Nature and Society:
An Imperative for Integrated Environmental Research

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THE NATION'S ENVIRONMENTAL RESEARCH NEEDS

OVERVIEW

In June of 2000, forty-four scientists gathered in Tempe, Arizona to discuss the needs and priorities for interdisciplinary environmental research, spanning natural sciences, social sciences, engineering, and humanities. Attendees came from over a dozen different fields, and represented thirty-one institutions. This report presents the consensus view that emerged from that workshop.

Participants unanimously agreed that increased support for interdisciplinary environmental research is required to meet the pressing national and international environmental challenges of the coming century. Participants also affirmed that interdisciplinary environmental research represents one of the most compelling intellectual frontiers for scientific inquiry.

Five research areas are in particular need of increased attention. These are:

- Evolution and Resilience of Coupled Social and Ecological Systems
- Ecosystem Services
- Coping with Uncertainty, Complexity, and Change
- Environmental Dimensions of Human Welfare, Health, and Security
- Communicating Scientific Information

Participants also agreed that increased funding alone would be insufficient to implement the required expanded research program. Recommendations concerning education and training, research infrastructure, and institutional changes at foundations and agencies are also presented below.

BACKGROUND

Since the dawn of agriculture, humans have significantly altered local ecosystems, hydrological dynamics, and biogeochemical cycles; it is believed that the degradation of local ecological resources has, at times, contributed to the demise of civilizations dependent on those resource (see, for instance, Braner & Taylor 1998, Redman 1999). More recently, humans have begun altering the global environment on an unprecedented scale (see, for instance, Vitousek *et al.* 1997). For example, as much nitrogen is now fixed by human activities as by natural processes, and this "excess nitrogen" is leading to the eutrophication of coastal zones, shifts in the health and composition of forests, and pollution of groundwater supplies (Kinzig & Socolow 1994, Matson *et al.* 1997, NRC 2000). Humans have greatly increased the atmospheric burden of certain "greenhouse gases", and these increases are expected to lead to elevated temperatures, a more vigorous hydrologic cycle, sea-level rise, shifts in the productivity and geographic distribution of biomes, and more frequent storms (IPCC 1995, IPCC 1997, Mahlman 1997). Land clearing for agriculture, forestry, and other human activities has led to species' extinction rates 100-1000 times greater than background levels, an irreversible loss with both moral and material consequences (Wilson 1992, Vitousek *et al.* 1997, Kinzig & Harte 2000).

These same human activities have led to unprecedented increases in prosperity, economic growth, and global flows of capital and resources. Infant mortality has declined by over 30% in the last two decades, while private consumption has grown at an average rate of 2.1% per year over the last 17 years (WRI 1998, World Bank 2000).[1] Life expectancy at birth has increased by an average of 6 years since 1975. The world economy has grown approximately 5-fold since 1950, and international trade has grown consistently faster than overall economic output since the Second World War (WRI 1998).

Alteration of the biosphere is a necessary, if unintended, consequence of the growth in human population and prosperity. Yet there is increasing evidence that some advances in prosperity have occurred in spite of, and not because of, the exploitation of resources (Arrow *et al.* 1995). For instance, New York City discovered in 1996 that replacement of the natural water

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[1] Corrected for distribution across income levels

purification services historically performed by the Catskill watershed would require a filtration plant with capital costs of about $8 billion and annual operating expenses of $300 million. In contrast, reversing watershed degradation and restoring its integrity would cost about $1.25 billion. In this case, maintenance of the existing natural capital made sense from an efficiency perspective, as well as from the perspective of protecting the watershed's ecosystems, and was the solution chosen (Chichilnisky and Heal 1998). But without a recognition of the importance of the ecosystem services provided by the Catskill watershed, and the need to evaluate resources and services that had previously been treated as free, the better solution may not have been chosen, leading to a net-present cost to society of about $17 billion.[2]

This example illustrates the intimate connection between human social systems and the ecological systems upon which they depend. It also suggests that the nation and the world will face several environment-related challenges in the coming century. These include improving and sustaining the ecological basis of our social and economic well being, reducing inter- and intra-national resource-driven conflicts, maintaining an adequate food supply without unacceptable environmental degradation, mitigating the impacts of environmental degradation on human health, and improving the capacity of institutions to make sound natural-resource-management decisions in the face of inevitable environmental change (see Box 1).

Several recent studies have called into question the nation's ability to meet these challenges given the current state of environmental research (Lubchenco *et al.* 1991, The House Committee on Science 1998, PCAST 1998, NSB 1999). The bipartisan Ehler Committee, for instance, concluded that environmental threats to the nation's prosperity have taken on an increased urgency, and represent a compelling rational for maintaining "a strong and sustainable scientific enterprise" (House Committee on Science 1998). Similarly, the National Science Board recently concluded that "Environmental research, education and scientific assessment should be one of the highest priorities of the National Science Foundation", and further noted that current resources for environmental research were inadequate to meet the challenges (NSB 1999).

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[2] Difference in capital costs plus net present value of $300 million annually with a 3% discount rate. Potential additional annual costs associated with watershed preservation are not included in this calculation, as estimates for such costs were not available.

Many of these groups have also emphasized the need for increased interdisciplinary research, joining natural- and social-science analyses to understand the dynamics of ecological and human systems, and the prospects for sustainable management and effective monitoring across a range of spatial and temporal scales.

Box 1: National and International benefits of increased interdisciplinary environmental research.

Increased investments in interdisciplinary environmental research will provide the information and understanding needed to

- Sustain delivery of economically important and societally beneficial ecosystem goods and services
- Increase scientific and institutional capacity to anticipate and cope with environmental change at all scales—local to global—with reduced social and economic disruption
- Reduce the incidence and spread of human diseases caused by ecological change
- Anticipate and reduce resource-driven conflict, both inter- and intra-nationally
- Develop indicators of human welfare and environmental quality, and warnings of potential and irreversible damage to important social and ecological systems
- Enhance development pathways that provide alternatives to economically costly and socially detrimental environmental degradation
- Improve dissemination of scientific information to policymakers and citizens, and improve understanding by scientists of societal values and goals

THE NEED FOR AN INTERDISCIPLINARY APPROACH

The relationships between human and ecological systems are sufficiently complex that a purely disciplinary approach to understanding past environmental change, and predicting or altering future change, is almost certain to miss crucial mechanisms and dynamics. Take, for instance, the issue of ecosystem services—those goods, such as pollination, water filtration, and regional climatic control, delivered by ecosystems and which enhance or maintain human well being. Economists, schooled in market analysis but not ecosystem ecology, have traditionally treated those services as free and inexhaustable. Even those economists who recognize that ecosystem services can be compromised through land conversion or changes in biodiversity lack the fundamental understanding of ecological systems needed to model or predict these compromises. Ecologists, on the other hand, have traditionally evaluated ecosystem-service delivery by relatively pristine systems, and have been reluctant to conduct economically relevant analyses that might focus on marginal changes in ecosystems. When ecologists have focused on these marginal changes, they have frequently done so based on assumptions about the ways in which human social and economic behavior alter ecosystems that are naïve relative to the more rigorous scenarios economists or other social scientists might supply. Both ecologists and economists are likely to lack the ability to ascertain which groups are likely to suffer most if these services become degraded, which of the ecosystem services of interest can be replaced by engineered and manufactured goods, and how these dynamics have played out in the past. Enter the political scientist, the engineer, and the archeologist. In places where people from outside the locality seek to preserve landscapes for economic, biological, or cultural reasons, an understanding of the needs and goals of local populations is indispensable to working out equitable and practical arrangements for conservation and preservation. Here, anthropologists, historians, and legal scholars are needed to work with biologists, engineers, and government.

To improve our ability to sustain crucial ecosystem services in the future while permitting the land conversion and resource use that supports the human endeavor, we must join disciplines to integrate analyses across natural sciences, social sciences, engineering, and humanities. Similar conclusions could e reached concerning other environmental issues and challenges—ecological and human systems cannot be fully understood if they are only examined in isolation from each other. Rarely does the expertise required for interdisciplinary analysis, however, reside within one individual; instead, we must foster cross-disciplinary collaborations. In addition, rigorous interdisciplinary analysis must rest on strong disciplinary foundations; increased interdisciplinary research depends upon continued strong disciplinary investments.

An examination of the dynamics of complex and interdependent social and ecological systems will reap significant intellectual benefits as well. Interdisciplinary research represents a compelling frontier of scientific inquiry in the 21st century.

Integrated and interdisciplinary analysis will stretch the boundaries of traditional disciplines, as existing discipline-based theories and paradigms are extended to new conditions and circumstances. The failures of existing theories and paradigms will indicate required directions for integrated analysis; the successes will increase confidence in our to explain real-world patterns and processes. Interdisciplinary analysis also promises to promote the development and adaptation of new methods and approaches in the science of complexity.

Interdisciplinary research devoted to understanding environmental problems and formulating solutions is not new; collaborations among natural and social scientists, engineers, and humanists, have been conducted for decades. Significant progress in linking ecological and social systems, however, continues to be fragmentary, uncoordinated, and slow. These failures arise in part from the training of our nation's scholars; researchers are taught to evaluate problems within the boundaries of a specific discipline, and are rewarded for doing so. Public support for research is similarly channeled along disciplinary lines—directorates within the National Science Foundation (NSF) for instance, are largely defined by disciplines, and program officers are asked to serve discipline-based constituencies. These approaches have worked well in promoting disciplinary research, but, when kept in place without exception, they raise the barriers to successful interdisciplinary environmental research unnecessarily high. Further, the numbers of people and projects able to scale those barriers remain too few for the problems we face and the resources we have as a nation. If we are too meet the environmental challenges of the coming century, the scientific community must improve its capacity for interdisciplinary environmental research and training in several crucial research areas (see Box 2.

At the same time, the limited Federal resources available for funding scientific inquiry means that assessment and prioritization of possible future research pathways is crucial if interdisciplinary research is to best serve society. As the National Science Board concluded (NSB 1999):

> "…there are clear needs for priority setting. The Board examined several examples where research or education agendas were defined in an inclusive and integrated manner. It became clear that this is an area that needs much more attention, in

particular where priorities are set in interdisciplinary areas."

Box 2: Summary of Research Recommendations

Increased interdisciplinary environmental research is needed in the following five areas:

The Evolution and Resilience of Coupled Social and Ecological Systems

The ways in which human social and economic systems evolve will depend on the ecological endowments of a region. The changes in these ecological systems over time will in turn depend on the extent, intensity, and types of human activities. This "coevolution" will determine the trajectories and resilience of social and ecological systems. Thus, integrated analysis of these systems is required if we are to improve our ability to forecast and respond to environmental change.

Ecosystem Services

Healthy ecosystems provide numerous economically important and societally beneficial services. Substantially more interdisciplinary research is required to advance our understanding of the key ecosystems and ecological structures required to sustain these services, the ways in which human activities alter these systems, the approaches for their proper valuation, and the institutions required for realizing this value.

