Integrative Science for Society and Environment: A Strategic Research Initiative

Developed by the Research Initiatives Subcommittee of the LTER Planning Process Conference Committee and the Cyberinfrastructure Core Team

Research Initiatives Subcommittee:
Scott L. Collins, Dept Biology, University of New Mexico, *Committee Chair*
Scott M. Swinton, Dept Agricultural Economics, Michigan State University
Charles W. (Andy) Anderson, Teacher Education, Michigan State University
Ted Gragson, Department of Anthropology, University of Georgia
Nancy B. Grimm, School of Life Sciences, Arizona State University
Morgan Grove, USDA Forest Service, Burlington, VT
Alan K. Knapp, Dept Biology, Colorado State University
Gary Kofinas, Resilience and Adaptation Program, University of Alaska
John Magnuson, Center for Limnology, University of Wisconsin
Bill McDowell, Dept Natural Resources, University of New Hampshire
John Melack, Ecology, Evolution and Marine Biology, Univ. of California, Santa Barbara
John Moore, Natural Resources Ecology Lab, Colorado State University
Laura Ogden, Dept Sociology and Anthropology, Florida International University
O. James Reichman, NCEAS, Univ. of California, Santa Barbara
G. Philip Robertson, Kellogg Biological Station, Michigan State University
Melinda D. Smith, Dept Ecology and Evolutionary Biology, Yale University
Ali Whitmer, Marine Science Institute, Univ. of California, Santa Barbara

Cyberinfrastructure Core Team:
Barbara Benson, North Temperate Lakes LTER, University of Wisconsin
James Brunt, LTER Network Office, University of New Mexico
Don Henshaw, Andrews LTER, USDA Forest Service, Corvallis, OR
John Porter, Virginia Coastal Reserve LTER, University of Virginia
John Vande Castle, LTER Network Office, University of New Mexico

Editor: Peter Taylor

Development of the ISSE was supported by a grant from the National Science Foundation (NSF) DEB-0435546.

LTER

OVERVIEW AND OBJECTIVES

We live in unprecedented times. The global human population may reach 10 billion by 2050, making significant demands on natural resources that result in rapid, extensive and pervasive changes in Earth systems (Steffen et al. 2004; Millennium Ecosystem Assessment 2005a,b,c). The environmental challenges faced by society demand solutions that meet human needs and protect essential ecosystem functions that vary in complex ways across different temporal and spatial scales. **A new, *transdisciplinary* effort is needed to detect change, to understand its basis and impacts on socio–ecological systems, and to inform the development of tenable solutions.** Collaborative partnerships are required among the geological, ecological, and social sciences. Highly coordinated research networks need to include knowledge exchange among key user groups, advanced information systems, new research technologies for synthesis, and innovative education and public outreach.

These needs are transdisciplinary in nature, and many have been identified already as national research needs (NSF 2000, 2003; NRC 2001, 2003). However, they are not currently being addressed by any federal research programs. **We thus propose here a research initiative — Integrative Science for Society and the Environment (ISSE) — that will elevate environmental science to the new level of integration, collaboration, and synthesis (Box 1) necessary for addressing current and emerging environmental research challenges.** The initiative has been developed by the broad environmental science research community with a 2-year NSF planning grant to the Long-term Ecological Research (LTER) Network. Through this planning process a diverse group of ecologists, geologists, and social scientists has developed a novel programmatic framework that explicitly identifies the fundamental socio-ecological linkages that must be explored and developed to provide the transformative knowledge needed to address pressing environmental challenges. In this document we provide the scientific rationale for new resources to carry out this synthetic research framework. If fully implemented, it would generate a unique transdisciplinary research program to help meet the socio-ecological challenges now facing society. (A list of acronyms used throughout this document can be found in Appendix 1.)

Box 1. Integration, Synthesis, and Collaboration

Integrative research brings together knowledge, capacities, programs, and infrastructure into a transdisciplinary network capable of providing understanding and solutions to complex problems. Synthesis combines diverse concepts and information into new knowledge and understanding. Collaboration provides opportunities for investigators to work together across disciplines to solve complex problems.

I. Background

The nature and scope of research in the geological, ecological and social sciences have changed dramatically during the last 100 years. Following the work of early pioneers and beginning with the International Geophysical Year (IGY) in 1957-1958, the scientific community recognized the need for large, integrated programs to address systems-level questions at large scales (Chapman 1959, NAS 2007). The IGY allowed the geosciences to develop integrated, experimental programs and research infrastructure to coordinate global measurements of earth, ocean, and atmosphere. The effort was notable for its geographic rather than disciplinary focus. Since then, ongoing measurements have been obtained from integrated, ground-based sensor networks together with oceanic buoys and atmospheric soundings from satellite and aircraft. This research has led to development of models that describe current conditions and future scenarios at global to regional scales.

Ecological research has also changed considerably over this period. Initially, ecological investigations were focused on short-term observations in relatively pristine systems. During the 1960s, the International Biological Program (IBP), modeled on the IGY, moved ecological research into the realm of "big science" (McIntosh 1985) (Figure 1). IBP and other research efforts enabled ecology's conceptual shift away from the "balance of nature" to a "dynamic equilibrium" paradigm. The shift was driven, in part, by greater recognition of the importance of natural disturbances and disturbance regimes (Pickett and White 1985, Wu and Loucks 1995). During this phase, the ecological sciences became more integrative, interdisciplinary, and collaborative; the questions being addressed became more complex; and ecological research moved away from its historical focus on what were perceived to be pristine systems (McIntosh 1985, Golley 1993). Larger efforts motivated by the scientific community, such as the LTER program and the National Center for Ecological Analysis and Synthesis (NCEAS), also played key roles in the transition from single-investigator, single-site studies to collaboration, integration and synthesis.

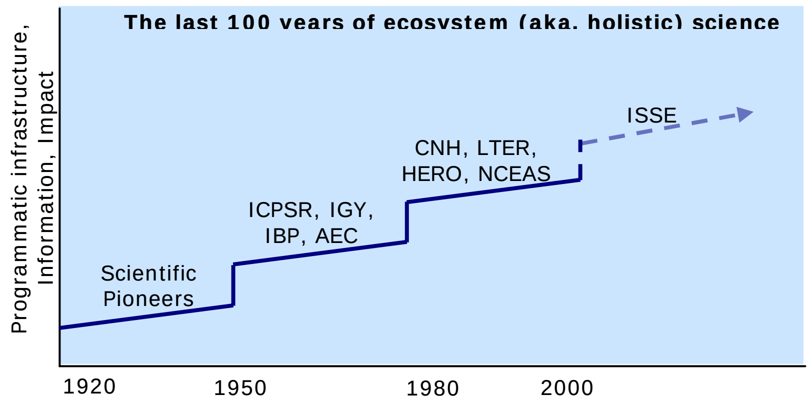


Figure 1. Evolution of the socio-ecological sciences to increasing holism through funding opportunities that led to greater integration within and among disciplines. We envision that the development of the Integrative Science for Society and Environment (ISSE) will be transformative because it will move socio-ecological research to a new level of synthesis and integration.

The social sciences represent a diverse and intellectually rich array of disciplines, including anthropology, economics, geography, and sociology that have undergone transitions in the past fifty years toward more integrative, interdisciplinary, and collaborative research (Sills and Merton 1968, Smelser and Baltes 2001, Singleton and Straits 2005). These disciplines have contributed to the collection and analysis of long-term data sets, such as censuses of population, agriculture, and economic activity (Sills and Merton 1968, Smelser and Baltes 2001, Singleton and Straits 2005). Additional innovations such as the Interuniversity Consortium for Political and Social Research have contributed to synthetic social science research. Recently, research centers have focused increasingly on humans as biological and cultural organisms embedded in social and ecological systems (Haberl et al 2006). Studies of socio-economic systems account more for the cognitive, behavioral and institutional dimensions that shape human choice. The research focus has shifted from static or linear descriptions of human populations and individuals toward explanations of the processes that create identity and agency within complex social structures and institutions. The result has been movement away from socio-cultural stereotypes to reveal the intricate historical and social diversity of places and regions.

The LTER program was the first funding program to focus explicitly and simultaneously on long-term, large-scale ecological phenomena. As ecology became a global-scale science, interdisciplinary collaborations evolved, fostered by global research programs such as the International Council of Scientific Union Scientific Committee on Problems of

BOX 2. MILLENNIUM ECOSYSTEM ASSESSMENT

The Millennium Ecosystem Assessment (or MEA) was conducted to meet demand from decision makers for scientific information about consequences for human well-being of changes in ecosystems. The MEA was written by more than 1300 physical, biological and social scientists from 95 countries, and published in 4 synthesis volumes plus several topical summaries in 2005 (see http://www.MAweb.org). The MEA provided an unprecedented global synthesis of 24 ecosystem services (Box 3), as well as multiscale assessments of 33 regions around the world. The MEA found that about two thirds of ecosystem services are being degraded. It evaluated plausible futures of ecosystem services to 2050, and assessed the efficacy of several dozen policy instruments for managing ecosystem services.

Although the intended audience of the MEA was decision makers, not scientists, gaps in data and knowledge became obvious in the course of the assessment (Carpenter et al. 2006a). These included many gaps in quantitative links among ecosystem processes, ecosystem services, and human well-being. Scientific capacity to integrate information at multiple scales, from local sites, to regions, to national and international networks, emerged as a key need. Many important research gaps involved quantification of ecosystem services to facilitate decision-making by markets and other institutions, as well as understanding by the general public. Lack of long-term data was perhaps the greatest barrier to assessment. Specifically, better long-term data were needed on land use change, desertification, changes in distributions of wetlands, stocks and flows of living resources, and trends in human reliance on ecosystem services (Carpenter et al. 2006b).

Environment and the United Nations Environment Program's International Geosphere-Biosphere Program (IGBP) and International Human Dimensions Program (IHDP) (Mooney 1998, Steffen et al. 2004, Schlesinger 2006, Carpenter and Folke 2006). Interactions among geoscientists and biologists have been important since the beginnings of ecosystem science. Linkages between ecology and the social sciences are more recent at a national level, such as LTER and Human-Environment Regional Observatory (HERO), and at a global level, such as the IHDP and Land Use and Cover Change. These collaborations have developed pathways for communicating with and educating society about important environmental issues. Intellectually, collaborations emerged from the need to understand how institutions and economies solve common property resource problems (NRC 1999, 2002). In practice, collaborations were driven by demand from decision makers for scientific information about the human consequences of changes in ecosystems (e.g., Boxes 2 and 3). Studies of ecosystem services (e.g., Daily 1997), which emerged from basic research in the 1970s, formed the core of the first global assessment of ecosystems conducted for decision makers.

BOX 3. ECOSYSTEM SERVICES

Research to understand the ecological foundations of society's wealth began in the 1970s under diverse rubrics including ecosystem services (Ehrlich and Mooney 1983), functions of nature (De Groot 1992), nature's services (Daily 1997) and natural capital (Jansson et al. 1994). One of the first tasks of the Millennium Ecosystem Assessment (2003) was to develop a standard approach for communication between scientists and decision-makers and across scientific disciplines. Provisioning ecosystem services are the products that people obtain from ecosystems, such as food, fuel, fiber, fresh water, natural biochemicals and genetic resources. Regulating services are benefits that people obtain from natural regulation of air quality, climate, erosion, disease, soil and water quality. Cultural services are nonmaterial benefits that people obtain from the aesthetic, educational, recreational and spiritual aspects of ecosystems. Ecosystem services directly support components of human well-being including security, basic material for a good life, health, good social relations, and freedom of choice and action.

