colding J and Folke, C. editors. *Navigating Social-Ecological Systems: Building Resilience for Complexity and Change.* Cambridge University Press, Cambridge.

Folke C and Kautsky N. 1989. The role of ecosystems for a sustainable development of aquaculture. *Ambio* 18, 234-243.

Folke C, Holling CS and Perrings C. 1996. Biological diversity, ecosystems and the human scale. *Ecological Applications* 6: 1018-1024.

Folke C, Jansson Å, Larsson J and Costanza R. 1997. Ecosystem appropriation by cities. *Ambio* 26, 167-172.

Folke C, Pritchard I, Berkes F, Colding J and Svedin U. 1998. The Problem of Fit Between Ecosystems and Institutions. International Human Dimensions Programme (IHDP). IHDP Working Paper No 2. www.uni-bonn.de/IHDP/public.htm

Frost TM, Carpenter SR, Ives AR and Kratz TK. 1995. Species compensation and complementarity in ecosystem function. In: Jones CG and Lawton JH. editors. *Linking Species and Ecosystems.* Chapman and Hall, NY. pp. 224-239.

Gadgil M, Berkes F and Folke C. 1993. Indigenous knowledge for biodiversity conservation. *Ambio* 22:151-6.

Gadgil M, Olsson P, Berkes F and Folke C. 2002. Exploring the role of local ecological knowledge for ecosystem management: three case studies. in Berkes F, Colding J and Folke C. editors. *Navigating Social-Ecological Systems: Building Resilience for Complexity and Change.* Cambridge University Press, Cambridge.

Gadgil M, Seshagiri Rao PR, Utkarsh G, Pramod P and Chatre A. and members of the People's Biodiversity Initiative. 2000. New meanings for old knowledge: The people's Biodiversity Register Program. *Ecological Applications* 10: 1307-1317.

German Advisory Council on Global Change. 2000. *World in Transition: Strategies for Managing Global Environmental Risks.* Springer-Verlag, Berlin.

Gibson CC, McKean MA and Ostrom E. 2000. *People and Forests. Communities, Institutions, and Governance.* MIT Press, Cambridge, MA.

Gomezpompa A and Kaus A. 1992. Taming the wilderness myth. *BioScience* 42:271-279.

Gren IM. 1995. The value of investing in wetlands for nitrogen abatement. *European Review of Agricultural Economics* 22:157-172.

Gunderson LH. 2001. Managing surprising ecosystems in southern Florida. *Ecological Economics* 37:371-378.

Gunderson LH and Holling CS. editors. 2002. *Panarchy: Understanding Transformations in Human and Natural Systems.* Island Press, Washington, DC.

Gunderson LH and Pritchard L. editors. 2002. *Resilience and the Behavior of Large-Scale Ecosystems.* Island Press, Washington, DC.

Gunderson LH, Holling CS and Light S. editors. 1995a. *Barriers and Bridges to the Renewal of Ecosystems and Institutions.* Columbia University Press, New York.

Gunderson LH, Light S and Holling CS. 1995b. Lessons from the Everglades: Learning in a turbulent system. *BioScience* Supplement S66-73.

Hammond A. 1998. *Which World? Scenarios for the 21st Century.* Island Press, Washington D.C.

Hanna S. 1998. Managing for human and ecological context in the Maine soft shell clam fisheries, pp-190-211 in Berkes F and Folke C. editors. *Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience.* Cambridge University Press, Cambridge.

Hanna S, Folke C and Mäler K-G. editors. 1996. *Rights to Nature.* Island Press,Washington DC.

Holland JH. 1995. *Hidden Order: How Adaptation Builds Complexity.* Addison-Westley, Reading, MA.

Holling CS, Berkes F and Folke C. 1998. Science, sustainability and resource management. In: Berkes F and Folke C. editors. *Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience.* Cambridge University Press, Cambridge.