Coping with Uncertainty, Complexity, and Change

Social and ecological systems are sufficiently complex that our knowledge of them, and our ability to predict their future dynamics, will never be complete. We must work to reduce uncertainties when possible, improve assessments of the likelihood of various important future events, and learn—scientifically, socially, and politically—to cope with environmental change that can elude precise prediction.

Environmental Dimensions of Human Welfare, Health, and Security

There is increasing recognition that local and regional environmental quality can significantly influence human welfare, including health and security. Human social arrangements—including the degree of political democracy or socioeconomic equity—can in turn profoundly influence welfare-environment interactions. Significantly more interdisciplinary analysis is required to assess the dynamics of these interactions, and to identify the approaches that can simultaneously improve human welfare and environmental quality.

Communicating Scientific Information

Interdisciplinary environmental research will not serve society unless the knowledge gained can be communicated effectively to policymakers and stakeholders at all levels of the social and political spectrums. At the same time, scientists must be responsive to society's articulations of goals and perceived national challenges. Yet there are significant differences in the ways in which different social and political groups access, interpret, and use scientific information. Research is required to better understand the ways in which scientific information is constructed and communicated, and to improve the process of information dissemination, from scientist to citizen and vice versa.

CONVENING A WORKSHOP

As a first step in that priority setting, forty-four researchers convened in Tempe, Arizona for a 4-day workshop in June of 2000. The meeting was funded by the National Science Foundation, and the attendees came from the fields of anthropology, archeology, biology, climatology, ecology, economics, engineering, epidemiology, geography, political science, public policy, and sociology, among others. They represented 31 different research and academic institutions in 20 states and 4 nations. (The list of attendees, and their affiliations, is given in Appendix A.)

The meeting was organized by an eight-person Steering Committee, with expertise in both the natural and social sciences (Appendix A). Seven "white papers"—which articulated possible research priorities or criteria for choosing among priorities—were solicited by the Steering Committee in advance of the meeting, and distributed to meeting attendees (see Appendix B). A literature search was conducted, in order to identify previous recommendations for interdisciplinary research in the area of the environment; the references consulted are listed in the bibliography.[3] The meeting was advertised via a web page, and comments solicited from those who, because of space constraints or scheduling conflicts, were unable to attend the meeting.

Attendees used the meeting time both to articulate possible priorities for interdisciplinary research, and to develop criteria for choosing among competing priorities when resources are limited. Most of this work was conducted in small working groups of 10-15 people—supplemented by plenary sessions—and the attendees were given wide latitude to define the agenda and formulate the recommendations during the four-day meeting.

This report, and the recommendations contained herein, are a product of that meeting, but have also been informed by circulating this report for approval among meeting participants. The meeting participants have unanimously approved the recommendations detailed below.

PRIORITIZING RESEARCH NEEDS

Participants at the workshop developed three primary criteria to use in determining which research areas should be counted as being among the highest priorities. These included (a) relevance in addressing urgent societal issues; (b) intellectual merit; and (c) the necessity of using an interdisciplinary approach.

The value of any particular research endeavor for society can be difficult to assess, but—given the limited (but we hope increasing) resources available for interdisciplinary environmental research—priority should be given to research endeavors that address the nation's most pressing environmental problems. These include not only problems readily identifiable today—such as emerging diseases, resource-driven conflict, land degradation, and species extinction, but problems we anticipate for tomorrow—degradation of urban environments, global climate change, and agricultural dilemmas, for instance. Thus, a portfolio of near-term and long-term research is warranted, both to improve human well

[3] While many of the recommendations we make in this document are consistent with those found in other reports, and in the white papers, we have chosen to omit citations in sections of the report in which we outline our recommendations. This was done to avoid falsely associating any group or report with the recommendations for which we are solely responsible. We are grateful to the authors and groups listed in the bibliography, as they have significantly influenced our own thinking on these matters.

being by addressing current crises and to develop the knowledge and tools required for tomorrow's challenges. In addition, decisions made today will affect the timing and severity of future challenges. Knowing more about this temporal dependence can lead to decisions now that will reduce the need for costly solutions later.

Because we cannot hope to successfully anticipate all of the environmental problems that might arise in the future, research also needs to be supported based on intellectual merit, and its ability to increase our basic understanding of the way the world works. It is this accumulated fundamental knowledge that will, after all, guide identification of the environmental threats and challenges facing our nation and the world in the future, and supply the methods and approaches required to formulate solutions.

Finally, not all intellectual or societal problems require interdisciplinary analysis; sometimes, a discipline-based examination will suffice both to illuminate the workings of a system and to formulate policies and approaches for solving problems or managing resources. In other cases, however, the social and biogeophysical systems cannot be successfully parsed—insights based on disciplinary analysis will be incomplete, or incorrect, or both. In these cases, discipline-based analysis can suggest inadequate and potentially detrimental solutions for environmental problems, and integrated and interdisciplinary research—particularly research crossing the natural- and social-science divide—must be promoted. In all cases, however, successful interdisciplinary research requires strong disciplinary foundations—interdisciplinary endeavors cannot succeed without continued advances and investments in all of the relevant disciplines associated with the environmental arena. We do not make specific recommendations for discipline-based research in this report, but the research agenda we propose is dependent on continued strong disciplinary research.

SUMMARY OF MAIN RESEARCH RECOMMENDATIONS

Participants agreed on research recommendations in five broad categories. These five categories all meet the criteria of societal relevance, intellectual merit, and interdisciplinary necessity outlined above, and include:

1. The evolution and resilience of coupled social and ecological systems
2. Ecosystem services
3. Coping with uncertainty, complexity, and change
4. Environmental dimensions of human welfare, health, and security
5. Communicating scientific information

Workshop participants believe that these five categories effectively capture the full breadth of urgently needed interdisciplinary environmental research. Under each of the main research categories, we list four or five more focused expositions of compelling research needs. Workshop participants were unanimous in their conclusions that additional funding for research in these areas was of the highest priority. At the same time, no single meeting, with the number of participants limited both by space and funding, could be expected to capture all of the most urgent areas for increased research. There may be some compelling questions we have—through limited time or expertise—overlooked. Thus, the research areas listed under each of the main categories should not be taken as a complete set of priorities, but examples of pressing research needs.

Inclusion of a research area below is not an indication that the recommended research is necessarily "new"; in many cases, research has been conducted in the relevant area for years or even decades. In most cases, however, the research has not received sufficient support, or been sufficiently interdisciplinary. Thus, increased investments in both effort and funding are warranted.

We therefore recommend that the National Science Foundation, other federal agencies, and private foundations substantially increase funding for interdisciplinary environmental research in these five categories and attendant sub-categories, in order to meet compelling national needs over the coming years and decades. Below, we briefly introduce the research topics covered under each category, and give more detail in a subsequent section.

The Evolution & Resilience of Coupled Social and Ecological Systems

Scientists have traditionally examined social systems in isolation from ecological systems, and vice versa. Yet the ways in which human social and economic systems evolve will depend on the ecological endowments of a region, and the changes in these ecological systems over time will in turn depend on the extent, intensity, and type of human activity. Moreover, the resilience of coupled social and ecological systems—their capacity to effectively withstand disturbance of both natural and human origin—will depend on the ways in which these systems have historically developed and are currently evolving. We also need to know when and under what circumstances a small perturbation might lead to a large change—a "non-linear" (out of proportion) response that have serious and unanticipated consequences. Some insights could e gained through long-term (including historical) studies that illuminate the situations under which gradual change suddenly becomes rapid or discontinuous. Thus, integrated analysis of social and ecological systems is required if we are to improve our ability to forecast and respond to environmental change. Important research areas in this category include:

- The evolution of social norms regarding the environment
- Understanding past and predicting future land-use change
- Feedback loops in social and ecological systems
- Disturbance and resilience in social and ecological systems
- Developing coupled models of social and ecological systems

Ecosystem Services

Healthy ecosystems provide numerous economically important and socially beneficial services. Yet substantially more interdisciplinary research is required to advance our understanding of the key ecosystems and ecological structures required to sustain these services, the approaches for their proper economic valuation, and the institutions required for mediating conflicts when different social groups assign different values to these services. We must also improve our understanding of the efficacy of possible manufactured substitutes for ecosystem services, and of the degree to which managed or compromised systems can replace pristine and unmanaged systems without unduly compromising ecosystem-service delivery. Important research areas in this category include:

- Human impacts on ecological structures and ecosystem-service delivery
- Valuation of ecosystem services
- Variations in ecosystem-service delivery and valuations from local to global scales
- Assessing manufactured or managed substitutes for ecosystem services

Coping with Uncertainty, Complexity, and Change

Social and ecological systems are sufficiently complex that our knowledge of them—and our ability to predict their future dynamics—will never be complete. We must learn—scientifically, socially, and politically—to reduce our uncertainty about the dynamics of complex environmental systems, and to cope with environmental change that cannot be accurately predicted. In order to build natural-resource management institutions that can be robust and flexible in a world of changing conditions, we must also improve our understanding of how institutions and other social groups "learn", and how they approaches they use for managing information and complexity promote or compromise goals of sustainability and environmental protection. Important research areas in this category include:

- Indicators of human welfare and environmental change
- Risk assessment and risk reduction for technology deployment
- Governance and management of common-pool resources
- Adaptive institutions and social learning

Environmental Dimensions of Human Welfare, Health, and Security

There is increasing recognition that local and regional environmental quality can significantly influence human welfare, including health and security. Human responses to changes in welfare can further alter environmental quality. Human social arrangements—including the degree of political democracy or socioeconomic equity—can profoundly influence welfare-environment interactions. Significantly more interdisciplinary analysis is required to fully assess the dynamics of these interactions, and to identify the approaches that can improve human welfare while simultaneously sustaining the environmental basis upon which that welfare depends. Important research areas in this category include:

- Environmental change and human health
- Environmental justice, poverty, and inequity
- The environmental dimensions of human conflict

Communicating Scientific Information

Interdisciplinary environmental research in the service of the nation's challenges will not be useful unless the knowledge gained can be communicated effectively, to policymakers and stakeholders at all levels of the social and political spectrums. Yet there are significant differences in the ways in which different social and political groups access, interpret, and use scientific information. Information flows are influenced by information technology, non-governmental organizations, and national differences in indigenous research, among other things. Research is required to better understand the ways in which scientific information is constructed and communicated, and to improve that process. Possible research areas in this category include:

- The effects of disparate access to science and scientists
- The impacts of information technology and non-governmental organizations on flows of scientific information
- Stakeholder participation in natural-resource management and policy formulation
- Effectiveness of interdisciplinary training

SUMMARY OF IMPLEMENTATION RECOMMENDATIONS

A vigorous program for interdisciplinary environmental research will require more than increased monetary investments to succeed. The National Science Foundation—and other funding agencies and foundations interested in promoting such research—will also have to pay careful attention to the advances in training and changes in institutional structure required for effective implementation. We therefore make the following recommendations.