More recently – and at the core of this initiative – is our current understanding that *humans are embedded in Earth's ecological systems* and studying ecological systems without consideration of the sociological system does little to advance our ability to solve complex environmental problems.

Major ecological change, such as altered biotic structure and biogeochemical and hydrological cycles, occurs within socio-ecological systems and must be understood in this context (Figure 2).

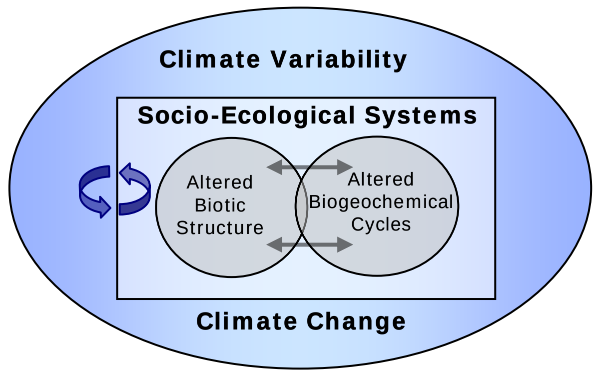


Figure 2. Hierarchical relationships and attendant feedbacks between climate variability and climate change, socio-ecological systems, and altered biogeochemical cycles and biotic structure. These research domains and their interactions, built around Environmental Grand Research Challenges (NRC 2003) form the basis of the proposed initiative on Integrative Science for Society and Environment (ISSE).

II. Motivation for this initiative

This initiative is motivated by fundamental observations about resource consumption and its interaction with human population growth, distribution, and re-distribution at international, national and local scales. Research has documented clearly the environmental consequences of population growth and the demands that the global human population will impose on ecosystem goods and services (Daily et al. 2000, MEA 2005c, Dietz et al. 2007). One of the most pressing environmental challenges is climate change caused

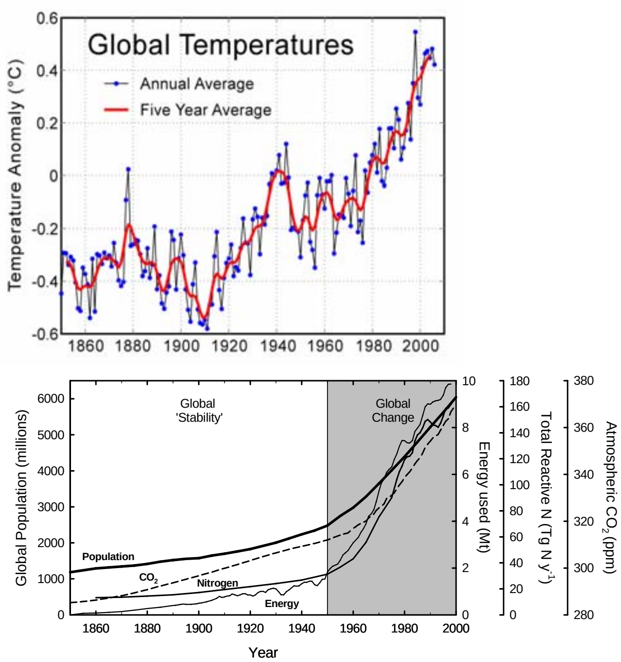


Figure 3. Changes in key ecological and sociological drivers over the last 150+ years. (Top) A plot of changes in global mean temperature based on instrumental records compiled by the Climatic Research Unit of the University of East Anglia and the Hadley Centre of the UK Meteorological Office (Brohan et al. 2006). Following IPCC protocols, zero is the mean temperature from 1961-1990. This figure recreates the controversial hockey stick diagram in Mann et al. (1998, 1999). (Bottom) A new hockey team diagram that along with temperature shows changes in human population, resource consumption (energy), atmospheric CO2 concentration, and N availability over the last 150 years (from Smith et al. in review). Population data are from the US Census Bureau (http://www.census.gov/); energy consumption from the US Department of Energy Information Administration (http://www.eia.doe.gov/); total reactive N from Galloway et al 2003; and atmospheric CO_2 concentrations from the Carbon Dioxide Information Analysis Center (CIDAC, http://cdiac.esd.ornl.gov/).

by rising levels of atmospheric CO_2 and other greenhouse gases (Houghton et al. 2001, Siegenthaler et al. 2005, Spahni et al. 2005, IPCC 2007). Global temperatures have risen dramatically during the last two decades (Mann et al. 1998, Figure 3) because of the increases in greenhouse gases. Climate change by itself, however, is only one of several pressing environmental concerns at global and regional scales. Indeed, global environmental change results from interactions among multiple factors including social and ecological variables related to human population growth and resource consumption (Tilman et al. 2001, Liu et al., 2003, Huston 2005, Dietz et al. 2007). Rising levels of atmospheric CO_2 and temperature in combination with population growth, increased nitrogen availability, and increased energy consumption have tremendous impacts on social and ecological systems. Yet we are far from understanding the consequences of interactions among these social and environmental drivers (Figure 3).

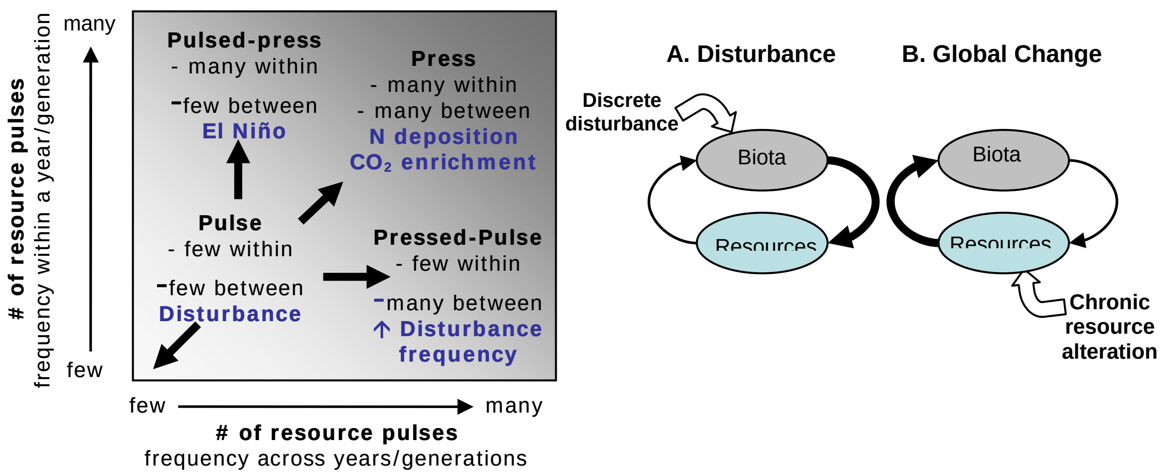


Figure 4. Changes in the nature of press and pulse perturbations in ecosystems in response to environmental change. Historically, natural disturbance regimes altered biotic structure and directly or indirectly altered resources for subordinate species. Environmental change (e.g., N deposition) is increasing the abundance of limiting resources, thus bypassing the role of natural disturbance regimes in ecological dynamics. Disturbance regimes still occur, but changes in the frequency and intensity of disturbances, and more importantly the interactions among new press and pulse perturbations will change species interactions, community structure and ecosystem processes (from Smith et al. in review).

Most ecological changes can be characterized as press or pulse events (Bender et al. 1984). Presses are environmental impacts driven by constantly increasing pressures on atmospheric and ecological systems, such as atmospheric CO_2 change that occurs slowly in ecological time (decades to centuries) relative to a baseline of pre-industrial atmospheric concentrations. In contrast, pulses are events that occur once or at periodic intervals, such as fire and extreme climatic events. Human-caused global environmental change is increasing the strength of press events and altering the frequency and intensity of pulse events (Figure 4). As a consequence, ecological systems are being decoupled from traditional drivers such as 100-year fire cycles or slow biogeochemical change (Smith et al. *in review*). For example, the widespread increase in reactive nitrogen—a key limiting ecological resource—is a press event that will dramatically affect species interactions, community structure and ecosystem processes (Schlesinger 1997, Galloway et al. 2003, Lui et al. 2003)(Figure 5). Changes in nitrogen loadings could lead to nitrate saturation of soils, loss of ecosystem services, increased leaching of nitrate into groundwater and streams, and ultimately threats to human health.

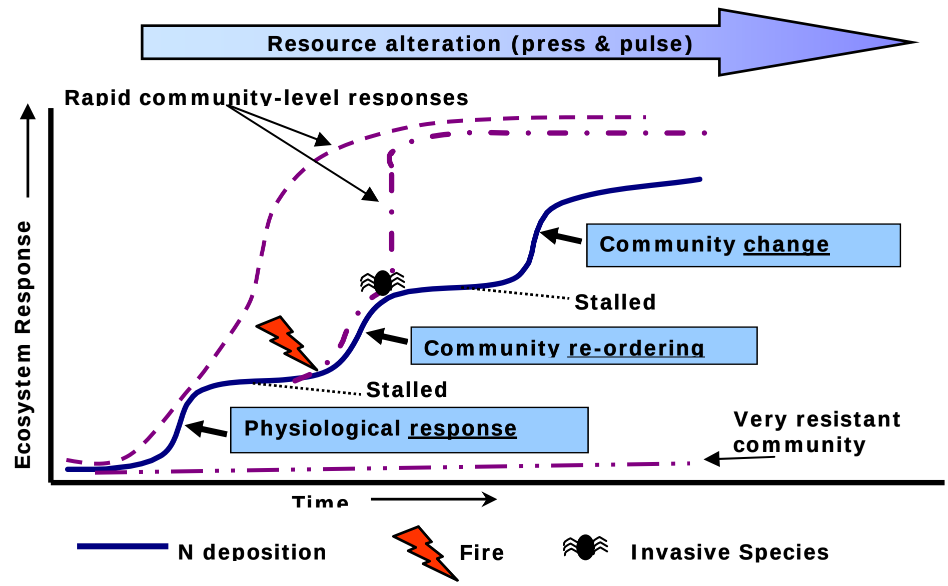


Figure 5. The interaction of press (e.g., N deposition) and pulse (e.g., intense fire) perturbations on organismal, community and ecosystem processes. The rate of change among sites is a function of system stability. The interaction of press and pulse disturbances may rapidly drive an ecosystem into an alternative stable state reducing ecosystem services that affect human behavior and outcomes which ultimately feedback to affect changes in ecosystem services (modified from Smith et al. in review).

What are the consequences of these unprecedented environmental changes? The global climate change community has produced an iconic map of climate change tipping points that threaten human well-being (Kemp 2005). A map of ecosystem tipping points for North America can be similarly constructed (Figure 6). These tipping points result from interactions of environmental change, altered land use and management practices, and human population changes. At global and national scales these ecological and sociological changes are creating an environmental crisis. Addressing this crisis will require transdisciplinary approaches that fully integrate geological, ecological and social science research.

Figure 6. Ecosystem tipping points in North America. Each tipping point results from the interaction of social and ecological drivers.

Transdisciplinary research is essential for generating the fundamental knowledge needed to understand and manage the biosphere in the face of unprecedented changes in human population distribution and the consumption of natural resources (Lubchenco et al. 1991, NRC 1999, NRC 2002, Palmer et al. 2004, Steffen et al. 2004). Environmental scientists now fully recognize that the human footprint is global and pervasive (Vitousek et al. 1997, Grimm et al. 2000, Millennium Ecosystem Assessment 2005a,b,c). That research must treat human activities as integral to ecosystems is widely acknowledged, as is the importance of forward-looking research to help maintain Earth life support systems while meeting human needs (Palmer et al. 2004, Schiermeier 2006). Schematically, we view socio-ecological systems as being embedded within and interacting with an increasingly variable and changing climate system (Figure 2).