Holling CS. 1996. Engineering resilience versus ecological resilience. In: Schulze PC, editor. *Engineering within Ecological Constraints.* National Academy Press, Washington DC.

Holling CS. 1986. The resilience of terrestrial ecosystems: local surprise and global change. In: *Sustainable Development of the Biosphere,* pp. 292-317, eds. WC Clark and RE Munn. Cambridge University Press, Cambridge.

Holling CS and Meffe GK. 1996. Command and control and the pathology of natural resource management. *Conservation Biology* 10: 328-337.

Holling CS. 2001. Understanding the complexity of economic, ecological and social systems. *Ecosystems* 4: 390-405.

Holling CS. editor. 1978. *Adaptive Environmental Assessment and Management.* Wiley, London.

Homer-Dixon T and Blitt J. editors. 1998. *Ecoviolence: Links among environment, population, and security.* Rowman and Littlefield publ., Lanham, MD.

Homewood K, Lambin EF, Coast E, Kariuki A, Kikula I, Kivelia J, Said M, Serneels S, and Thompson M. 2001. Long-term changes in Serengeti_Mara wildebeest and land cover: Pastoralism, population, or policies? *Proceedings form the National Academy of Sciences* 98:12544-12549.

Hudak AT. 1999. Rangeland mismanagement in South Africa: Failure to apply ecological knowledge. *Human Ecology* 27: 55-78.

Imperial MT. 1999. Instiutional analysis and ecosystem-based management: the institutional analysis and development framework. *Environmental Management* 24:449-65.

Ives AR., Gross K and Klug JL. 1999. Stability and variability in competitive communities. *Science* 286: 542-544.

Jackson JBC, Kirb, MX, Berher WH, Bjorndal KA, Botsford LW, Bourque BJ, Bradbury RH, Cooke R, Erlandsson J, Estes JA, Hughes TP, Kidwell S, Lange CB, Lenihan HS, Pandolfi JM, Peterson CH, Steneck RS, Tegner MJ and Warner RR. 2001. Historical overfishing and the recent collapse of coastal ecosystems. *Science* 293: 629-638.

Jansson Å, Folke C and Langaas S. 1998. Quantification of the nitrogen retention capacity in natural wetlands in the Baltic Drainage Basin. *Landscape Ecology* 13:249-62.

Jansson Å, Folke C, Rockström J and Gordon L. 1999. Linking freshwater flows and ecosystem services appropriated by people: the case of the Baltic Sea drainage basin. *Ecosystems* 2: 351-366.

Kasperson JX and Kasperson RE. editors. 2001a. *Global Environmental Risk.* United Nations University Press/Earthscan, London.

Kasperson RE and Kasperson JX. 2001b. *Climate change, vulnerability and social justice.* Stockholm Environment Institute, Stockholm.

Kasperson RE and Kasperson JX. 1996. The social amplification and attenuation of risk. *Annals of the American Academy of Political and Social Sciences* 545: 95-105.

Kasperson JX, Kasperson RE and Turner BL. 1995. *Regions at Risk: Comparisons of Threatened Environments.* United Nations University Press, NY.

Kates RW and Clark WC. 1996. Expecting the unexpected. *Environment* March 1996: 6-11, 28-34.

Kates RW, Clark WC, Corell R, Hall JM, Jaeger CC, Lowe I, McCarthy JJ, Schellhuber HJ, Bolin B, Dickson NM, Faucheux S, Gallopin GC, Grubler A, Huntley B, Jäger J, Jodha NS, Kasperson RE, Mabogunje A, Matson P, Mooney H, More III B, O'riordan T and Svedin U. 2001. Sustainability science. *Science* 292: 641-642.

Kauffman S. 1993. *The Origins of Order.* Oxford University Press, New York.

Kinzig AP, Pacala SW and Tilman D. editors. 2002. *The Functional Consequences of Biodiversity.* Princeton University Press, Princeton, N.J.