Education and Training

The current approaches to education and training at all levels emphasize disciplinary training while neglecting—or even actively discouraging—interdisciplinary education. The National Science Foundation should ensure that the knowledge and capacity required for effective interdisciplinary communication and collaboration is promoted, both among today's policymakers and scientists, and tomorrow's. The NSF should therefore:

- Promote research to identify effective approaches in interdisciplinary education
- Increase resources for development of interdisciplinary environmental courses or programs
- Increase funding for innovative graduate and post-graduate interdisciplinary fellowships
- Offer greater opportunities and resources for faculty sabbaticals that promote interdisciplinary training and collaboration
- Develop new programs to promote exchange among the nation's researchers, media professionals, and policymakers.
- Create opportunities for international interdisciplinary collaboration

Research Infrastructure

The fundamental features of interactions among social and ecological systems, or the ways in which ecological status and dynamics can influence human welfare, can span generations and continents. This creates research challenges at unprecedented scales. Many earlier reports have shown that the organizations of existing research institutions tend to promote inward-looking disciplinary exchange while inhibiting interdisciplinary collaboration. The National Science Foundation should therefore:

- Promote long-term interdisciplinary environmental research, perhaps by increasing integrated and interdisciplinary research within the existing national and international LTER networks
- Establish a national center or centers for interdisciplinary environmental research
- Promote scientific assessments at relevant regional scales (e.g., in ocean basins, along migratory routes, in metropolitan slums) as a way of synthesizing and disseminating crucial, policy-relevant scientific conclusions.

The National Science Foundation

The National Science Foundation has proven extraordinarily effective in promoting discipline-based research, but modifications to existing programs and approaches will be required for effective promotion of interdisciplinary environmental research. We therefore recommend that the National Science Foundation:

- Establish a unit with explicit budgetary authority for promoting interdisciplinary research and for facilitating cross-directorate research
- Ensure that the existing peer-review process promotes equitable and effective review of interdisciplinary proposals while maintaining standards of intellectual quality
- Charge the newly established advisory board for interdisciplinary environmental research with continued development of research priorities and assessment of progress in promoting interdisciplinary research

We give further details of each of the research and implementation recommendations in the sections below.

MAIN RESEARCH RECOMMENDATIONS

THE EVOLUTION & RESILIENCE OF COUPLED SOCIAL & ECOLOGICAL SYSTEMS

Introduction

One of the great challenges in understanding our planet is the integration of socioeconomic and ecological systems across tremendous scales of space, time and organizational complexity. In ecological communities and human societies alike, individual behaviors are shaped by natural and cultural evolution. But individuals interact, giving rise to larger-scale patterns—the sum of individual attitudes gives rise to a nation's culture, for instance, and the sum of the individual behaviors of organisms influence the structures and patterns of entire ecosystems. To complicate things further, the causation is not one-way, as emergent large-scale properties of ecosystems, economies and societies feed back to influence individual behaviors and their evolution. These influences not only cross scales, but act between human and ecological systems as well. For instance, human intervention can alter characteristic spatial and temporal scales of ecological processes, and physical and biotic features of a region can influence the evolution of cultures and societies. Coupled complex systems also exhibit complex dynamics—several steady states or "basins of attraction"[4] can exist, with unanticipated and rapid transitions from one state to the next.

Research in this category should elucidate the emergent patterns in coupled socioecological[5] systems, examine the dynamics

[4] The set of states that tends to go towards a particular steady state; the equilibrium or steady state is sometimes called an "attractor". In dynamical systems where there is more than one steady state, non-steady states may tend towards a particular equilibrium—these non-steady states would be in the "basin of attraction" for that equilibrium point.

[5] We have used the phrase "socioecological" to mean integrated systems—consisting of human institutions and behaviors, non-human ecological systems, and biogeophysical templates—that can't easily or legitimately be parsed into component parts. There is no perfect phrase to describe this concept—"human

of state transitions, and use both pieces of information to develop models of future dynamics in socioecological systems. Several specific examples of possible research topics are given below. The human institutional arrangements required to manage complex systems will be discussed in a later section ("Coping with Change, Uncertainty, and Complexity").

Research Recommendations

The evolution of social norms concerning the environment

Social norms will vary depending on settlement patterns, landscape configurations, level of development, culture, and endowments of natural capital, among other things. These social norms will influence how people perceive the environment, their awareness of its contribution to their well being, and their development of policies for managing, conserving, or exploiting natural resources. Moreover, social norms can be constructed and influence behavior across several levels of social organization—from local communities to states, nations, and international organizations. Understanding these variations in social norms will be particularly important when there are conflicting or contested norms that must be made explicit and mediated in order to achieve goals of ecological sustainability or improved human welfare. Finally, variations in social norms means that there will not be a "one size fits all" approach to natural resource policies; local, state, national, and international policies may need to be tailored to the prevailing customs and attitudes of a region.

Research in this area should focus on variations in social norms, and hence attitudes towards the environment, among nations, and for different cultural or socioeconomic groups within nations. These differences should be related to the human history of a region, as well as the biotic and physical features of a landscape. Religious and spiritual traditions may also be of crucial importance. Comparative research in areas where there has been recent (within 2 or 3 generations) human dislocations—from one nation to another, or from rural to urban environments—might prove particularly useful, as will research in which two groups have occupied a region for a similar timespan, but have settled different ecosystems within that region (e.g., lowland and upland systems in

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ecological" systems seems to imply humans are not ecological creatures, for instance—and various other proposed phrases suffer from the same limitation. For want of a better substitute, we have chosen socioecological.

the desert southwest, or northern and southern Europe). Additional case studies examining the influence of different religious or spiritual practices—particularly among groups differing in these traditions but occupying the same biogeographic region—on perceptions of environmental integrity and variability, and on natural-resource management practices, would also be warranted.

Understanding past and predicting future land-use change

Land-use change is one of the biggest drivers of loss of biodiversity, and influences regional climate, regional and local hydrological patterns, human exposure to pathogens, and soil erosion and agricultural productivity, among other things. Patterns of land use will be influenced by local physical and biotic features, such as topography, soil fertility, and rates of ecological succession, as well as the types and scales of human institutions promoting or governing land conversion, and ensuring property rights.

Predicting the potential dynamics of land-use change, particularly under ecological change (such as climate change) or under new political systems or policies, will be crucial if we are to design sensible policies for meeting the needs of humankind while simultaneously preserving habitat for the other creatures with whom we share the planet.

Research in this area should focus on understanding past patterns of land-use change, particularly as they are determined by local or regional environmental endowments (e.g., topography, soil and other ecological characteristics, and climate) and influenced by political systems and other institutional arrangements. Comparative studies between or among regions with similar biogeophysical characteristics but different political or social institutions, or with similar governing bodies but different environmental endowments, will be particularly useful. These studies could be historical or present day. Examination of changes in land-conversion patterns under rapid socioecological change (e.g., end of segregation, institution of land reform) might prove fruitful, as would comparisons among different biogeographic regions where agriculture or urbanization started at similar times.

Additional research should focus on models for producing scenarios of future land-use and land-cover change, drawing on the causal mechanisms identified in the above projects. These researchers should produce models that would complement existing efforts to model future climatic changes and future changes in global and regional biodiversity.

Feedback loops in coupled social and ecological systems

Human intervention on a landscape can alter the characteristic spatial and temporal scales of ecological dynamics. For instance, rates of ecological succession can vary as we move from city centers to more rural settings; the spatial scales of foraging and dispersal of non-human animals can also be influenced by human settlement patterns or natural-resource policies. The ways in which the ecological dynamics change will be influenced by the ways in which humans manage and influence the local biota.

Changes in the ecological system can, in turn, induce changes in the human groups or institutions that rely on the local or regional ecological endowments. Understanding these "feedback loops"—how human action can influence ecological systems, and how ecological systems in turn will alter human behavior—will be crucial if we are to design robust policies for natural-resource use and conservation. That is, we can't assume policies will work as intended—human behaviors and institutions may change as policies alter characteristics of the natural-resource system. Of particular interest is the tendency of policy-making bodies to develop "perverse policies"—those that can, in implementation, lead to outcomes contrary to the original goals for management and sustainability.

Research in this area should focus on changes in ecological dynamics under human intervention—particularly changes in the spatial and temporal signatures of those dynamics—and how those changes relate to characteristics (spatial and temporal structure) of human institutions. Archeological and other historical evidence may be especially crucial here—particularly in cases where the structures of socioeconomic systems were changing rapidly (e.g., emergence of regional trading blocks). In addition, research on urban to rural gradients, or trans-boundary analyses (e.g., crossing tribal or national lines) would be warranted.

Additional research should focus on changes in socioeconomic structures as a result of ecological change, particularly in cases of rapid ecological change. How do humans respond to changing environments, across scales of organization? Such reorganizations should be related to the characteristics of the ecological change—its spatial extent, for instance, and the rapidity of change. Again, archeological evidence would be relevant, as would evidence from urban systems, or Green Revolution nations. Examination of reorganization of institutions and the changing social construction of environmental hazards following disturbances—such as Hurricane Hugo—and comparison of such responses across nations or cultures, would also be informative.

Disturbance and resilience in social and ecological systems

Complex systems can exhibit sudden transitions from one basin of attraction to another. These transitions can occur as the result of internal dynamics (e.g., via gradual shifts in slowly changing variables) or in response to exogenous disturbances. Human institutional arrangements can alter the existence of domains of attraction in biogeophysical systems, or the frequency of transitions among them. If socio-economic expectations are organized around a particular state of the biogeophysical system, and a rapid shift to a new state occurs, the resulting surprises can have deleterious consequences.

State transitions can be preceded by characteristic dynamics that would serve as an “early-warning indicator” of change. At the same time, human institutions can vary in their capacity to perceive these warnings. This capacity can vary across levels of institutional organization (e.g., local versus national), and can vary within an organization over time, as monitoring strategies change in response to political change and/or perceived environmental change. Understanding and improving the capacity to monitor early-warning indicators of detrimental transitions, and to mediate the distribution of costs and benefits when such transitions do occur, is a crucial component of improved stewardship of natural resources.

Research in this area should focus on the determinants of basins of attraction in complex biogeophysical systems, and the causal mechanisms for transitions among them. This requires a focus on slowly changing ecological and social variables (such as soil formation, or cultural legacies) and their interactions with variables that change on faster time scales (such as life spans of individual organisms or business cycles). Paleoecological and other historical evidence could be employed, as could models of complex biogeophysical systems. Dynamics should be examined across the full range of spatial and temporal scales. Additional research should examine the changes in natural-resource monitoring strategies—particularly the frequency and spatial extent of monitoring—as human systems and institutions develop, and compare those scales to those scales likely to reveal early-warning indicators of change.