This view makes it vital to understand the cognitive, behavioral, and institutional dimensions of socio-ecological systems in a spatial and temporal context. The human population is projected to soar to 10 billion during this century (Lutz et al. 2001, Cohen 2003). However, this growth will not be distributed uniformly at global or regional scales. For example, US census statistics show that from 2000-2005 the US population grew 5.3%. Yet during this period two states with comparably sized populations, Wisconsin and Arizona, grew 3.2% and 15.1% respectively. Not only are US state populations increasing at different rates, but exurbanization, or low-density residential development outside the urban fringe, is among the fastest growing forms of land use in the US (Brown et al. 2005, Hansen, et al. 2005, Clark et al 2005). Yet the push-pull drivers of exurbanization and their ecological implications are poorly understood (Dale et al. 2005, Hansen et al. 2005).

Box 4. Sea-Level Rise: Natural Disasters and Change Affect Coastal Socioecosystems

In the Everglades, climate change is most strongly manifest as sea-level rise (a press disturbance) and hurricanes (pulse disturbances). Sea-level rise, coupled with dramatically reduced freshwater inflows to Everglades estuaries in the last century, has led to a landward expansion of mangrove wetlands. Hurricane storm surges accelerate landward transgression across this very flat landscape. Sea-level rise also leads to saltwater intrusion into the shallow Biscayne Aquifer that supplies over 6 million people with water. Thus both sea-level rise and changes in the frequency and intensity of storms threaten the long-term sustainability of freshwater supply to a growing human population. This future is confounded by Everglades Restoration, which is seeking to increase freshwater flows to the coastal Everglades. Restoration may well slow the landward encroachment of sea level rise—at least temporarily—while it enhances recharge of the critical Biscayne Aquifer. New research at the Florida Coastal Everglades LTER Program is integrating social and natural science to assess the complex interactions of Everglades Restoration, land-use changes driven by a growing human population, and water supply issues. The importance of this integrated research approach is regularly brought home by news of yet another hurricane landfall—of which Hurricanes Katrina and Rita are the most recent and dramatic examples.

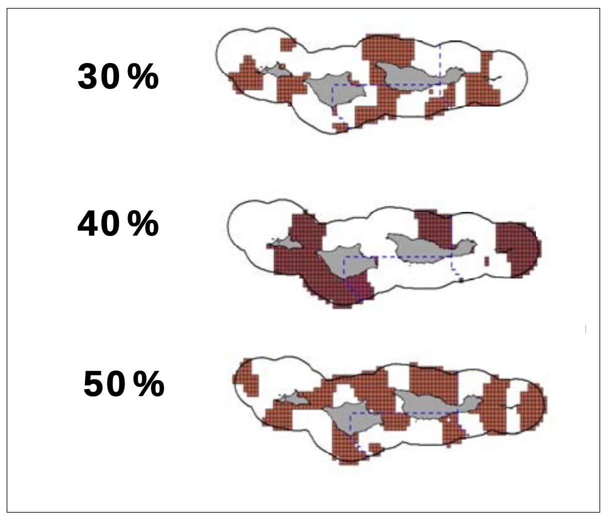
The mangrove forest at Florida Coastal Everglades LTER Program (SRS-6 site about 2 km from the Gulf of Mexico) before (top) and after Hurricane Wilma's landfall in October 2005 (see http://fcelter.fiu.edu for details).

Boxes 4-7 illustrate some of the environmental challenges for which transdisciplinary and synthetic research are needed to advance understanding and develop science-based solutions. These solutions will enable society to better manage the ecosystem goods and services on which we depend.

At the most abstract level, geologists, ecologists, and social scientists examine how systems (in their broadest possible definition) are organized and the roles played by internal versus external influences (Pickett et al. 2001). Moving environmental science to a new level of research collaboration, synthesis, and integration requires a shift from viewing humans as external *drivers* of natural systems to that of *agents* acting *within* socio-ecological systems (Grimm et al. 2000). As human population continues to expand over the next few decades (Lutz et al. 2001, Cohen 2003) with attendant land-use, technological, and economic changes, additional demands will be placed on ecosystem services (Daily et al. 2000). These demands will require integrated, long-term research that spans multiple disciplines and ultimately can provide solutions for the environment and society.

Box 5. Synthesis at NCEAS and the Establishment of Marine Reserves

Efforts to design reserves to protect marine ecosystems are hindered by the fact that many of species in an area swim or float in, often from long distances. Thus, unlike terrestrial reserves in which virtually all of the organisms are born in or near the protected area, marine reserves must deal with long distance dispersal and the effects of current that impinge of prospective reserves. To address this distinction, the National Center for Ecological Analysis and Synthesis (NCEAS; www.nceas.ucsb.edu) supported a Working Group to analyze the implications of the distinctive circumstances in marine systems with regard to the establishment of reserves. Scientists in the group relied on years of research by many scientists to develop general theories and rules of thumb about marine reserve design. At about the same time the Channel Islands National Marine Sanctuary, just off the coast from NCEAS, was developing a new management plan and the managers decided to incorporate marine reserves into the sanctuary. When made aware of the effort at NCEAS, the planners asked the scientists to get involved in the process (as one scientist put it "they called our bluff") and actually make recommendations. After a complicated process involving many constituencies, including environmentalists, fishers, agency officials, and interested citizens, reserves were set aside and are now being monitored for their effectiveness.



Alternative plans for setting aside 30%, 40% or 50% as marine reserves in the Channel Island Marine Sanctuary near Santa Barbara, California.

Box 6. Urbanization in a Water-limited Region

Swimming pools are a common feature of the hot, desert city of Phoenix, AZ. The urban heat island has worsened summer heat. For more information, see http://caplter.asu.edu

In Phoenix, Arizona urbanization has produced wholly new environments with different thermal and hydrologic characteristics than the ecosystems they replaced. Understanding ecological consequences of these changes relies on an understanding of their impacts on social systems and the reciprocal interactions that characterize an urban socio–ecological system. For example, the urban heat island in Phoenix presents a challenge both to trees (which show reduced growth in response to high temperature) and people (who increase their water use to cope with high temperature). But there are further interactions between heat, water, plants, and people that provide excellent examples of the need for integration. An unequal distribution of high summer temperatures disproportionately affects the poor and non-white residents, who also have lower plant diversity in their neighborhoods. Detecting this pattern required access to remote-sensing methods from the geosciences and social distribution data from the social sciences, as well as ecophysiological studies of thermal responses of trees and spatially referenced measurement of plant diversity. In terms of water systems, major hydrologic modification and redistribution of water resulting from over 100 years of human decisions, has greatly enhanced plant productivity throughout the urban area at the expense of a major pre-settlement river-riparian ecosystem. Since 1938, the region's major river has not supported streamflow except during floods. Recent riparian restoration projects along the Salt River have involved school children in low-income South Phoenix. One outcome of this educational program has been the transfer of knowledge about rivers and riparian ecosystems through families and communities.

Box 7. Social and Ecological Cycles in Lake Management

Point- and non-point pollution with phosphorus in lakes of the North Temperate Lakes LTER can cause blooms of toxic and noxious cyanobacteria. For more information, see http://lter.limnology.wisc.edu

Human activity and lake resources of Madison, Wisconsin, have undergone several cycles of change since European settlement of the region in 1840 (Carpenter et al. 2006b). Each cycle involved changes in human activities, some of which had direct effects on hydrology, water chemistry, or the food web. As the ecosystem response unfolded, there were changes in ecosystem services such as lake water levels, quality of water for human use, fisheries, or recreation. These changes in ecosystem services evoked social responses, including formation of new institutions for lake management or changes in mandates of existing institutions, intended to modify human activity and the ecosystems, and thereby improve ecosystem services. Each of these cycles led to surprises as new problems arose just as managers were gaining traction on the problems of the past. We present just one example. In the late 1940s, water quality deteriorated sharply due to rising sewage inputs and fertilizer use in agriculture. By the mid-1950s, obvious degradation of the lakes spurred political conflict leading to diversion of sewage inputs in 1971. However, the lake failed to respond as hoped. Thirty years of intensive fertilizer use had enriched the soils of the watershed and increased non-point pollution. In the early 1980s, an initial attempt to mitigate non-point pollution failed because of inadequate attention to farmer behavior and farm microeconomics. From 1987-1994, the lake food web was manipulated by restoring game fish, which led to heavier grazing on nuisance algae and improvement of water quality. Despite these improvements, toxic algae blooms episodically choked the lakes. In 1997, a new non-point pollution program was started, employing a wider diversity of policy instruments. By now, however, the expansion of impervious surface due to development of the watersheds is having obvious impacts on hydrology, causing greater variation in lake levels and flushing rates.

AN INTEGRATED RESEARCH FRAMEWORK

Today's environmental issues cannot be investigated fully with existing disciplinary approaches or with the limited interdisciplinary funding opportunities that are currently available. Scientists have repeatedly called for more opportunities for collaborative research between the ecological, geological, and social sciences (Grimm et al. 2000, Palmer et al. 2004, Robertson et al. 2004, Newell et al. 2005, Pickett et al. 2005, Kremen and Ostfeld 2005, Balmford and Bond 2005, Farber et al. 2006, Haberl et al. 2006). They often identify needs yet rarely put forward viable mechanisms for promoting trandisciplinary science. A comprehensive framework is needed to encourage relevant disciplinary research and enable integrative research among disciplines.

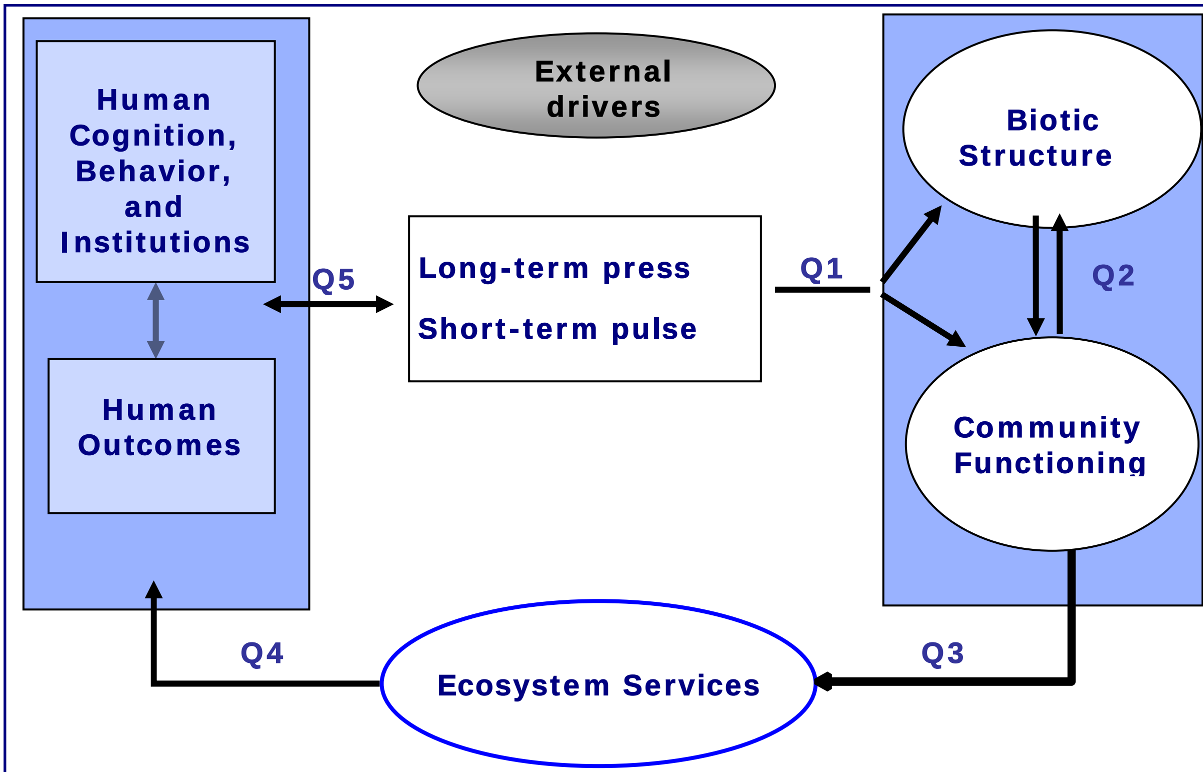


Figure 7. An integrative and iterative conceptual framework for socio-ecological research. Interactions within this framework are driven by a set of general questions (Q1-Q5, see Box 8) that create information pathways for linking the ecological, geological and social sciences. This very general framework can be operationalized for a variety of ecosystem types (See Appendix 2 for three examples), and across spatial scales. Indeed, this framework is designed to accommodate the potentially disparate scales of research across these disciplines.