Lambin EF, Turner II BL, Geist HJ, Agbola SB, Angelsen A, Bruce JW, Coomes OT, Dirzo R,. Fischer G, Folke C, George PS, Homewood K, Imbernon J, Leemans R, Li X, Moran EF, Mortimore M, Ramakrishnan PS, Richards JF, Skånes H, Steffen W, Stone GD, Svedin U, Veldkamp TA, Vogel C and Xu J. 2001. Our emerging understanding of the causes of land-use and land-cover change. *Global Environmental Change* 11:261-269.

Lawton JH. 2000. *Community Ecology on a Changing World.* Excellence in Ecology Series no. 11. Ecology Institute, Oldendorf, Germany. 227 pp.

Lee KN. 1993. *Compass and Gyroscope: Integrating science and politics for the environment.* Island Press, Washington DC.

Levin S, Barrett S, Aniyar S, Baumol W, Bliss C, Bolin B, Dasgupta P, Ehrlich P, Folke C, Gren I-M, Holling CS, Jansson AM, Jansson B-O, Martin D, Mäler K-G, Perrings C, Sheshinsky E. 1998. Resilience in natural and socioeconomic systems. *Environment and Development Economics* 3: 222-235.

Levin S. 1999. *Fragile Dominion: Complexity and the Commons.* Perseus Books, Reading, MA.

Lindgren E. and Gustafson R. 2001. Tick-borne encephalitis in Sweden and climate change. *Lancet* 358:16-18.

Loreau M, Naeem S, Inchausti P, Bengtsson J, Grime JP, Hector A, Hooper DU, Huston MA, Raffaelli D, Schmid B, Tilman D, and Wardle DA. 2001. Biodiversity and ecosystem functioning: Current knowledge and future challenges. *Science* 294: 804-808.

Low B, Ostrom E, Simon C, Wilson J. 2002. Redundancy and diversity in governing and managing natural resources. In: Berkes F, Colding J and Folke, C. editors. 2002. *Navigating the Dynamics of Social-Ecological Systems: Building Resilience for Complexity and Change.* Cambridge University Press, Cambridge, UK. In press.

Ludwig D, Mangel M and Haddad B. 2001. Ecology, conservation, and public policy. Annual *Review of Ecology and Systematics* 32: 481-517.

Ludwig D, Hilborn R and Walters C. 1993. Uncertainty, resource exploitation and conservation: lessons from history. *Science* 260: 17, 36.

Mäler K-G. 2000. Development, ecological resources and their management: A study of complex dynamic systems. *European Economic Review* 44: 645-665.

Malhotra Y. 1999. Toward a knowledge ecology for organizational white-waters. *Knowledge Management*, March 1999, pp.18-21.

McFarlane DJ, George RJ and Farrington P. 1992. Changes in the hydrologic cycle. Pages 146-186 in Hobbs RJ and Saunders DA. Editors. *Reintegrating Fragmented Landscapes.* Springer-Verlag, New York.

McGinnis M. 1999. *Polycentricity and Local Public Economies.* University of Michigan Press, Ann Arbor.

McGinnis M. 2000. *Polycentric Governance and Development.* University of Michigan Press, Ann Arbor.

McIntosh RJ, Tainter JA and McIntosh SK. Editors. 2000. *The Way the Wind Blows: Climate, History and Human Action.* Columbia University Press, New York.

McMahon TA, Gan KC and Finlayson BL. 1992. Anthropogenic changes to the hydrological cycle in Australia. In: Gifford RM and Barson MM. editors. Australia's Renewable Resources: Sustainability and Global Change. Parkes: Bureau of Rural Resources proceedings No14 and CSIRO Division of Plant Industry.

McMichael AJ, Bolin B, Costanza R, Daily G, Folke C, Lindahl-Kiessling K, Lindgren E and Niklasson B. 1999. Globalization and the sustainability of human health. *BioScience* 49:205-210.