Developing coupled models of social and ecological systems

Predicting the future dynamics of coupled socioecological systems will require development of a hierarchy of models, ranging from highly aggregated ("reduced form") descriptions of coupled physical, biological, and social sub-systems to very disaggregated, spatially resolved, multi-sectoral models. Such an approach is required because we still do not know enough about the appropriate methods for coupling models of biogeophysical and socioeconomic systems, or the degree of detail and aggregation needed to capture key features of the dynamics. Producing a suite of models across levels of aggregation will allow comparison of the properties and predictions of the models, and inform future modelling efforts. Models should be run over time scales sufficient to explore the possibility of emergent properties of the coupled system—at least several centuries if long-time scale systems like oceans, forests, and glaciers are to be included, and if potential irreversibility is to be considered. Testing these suites of models against historical data will also be necessary if policymakers and scientists are to have faith in generated scenarios of future dynamics.

The models should also be used to disseminate information about the dynamics of complex coupled systems. The models should permit users to vary social development options, trade, values of ecosystem services, distributional constraints, technological changes, land-use patterns, deteriorating productivity of landscapes, and exogenous shocks (e.g., new diseases, rapid climatic change, a breakthrough in technological capacity, a redefinition of terms of trade, new potential alliances or military conflicts).

ECOSYSTEM SERVICES

Introduction

Scientists have long known that functioning ecosystems contribute to human well-being in a variety of ways, by producing both tangible goods (e.g., food, fodder, fuel, and fiber) and less tangible services (e.g., water filtration and purification, crop pollination, erosion control). We still have inadequate information, however, on the "scaling functions" that allow prediction of degradation of ecosystem services under loss of species or habitat, or on the possible manufactured substitutes for ecosystem services, and their costs. Information is also lacking on the ways in which different social or political groups might differentially value ecosystem services, or how the value of essential ecosystem services might vary according to the scale at which value is being assessed or realized (e.g., local, national, or global). Institutions are also needed for mediating these conflicts or for ensuring an adequate flow of benefits to local stewards of ecosystems that deliver regional or global services.

If we are to make societally optimal or efficient decisions regarding ecosystem preservation, management, or conversion we must increase our knowledge of the various types of ecosystem services, the ecological structures and arrangements required to maintain those services at reasonable levels, the institutions required to mediate among conflicting uses of ecosystem services, and the potential substitutes under circumstances where certain ecosystem services already are, or will be, degraded. Several specific examples of possible research topics are given below.

Research Recommendations

Human impacts on ecological structure and ecosystem-service delivery

Scientists have developed a relatively complete list of essential ecosystem services, but are still uncertain as to the ecological structures and arrangements required to maintain those services. For society to make sensible decisions about land conversion or conservation, a richer understanding of the relationship between changes in ecosystem extent or structure and loss or degradation of ecosystem services is required. For economic and planning purposes, there is a particular need for a “marginal theory” that describes how small, incremental changes in ecosystems induce progressive changes in ecosystem processes. At the same time, the potential for irreversible or non-linear changes in the delivery of ecosystem services under ecological conversion implies a need for additional theoretical and empirical work. Both developments are essential prerequisites to the development of a genuine integration of ecological and economic theory.

Scientists must therefore make the connections between essential ecosystem services, the types of biomes or ecosystems that contribute most to those services, and the fundamental ecological structures required to maintain those services. For instance, can some degree of biodiversity loss or habitat fragmentation occur with little or no degradation of service? How does this depend on the service or ecosystem of interest? Scaling rules or "production functions" are required to relate changes in ecosystem extent or ecological structure to changes in the delivery of ecosystem goods and services. In addition, scientists need to identify those ecosystem services whose delivery is most precarious, either because the ecosystems delivering them are most threatened with conversion or degradation, or the delivery of the service itself is sensitive to slight alterations in the structure or landscape arrangements of ecosystems. Research of this sort will be crucial if we are to identify the "hot spots" of potential loss of essential ecosystem services, and effectively deploy the limited resources at our disposal for preserving those ecosystem services at acceptable levels.

Research in this area should focus on quantifying changes in the delivery of ecosystem services under ecological change—such as loss of biodiversity, increases in habitat fragmentation, or simplification of ecological structure. Both historical and present-day analyses are warranted. Analyses should, ideally, make comparisons between or among different biogeographic regions, different ecosystem services, and across degrees of ecological change, from moderate to severe. The potential for sudden and/or irreversible changes in the delivery of ecosystem services under ecological conversion should be identified, with particular emphasis on identifying the most susceptible services and biomes. Both field and modeling studies should be employed in identifying these thresholds and irreversibilities.

Additional research should thus focus on identifying those regions or biomes of the world where the threat to delivery of essential ecosystem services is highest. This should be done by cataloguing the nature and extent of threats to ecosystem integrity in different biogeographic regions of the world, and correlating those losses with potential losses in delivery of ecosystem services using the "production functions" obtained above. If possible, the political policies or social forces driving ecosystem loss or conversion should be identified, including the scale (e.g., local, national, international) at which the policies are operating, and including an analysis of any potential economic or institutional failures contributing to the threat (e.g., externalities, inadequate or inappropriate property-rights regimes).

Valuation of ecosystem services

The valuation of ecosystem services has been a rapidly growing field of study in the last decade. The strengths and limitations of most methodologies are known in principle, including the limitation of the most widely used economic approaches to the evaluation of marginal changes in the level of services. Widely used approaches include the use of market prices, hedonic prices, travel costs, and contingent valuation. Replacement cost data can also be used to make inferences about values. To date there have been few valuation exercises carried out on non-incremental changes, such as a substantial change in the hydrological cycle. Studies of this type could prove to be useful cases in view of the non-marginal nature of many human impacts on natural systems.

Studies of the option values associated with ecosystem preservation would also be of interest. Although the theoretical potential of such values has been widely noted in the literature, specifically with respect to biodiversity conservation and bioprospescting, there are few attempts to operationalize them. Non-economic methods of valuation should also be examined.

Research in this area should focus both on comparisons of the incremental methods for valuing ecosystem services, and the suitability of such approaches for assessing value under non-incremental changes. Ecological analyses will be required to complement the economic investigations, particularly with respect to identification of the potential non-incremental changes in ecological systems, and with regard to the spatial and temporal characteristics of ecosystem-service delivery. Additional research should examine the approaches used for operationalizing or realizing the assessed value. Case studies that identify when and under what circumstances local stewards of ecosystems were or were not able to realize the assessed value of essential ecosystem services would be particularly useful.

Variations in ecosystem-service delivery and valuation from local to global scales

Under an increasingly global economy, there can be significant mismatches among scales of resource extraction, resource use or conservation, accrual of benefits, and visitation of costs. These scale “mismatches” can lead to perverse outcomes, whereby, for instance, conservation of an intact forest for biodiversity best serves the interests of the global community, management of a fast-growing forest for carbon sequestration best serves the interests of the national community, and cutting of forest for timber best serves the interests of the local community. One set of interests could be served at the expense of the others, or all interests could be met imperfectly. Which interests are served will depend intimately on the operating economic and political institutions and the behavioral incentives to which these institutions give rise.

Information on management of natural resources is particularly crucial today, as governing institutions are changing through both aggregation (e.g., regional and global trading blocks) and disaggregation (e.g., break up of the Soviet Union). Natural resources and ecosystem services may come under the jurisdiction of one level of the sociopolitical structure, with under-representation of the legitimate interests and needs expressed at other levels of the hierarchy. Shifting power can alter the natural-resource management regimes of the past, with consequent implications for future sustainability trajectories and delivery of ecosystem services.

Research in this area should thus focus on identifying the characteristics of the natural resources and ecosystem services, and the institutional structures, for which the most severe scale mismatches occur. The process by which institutions at various levels of the sociopolitical hierarchy mediate these conflicts should be examined, and changes in the exercise of power with respect to natural-resource management identified. Case studies examining local and regional action under recent international treaties (e.g., Convention on Biodiversity, Montreal Protocol) would be appropriate, as would case studies of natural-resource management under substantial changes in political structures. Additional research is required to explicate the institutions and approaches required to mediate among competing interests. How might both costs and benefits be distributed so as to minimize the interest mismatch at various levels of the sociopolitical structure, and how might that redistribution be operationalized?

Assessing manufactured or managed substitutes for ecosystem services

Some ecosystem services may be replaceable with produced or manufactured counterparts. For example, watersheds purify water, as do filtration plants. Beneficial organisms can control crop pests, as can pesticides. Irrigation can be employed when a sufficiently wet climate is absent. In addition, managed ecosystems may be able to provide some of the ecosystem services of more pristine systems. A diverse managed forest with rotational cropping may be able to replicate the services of an intact, unmanaged forest.

At the same time, ecosystems provide a variety of services, while manufactured counterparts or managed ecosystems can only substitute for one or a sub-set of those services. Moreover, the effectiveness of substitutes may change over time. An effective pesticide today can become ineffective as pests evolve resistance. Effective delivery of services will also depend on spatial scale—an individual farmer, for instance, may be unable to rely on natural pest control if neighboring farms are using chemical pesticides that damage the populations of pest predators upon which the individual farmer is relying.

Research in this area should focus on elucidating the effectiveness of potential manufactured or managed substitutes for essential ecosystem services. Case studies of situations where the natural ecosystems providing services were lost and “replaced” would be particularly relevant. These case studies could be current, or span the archeological record. Attempts to substitute for lost ecosystem services in civilizations that either successfully survived ecological change, or collapsed as a result of ecological degradation, would be one example of a fruitful case study. Present-day examples of effective substitutes for ecosystem services, or initially effective substitutes that lost effectiveness either over time, or as the result of too rapid or too limited a deployment, are also warranted.

Additional research should focus on the methodologies required to effectively analyze—prior to loss of ecosystem services or deployment of a substitute—the effectiveness of substitutes. The methodologies should be able to account for the full suite of ecosystem services provided by unmanaged and/or intact ecosystems, the effectiveness of the substitution for those services, and the full suite of benefits to be obtained by converting unmanaged and/or intact ecosystems. Investigation across the relevant temporal and spatial scales is necessary. Methodologies should be made accessible to natural-resource managers and decisionmakers at several levels of institutional organization (e.g., local, regional, national).

COPING WITH UNCERTAINTY, COMPLEXITY, & CHANGE

Introduction

Socioecological systems are sufficiently complex that our knowledge of them will never be complete. Thus, there will always be some uncertainty concerning the environmental and societal benefits and impacts of our actions. In some cases the probabilities of various outcomes or impacts can be estimated, but in many important cases analysts and policymakers will have no, or only a limited, basis for estimating the probabilities of potential future outcomes. Thus the nature and dynamics of uncertainty lie at the heart of any attempt to anticipate or manipulate environmental change. One can attempt to reduce uncertainty by increasing understanding, or reduce its impacts by designing policies that are less sensitive to uncertainty, but both types of strategies can be difficult to achieve in practice. Moreover, the attempts to cope with uncertainty become even more challenging under rapid change, when our understanding of the system may be based on a previous, rather than a current, state. Therefore the study of uncertainty itself, along with the contributions of complexity and change to that uncertainty, becomes crucial to understanding the dynamics of coupled socioeconomic and biogeophysical systems.