Figure 7 (see also Box 8) presents the basic components of such a framework. These components were identified through a series of workshops that included ecologists, geoscientists and social scientists. This general framework explicitly integrates social, ecological, and geological disciplines via a series of broad questions. These questions can be operationalized locally, regionally, and globally to address specific, fundamental questions related to biophysical systems, ecosystem services, and human responses and outcomes (see Appendix 2 for examples). Unlike other more linear approaches (e.g., Kremen and Ostfeld 2005), this framework is iterative with linkages and feedbacks between biophysical and social sciences. This framework will rely on theoretical, empirical and methodological contributions from ecological, geological and social science disciplines. Application of this framework will contribute substantially to development and testing of theory within these disciplines, and it will help build a transdisciplinary science of socio-ecological systems. Components of the framework can be pursued through research by individual investigators or research networks. A network-level, long-term integrated program with fully shared intellectual partnerships among disciplines will be unique and transformative for environmental sciences. Such a program is essential to better understand human-environmental systems, to generate shared data sets, and to reveal generality through synthesis.

BOX 8: FRAMEWORK QUESTIONS:

Q1: How do long-term press disturbances and short-term pulse disturbances ***interact*** to alter ecosystem structure and function?

Q2: How can biotic structure be both a ***cause and consequence*** of ecological fluxes of energy & matter?

Q3: How do altered ecosystem dynamics affect ecosystem services?

Q4: How do changes in vital ecosystem services ***feed back*** to alter human behavior?

Q5: Which human actions influence the frequency, magnitude, or form of press and pulse disturbance regimes across ecosystems, and what determines these human actions?

NSF has played an active role in helping to change the culture of research. It has provided resources to encourage collaborative, interdisciplinary research (Figure 8) and to integrate education into the research enterprise. Therefore, NSF, in conjunction with other lead agencies, should continue to bring about the paradigm-shifting changes needed in US science by funding short- and long-term research and education that acrosses disciplines. This initiative is our effort to identify how this new level of transdisciplinary science might be addressed and facilitated by NSF.

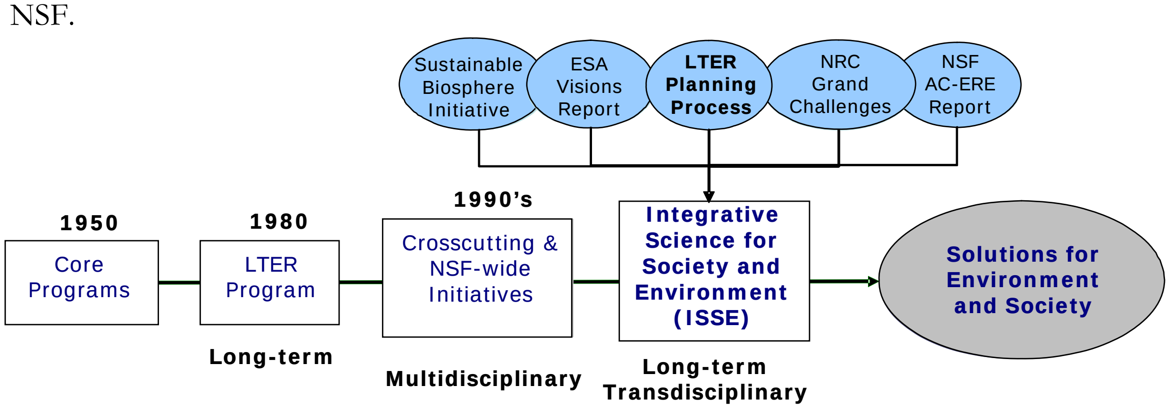


Figure 8. Trajectory of NSF programs supporting socio-ecological research and a proposed new cross-directorate research initiative: Integrative Science for Society and Environment. Historically, NSF core programs have funded individual investigators to conduct short-term disciplinary research. In recognition of the long time frame of ecological phenomena, NSF initiated the LTER program in 1980 and that program has expanded to include research in the social sciences. Similarly, because the complexity of ecological systems demands expertise from a variety of disciplines, several crosscutting programs were started in the 1990s with the primary goal of supporting multidisciplinary research and synthesis (e.g., NCEAS). Despite these highly successful programs, the scientific community has repeatedly called for new and innovative research approaches to address the most pressing environmental and societal problems. The proposed ISSE initiative will answer this call by supporting basic research that is integrative, long-term, multi-site, and transdisciplinary.

Several recent planning activities have identified a set of grand research challenges for the coming century (e.g., NSF 2000, 2003; NRC 2001, 2003; MEA 2005, Palmer et al. 2005). Global climate change, altered biogeochemical cycles, altered biotic structure, and the consequent loss of ecosystem function are some of the most pressing environmental challenges facing society today. Fundamental questions that address these challenges go beyond the consequences of human activity in general to consider environmental equity and justice; science policy, governance and decision-making; disaster-management stemming from natural and infectious agents; ecological literacy; and the consequences of globalization on local environments and resources. Developing solutions to these challenges will require strong transdisciplinary partnerships. This means increasing the capacity to collaborate, establishing highly coordinated research and education networks, developing cyberinfrastructure to create, maintain and use information, and to deliver that information to educators, decision makers and the general public.

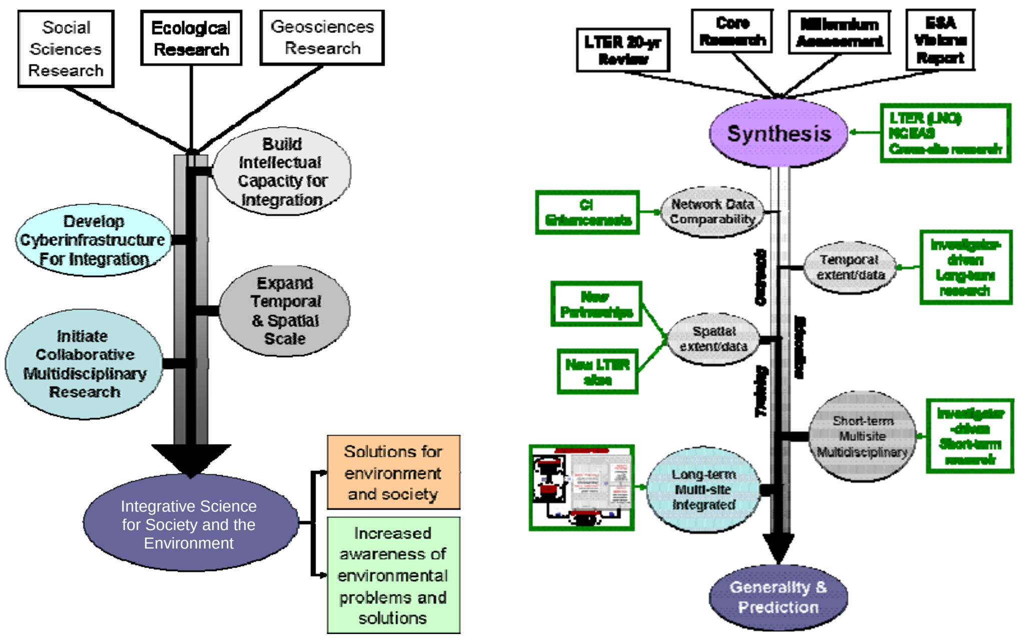


Figure 9. General and specific components of Integrative Science for Society and the Environment. Reports such as the LTER 20-yr review (Krishtalka et al. 2002) and ESA Visions (Palmer et al. 2005) identified critical barriers to creating knowledge that can provide the generality and predictive capabilities needed for solutions to environmental and societal problems. Thus, our ability to tackle complex problems and generate synthesis research over space, time, and disciplines has been limited by impediments to data integration, the need for increased spatial coverage and additional long-term measurements, and coordinated, cross-disciplinary research which fully integrates social, geophysical, and ecological sciences. Specific points of enhancement recommended in ISSE include more opportunities for individual investigator and team-based long-term research, more resources for interdisciplinary research, more opportunities for synthesis of existing research, and a new network-scale, interdisciplinary, long-term research program.

This is also a time when environmental scientists should engage K-16 educators, decision makers, and the general public. The current science curriculum still focuses on the "balance of nature" in pristine ecosystems rather than on the science of socio–ecological systems. The environmental research community is less diverse than and not well connected to the broader population; most people understand less about environmental science than is necessary for informed decision making. Along with these problems come opportunities. Studies of science education are deepening our understanding of how people learn and reason about their environment. These findings should be used to modernize school curriculums and to engage the public more fully in environmental issues. Future scientists trained now in interdisciplinary research and broad participation in the scientific community will be able to develop the understanding and solutions that society needs.

RECOMMENDATIONS

The ISSE will increase society's awareness of environmental problems and its ability to develop solutions by (1) expanding spatial and temporal scales of understanding, (2) developing cyberinfrastructure for integration and collaboration, and (3) building intellectual capacity for integration and public engagement (Figure 9). These recommendations are aimed primarily at NSF although we recognize that achieving ISSE goals will require efforts beyond NSF and that these must occur within an international context. We elaborate on each of these elements below.

I. Expand spatial and temporal scales of understanding. In order to fulfill the ISSE research goals described above we recommend the following actions:

1. Enhance and expand collaborative research opportunities. Human activities are an integral part of ecosystems, and environmental research must become more forward-looking and focused on maintaining Earth systems and meeting human needs (Palmer et al. 2004, MEA 2005b,c). Challenges include organizing interdisciplinary partnerships, coordinating research networks, and making information more readily available. A long-term approach is essential to understand complex socio-ecological systems where events are interdependent, play out in the long term, and respond strongly to both press and pulse dynamics. Crucial scientific questions can only be answered with long-term data, yet programs supporting such investigations are few and those that do exist are insufficiently funded. It is imperative that social science be an integral part of these long-term research and education initiatives (Briggs et al. 2006, Magnuson et al. 2006), otherwise ecologists may not exploit fully the most cogent or important connections of their research (Grimm et al. 2000, Pickett et al. 2001).

NSF should continue to fund programs that support interdisciplinary environmental and social science research with a focus on long-term stability of funding. This encouragement of transdisciplinary environmental science should include a rich array of programs, such as individual investigator projects, site- and network-based programs such as LTER, and synthetic and retrospective activities such as those that occur at NCEAS. Individual grants, the basis of most NSF programs, are uniquely able to address some socio-ecological research questions and theory. They greatly enhance the capabilities of long-term and network-based research programs. They add flexibility to address emerging socio-ecological research questions, and they add spatial scope to long-term programs by facilitating research at different scales. Sustained research programs also provide a solid context for individual grantees.