McNeill J. 2000. *Something New under the Sun: An environmental history of the twentieth century.* The Penguin Press, London.

MDBC (Murray-Darling Basin Ministerial Council). 1999b.The salinity audit of the Murray-Darling Basin. A 100-year perspective. Canberra: Murray-Darling Basin Commission.

Messer E, Cohen MJ and Marchione T. 2001. Conflict: A Cause and Effect of Hunger. The Woodrow Wilson Center Environmental Change & Security Project Report, Issue 7 (Summer 2001), pp. 15-25. [http://ecsp.si.edu/PDF/ECSP7-featurearticles-1.pdf]

Milly PCD, Wetherald RT, Dunne KA and Delworth TL. 2002. Increasing risk of great floods in a changing climate. *Nature* 415:514-517.

Moberg F. and Folke C. 1999. Ecological goods and services of coral reef ecosystems. *Ecoogical Economics* 29, 215-233.

Nakicenovic N. and Swart R. edtors. 2000. *Emissions Scenarios.* Cambridge Univ Press, London.

Nabhan GP and Buchmann SL. 1997. Services provided by pollinators. In: Daily G. editor. 1997. *Nature's Services: Societal Dependence on Natural Ecosystems.* Island Press, Washington D.C.

Naylor R, Goldburg R, Mooney H, Beveridge M, Clay J, Folke C, Kautsky N, Lubchenco J, Primavera J and Williams M. 1998. Nature's subsidies to shrimp and salmon farming. *Science* 282: 883-884.

Naylor R, Goldburg R, Primavera J, Kautsky N, Beveridge M, Clay J, Folke C, Lubchenco J, Mooney H and Troell M. 2000. Effect of aquaculture on world fish supplies. *Nature* 405: 1017-1024.

Niamir-Fuller M. editor. 1999. *Managing Mobility in African Rangelands. The Legitimization of Transhumance.* Intermediate Technology Publications Ltd, London

NLWRA (National Land and Water Resources Audit). 2001. Australian Dryland Salinity Assessment 2000. Extent, impacts processes, monitoring and management options. Canberra: National Land and Water Resources Audit.

Norgaard RB. 1994. *Development Betrayed: The End of Progress and a Coevolutionary Revisioning of the Future.* Routledge, New York.

Nyström M, Folke C and Moberg F. 2000. Coral-reef disturbance and resilience in a human-dominated environment. *Trends in Ecology and Evolution* 15: 413-417

Nyström M and Folke C. 2001. Spatial resilience of coral reefs. *Ecosystems* 4:406-417.

O'Neill RV and Kahn JR. 2000. Homo economus as a keystone species. *BioScience* 50:333-337.

Ohlsson L. 2002. The risk of livelihood conflicts and the nature of policy measures required. In: Kittrie NN et al. editors. *Seeds of True Peace: Responding to the Discontents of a Global Community.* The Eleanor Roosevelt Institute for Justice and Peace, Washington DC.

Olsson P and Folke C. 2001. Local ecological knowledge and institutional dynamics for ecosystem management: A study of Lake Racken watershed, Sweden. *Ecosystems* 4: 85-104.

Ostrom E. 1999. Coping with Tragedies of the Commons. *Annual Review of Political Science.* 2: 493-535.

Ostrom E, Dietz T, Dolsak N, Stern P, Stonich S and Weber EU. 2002. *The Drama of the Commons.* National Research Council. 2002. National Academy Press, Washington, DC.

Ostrom E, Burger J, Field CB, Norgaard RB and Policansky D. 1999. Revisiting the commons: Local lessons, global challenges. *Science* 284: 278-282.

Paine RT, Tegner MJ and Johnson EA. 1998. Compounded perturbations yield ecological surprises. *Ecosystems* 1:535-545.

Palmer TN and Räisänen J. 2002. Quantifying the risk of extreme seasonal precipitation events in a changing climate. *Nature* 415:512-514.