Research in this category should focus on how uncertainty is recognized, perceived, and constructed among different groups within societies. The relationships of uncertainty to ambiguity—that is, situations in which the probability of various outcomes are unknown and unknowable, or potentially critical outcomes cannot even be identified—should be explored. The means employed to reduce uncertainty should also be identified, and their efficacy in reducing uncertainty analyzed. The perceptions of uncertainty—and the ways in which institutions cope with uncertainty—should be evaluated in light of the underlying complexity of the biogeophysical system, the ambiguity of potential outcomes, and the rapidity of change in both biogeophysical and socioecological systems. The effects of different approaches for communicating, negotiating, or manipulating uncertainty on the decision process and on ecosystem dynamics should be identified. Methods for designing policies that are relatively insensitive to uncertainty—and crafting institutions that can best manage uncertainty while still achieving societal goals—should be analyzed. Several examples of specific research areas are given below.

Research Recommendations

Indicators of human welfare and environmental change

In order for individuals and social institutions to achieve their goals in the face of change, measurements and indicators of that change are required. Many of the current indicators used in the decision-making process track economic changes or, occasionally, social changes. The failure to develop monitoring systems that combine socioeconomic and biophysical indicators is a major barrier to learning about, and to coping with, change in those systems.

Research in this area should focus on development of indicators that can capture the complex dynamics of change in coupled socioecological systems in a distilled fashion. Indicators could be developed for, among other things: global and regional availability of crucial resources required for meeting certain human needs; planetary circulatory systems, including physical and biotic movements; critical regions—those most in danger of failing to meet human needs and/or imposing irreversible damage on ecological systems; metropolitan ecosystem services; and eco-region scale conservation. Where appropriate, the indicators should be evaluated at a variety of spatial scales, and over time. Additional research should focus on the efficacy of various indicators in conveying information to decision-makers and stakeholders, and the use of indicators in the decision-making process.

Risk assessment and risk reduction for technology deployment

Technological change is both necessary—to increase human welfare while reducing the environmental impacts of human activities—and inevitable, since it is impossible to stifle the creative process. Many technologies that have been introduced in the marketplace, however, are later revealed to be costly to society with regard to human health or environmental degradation (e.g., DDT, CFC's). These "surprises" derive in part from incomplete assessment of the potential impacts of technologies, and in part from "scale mismatches" in interests; firms can concentrate the profits from technological innovation in their own coffers, while distributing the costs either regionally or globally. In many of these cases, proper assessment of the impacts of deployment and proper distribution of the costs and benefits (by, for instance, internalizing the externalities) would have led to different, and more socially beneficial, outcomes. The technologies that are, or should be, most worrisome are those that have the potential to visit either long-term or irreversible degradation on the planet's biogeophysical systems, or have significant negative impacts on human health or welfare. Evaluation of different approaches of technological risk assessment may reveal that some are more effective than others in identifying or avoiding unpleasant "surprises", either by preventing dissemination of detrimental technologies, or by managing dissemination in a way that reduces risk.

Research in this area should thus focus on developing methods of technological risk assessment. Case studies where adequate risk assessment was performed, but failed to influence decisions about technology deployment, would be particularly informative, as would case studies demonstrating inadequate risk assessment through either a failure to capture impacts through time or through a failure to address environmental or human-health sectors. How do the failures in the risk-assessment process correlate either to the characteristics of the technology being developed, or to the characteristics of the sector or corporation performing the assessment? Additional research should compare and contrast various national approaches for managing and monitoring technological dissemination. Are some approaches more effective than others in identifying, and avoiding, potential "surprises"?

Governing and management of common-pool resources

Common-pool resources are those for which the assignment of private property rights is either impossible (as with fish in the ocean) or undesirable (as in the case of cattle grazing when the cost of fencing is high). Economists have studied such problems but usually in a context where the resource system exhibits (or is assumed to exhibit) minimal ecological complexity, and where little in the way of outcomes is considered except the direct economic benefit from the resource. This approach can and does lead to outcomes contrary to the public interest.

The success of managing common-pool resources also varies widely from case to case, even when taking the narrow view that the direct economic benefit is the objective. One of the reasons for this variation has to do with the historical variations in institutional structure and/or the inability of institutions to adapt in response to changing economic or ecological conditions, as well as their inability to perceive changes in those systems.

Research in this area should thus focus on both historical and present-day institutions for managing common-pool resources. Evolution of institutions over time, particularly in cases where the ecological resource base has changed significantly (e.g., overfishing), or scientific knowledge concerning the dynamics of the natural-resource base has increased significantly, would be particularly informative. Cognizance of the underlying ecological dynamics should be assessed in both traditional (pre-industrial) and industrial common-pool regimes, and the near-term and long-term impacts of a lack of ecological understanding elucidated. Additional research should focus on the ways in which interests other than direct economic benefit are manifested in institutional decision-making about common-pool resources, and how that manifestation varies by institutional structure, level of sociopolitical organization, and characteristics of the resource base (e.g., rapidly replenished versus slowly replenished resources).

Adaptive institutions and social learning

Institutions for addressing environmental change are a nexus of interaction between ecosystem and social dynamics on multiple temporal and spatial scales. We define biogeophysical resilience as the capacity of the system to persist in a particular state, with continued delivery of goods and services. Institutional resilience, in contrast, should not be defined in terms of the persistence of the institution itself, but in terms of its continued ability to meet societal interests with respect to the natural-resource base. Because coupled socioecological systems are complex, and exhibit dynamics and change on multiple temporal and spatial scales, institutions for addressing environmental change and managing the natural-resource base must be flexible, adaptive, and responsive to change. In addition, institutions can never hope to monitor the full complexity of socioecological systems; the ways in which institutions evolve to reduce or manage complexity (by, e.g., monitoring some ecosystem sub-components and not others, or by sifting information through various levels of the institutional hierarchy) can also influence success in persistent ability to meet societal goals.

Research in this area should focus on identifying a large set of institutional variables that can be related to flexibility, adaptation, and beneficial reduction in complexity, such as strength of leadership, commitment to exploration of novelty without strong negative sanctions for failure, explicit monitoring, evaluation and learning mechanisms, and integration of state-of-the-art knowledge into the decision-making process. These variables should be measured, along with indices of success in resource management, for a selected set of contrasting organizations that have tried to cope with uncertainty in environmental management. Researchers expect that some properties of organizations will correlate with success while others will not, and the variables that do correlate with success could be used to guide the improvement of institutions for managing the environment. Additional research should focus on the ways in which institutions grapple with the complexity of socioecological systems, and convey uncertainty and complexity. Does, for instance, the assessment of uncertainty correlate to the level of complexity in either the biogeophysical or socioecological system? Researchers could develop independent measures of complexity and uncertainty, and test their efficacy in conveying information through the use of focus groups or field trials in which negotiations involving uncertainty are already underway.

ENVIRONMENTAL DIMENSIONS OF HUMAN WELFARE, HEALTH, & SECURITY

Introduction

The welfare of human populations is linked to the quality of their surrounding environment in many ways. Environmental degradation can be both a driver and a reflection of declining quality of life, and can lead to positive feedback cycles whereby a decline in welfare motivates increased demands on the environment, leading to additional degradation, further reducing human welfare and health, and so on. Similar cycles can be discerned with respect to human conflict. Degradation in biotic resources can lead to decreased access to resources or decreased delivery of ecosystem services, leading to greater conflict over allocating scarcer resources, leading to further degradation in the biotic resource, etc. In contrast, as human welfare improves, changing societal perceptions of the value of a healthy environment can lead, for example, to greater investments in areas such as clean air and water for improving human health, or better land-use planning for increased delivery of, and more equitable access to, the delivery of ecosystem services. In other cases, increasing wealth can further drive environmental degradation.

Understanding the complex interactions of evolving human societies, particularly with respect to how they modify and respond to modifications in the environment, is a fundamental area of research. The complex pathways by which social, behavioral, physical, and economic factors combine to alter welfare are, by their nature, difficult to analyze, model, and predict. Therefore, interdisciplinary studies that integrate the insights, tools, and conceptual frameworks of various intellectual approaches are needed. Indeed, the future of the human condition rests squarely on the urgency of understanding these interactions so as to better influence their direction, and improve the likelihood that the environmental resources required to sustain human well being will continue indefinitely into the future. All are fundamentally interdisciplinary problems that lie at the interface of resource use, changing dynamics of human populations, socially- and environmentally-determined differences in the perception of welfare, and economic behavior.

Research in this category should focus on clarifying the environmental dimensions of human welfare, health, and security. The nature of the feedback loops should be examined—how does degradation in a resource influence human well being, and how do changes in human well being further influence the trajectory of the biotic resource? The time lags associated with these feedback loops, and the spatial and social scales over which they operate, should be elucidated. Heterogeneity in access to and utilization of ecological and environmental resources, and the implications of those inequities for human well being across all levels of social organization, should be an important focal area. Examples of specific research areas are given below.

Research Recommendations

Environmental change and human health

Ecological and socioeconomic factors are among the most fundamental determinants of human health; the state of human health, in turn, influences our perception and modification of the environment. The physical and social environments influence human health in myriad ways. Ecological, technological, and social environments, for instance, influence both food production and distribution, and thus malnutrition. Environmentally driven human migrations can influence health through exposure to new diseases or psychological stress. Toxic exposure is determined both by the physical laws governing movements and dispersal of toxics, and by the political and social forces that concentrate toxic wastes or waste facilities near particular groups of people. Thus, human health is both directly and indirectly a result of diverse interactions that are fundamentally environmental, but also demographic, economic, and behavioral. For this reason, human health is inextricably intertwined with the use and sustainability of our earth and its natural resources. We define, create, modify, and exchange our environments and their products in order to improve our individual or collective welfare.

Research in this area should focus on both the direct and indirect impacts of ecological and environmental change on human health. Direct impacts would include the relationship between land use, land conversion, or ecological simplification—including agriculture, forestry, transportation networks, and urbanization—and the dynamics and distributions of disease hosts and vectors (including changes in resistance), and human susceptibility to disease. Indirect impacts would include changes in nutritional status or psychological stress accompanying local land conversion or inequitable access to natural resources. Both case studies and modelling/epidemiological analyses would be warranted. Case studies in which rapid land conversion (e.g., opening of new areas to agriculture) or ecological simplification (e.g., replacement of native vegetation with single-species plantations) occurred would be particularly useful, with both human epidemiological and ecological analyses.