NSF should encourage transdisciplinary environmental science by expanding its interdisciplinary research programs that focus on understanding the complexities of socio–ecological systems. Existing and planned networks and other site-based research can be the platform for integrative analyses within and across ecosystem types at multiple spatial scales. Initiatives such as the

National Ecological Observatory Network (NEON), Ocean Research Interactive Observatory Networks (ORION), Consortium of Universities for the Advancement of Hydrological Sciences, Inc (CUAHSI), and Collaborative Large-scale Engineering Analysis Network for Environmental Research (CLEANER) will provide the infrastructure for such studies. ISSE's conceptual framework capitalizes on these and other research infrastructure programs. It will accelerate environmental science towards the goals articulated in NSF's vision for environmental research and education (NSF 2000, 2003).

2. Expand opportunities for transdisciplinary collaboration. The creation by NSF of the Dynamics of Coupled Natural-Human Systems (CNH) program area is a critically needed and exciting development. To achieve the goals outlined in the ISSE, the CNH program will need to be enhanced in two ways. First, the transdisciplinary capacity of CNH research projects needs to be promoted by increasing the funding for the CNH program, enabling a broader range of investigators to be included on these awards. Second, long-term research needs to be supported by allowing CNH research projects to be funded for three to five years with the opportunity for competitive renewal. The former Land-Margin Ecosystem Research program in the geosciences is a potential model for larger, integrated CNH awards.

3. Expand opportunities for long-term research. Representation of the diversity of ecosystems–particularly human-dominated systems—is limited in the LTER Network. Additional LTER sites would make it possible to represent a greater range of ecosystem types that are being influenced by climatic, biogeochemical, and biodiversity change and to complement developing NEON sites in areas where only minimal or poorly coordinated long-term research is underway. Better representation of ecosystem types within the LTER Network will address two problems: 1) many ecosystem types in the US have no long-term, site-based integrated research programs, and 2) there is a general lack of long-term research across the full range of human-influenced environments. We applaud and further encourage the USDA's National Research Initiative (NRI) to establish a network of Long-term Agricultural Research projects, yet other human-influenced systems, particularly suburban and exurban areas, require much greater research attention (Hanson and Brown 2005).

Also lacking in many disciplines are mechanisms to support long-term research by individual investigators. The Long-term Research in Environmental Biology program is an excellent model program. Similar long-term funding should be developed in the geological and social sciences. The USFS Experimental Forests and the LTER Network provide two of many possible compelling examples of the value of long-term research. Clearly, more long-term funding opportunities are needed in the social and geological sciences.

4. Expand opportunities for synthesis. Understanding the complex interactions in socio-ecological systems requires new levels of information synthesis as huge quantities of data—often highly detailed from diverse sources—become available and as the issues we face become more urgent and interdependent. The importance of both retrospective and predictive synthesis has never been greater. Vehicles by which NSF currently fosters such synthesis include NCEAS, the LTER Network Office, and Research Collaboration Networks. NSF should encourage and fund creative analogs to these programs while allowing existing synthesis centers to increase their reach and effectiveness.

5. Create a network-based, long-term, multi-site transdisciplinary research program. Many issues facing society today are complex and occur over long time periods and broad spatial scales. Yet no mechanisms currently exist for network-scale, long-term, multi-site, transdisciplinary research program built on a socio-ecological framework as shown in Figure 7 and appendices. Such a program will require careful planning and coordination from its inception. It would generate vast data streams requiring sophisticated information technology and would serve as the foundation for creative education and outreach activities of broad relevance to society. Network-scale transdisciplinary research would address fundamental theoretical issues in socio-ecological research and lay the groundwork for the syntheses of the future. No such broadly-based long-term program in socio-ecological research exists anywhere in the world and yet human-environment interactions and feedbacks, as illustrated in Figure 7, are inherently iterative. These interactions play out over the long-term, and thus they require a secure long-term research funding base to generate significant understanding. Such a research network would be fully prepared to participate in and utilize the community of existing and emerging long-term research and infrastructure programs (e.g., LTER, NEON, CUAHSI, CLEANER), as well as international networks, such as the IGBP and the International LTER Network (ILTER), to ensure integration across sites, time and disciplines.

II. Develop cyberinfrastructure for integration and collaboration

A detailed cyberinfrastructure (Box 9) strategic plan for the LTER Network is being developed separately under the LTER Planning and Visioning process. Here we present some key cyberinfrastructure (CI) goals and needs within the context of ISSE and the envisioned socio-ecological research and education initiatives.

> **Box 9. Cyberinfrastructure**
>
> **Cyberinfrastructure (CI) describes research environments "that support advanced data acquisition, data storage, data management, data integration, data mining, data visualization and other computing and information processing services over the Internet. In scientific usage, CI is a technological solution to the problem of efficiently connecting data, computers, and people with the goal of enabling derivation of novel scientific theories and knowledge" (Atkins et al. 2003). CI also includes people and organizations that operate and maintain equipment, develop and support software, create standards and best practices, and provide other key services like security and user support.**

Meeting the challenges of the ISSE initiatives for integrative research and education at multiple scales, across disciplines, and spanning resources, data, and expertise at geographically distributed sites requires investments in cyberinfrastructure and workforce development, creating new capacity for collaboration, scientific integration and information transfer (National Science Board 2020 Vision for the National Science Foundation). Cyberinfrastructure challenges span a range of research program needs and levels of cross-program integration. These expanding research initiatives require more coherent, interoperable systems to locate, access, and integrate information from multiple disciplines as well as provide findings in forms useful to educators and the public. Curated repositories for data and the promotion of standards for data accessibility and documentation can expand the knowledge base for synthetic research. Development of interoperability across environmental networks would support the facile discovery and integration of data resources that the new integrative research will demand (Green et al. 2005, Ellison et al. 2006). In addition, derived data sets from syntheses may be ideal tools for science education, so these products need to be easily available and intuitive. Ongoing communication and collaboration among the emerging environmental observatories (e.g., NEON, CUASHI, ORION) and existing centers (e.g., NCEAS) and networks (e.g., LTER, Organization of Biological Field Stations) would maximize the return on investments in cyberinfrastructure, promote the desired interoperability, and help disseminate the products of synthetic research to user groups.

CI domain experts such as computer scientists, information scientists, and computer engineers must be full partners in the planning and conducting of ISSE research. Significant new investment in information technology must include programs for technology transfer and training of information specialists, domain scientists and educators. The need for trained personnel, including cross-trained informatics experts and informatics-adept students and scientists, requires ongoing investment in workforce training and education, including organizational learning (Box 10).

Box 10. Training: Integrating Cyberinfrastructure into Socio-ecological Research and Education

Advances in information technologies enable more effective information acquisition, integration, transfer, analysis, and communication, yet the technologies must be harnessed by users who have specific goals in mind and understand which technologies will best accomplish those goals. Thus, integration of new cyberinfrastructure including advanced tools for analysis and synthesis within the research process will require training of students, scientists, and technical staff. These challenges can be met by developing programs of workforce training and education and multiple goals:

- **Provide training in new technology and methods to information managers and technical professionals who are engaged in data acquisition and management,**
- **Provide training in the use of advanced informatics tools to natural social scientists who are engaged in ISSE research,**
- **Maintain a cross-trained cadre of information managers who can be quickly deployed with a standard curricula and training materials for working with research programs,**
- **Develop educational materials tailored to video-teleconferencing, web-based seminars, distance learning, and other paths by which informatics training can be conducted remotely.**

The ISSE can produce a tremendous volume of data and information. Institutional programs designed to train domain scientists in informatics are currently non-existent. A training curriculum for this new generation of students and professional scientists can bring the latest technologies and cyberinfrastructure to bear on the problem of design, conduct, and communication of interdisciplinary research.

Creating virtual organizations of science teams and working groups through implementation of collaboration technology will be a crucial component of the information technology-enabled knowledge environment for ISSE science. Video-teleconferencing capability and other environments for virtual meetings along with portal tools for co-development and sharing of approaches and algorithms can provide a platform for collaborative science by teams of geographically dispersed investigators. To integrate, configure, and deploy these technologies requires investment in hardware, software integration, and support personnel. To design effective technology for collaboration, scientists must be engaged from the start.

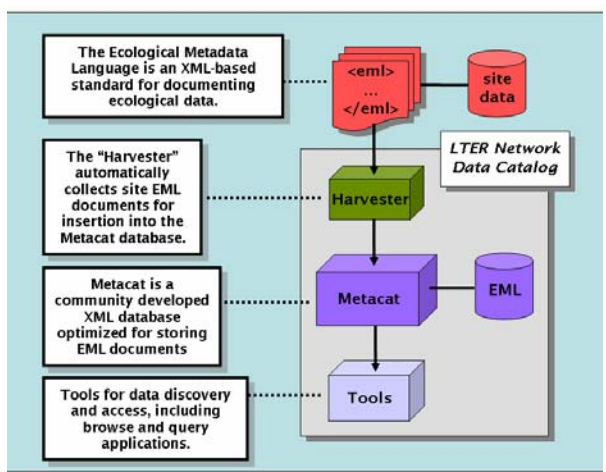
Increasing the capacity for ***data acquisition, management, and curation*** can provide the foundation for integrative science. Existing online data and documentation are valuable resources for integrative, synthetic research, but new data volumes and data types create challenges for data throughput and quality. New kinds of data can be collected in a broad range of geological, ecological and social settings by leveraging emerging sensor technologies to study socio-ecological systems. Data generated by truly transdisciplinary socio-ecological research will likely stretch the capabilities of contemporary data-indexing systems and relational databases. Large-scale, multi-investigator experiments to date have shown that the usual tools for data management such as spreadsheets and email do not scale well with increasing data volume, data complexity, and requirements for research coordination. An integrated framework of tools and expertise is necessary to support these large-scale experiments. In addition to creating economies of scale, the framework can provide incentives for researchers to use standardized protocols. In return, they gain access to powerful analytical tools and secure data.

Advances in ***data discovery, access, and integration*** are needed to take advantage of the wealth of data that exists now and that can be generated by the ISSE initiatives. Development of interoperability across research programs and networks is essential for the discovery and integration of data resources. Groups such as the LTER Network and its ecoinformatics research partners (SDSC, NCEAS, University of Kansas) have made significant progress, such as development of the Ecological Metadata Language (Fegraus et al. 2005), a metadata standard (Box 11). However, major barriers exist for researchers who need to discover, access, and integrate data, for data service providers who need to deliver quality integrated products, and for educators interested in using them. These barriers result from wide variation in cyberinfrastructure capabilities, the inherent data heterogeneity of ecological studies (e.g., differences in format, precision, scale, semantics, and quality control/assurance), and the unique challenges of historical socio-ecological data sets. Resolving these issues will involve expanded resources of people, technology, and capacity at dispersed sites and at centralized facilities.

Box 11. Ecological Informatics Research

The Knowledge Network for Biocomplexity, an NSF Knowledge and Distributed Intelligence project including collaborators from the Naional Center for Ecological Analysis and Synthesis, Texas Tech, LTER, and the San Diego Supercomputer Center, developed tools and techniques for the management of ecological metadata, including Ecological Metadata Language (EML), and the Metacat XML repository. These tools facilitate cross-program data discovery and access for researchers and have been used to create an LTER Network Data Catalog as illustrated below.

Current partner collaborations include an NSF Large Information Technology Research project, the Science Environment Ecological Knowledge (SEEK), that is ecoinformatics developing analytical workflow tools including Kepler and techniques for ontological annotation of ecological data. Kepler is a community-based, cross-project, open source collaboration on a scientific workflow application that can use web services as basic building blocks.