Palumbi SR. 2002. Humans as the World's greatest evolutionary force. *Science* 293:1786-1790

Pauly D, Christensen V, Dalsgaard J, Froese R and Torres F. 1998. Fishing down marine food webs. *Science* 279:860-863.

Perrings CA, Folke C and Mäler K-G. 1992. The ecology and economics of biodiversity loss: the research agenda. *Ambio* 21:201-211.

Perrings CA, Mäler K-G, Folke C, Holling CS and Jansson B-O. editors. 1995. *Biodiversity Conservation: Problems and Policies.* Kluwer Academic Publishers, Dordrecht.

Peterson GD, Allen CR and Holling CS. 1998. Ecological resilience, biodiversity, and scale. *Ecosystems* 1:6-18.

Peterson GD, Cumming GC and Carpenter SR. 2002. Scenario planning: a tool for conservation in an uncertain world. *Conservation Biology:* in press.

Pinkerton E. editor. 1989. *Co-operative management of local fisheries: new directions for improved management and community development.* University of British Columbia Press, Vancouver, BC.

Pinkerton E. 1998. Integrated management of a temperate montane forest ecosystem through wholistic forestry: A British Columbia example. In: Berkes F and Folk, C. editors. 1998. *Linking Social and Ecological Systems. Management Practices and Social Mechanisms for Building Resilience.*: Cambridge University Press, Cambridge.

Pomeroy RS. 1995. Community-based and co-management institutions for sustainable coastal fisheries management in Southeast Asia. *Ocean and Coastal Management* 3:143-62.

Post JR., Sullivan M, Cox S, Lester NP, Walters CJ, Parkinson EA, Paul AJ, Jackson L and Shuter BJ. 2002. Canada's recreational fisheries: The invisible collapse? *Fisheries* 27: 6-17.

Postel S. 1999. *Pillar of Sand: Can the irrigation miracle last?* WW Norton, New York.

Quarantelli EL. editor. 1998. *What is a Disaster? Perspectives on the Question.* Routledge, London.

Raskin P, Gallopin G, Gutman P, Hammond A and Swart R. 1998. *Bending the Curve: Toward Global Sustainability.* Stockholm Environment Institute, PoleStar Report Number 8.

Raskin P, Banuri T, Gallopin G, Gutman P, Hammond A, Kates R and Swart R. 2002. *Great Transition: The Promise and Lure of the Times Ahead.* Stockholm Environment Institute, Stockholm.

Redman CL. 1999. *Human Impact on Ancient Environments.* The University of Arizona Press, Tucson, AZ.

Riedlinger D and Berkes F. 2001. Contributions of traditional knowledge to understanding climate change in the Canadian Artic. *Polar Records* 37: 315-328.

Rockström J. 2000. Water resources management in smallholder farms in Eastern and Southern Africa: an overview. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere* 25: 279 – 288

Rockström J and Tilander Y. 1998. Options for sustainable agriculture in the Sahel: Landscape potential, human manipulations and livelihood security. In: Berger A. editor. *Twice Humanity – Implications for local and global resource use.* pp 117 – 137. The Nordic Africa Institute and Forum for Development Studies, Uppsala, Sweden.

Rockstrom J, Gordon L, Falkenmark M, Folke C and Engvall M. 1999. Linkages among water vapor flows, food production, and terrestrial ecosystem services. *Conservation Ecology* 3(2): 5. [online] URL: http://www.consecol.org/vol3/iss2/art5

Rockström J, Kaumbutho P, Mwalley P and Temesgen M., 2001. Conservation farming among small-holder farmers in E. and S. Africa: Adapting and adopting innovate land management options. In: Garcia-Torres L, Benites J and Martinez-Vilela A. editors. *Conservation Agriculture: A worldwide challenge.* 1st World Congress on Conservation Agriculture, Volume 1: Keynote Contributions, 39: 363 – 374, FAO, Rome, Italy.