Additional research should focus on the presence of medicinal biological products in different biomes of the world, and how current management practices and institutional arrangements (e.g., intellectual property-rights regimes) might aid or hinder discovery of these substances. “Hot spots” of medicinal value—where extant potential for production of medicinal substances is high but current practices threaten that potential—should be identified.

Environmental justice, poverty, and inequity

Poverty, inequity, population growth, and environmental quality are interrelated. Together they pose one of the great human problems associated with economic development. The maldistribution of land and its associated economic, political, and environmental problems in underdeveloped countries serves as one example of this phenomenon. Rural people in many underdeveloped countries have been forced on to marginal agricultural land. Their use of that land can reduce forest cover and leads to erosion, with indirect effects such as downstream flooding. Such land is often the last refuge of biodiversity in underdeveloped countries, and in other circumstances might serve as a focus for preservation. The land is frequently poorly suited for agriculture, and so is unproductive, which perpetuates low incomes. In turn, poverty is thought to be a prime motivation for large families, which fuels high rates of population growth. The above situation is often interpreted as a symptom of "the population problem". But it may just as easily be viewed as a resource-distribution problem, or a problem of political access or economic opportunity. The narrow focus on population can obscure the need for deeper analysis that could lead to solutions that could be more socially and environmentally benign.

Similarly, deteriorating climate and population growth are often seen as the major causes of desertification. Yet it has been argued that much of Africa is, from an economic point of view, short of labor rather than over-populated. The causes of desertification are likely to be complex, involving inappropriate political systems, the introduction of cash crops, and the disruption of traditional patterns of land use. The societal maladies of this region are likely to be greatly exacerbated by the AIDS epidemic. Both of these are examples of areas where socio-economic and environmental processes are especially intertwined and need to be much better understood. Of particular importance is the relationship between political democratization, economic equity, and environmental conservation—how is environmental degradation or improvement differentially affected by political, social, and economic inequities?

Research in this area should thus focus on understanding the relationships between socioeconomic and political status, natural resource management and access, and environmental protection and degradation. Case studies should be conducted to study the impact of rural development—including particularly agricultural and forestry development or energy development (dams, biomass plantations)—on the conditions of the rural residents, and how those impacts depend on social, economic, and political status. These impacts should also be related to the nature of the biotic resource, and the labor, technical expertise, and capital required to exploit it. Similar case studies should be conducted in urban environments with respect to, e.g., siting of urban parks, transportation networks, etc. Additional research should focus on how programs designed to spur economic development or reduce family size—such as empowerment of the poor to control local resources, or increased educational access for females—influence environmental protection. Again, case studies—either across time in a particular location, or across locations experiencing different degrees and qualities of social policies—would be warranted.

The environmental dimensions of human conflict

War—the most dramatic expression of conflict within and between states—uses resources, shifts land uses, results in environmental destruction, creates refugees, and makes those environmental-management institutions that were functional in times of peace irrelevant. Not so extreme, but important because of their prevalence, conflicts between different groups within many states, developing and developed, are not being resolved on an on-going-basis by existing institutions and result in human behavior “outside a social contract” that seriously jeopardizes environmental management (dominant *vs.* indigenous peoples, tribal rivalries, tree-spiking environmentalists, etc). Just as importantly, environmental degradation itself can lead to escalation of conflict or violence, particularly when the degradation is associated with a crucial or scarce resource.

Research in this area should focus on documenting the extent of environmental damage from human behavior “outside a social contract”. Ecologists will be especially important for documenting how past ecosystems have responded to the direct and indirect effects of human conflict and how recently affected systems will respond over time. Social scientists are needed to document the dynamics of escalation from discontent to violence. Both working together are necessary to identify how environmental management breaks down during conflict and the interactions between environmental and social dynamics. Research should be encouraged into the full range from violent conflict to “milder” behaviors outside social contracts. These case studies should be used to generate insights into the types of resources or environmental changes that might cause future conflicts. Additional research should focus on the causes and consequences of environmental refugees. Researchers should examine the demographic structure, and the social, economic, and political status of environmental refugees, and examine how the spatial extent or rapidity of environmental degradation corresponds to the extent and rate of the migration of refugees. The environmental consequences of the movement of refugees through a territory should be quantified, and the implications of potential degradation on the successful return of refugees elucidated.

COMMUNICATING SCIENTIFIC INFORMATION

Introduction

The research conducted above will only be effective if it can be communicated to those who will use scientific knowledge in making decisions about conserving and using natural resources, or in responding to environmental change. Our care and utilization of the environment and natural resources will, in turn, only be successful in improving societal well being if it is informed by the best scientific understanding. Earlier models of the academic science-policy or science-public interface suggested that scientists belonged in the laboratory, communicating their results to other scientists, and publishing their findings primarily in professional journals. Journalists, educators, and scientists working in policy arenas were responsible for disseminating that information. It is now recognized that a different model is needed—that there is a need for research scientists to participate more fully in the dissemination process, and they have a responsibility to do so given their publicly funded status. Yet there is still little information on what constitutes effective communication—how different means of delivering information may be required with different groups, and the methods by which scientists can determine public needs and priorities. Moreover, most scientific research is conducted in the wealthier, developed nations of the world, whereas many of the most compelling environmental and social challenges are found in the poorer, developing nations of the world. This disconnect between where much of the science is being conducted (both geographically and socially) and where it is needed could have profound implications for the pathways chosen for addressing environmental ills.

Therefore, there is a compelling need to understand how scientific information is disseminated; how this information is accessed, interpreted, and used by different groups; and how effective that process is. Oftentimes, scientific information is called for under circumstances in which there is limited consensus on how to proceed; the use of scientific information in an atmosphere of conflict should be elucidated. Understanding how the full process of conveying information works in a variety of different venues is essential, particularly as the ways in which scientific information is communicated are rapidly evolving through the increasingly important role of non-governmental organizations and the widespread availability of inexpensive technology for transmitting and storing information.

Research Recommendations

The effects of disparate access to science and scientists

Science is done predominantly in wealthier developed nations and by scientists in institutions in privileged communities. The results of this work are reported in scientific and popular literatures, again mainly in developed economies. These inequities with respect to the communities and geographic locations in which science is conducted, and in which scientific results are reported, could have implications for the scientific understanding policymakers have of environmental problems on local to global scales, and on the policies formulated to address those problems. Research is required not only to understand the extent of current inequities and their impacts, but to improve the process by which scientific information is disseminated to policymakers at all levels, and of all socioeconomic persuasions, in this nation and in others.

Research in this area should focus on documenting disparate access to scientific information, and correlating that disparate access to the types and extents of environmental policies. Disparate access would include both the quantity and quality of scientific information made available. The implications of these disparities for environmental conditions should also be assessed. Case studies examining different groups within a geographic region, or groups with a similar position on the socioeconomic hierarchy (e.g., middle class) between developed and developing nations, would be particularly appropriate. Documentation of changing access to scientific information over time (either increased or decreased access), and the implications of that changing access for environmental policies and conditions would also be warranted. Additional research should focus on the role that access to scientific information and scientists, or the lack thereof, plays in “environmental justice” situations (e.g., siting of incinerators, land reform and the quality of land distributed), and the most effective methods for disseminating scientific information to traditionally disenfranchised groups.

The impacts of information technology and non-governmental organizations on flows of scientific information

Over the past generation, environmental science, high-capacity and high-speed information storage and transfer, and non-governmental organizations have all expanded rapidly. These changes impact the quantity and quality of scientific information used in the decision-making process. While it is widely believed that the increase in available information, and the increase in the number of reputable parties working to disseminate that information, will improve the decision-making process, it is possible that in some situations both the quantity and quality of information used could deteriorate. Research is required to determine how the public and policymakers find and receive scientific information regarding the environment, and to determine the quality both of the information received and its interpretation.

Research in this area should focus, in a given geographic region, on the changes in scientific information used in environmental decision-making processes as information technology evolved or non-governmental organizations proliferated. Analysis of the impact of the recent increase in both NGO's and computer access in developing nations on the policy process would be particularly relevant. Alternatively, researchers could conduct comparative studies among regions facing similar environmental issues or crises, but with different endemic endowments of either local or regional non-governmental organizations, or information technology, or both. The capacity of information users to discriminate among different types of scientific information (e.g., peer-reviewed, popular, or junk science) should also be assessed, and correlated both to the scientific field (e.g., ecology versus economics) and stakeholder group (political, economic, or social status).

Stakeholder participation in natural-resource management and policy formulation

There is increasing evidence that local resource-management plans are most effective when citizens are able to participate in their design and implementation. Such local or regional involvement also increases the flow of information to scientists concerning public priorities for environmental science, and concerning the efficacy with which scientific information is being communicated to the public. There are several different models, however, for how this citizen involvement is to be achieved, ranging from those with equitable participation throughout to those in which citizen feedback on plans developed by "experts" is solicited. Approaches for involving the public can also evolve throughout a particular decision-making episode, with either an increase or decrease in democratic and equitable participation through time. The particular approach taken, and its evolution through time, will have implications both for the scientific and political soundness of the final product, and for its social acceptance and therefore the efficacy of implementation.

Research is required to assess the implications of different means of involving the public in environmental decision-making. "The public" should be taken to include the full range of stakeholder groups (e.g., across the full range of social, economic, and cultural attributes of the citizens of a region), and effective methods for involving different groups identified. Methods ranging from the use of complicated integrated assessment models to simple qualitative indicators for assessing resource-management or policy options should be evaluated. Outcomes—in terms of scientific soundness, political feasibility, and degree of public support—should be assessed, and correlated to the degree of democracy and equity inherent in the decision-making process, as well as the scale at which the process is being conducted (e.g., local versus regional). Additional research should focus on the efficacy with which public concerns and priorities are relayed to the expert scientists, and how scientist's perceptions of those concerns and priorities are related to the stakeholder groups expressing them, and the degree of political conflict surrounding the decisions to be made.

Effectiveness of interdisciplinary training

Over the last two decades, there have been a few interdisciplinary education programs—crossing natural sciences, social sciences, engineering, and humanities—that have had great success in training students to apply a comprehensive and integrative approach to solving environmental problems. These programs have been at the forefront of innovative teaching and research methods that are specifically designed to meet the challenge of understanding integrated socioecological systems. The most successful programs have stressed the need for training students who are capable of combining rigorous disciplinary inquiry with broad interdisciplinary thinking. Despite the unquestioned success of these few particular programs, many questions remain about the best approach for interdisciplinary, educational programs generally. Understanding what programs work best, and at what level, will be crucial if tomorrow's world is to contain not only the scientists capable of the kinds of interdisciplinary analysis needed to answer the research questions listed above, but the citizens and policymakers schooled in the means of interpreting that information.