A vital CI enhancement will be tools for data integration that allow heterogeneous and dispersed data sources to be combined into single, unified products and provided to users and applications. In many cases, the proposed data mediation solutions such as ontology development, knowledge services, and data provenance are still areas of active research in information technology. Socio-ecological research projects of the ISSE represent a valuable opportunity to test and implement these evolving technologies.

An ***advanced environment of analysis and synthesis tools and computational capacity*** can support integrative research and foster development of generic models of ecological processes and cross-disciplinary models. ISSE demands the development of new integrative models, advanced analytical and visualization tools, and scientific workflow environments for defining and executing complex workflows involving multiple, heterogeneous applications and/or models (Jones et al. 2006). New resources are needed to co-develop and support workflow and analytical environments, build model repositories for the community, and foster the sharing of source code and model validation. The atmospheric sciences provide a model and a potential partner in these efforts.

To understand temporal dynamics across broad spatial scales requires the acquisition of long-term geological, ecological, and social science data sets. Use of these data in formal and informal education settings and policy arenas requires understanding the data needs of these communities and data access and privacy issues. The transdisciplinary goals of ISSE thus present challenges for data acquisition, integration, and availability. Achieving these goals will require stronger incentives from funding agencies and journals to make research data available and usable by future scientists, students, educators, and policymakers. The value of long-term geological, ecological, and social science data likely transcends the lifespan of scientists and their research projects.

The research goals of the ISSE are data-driven and most new discoveries and advances will be data-dependent. The research initiatives will require reliable, usable, and extensible information systems to achieve their objectives. Most of these recommendations do not fall within existing NSF programmatic areas because substantial components include integrating, coordinating, and maintaining data. These are non-traditional goals for the NSF. With the vision of the important scientific advances that can be made through ISSE, we recommend:

1. Support for the deployment, integration, and interoperability of cyberinfrastructure, standards, and people across environmental networks. Reaching the full potential of ISSE research will require NSF-wide investments in cyberinfrastructure. While advances are being made across the CI arena, most of these advances are observatory specific or focused on the minutiae of interoperability within broader, grid-based solutions. Much more needs to be done to actively bring CI developers and environmental informatics groups together, to encourage integrative cyberinfrastructure development, and to support the deployment of existing cyberinfrastructure. Programmatic funding can solve these problems.

2. Support curated repositories for data and models to expand the knowledge base for synthetic research. The development, mining and aggregation of foundational data collections can create breakthroughs in understanding and accelerate new discovery on issues and in areas that were not possible before. Investing in the long-term support of curated data repositories can provide a crucial resource for generating new knowledge from ISSE research. Scientists have an increasing need for community data repositories that are able to transcend the evolution of technology and ensure data availability to future generations of researchers, educators, and decision makers. There are small NSF programs that support biological collections for general scientific and educational use, but there are no programmatic mechanisms at NSF for long-term support of curated data repositories for general scientific and educational use.

3. Investment in programs for technology transfer and training of information specialists and domain scientists. Integration of new cyberinfrastructure including advanced tools for analysis and synthesis, within the research process will require training students and scientists to fully reap the benefits of the new technology. There is also a critical training need for technical staff to be kept conversant with new technology and its applications. Within existing networks such as the LTER Network, new resources to support training are needed. Institutional programs designed to train domain scientists in informatics are currently non-existent. These challenges can be addressed by the development and implementation of training curricula for graduate students, research scientists, and technical professionals. These programs would include training workshops held at centralized facilities well equipped for hands-on learning as well as other training methods that can be more localized or remotely accessed. Advances in the technology for remote learning environments can make a significant contribution to these efforts. Programs should include a focus on overcoming barriers to data access and use by educational and decision-making communities. This goal can be achieved through core funding increases in DEB and cross-directorate programs.

4. Support key technology developments in the area of socio-ecological informatics. Developing toolkits of solutions to yet unmet and in some cases unarticulated technical challenges that are grounded in the needs of advancing socio-ecological sciences requires innovative new CI research. Understanding the complex information content of socio-ecological systems, the exchanges of this information, and the responses to these information exchanges is an area in which informatics research can make fundamental contributions in developing new ways to encode, analyze, and visualize information structure. Toolkits for data integration, mining, validation, and analysis must be developed for the wealth of administrative, transactional, and other kinds of data collections commonly used by social scientists and must facilitate information integration with data from other disciplines. Investment in key technology development in areas of data mediation, knowledge representation, advanced analytical and visualization tools, and scientific workflows that use socio-ecological research under the ISSE as test beds will help to advance these capabilities. This goal will require cross-directorate cooperation among entities such as SBE, GEO, BIO, CISE and OCI to develop a truly integrative solution.

5. Enhance data collection and information management systems relevant to socio-ecological research. New investment in cyberinfrastructure for data acquisition, management, curation, discovery, access, and integration relevant to socio-ecological data will ensure the realization of the full potential of ISSE. Capacity is needed to manage a wide variety of sensor, text, audio, video, and other forms of data in information systems that are capable of organizing, accessing, annotating, indexing, integrating and managing such data collections to facilitate integrative scientific investigations. The LTER Network serves as a model for advancing ecological science through calculated and systematic investments in information technology. Investing in the capacity of research networks to pioneer the data pipeline for socio-ecological science will lay the groundwork for the future new knowledge to be gained from ISSE. This goal can be achieved through core funding increases in DEB, GEO, and SBE.

III. Building intellectual capacity for integration and public engagement

The nature and scope of environmental science as described above requires a new model of recruiting and training future scientists at the undergraduate and graduate levels. Fundamentally we must enable the research community to reflect the diverse public that we serve and from whom we seek support (COSEPUP 2005, Ortega et al. 2006). We also must engage students in scientific inquiry that includes an interdisciplinary approach to understanding global issues. We can accomplish these goals through ***innovative curriculum*** and ***research experiences***, which include components aimed at expanding recruitment and retention of a diverse student body. National reports have identified specific needs and called for action in undergraduate education, which can guide our efforts in this arena (reviewed in Project Kaleidoscope *Report on Reports* 2002, 2006).

We recognize these two goals—engaging a more representative student body and improving science education, particularly in the realm of socio-ecological sciences—as separate but interconnected. Indeed, studies have demonstrated that an innovative, authentic curriculum improves recruitment and retention of students from diverse ethnic and gender groups (Kardash 2000, Bauer & Bennett 2003, Rahm *et al.* 2003, 2005, Lopatto 2004, Seymour *et al.* 2004, Russell 2005). Efforts to achieve gains on either front should be developed with both goals in mind. For example, curriculum recommendations made in the report *Using Data in Undergraduate Science Classrooms* (2002) and teaching methods supported by *Teaching Issues and Experiments in Ecology* (http://tiee.ecoed.net/ accessed January 2007), a peer-reviewed web-based collection of ecological educational materials, address pedagogical approaches that support student retention broadly. Similarly, undergraduate research programs such as the Ecology Society of America's SEEDS (Strategies for Ecology Education, Development and Sustainability) program (http://www.esa.org/seeds/ accessed January 2007) focus on diversity through an inquiry-based approach. These initiatives and programs provide models for some elements of the undergraduate initiative proposed by ISSE. We propose expanding those models through an integrative approach to diversity and curriculum. For example, through implementing near-peer mentoring, promoting collaboration in undergraduate research, integrating curricula across biophysical and social science disciplines, and broadening our definition of ecological science career pathways.

At the graduate level, increasing numbers of students must be engaged in interdisciplinary research that includes broad spatial and temporal perspectives. To achieve this goal, we can work to integrate best practices learned from programs that focus primarily on either interdisciplinary work or long-term research. For example, a recent evaluation of NSF's Interdisciplinary Graduate Education and Research Traineeship (IGERT) program concludes that students trained in IGERT programs receive different experiences than those in traditional single disciplinary degree programs, which better prepare them for the science of the future (Abt Assoc. 2006). Further, these programs have catalyzed cultural and institutional change that further facilitates interdisciplinary research and education. Likewise, LTER graduate students develop their research projects in the context of long-term and often broad spatial scales and engage in synthetic research over these scales (Box 12). Both of these programs begin to address national concerns about preparing scientists to lead American competitiveness in the global economy and on global scale science and technology initiatives (COSEPOP 2005). The issues described by the ISSE, however, will require graduate student training that includes both interdisciplinarity *and* long-term, spatially distributed research. The urban LTER programs—Central Arizona Phoenix and Baltimore Ecosystem Study—both have fully-integrated social science components in their long-term research. Similarly, the American Society of Limnology and Oceanography has actively promoted improving interdisciplinary education through two prominent graduate programs: DIALOG (Dissertations Initiative for the Advancement of Limnology and Oceanography), which integrates across the full range of aquatic sciences; and DISCCRS (pronounced "discourse"; Dissertations Initiative for the Advancement of Climate Change Research), which brings together graduates across the entire spectrum of natural- and social-science fields relevant to climate change and impacts. These types of programs provide models for ISSE initiatives, particularly when coupled with goals related to broadening participation of underrepresented groups.

Box 12. Example of Synthetic Research in Graduate Education

Within the LTER network a 2005 Graduate Student Collaborative Research Symposium held at the H.J. Andrews LTER site was designed to facilitate graduate student interactions and stimulate student engagement in comparative and cooperative research efforts. The meeting, which was initiated by the graduate students and funded by NSF, was a productive venture that exposed graduate students to research being conducted at US LTER and International LTER (ILTER) sites and generated focused cross-site collaborations. It also resulted in a funded proposal to establish a graduate student symposium series to facilitate cross-site collaborative research including the synthesis of existing long-term datasets. Each symposium will focus on a fundamental research theme that allows the inclusion of a large array of sites and their data. The 2006 LTER Student Symposium theme is "Patterns and Control of Primary Production."

Environmental science provides society with valuable insights into the challenges of 21st century; the public must understand the constraints and opportunities embodied in these environmental issues, to move us wisely into the future. Educators and scientists cannot fully anticipate the environmental issues that will be faced by future generations, or the policies and practices that will be most appropriate in responding to them. They can, however, provide students with opportunities to develop two critical abilities that, in combination, define *environmental science literacy* for all citizens:

- understanding and evaluating arguments from evidence, and
- using scientific knowledge effectively in arguments and decisions about human freedom, opportunity, and justice.

The goal of **attaining environmental science literacy** can serve as an organizing framework for research and outreach activities of the environmental science community. Initiatives at the national level will focus on identifying relevant socio-ecological content in K-12 education, understanding how students learn this content, and promoting implementation of teaching practice and standards to facilitate environmental science literacy. Local and regional efforts will engage teachers and students directly and will foster relationships among scientists, undergraduate and graduate students, and the K-12 community. Recognizing that environmentally literate decision makers and public come from our K-16 education systems will form the basis for initiatives that engage environmental scientists and the science education community.

The scope and urgency of environmental issues obliges us to prepare future scientists and a public that understands the complexity, nature, and limitations of our shared resources. To achieve this we recommend the following actions:

1. Support environmental education research focusing on learning progressions, curriculum development, and pedagogy that facilitates science literacy. In recent years the Education and Human Resources (EHR) directorate has provided funding for environmental education through their EdEn grants. However, permanent funds for this program do not exist. We recommend permanent funding for this program to encourage a broad range of scientists to integrate their research with formal and informal science education activities.

2. Support network-level efforts to engage broad participation representing our diverse society. NSF recognizes and supports programs aimed at recruiting and retaining underrepresented students in the sciences. Continued focus and efforts are necessary in order to meet the goal of developing a science community that reflects the diversity of our society. Currently programs focus on K-12 students and teachers and undergraduate students. However, funds do not exist to support students in their critical transition from K-12 to college (e.g., post-high school, pre-college summer). Therefore, in addition to strong support for continuing existing programs, we recommend developing a funding program to support pre-college students from underrepresented groups.