Rönnbäck P. 1999. The ecological basis for economic value of seafood production supported by mangrove ecosystems. *Ecological Economics* 29:235-252.

Savenije HHG. 1995. New definitions for moisture recycling and the relation with land-use changes in the Sahel. *Journal of Hydrology,* 167:57-78.

Savenije HHG. 1996a. The runoff coefficient as the key to moisture recycling, *Journal of Hydrology,* 176: 219-225.

Savenije HHG. 1996b. Does moisture feedback affect rainfall significantly? *Physics and Chemistry of the Earth* 20: 507-513.

Scheffer M, Brock W and Westley F. 2000. Mechanisms preventing optimum use of ecosystem services: An interdisciplinary theoretical analysis. *Ecosystems* 3:451-471.

Scheffer M, Carpenter SR, Foley J, Folke C and Walker B. 2001. Catastrophic shifts in ecosystems. *Nature* 413:591-696.

Scoones I. 1999. New ecology and the social sciences: what prospects for a fruitful engagement? *Annual Review of Anthropology* 28: 479-507.

Shannon MA and Antypas AR. 1997. Open institutions:Uncertainty and ambiguity in 21st-century forestry. In: Kohm KA and Franklin JF. editors. *Creating a Forestry for the 21st Century: the Science of Ecosystem Management.* Island Press, Washington DC

Shiomoto A, Tadokoro K, Nagasawa K and Ishida Y. 1997. Trophic relations in the subarctic North Pacific ecosystem: possible feeding effect from pink salmon. *Marine Ecology Progress Series* 150: 75-85.

Steele JH. 1998. Regime shifts in marine ecosystems. *Ecological Applications* 8: S33-S36.

Svedin U, O´Riordan T and Jordan A. 2001. Multilevel governance for the sustainability transition. In: O´Riordan T. editor. *Globalism, Localism and Identity.* Earthscan, London, pp. 43-60.

Tainter JA. 1988. *The Collapse of Complex Societies.* Cambridge University Press, Cambridge.

Terborgh J, Lopez L, Nunez P, Rao M, Shahabuddin G, Orihuela G, Riveros M, Ascanio R, Adler GH, Lambert TD and Balbas L. 2001. Ecological meltdown in predator-free forest fragments. *Science* 294: 1923-1926.

Thompson M, Ellis R and Wildavsky A. 1990. *Cultural Theory.* Westview, Boulder, CO.

Turner BL, Clark WC and Kates RW. editors. 1990. *The Earth as Transformed by Human Action: Global and regional changes in the biosphere over the past 300 years.* Cambridge University Press, Cambridge, UK.

van der Leeuw S. 2000. Land degradation as a socionatural process. In: McIntosh RJ, Tainter JA and McIntosh SK. editors. *The Way the Wind Blows: Climate, History, and Human Action.* Columbia University Press, New York.

Van Wilgen BW, Le Maitre DC and Cowling RM. 1998. Ecosystem services, efficiency, sustainability and equity: South Africa's Working for Water programme. *Trends in Ecology and Evolution* 13: 378.

Vitousek PM, Mooney HA, Lubchenco J, Melillo JM. 1997. Human domination of earth's ecosystems. *Science* 277:494-9.

Vitousek PM and Walker LR. 1989. Biological invasion by *Myrica faya* in Hawaii: plant demography, nitrogen fixation, ecosystem effects. *Ecological Monographs* 59:247-265.

Walker BH. 1992. Biological diversity and ecological redundancy. *Conservation Biology* 6:18-23

Walker BH, Kinzig A and Langridge J. 1999. Plant attribute diversity, resilience, and ecosystem function: the nature and significance of dominant and minor species. *Ecosystems* 2: 95-113.

Walker BH. 1993. Rangeland ecology: understanding and managing change. *Ambio* 22:80-87.