Research in this area should focus on approaches for interdisciplinary education at all levels of the educational spectrum, from pre-school to post-graduate. Research should assess the age at which students become capable of synthetic, integrative learning, how those capabilities might rest on the requisite disciplinary training, and how student capabilities for such learning change over time. Case studies that compare students from similar socioeconomic backgrounds, with similar disciplinary training but different access to interdisciplinary education, would be particularly useful. Additional research should focus on developing the criteria for what should constitute success in interdisciplinary education, and evaluate existing programs based on those criteria. Particularly effective programs, and the means they employ for education, should be identified.

CONCURRENCE WITH THE NATIONAL SCIENCE BOARD RECOMMENDATIONS

The National Science Board (NSB) made several recommendations for increased support of research in the area of the environment, spanning both discipline-based and interdisciplinary research. Thus, the scope of the NSB analysis differs from what we present here. Nonetheless, in those areas in which the NSB addressed interdisciplinary needs, there is encouraging agreement between the two sets of recommendations, though they were independently derived. Table 1 summarizes the research recommendations given in this report, and the concurring recommendations to be found in the NSB report.

Table 1: A Comparison of research recommendations by the National Science Board (1999) and those found in this report

This Report		**NSB Report**[1]	
Main Research Category	*Sub-category*	*Programmatic Area*	*Description*
Evolution and Resilience of Coupled Social and Ecological Systems	Evolution of social norms	Biosphere & Society	Research on risk, existence values, ethics, and intergenerational trade-offs of well being
	Land-use change		Historical ecology—tracing human-environment relations by integrating evidence from physical, biological, and social sciences and the humanities over space and time
	Feedback loops	Integrated Environmental Systems	Spatially explicit studies of … land cover and land use.
	Disturbance and resilience		Systems theory / complexity theory interface
	Developing coupled models	Strategic Environmental Technologies	Industrial ecology: … studies of urbanization / transportation and land use Energy and environment implications of emerging 21st century patterns
Ecosystem Services	Ecological structures and ecosystem-service delivery	Ecosystem Services	The interface between ecology and economics, especially mechanisms for incorporating ecosystem services into market systems
	Valuation of ecosystem services		Relationship between biodiversity, the area occupied by the ecosystem, and the delivery of crucial services
	Ecosystem services and valuation across scales		
	Assessing manufactured or managed substitutes		

Table 1 (continued).

This Report		NSB Report	
Main Research Category	*Sub-category*	*Programmatic Area*	*Description*
Coping with Uncertainty, Complexity, and Change	Indicators	Biosphere & Society	Social ecology: e.g., studies of social, cultural, and economic processes, societal institutions, and public policies in relation to the environment and its spatial context
	Risk reduction for technology deployment		
	Governance of common pool resources		Research on the innovation process for environmentally benign materials, designs, and processes
	Adaptive institutions and social learning		Valuation and decision-making research on risk
Environmental Dimensions of Human Welfare, Health, & Security	Environmental change and human health	Biosphere and Society	Ecology of infectious diseases
	Environmental justice, poverty, and inequity		
	Environmental dimensions of human conflict		
Communicating Scientific Information	Disparate access to science and scientists		
	Information technology, NGO's, and scientific information		
	Stakeholder participation in natural-resource decisions		
	Effectiveness of interdisciplinary training		

Notes: [1] Summary taken from Table 4 of the NSB report, page 44

IMPLEMENTATION RECOMMENDATIONS

Articulating a set of interdisciplinary research priorities will not suffice for engendering such research. There has been past significant interest in, and efforts towards, promoting interdisciplinary research in the area of the environment, with limited success. These limits derive from various barriers—in training and education, in research traditions and approaches, and in funding-agency programs and budgets. We address each of these barriers—and some proposals for reducing or eliminating them—below.

TRAINING & EDUCATION

Current Barriers

In today's universities, there exist a variety of barriers to interdisciplinary collaboration and discourse and, perhaps more importantly, education and training. In particular, academic institutions have evolved to reward specialization. Colleges and universities offer primarily narrow curriculum options. At both the undergraduate and graduate levels of education, students of natural and social sciences have been encouraged to specialize within a single discipline, and discouraged from seeking out information from a wide array of disciplines that might help to place their academic work in a broader societal context. Often graduate students with broad interdisciplinary interests will be viewed as unfocussed, not fundable, not serious, incapable of academic rigor, or, worse, unemployable. Critics of the current interdisciplinary graduate programs claim that graduates are ill prepared to meet the disciplinary demands of today's professional world and stress that there are few professional opportunities for interdisciplinary graduates in an institutionally disciplinary world. Part of the difficulty may lie with the perception that academia is the primary or most desirable source of jobs for new graduates. In fact, scientists with interdisciplinary training may find their talents especially appreciated in both the government and private sector, with fewer barriers to advancement.

These difficulties in interdisciplinary training flow, in part, from the limitations of faculty, who have themselves been trained to conduct research in fairly narrow, discipline-based fields. Faculty members are further constrained by the departmental structure of most academic institutions. Faculty members are evaluated and rewarded by colleagues within their department—a reward system that can discourage interdisciplinary collaboration due to the lack of personnel trained to properly evaluate such research. Worse yet, interdisciplinary research is often viewed as "soft" and therefore of poor quality from the outset, even prior to evaluation of a particular research project. Further, the "publish or perish" environment that frequently emphasizes quantity of publications over quality can discourage faculty members—particularly young faculty members—from pursuing interdisciplinary research. Instead, the incentives are such that academic researchers may narrow their research horizons and shorten their aims to projects that can be completed relatively quickly, and published in the leading, discipline-based journals in their field.

Increasing the resources for interdisciplinary education, training, and research can only partially ameliorate these barriers. Yet there is evidence that such an increase in resources—including, for example, the NSF-sponsored Interdisciplinary Graduate Education and Training Grants (IGERT), the limited funds available for interdisciplinary research, and the journals devoted to interdisciplinary research—can serve to provide foundations and centers within academic institutions upon which future interdisciplinary programs can be built. At the same time, it should be recognized that there is no "one size fits all" approach to interdisciplinary education and training. Researchers engaged in research on complex environmental problems will range from those who conduct their analyses strictly on a disciplinary basis; to those whose analysis is primarily disciplinary, with some synthesis involving other disciplines; to those who are fully interdisciplinary, integrating across two or more different disciplines. These different research approaches would benefit from different training programs and opportunities. Thus, in presenting recommendations below, we recommend a variety of training programs and educational opportunities, to accommodate the different needs and types of interdisciplinary research endeavors.

Education and Training Recommendations

Undergraduate training

1. Provide funds for course and curriculum development in interdisciplinary environmental issues. Grants could be provided at a variety of levels within the educational hierarchy—to individual faculty members, departments, colleges, or universities submitting appropriate proposals.

Graduate education and research

2. Provide block grants at the level of the institution to promote integrative, interdisciplinary research and training in complex environmental issues, focused on the research areas presented above (similar to the current IGERT grants sponsored by the NSF, but focused on environmental issues). Students receiving these scholarships would be involved in interdisciplinary training throughout their graduate career.
3. Provide funding for pre-doctoral and post-doctoral fellowships in interdisciplinary research that explicitly encourages collaboration among natural and social scientists, humanists, and engineers. Such grants would be awarded to individuals within existing disciplinary or interdisciplinary programs, and would encourage interdisciplinary doctoral research.
4. Develop cross-training placement programs with funding that allows graduate students in the natural sciences to apply their disciplinary techniques to the social sciences, and vice versa. Funding might be structured, for instance, to allow a graduate student to extend his or her training for one additional year for purposes of conducting research or taking courses in a department outside of his or her major. Training for such graduate students would be primarily disciplinary, with one year of intensive training in another discipline.

Faculty education and research

5. Develop and fund intensive, two-week workshops for young faculty members aimed at promoting interdisciplinary research and education. These workshops would be taught by the principal investigators of the

interdisciplinary research grants funded by the National Science Foundation under this same initiative. This program would both serve to train new investigators and develop a network of potential collaborators.

6. Provide funding for sabbaticals for the first year after tenure for interdisciplinary research and training opportunities.
7. Provide funding for "co-sabbaticals" whereby two or more faculty members from different disciplines take simultaneous sabbaticals at a common institution.
8. Require that that all interdisciplinary research proposals contain education and outreach components with the intent to catalyze a cultural change in promotion and dissemination of information from the interdisciplinary research activities.

Public Communication

9. Provide internship funding for traditionally trained M.A., M.S., and Ph.D. natural-science, social-science, or engineering graduates who wish to pursue careers in dissemination of scientific information in the mass media (journalism, TV, movies, etc.).
10. Establish leadership and communication training programs, to train academic researchers to communicate with the media, non-governmental organizations, policymakers at all levels, and members of the private sector.
11. Develop and provide funding for a fellowship program for journalists to participate in the research process and to develop materials to communicate important advancements in environmental research to the public;
12. Develop and provide funding for a fellowship program for scientists to work with museums and other educational institutions on interdisciplinary, environmental projects; and
13. Initiate the development of new television and radio programs, web sites, games, and other innovative learning materials.

THE NATIONAL SCIENCE FOUNDATION

Existing Constraints and Barriers

While much of the interdisciplinary research conducted in this nation to date has been sponsored by the National Science Foundation, and the resources available for interdisciplinary research have expanded under several new initiatives and programs within the NSF, existing support for interdisciplinary research is still insufficient to meet the research challenges outlined above. Moreover, there are several institutional barriers within the NSF that may delay or prevent implementation of a vigorous interdisciplinary environmental research program. These include:

1. The lack of a "home" for interdisciplinary research. No directorate or division is explicitly charged with promoting or coordinating interdisciplinary or cross-directorate research, and there is insufficient incentive, within the existing structure of NSF, for program and division officers to promote such research, or divert resources for it.
2. The lack of experience among NSF personnel. In some (but certainly not all) cases, NSF program officers and division heads suffer from the same lack of interdisciplinary training that plagues their colleagues in academic institutions. This lack of training can reduce appreciation for interdisciplinary research, or reduce a program officer's ability to implement an effective program even when interdisciplinary research is sufficiently valued.
3. The lack of interdisciplinary expertise in NSF panels. The panels convened to review proposals within the NSF do not, by and large, cover a sufficient range of disciplinary bases, or contain a sufficient number of researchers engaged in interdisciplinary research, to effectively evaluate truly integrated programs, particularly those spanning the natural and social sciences, engineering, and humanities. Lack of appreciation for the challenges and rigor of interdisciplinary research among many panel members can also hamper the prospects of interdisciplinary proposals.

In light of these obstacles, we propose several solutions below.