3. Engage K-16 students in inquiry-based science education that integrates socio-ecological disciplines and focuses on working with data. NSF has pioneered innovative programs for K-16 science education including programs such as Graduate Teaching Fellowships in K-12 Education (GK-12) and supports interdisciplinary education for undergraduates (e.g., Interdisciplinary Training for Undergraduates in Biological and Mathematical Sciences). We recommend continued and expanded funded for GK-12 with a focus on socio-ecological themes. Programs that fund interdisciplinary education for undergraduate students must be developed that would support collaborations, curriculum development, and multi-site research opportunities across the geological, ecological and social sciences.

4. Provide opportunities for graduate students to conduct transdisciplinary research within the context of long temporal and broad spatial scales. We encourage continued support of graduate education programs such as the Integrative Graduate Education and Research Traineeship (IGERT) program and Doctoral Dissertation Improvement Grants (DDIG). In particular we recommend that the IGERT program focus on projects that integrate across socio-ecological systems and that they encourage the development of network-scale research opportunities for IGERT fellows and network-scale IGERT programs. Similarly, DDIG should provide funds for collaborative, synthetic research projects for teams of graduate students working in this area. In addition to the continued support for graduate student mentoring of K-12 students through the GK-12 program, we recommend support for graduate students to work with undergraduate students in near-peer mentoring relationships. Finally, creative opportunities for integrative collaboration among graduate students are needed as well. The Distributed Graduate Seminars supported by NCEAS are ideal opportunities to combine interdisciplinary teaching with CI technologies to generate cross-collaborative learning experiences. We recommend additional funding for NCEAS to support more of these seminars.

INTERNATIONAL PERSPECTIVES

One theme that will run through the entire ISSE initiative—from research to cyberinfrastructure to education—is the need to incorporate international awareness and participation.

For research, much is to be gained from working with colleagues around the world—with their models, data, and expertise. Furthermore, to truly understand the role of humans in the environment, we need to understand the role of all humans and their cultures. This will naturally involve a broader section of the social science community. Ultimately, the initiative must go beyond simple understanding of the role of humans in the environment. It must help policy makers translate understanding into action. But action is culture dependent, and thus the need to understand culture is critical.

The entire notion of cyberinfrastructure is international. Technologies do not stop at national boundaries any more than do ecological issues. With the infrastructure for collaboration, with the globally distributed set of resources, data and expertise, we can and must engage partners interested in this initiative, independent of location. This is exactly what cyberinfrastructure can do—it can remove space as an impediment to collaboration, and creatively translate and convey the results of socio-ecological research to students, educators, decision makers and members of the general public.

Finally, just as students who are trained to work in interdisciplinary teams are better able to address the science of the future, students who can work in multi-cultural teams will be better able to compete in the global workforce and will be better in problem solving.

THE CHALLENGE AND THE POTENTIAL

Rapid, extensive changes in Earth systems, the conditions responsible for the changes, and the societal responses to them demand a new, transdisciplinary science. The proposed Integrated Science for Society and Environment initiative will significantly increase the capacity of the research community to detect, understand, and respond to the known and anticipated changes to our socio-ecological systems, and transfer that information to key user groups. These anticipated changes include the following:

- Global climate change, variability, and related risk.
- Altered hydrologic cycles.
- Altered biogeochemical cycles.
- Altered biotic structure.
- Dynamics of land use, land management, and land cover.
- Altered ecosystem function and ecosystem services.
- Changes in human health, well-being, and security.

The Integrated Science for Society and Environment initiative can move us to a new level of science and education that is recognized as essential in these unprecedented times. ISSE will increase the capacity of educators and society to respond to these challenges. ISSE will encompass the diversity of socio-ecological science; generate the scientific and cyberinfrastructure tools needed to understand complex socio-ecological systems; and establish the educational programs that are necessary for the next generation.

APPENDIX 1: LIST OF ACRONYMS

AC-ERE – Advisory Committee for the Environmental Research and Education Committee

BIO – NSF Directorate for Biological Sciences

CI – Cyberinfrastructure

CISE – NSF Directorate for Computer & Information Sciences & Engineering

CLEANER - Collaborative Large-Scale Engineering Analysis Network for Environmental Research

CNH – Dynamics of Coupled Natural and Human Systems Program

CUAHSI – Consortium of Universities for the Advancement of Hydrological Science, Inc

GEO – NSF Directorate for Geosciences

HERO – Human-Environment Regional Observatory

IBP – International Biological Program

ICPSR – Interuniversity Consortium for Political and Social Research

IGBP – International Geosphere-Biosphere Programme

IHDP – International Human Dimensions Programme

ILTER – International LTER

IPCC – Intergovernmental Panel on Climate Change

ISSE – Integrated Science for Society and Environment

IGY – International Geophysical Year

LTAR – Long-Term Agricultural Research

LTER – Long-Term Ecological Research

MEA – Millennium Ecosystem Assessment

NCEAS – National Center for Ecological Analysis and Synthesis

NEON – National Ecological Observatory Network

NSF – National Science Foundation

OCI – NSF Office of Cyberinfrastructure

ORION – Ocean Research Interactive Observatory Networks

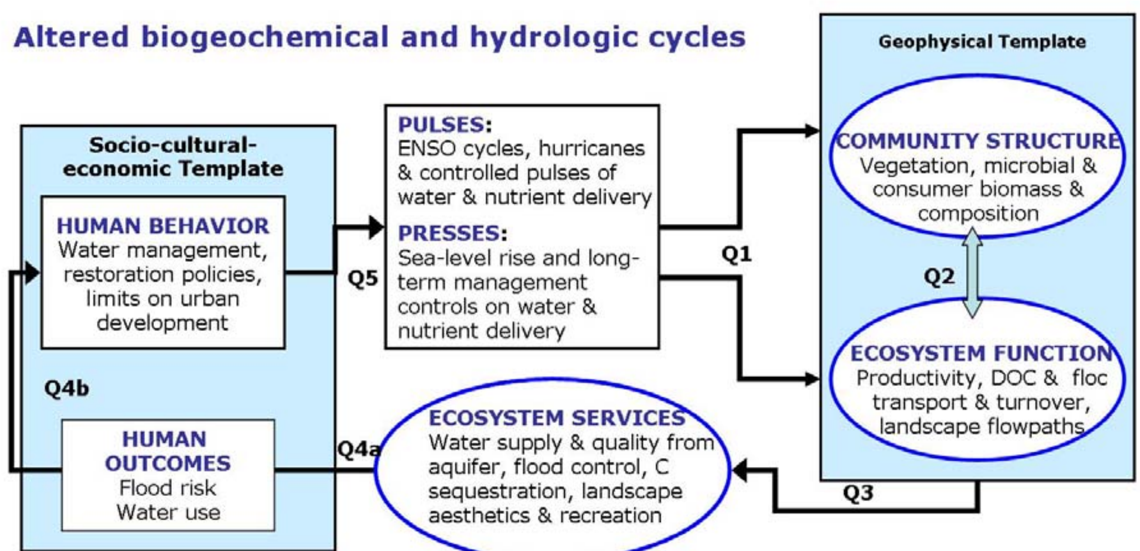
SBE – NSF Directorate for Social, Behavioral, and Economic Sciences

USDA – United States Department of Agriculture

USFS – United States Forest Service

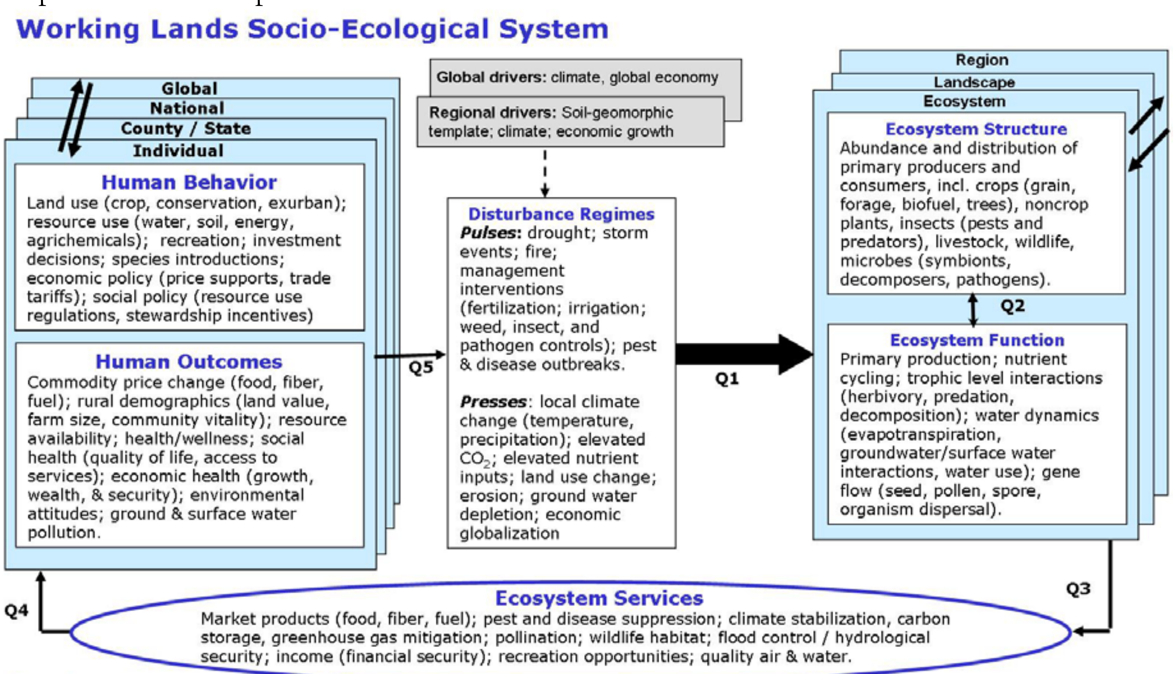
APPENDIX 2: EXAMPLES OF FEEDBACK LOOPS

Example 1. A large proportion of the U.S. population lives within 50 km of a coastline, and ecosystems in these regions are subject to a variety of unique press and pulse dynamics. In southeast Florida, for example, hurricanes, large-scale climate oscillations, and water management for flood control and water supply are pulse events that occur within a matrix of long-term press dynamics that include sea-level rise and chronic nutrient inputs from upstream agricultural and urban landscapes. These disturbances combine to affect the biotic composition of estuaries and coastal marine systems by changing vascular plant communities, benthic algal assemblages, and higher level trophic groups such as zooplankton, fish, and birds. In turn, the ability of coastal ecosystems to provide key services such as flood control, quality water, carbon sequestration, pest and disease suppression, and aesthetics and recreation are affected. Humans respond to changes in these services in a variety of ways. Changes in land values and insurance premiums affect economic vitality, as do opportunities for recreation and tourism. Increasing flood and environmental health risks affect settlement patterns and demographic structure. These responses, together with resulting changes in legal frameworks and government policy, feed back and alter the vulnerability of human-natural coastal systems to pulse and press dynamics. Effective management of these landscapes, which are generally dominated by humans, requires a socio-ecological understanding of linkages as disparate as algal community dynamics, tourism, and climate oscillations.



Q1. Determine sources & timing of water, P delivery, & biogeochem. cycling to estuarine ecotone & disturbances that affect both.
Q2. Determine feedbacks between changing productivity (shorter term) and changing landscape flowpaths (longer term).
Q3. Determine surface water-groundwater interactions & flooding FX, & how changes in both alter purveyance of fresh water to humans (ecosystem service).
Q4. Cost-benefit type analysis of values of key ecosystem services (water supply, flood control, aesthetic & spiritual, recreation, etc) and their tradeoffs; determine the politics of environmental decision-making.
Q5. Examine restoration in response to press & pulse disturbances on both natural and human systems.
Q5. Link human interventions & activities to local water cycles (increased impervious surface leads to decreased aquifer recharge).