Walker BH. 1997. Functional types in non-equilibrium ecosystems. pp 91-103 In: Smith TM, Shugart, HH and Woodward FI. editors. *Plant Functional Types.* Cambridge University Press, Cambridge.

Walters CJ. 1986. *Adaptive Management of Renewable Resources.* McGraw Hill, New York.

Walters CJ and Kitchell JF. 2001. Cultivation/depensation effects on juvenile survival and recruitment: mplications for the theory of fishing. Canadian Journal of Fisheries and Aquatic Sciences 58: 1-12.

Warren-Rhodes K and Koenig A. 2001. Ecosystem appropriation by Hong Kong and its implications for sustainable development. *Ecological Economics* 39:347-359.

Westley F. 2002. The devil in the dynamics: Adaptive management on the front lines. In: Gunderson LH and Holling CS. editors. 2002. *Panarchy: Understanding Transformations in Human and Natural Systems.* Island Press, Washington, DC.

Wilson EO. 1984. *Biophilia: The human bond with other species.* Harvard University Press, Cambridge, MA.

Wilson JB and Agnew ADQ. 1992. Positive-feedback switches in plant communities Advances in Ecological *Research* 23: 263-336.

WRI. 2001. *People and Ecosystems: The fraying web of life.* World Resources Institute, Washington DC.

Zimov SA, Chuprynin VI, Oreshko AP, Chapin FS, Reynolds JF and Chapin MC. 1995. Steppe-tundra transition: a herbivore-driven biome shift at the end of the Pleistocene. American Naturalist 146:765-794.

Appendix

Key terms

Resilience

Ecological resilience - The amount of change a system can undergo and still remain within the same state or domain of attraction, is capable of self-organization, and can adapt to changing conditions (Carpenter et al. 2001). Holling (e.g. 1986, 1996) defined ecological resilience as the magnitude of disturbance that a system can experience before it moves into a different state (stability domain) with different controls on structure and function, and distinguished it from engineering resilience (see below). More recent work emphasize the possibility of a system to adapt to change as a major component of ecological resilience, in addition to recovery or reorganization after disturbances (Carpenter et al. 2001, Gunderson and Holling 2002).

Engineering resilience - A measure of the rate at which a system approaches steady state following a perturbation (e.g. deAngelis 1992), also measured as the inverse of return time. Holling (e.g. 1986, 1996) pointed out that engineering resilience is a less appropriate measure in ecosystems and other systems that often have multiple stable states.

Social resilience - The ability of human communities to withstand external shocks or perturbations to their infrastructure, such as environmental variability or socal, economic or political upheaval, and to recover from such perturbations (Adger 2000).

Other terms

Ecological memory - The network of species, their interactions between each other and the environment, and the structures that make reorganization after disturbance possible. Its composition is determined by the past ecological and evolutionary history of the system. The ecological memory can be divided into the internal memory present within the disturbed area (also termed 'biological legacies'), and the external memory that provides source areas and propagules for colonization from outside the disturbed area (Bengtsson et al. 2002).

Social memory - The accumulation of experiences concerning management practices and rules-in-use that ensure the capacity of social systems to monitor change and to build institutions (formal and informal norms and rules) that enable appropriate responses to signals from the environment (McIntosh 2000).

Ecosystem functioning - A summary term for system level processes that are carried out in or by ecosystems. Some examples are primary production, nutrient cycling, hydrological regulation, nitrogen fixation, filtration, pedogenesis, maintenance of biodiversity, community (population) regulation, erosion control.

Functional groups - Groups of species that have similar traits or a similar function in ecosystems. Examples of functional groups among plants are nitrogen fixers and plants that draw water from deep in the soil. Other examples are decomposer organisms, mycorhizal fungi, and predators on pest insects.

Reorganization – re-structuring the biological and social composition of a system and re-establishing the functioning of the system following disturbance.

Vulnerability - The propensity of social or ecological systems to suffer harm from external stresses and perturbations. Involves the combination of sensitivity to exposures and adaptive measures to anticipate and reduce future harm (Kasperson et al. 1995).