Programmatic Structure & Personnel Training

1. The NSF should establish explicit authority for promoting interdisciplinary programs. This could be accomplished either through an extra-programmatic or extra-directorate office to coordinate cross-programmatic/directorate programs, or through a new division or directorate for interdisciplinary research. In order to be effective, any office established for promoting integrated environmental research must have explicit budget authority.
2. The NSF should establish a training program to school grant-awarding personnel in the challenges and merits of interdisciplinary research. This training could draw on similar training programs outlined in the section above, involving both NSF-based personnel and academic researchers in seminars and workshops.
3. The NSF should increase recruitment of interdisciplinary researchers to serve as program officers. There should be an emphasis on achieving a practical mix of disciplinary and interdisciplinary program officers in each directorate and division.
4. The NSF should charge its newly established advisory board for interdisciplinary environmental research with continued assessment of environmental research priorities, and of the efficacy of changes made in institutional structures, personnel training, or the peer-review process to promote interdisciplinary environmental research within the National Science Foundation.

Peer-Review Process

The current peer-review process may constitute one of the largest threats to enhanced interdisciplinary research sponsored by the National Science Foundation. We believe there are a number of ways to improve this process, detailed below.

1. Move away from aggregated ratings for proposals. Such aggregated measures hide the contrasting ways in which different disciplines evaluate research, and can make it difficult for integrated research proposals to pass muster

due to the conflicts that can remain tacit. In particular, panels must be able to independently analyze the contributions to disciplinary "state of the art" analysis, to development of new methods or approaches for interdisciplinary research, and to addressing compelling societal concerns.

2. Educate panel members in interdisciplinary approaches and goals. If interdisciplinary proposals are to be judged fairly in ways that honor the creative and novel questions, approaches, and domains, panels must be able to put their disciplinary concerns in the service of the interdisciplinary outcomes. Panels must learn how to balance specific disciplinary criteria for evaluation with those that recognize the needs of successful integrated research. Several steps can be taken to increase the ability of panels to deal effectively with interdisciplinary proposals. All panel members should receive a comprehensive orientation concerning the goals of the specific program they are charged to assist. Conferences can be a useful way to achieve this goal. Such conferences can be via telephone, video, or by preliminary face-to-face meetings at the review site. It should be recognized, however, that a "crash course" in the value and process of interdisciplinary work will likely have limited effectiveness in training scholars with no prior experience in conducting interdisciplinary work, or in collaborating across disciplines. Therefore, panels should, whenever possible, be comprised of individuals with proven track records in inter- or multi-disciplinary collaborations.

3. Promote continuity in interdisciplinary panels. Continuity in these panels is perhaps more important than in disciplinary panels, because the culture of individual disciplines is a subject of disciplinary training and experience. The culture of interdisciplinary research may have to be constructed and reinforced. Panel continuity can promote such cultural development and transfer. The panel processes in the European Union and in Canada can serve as good models for evaluation of interdisciplinary proposals. Typically such panels meet for extended periods during which interdisciplinary negotiations are promoted, criteria for appropriate evaluation of integrated research are established or reinforced, and damaging disciplinary narrowness may be overcome. The practice in those panels typically evaluates proposals separately on their basis of scientific merit and relevancy. NSF might consider

involving more foreign scholars on review panels, particularly those with experience reviewing proposals under the Canadian or EU systems.

4. Use pre-proposals and incubation proposals to initiate a dialogue among researchers, and between researchers and program officers. Short (3-10 page) pre-proposals could be used to initiate a constructive dialog between the panel and a research team that would ensure proposals that more effectively address the goals of the relevant interdisciplinary program. An added benefit of pre-proposals is that teams with proposals unlikely to be funded would be saved the considerable effort of preparing a full proposal. Given the challenges of interdisciplinary research, and the complexities of environmental phenomenon, liberal use of incubation grants should be considered, particularly in the early stages of an expanded interdisciplinary environmental research program.

5. Allow greater length for some interdisciplinary proposals. A 15-page limit can constrain needed description, particularly when the proposed research involves several PI's ranging across several disciplines.

6. Expand the number of non-panel reviewers. NSF should consider having more than three reviewers rate the proposal prior to a panel meeting, particularly when the proposals are multi-disciplinary and span the natural- and social-science, humanities, and engineering arenas. Again, reviewers should not develop one, aggregated index for the proposal, but should instead rank intellectual merit, societal relevance, and promotion of interdisciplinary training and education separately.

RESEARCH INFRASTRUCTURE

Long-Term Research

Much of the environmental research in this nation suffers from the short duration of funding and the limited spatial scale over which analyses can be conducted, and the limited interdisciplinary analysis being conducted to date is no exception. Recognition of the limits to knowledge imposed by these short temporal and limited spatial scales prompted the National Science Foundation to establish, beginning in 1980, a Long-Term Ecological Research Program (LTER). As the title implies, these sites (of which there are now 24) concentrate on examining ecological phenomenon.

A similar program is required for interdisciplinary environmental research if researchers are to adequately capture the full range of dynamics and patterns of relevance to society as it struggles with formulating an improved and sustainable future. One approach would be to draw on the existing LTER structure. The NSF should encourage—and provide the resources for—expanded LTER programs that would include more explicitly integrated social-science and interdisciplinary research. Special competitions could be held, with interdisciplinary proposals—concentrating on the research areas highlighted above—submitted by existing LTER sites.

One limitation of this approach, however, is the preponderance of LTER sites that concentrate on analyzing relatively "pristine" ecosystems—either with study sites located in areas not subject to intensive human activity, or with study designs that do not perceive or account for that activity. There are two relatively recent urban additions to the LTER network—in Phoenix and Baltimore—and another LTER site devoted to agricultural systems (W.K. Kellogg Biological Station) Capturing the full range of important human activities and the ecosystems in which these activities take place, however, will require adding additional sites to the LTER network, focused on the ecological dynamics of the human-environment interaction. Thus, any additions to the LTER network should emphasize a capacity to elucidate social and ecological phenomena in understudied systems. Moreover, long-term interdisciplinary analysis of environmental conditions and human responses to those conditions should take place in both developed and developing nations, suggesting a greater role for the network of international LTER sites.

National Centers

Most research centers and many universities are structured to promote and reward discipline-based research and collaboration, both through the physical arrangements of laboratories and offices and through the promotion and tenure-review process. The establishment of an independent national center for interdisciplinary environmental research would be an excellent way to promote cross-disciplinary and cross-institutional communication. At the same time, national or regional centers can increase the efficiency with which information is stored, exchanged, and analyzed. Up-to-date databases on key social and ecological environmental phenomenon should be maintained, and computing and database personnel who can serve as key national resources should be recruited and housed . Meeting participants strongly recommend establishment of such a center or centers, with research mandates spanning the full range of opportunities described above. Such a centers could also be used to implement many of the training and education programs recommended in this agenda. Finally, a highly visible and adequately funded national center or centers could alter university and research-center approaches to and attitudes towards interdisciplinary research. Without such centers serving as a national focal point for interdisciplinary research, workshop participants fear that progress in promoting interdisciplinary analysis will continue to be piecemeal, inefficient, and slow.

Scientific Assessments

Individual research projects—however interdisciplinary or extensive the collaboration—are rarely, by design, extensive enough or integrated enough to provide adequate guidance to policymakers and managers. Instead, individual research projects focus on a particular set of circumstances, a particular region or system, or a particular problem. It is the sum of knowledge from numerous research projects, spanning an adequate range of circumstances, that must find its way into the policy process. The magnitude of the scientific endeavor, and the complexity of knowledge generated, is such that dissemination of information to policymakers and managers needs to be considered and planned; it cannot be expected to happen of its own accord, with policymakers turning to individual scientists or research institutions to supply their information needs.

There are currently very few resources available for assessment activities within the National Science Foundation—the NSF provides just $4 million annually for assessment activities (NSB 1999). If the knowledge gained from scientific research projects outlined is to effectively serve the citizens funding such research, then synthesis and dissemination of accumulated information is a must; this assessment and dissemination should be considered a fundamental component of basic research. This process may be particularly crucial for the research areas outlined above, where the number of disciplines and circumstances spanned in advancing knowledge is great, and the societal need for answers compelling.

We therefore recommend that the National Science Foundation significantly increase the resources available for scientific assessment, defined as “the synthesis, evaluation, and communication of scientific understanding” (NSB 1999). Resources for scientific assessment should be expanded in all environmental research areas—interdisciplinary as well as disciplinary.

International Collaborations

All participants affirmed the need for increased international coordination and cooperation on interdisciplinary environmental research. Wherever possible, the education, training, and research opportunities outlined above should be extended to international participants. Workshop attendees encourage the National Science Foundation, its newly established advisory board for interdisciplinary environmental research, other federal agencies, and foundations to explore and promote opportunities for such international collaboration.

Information Technologies

The evolution and dissemination of increasingly sophisticated information technologies will change the way research is conducted in this nation and around the world. Tackling the role of information technology under an enhanced interdisciplinary environmental research agenda was beyond the scope of our workshop. Participants emphasized the need, however, for integration of state-of-the-art information technologies in integrated research; the national centers called for above could play a crucial role in assuring the accessibility and use of information technologies and databases in integrated environmental research.

CONCLUSIONS

The nation faces a tremendous opportunity for increasing interdisciplinary environmental research, thereby improving our ability to promote human welfare while bettering and sustaining the ecological basis of that welfare. There is increasing political and public recognition of, and support for, such a research endeavor. Moreover, the disciplinary understandings of complex ecological and social systems are sufficiently advanced to warrant such increased investments in interdisciplinary analyses today. Finally, there is a growing realization among scientists, policymakers, and other stakeholders that we can never "get it right"—never adequately capture the complexities of social systems and the ecological systems on which they depend, nor adequately allocate or sustain natural resources—if there is not substantially increased dialogue, among professional scientists, between scientists and policymakers, and with the public.

Implementation of the recommendations detailed in this report would be a first step towards realizing the vision of an environmentally sound and socially beneficial future, based on an adequate understanding of our complex world and the way it works. Future steps would be required, with priorities expanded and modified based on the knowledge gathered in earlier programs, and on evolving political and public recognition of environmental problems and desires for social trajectories. But to falter in this first step today would be to deprive ourselves of a better world tomorrow.

APPENDIX A: WORKSHOP PARTICIPANTS

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APPENDIX B: WHITE PAPERS PREPARED FOR WORKSHOP

Antle, John, Susan Capalbo, Edward Elliot, William Hunt, Siân Mooney, and Keith Paustian. *Understanding and predicting the behavior of managed ecosystems: Lessons from agroecosystem research.*

Ascher, William. *Coping with complexity and organizational interests in natural-resource management.*

Brock, William A. *White paper for NSF workshop.*

Ewel, Katherine C. *Resource management: The need for interdisciplinary collaboration.*

Hanna, Susan. *Managing the human and ecological interface: Marine resources as an example laboratory.*

Ludwig, Don. *The era of management is over.*

Oppenheimer, Michael. *Anticipating rapid change: Insights from non-linear geophysical systems.*

Root, Terry L. *Some thoughts—focusing on animals—concerning developing a research agenda for management.*

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