Contributors

Jan Bengtsson, Department of Ecology and Crop Production Science, Swedish University of Agricultural Sciences, Uppsala, Sweden.

Fikret Berkes, Natural Resources Institute, University of Manitoba, Winnipeg, Manitoba, Canada.

Johan Colding, Beijer International Institute of Ecological Economics, Royal Swedish Academy of Sciences, Stockholm, Sweden.

Steve Carpenter, Center for Limnology, University of Wisconsin, Madison, WI, USA.

Kjell Danell, Department of Animal Ecology, Swedish University of Agricultural Sciences, Umeå, Sweden.

Thomas Elmqvist, Department of Systems Ecology, Stockholm University, Sweden.

Malin Falkenmark, Stockholm International Water Institute (SIWI) and Department of Systems Ecology, Stockholm University, Sweden.

Carl Folke, Center for Research on Natural Resources and the Environment (CNM) and Department of Systems Ecology, Stockholm University and Beijer International Institute of Ecological Economics, Royal Swedish Academy of Sciences, Stockholm, Sweden.

Line Gordon, Department of Systems Ecology, Stockholm University, Sweden.

Lance Gunderson, Department of Environmental Studies, Emory University, Atlanta GA, USA

CS Holling, Cedar Key, Florida, USA.

Roger Kasperson, Stockholm Environment Institute, Stockholm, Sweden.

Nils Kautsky, Department of Systems Ecology, Stockholm University and Beijer International Institute of Ecological Economics, Royal Swedish Academy of Sciences, Stockholm, Sweden.

Ann Kinzig, Department of Biology, Arizona State University, Tempe, AZ, USA.

Simon Levin, Department of Ecology and Evolutionary Biology, Princeton University, NJ USA.

Karl-Göran Mäler, Beijer International Institute of Ecological Economics, Royal Swedish Academy of Sciences, Stockholm, Sweden.

Fredrik Moberg, Albaeco, Stockholm, Sweden.

Leif Ohlsson, Department of Peace and Conflict Research, Göteborg University, Sweden.

Per Olsson, Department of Systems Ecology, Stockholm University, Sweden.

Elinor Ostrom, Workshop in Political Theory and Policy Analysis and Center for the Study of Institutions, Population, and Environmental Change (CIPEC), Indiana University, Bloomington, Indiana, USA.

Walter Reid, Millennium Ecosystem Assessment, ICLARM Office, Penang, Malaysia

Johan Rockström, International Institute for Infrastructural, Hydraulic and Environmental Engineering (IHE), Delft, the Netherlands and Department of Systems Ecology, Stockholm University, Sweden.

Hubert Savenije, International Institute for Infrastructural, Hydraulic and Environmental Engineering (IHE), Delft, the Netherlands.

Uno Svedin, the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (Formas).

Brian Walker, CSIRO Sustainable Ecosystems, Canberra, ACT, Australia.

ICSU Series on Science for Sustainable Development

1. Report of the Scientific and Technological Community to the World Summit on Sustainable Development, 20 pp. 2002.

2. Energy and Transport, 20 pp. 2002.

3. Resilience and Sustainable Development, 37 pp. 2002.

INTERNATIONAL COUNCIL FOR SCIENCE

51, Boulevard de Montmorency
75016 Paris, France
Tel.: 33 (0) 1 45 25 03 29
Fax: 33 (0) 1 42 88 94 31
E-mail: secretariat@icsu.org
http://www.icsu.org

ICSU's Mission

To identify and address major issues of importance to science and society, by mobilising the resources and knowledge of the international scientific community; to promote the participation of all scientists, irrespective of race, citizenship, language, political stance or gender in the international scientific endeavour; to facilitate interactions between different scientific disciplines and between scientists from 'Developing' and 'Developed' countries; to stimulate constructive debate by acting as an authoritative independent voice for international science and scientists.