Example 2. About 65% of the total U.S. land base is actively managed for human consumption: farmland, rangeland, and forests provide food, fiber, and fuel for rural economies that are undergoing steady change in response to globalization, emerging biofuel markets, and exurbanization pressures. On top of these long-term press dynamics are more pulsed events such as droughts, storms, invasive pest and disease outbreaks, and fire. All of these disturbances affect the structure and function of managed ecosystems at local, landscape, and regional scales: the abundance and distribution of primary producers that include field crops, forage, trees, and invasive weeds; the dynamics of consumers that include livestock, insects, and the predators and pathogens that prey on them; and subsequent effects on ecosystem processes such as nutrient loss, energy flow, carbon capture, and water availability. Ecosystem services follow – market products and economic security, pest and disease suppression, greenhouse gas mitigation, pollination, high-quality groundwater, wildlife diversity, flood control, and aesthetic and cultural amenities such as open space and rural quality-of-life issues are but a few. How these services are perceived and valued has a huge impact on human behavior. Changes in market prices affect land values and how society uses land. Changes in aesthetic and cultural amenities affect rural demographics, community vitality, and land ownership patterns. Investment decisions and species introductions follow from environmental attitudes and resource availability. All of these decisions and behaviors aggregate at larger scales and circle back to affect disturbance regimes: for example, land use and the types of crops that are grown affect management interventions, the intensity of fertilizer and pesticide use, and even global climate. Understanding the whole picture requires a transdisciplinary effort carried out in a variety of working landscapes at long temporal and broad spatial scales.



Questions

Q1. How does intensive management (introduced species, subsidized resources, pest & fire protection) interact with the long-term press regime to affect biotic structure and ecosystem function? Do long-term presses affect potential ecosystem responses to intentional or unintentional pulses?

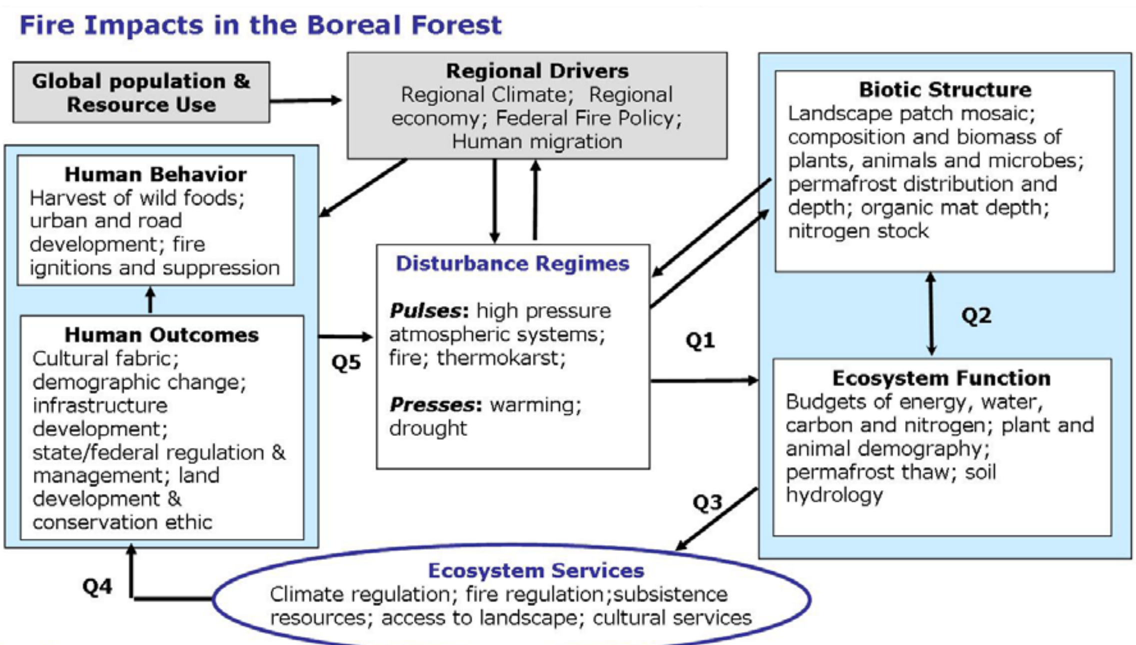
Q2. What are the indirect effects of intentional management (e.g. introduced species and accelerated decomposition and biomass removal) on plant, microbial, insect, and vertebrate populations and the ecosystem functions that they mediate?

Q3. As ecosystem functions change due to press and pulse events, how are ecosystem services affected – what are the relative tradeoffs in the magnitude of services?

Q4. How do changes in the valuation of services influence human outcomes such as market and policy behavior, rural demographics, resource availability, personal and community health and well-being, environmental attitudes, and economic growth, wealth, and security?

Q5. How do social structural, institutional, and economic factors affect human decisions about ecosystem management.

Example 3. Ecosystems at northern latitudes cover vast areas at severe risk of climate change: as northern regions warm disproportionately, they become differentially sensitive to press and pulse events, with implications for regions both local and distant. In the boreal forest region of interior Alaska, for example, long-term warming and changes in precipitation create a press regime. Within that regime, pulses such as fires and land development interact to dramatically affect ecosystem structure and function. Changes in water tables and the extent of wetlands and ponds affect forest and wetland plant communities, consumers and predators that live within them, and microbes, all of which result in changes to primary productivity; water flux; and the cycling of nitrogen, phosphorus, and even trace metals such as mercury. These changes have broad consequences for the services provided by the boreal forest. The loss of soil surface stability affects access to land and transportation corridors; the lowered water table makes surface vegetation more flammable; and climate stability is affected by the transfer of tree and soil carbon pools to atmospheric CO_2 and by increased methane fluxes. Changes in these services in turn affect human behaviors and outcomes. Infrastructure development is hindered, affecting settlement patterns and economic health, and changes in tree species composition and fire frequencies affect wildlife habitat and dependent cultural and recreational activities such as hunting and fishing. These activities together can circle back to affect the disturbance regimes: long-term climate feedbacks, human settlement, and resource extraction, in particular. Without an understanding of the socio-ecological linkages in these landscapes, it will be extremely difficult to predict the environmental impacts of human decisions on local landscapes or to understand how environmental change in northern latitudes will have rippling effects to other latitudes—and even more difficult to craft lasting solutions.



Questions:

Q1: How do long-term trends in climate and fire regime interact to alter the boreal forest of Interior Alaska and to feedback to the climate system?

Q2: How are feedbacks between landscape and stand structure (biotic composition, permafrost, soils) and functioning (ecosystem budgets, demographic processes, permafrost/soil dynamics) affected by climate warming & changing fire regime?

Q3: How do ecological changes caused by altered climate and fire regime affect climate and fire regulation by landscapes and the supply of subsistence and cultural resources to local residents?

Q4: How will the human population of Interior Alaska respond to recent and projected changes in fire regime and subsistence and cultural services?

Q5: How do humans decisions and actions affect the fire regime of Interior Alaska?

LITERATURE CITED

Atkins, D., K. Kroegemeier, S. Feldman, H. Garcia-Molina, M. Klein, D.G. Messerschmitt, P. Messina, J.P. Ostriker and M.H. Wright. 2003. Revolutionizing science and engineering through cyberinfrastructure: report of the National Science Foundation Blue-Ribbon Advisory Panel on Cyberinfrasturcuture. Arlington, VA: National Science Foundation. (viewed February 2007).

Balmford, A. and W. Bond. 2005. Trends in the state of nature and their implications for human well-being. *Ecology Letters* **8**: 1218-1234.

Bauer, K.W. and J.S. Bennett. 2003. Alumni perceptions used to assess undergraduate research experience. *The Journal of Higher Education* **74**: 210-230.

Bender, E.A., T.J. Case and M.E. Gilpin. 1984. Perturbation experiments in community ecology: theory and practice. *Ecology* **65**: 1-13.

Briggs, J.M., K.A. Spielman, H. Schaafsma, K.W. Kintigh, M. Kruse, K. Morehouse and K. Schollmeyer. 2006. Why ecology needs archaeologists and archaeology needs ecologists. *Frontiers in Ecology and the Environment* **4**: 180-188.

Brohan, P., J.J. Kennedy, I. Haris, S.F.B. Tett and P.D. Jones. 2006. Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850. *Journal of Geophysical Research* **111**: D12106. DOI:10.1029/2005JD006548 (viewed February 2007)

Brown, D.G., K.M. Johnson, T.R. Loveland and D.M. Theobald. 2005. Rural land-use trends in the conterminous United States, 1950-2000. *Ecological Applications* **15**: 1851-1863.

Carpenter, S.R., R. DeFries, T. Dietz, H.A. Mooney, S. Polasky, W.V. Reid and R.J. Scholes. 2006a. Critical research needs revealed by the Millennium Ecosystem Assessment. Unpublished manuscript.

Carpenter, S.R. and C. Folke. 2006. Ecology for transformation. *Trends in Ecology and Evolution* **21**: 309-315.

Carpenter, S.R., R.C. Lathrop, P. Nowak, E.M. Bennett, T. Reed and P.A. Saranno. 2006b. The ongoing experiment: restoration of Lake Mendota and its watershed. Pp. 236-256 in J.J. Magnuson, T.K. Kratz and B.J. Benson, Editors. Long-term dynamics of lakes in the landscape. Oxford Univ. Press, London, UK.

Chapman, S. 1959. IGY: Year of Discovery; the Story of the International Geophysical Year. University of Michigan Press, Ann Arbor, MI.

Clark, J.K., R.McChesney, D.K. Munroe and E.G. Irwin. 2005. Spatial characteristics of exurban settlement pattern in the U.S. 52nd Annual North American Meetings of the Regional Science Association, Las Vegas, NV.

Cohen, J.J. 2003. Human population: The next half century. *Science* **302**: 1172-1175.

Committee on Science, Engineering and Public Policy (COSEPUP). 2005. Rising above the gathering storm: energizing and employing America for a brighter economic future. National Academies Press. Washington, DC.

Daily, G. C. 1997. Valuing and safeguarding earth's life-support systems. Pages 365-375 *in* G. C. Daily, Editor. Nature’s services: societal dependence on natural ecosystems. Island Press, Washington, DC.

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

Dale, V., S. Archer, M. Chang and D. Ojima. 2005. Ecological impacts and mitigation strategies for rural land management. *Ecological Applications* **15**: 1879-1892.

De Groot, R.S. 1992. Functions of nature. Wolters-Nordhoof, the Netherlands.

Dietz, T., E.A. Rosa and R. York. 2007. Driving the human ecological footprint. *Frontiers in Ecology and the Environment* **5**: 13-18.

Ehrlich, P. and H.A. Mooney. 1983. Extinction, substitutions and ecosystem services. *BioScience* **33**: 248-254.

Ellison, A.M., L.L. Osterweil, J.L. Hadley, A. Wise, E. Boose, D.R. Foster, A. Hanson, D. Jensen, P. Kuzeja, E. Riseman H. Schultz. 2006. Analytic webs support the synthesis of ecological datasets. *Ecology* **87**:1345–58.

Fegraus, E., S. Andelman, M.B. Jones and M. Schildhauer. 2005. Maximizing the value of ecological data with structured metadata: an introduction to ecological metadata language (EML) and principles for metadata creation. *Bulletin of the Ecological Society of America* **7**: 158-168.

Galloway, J.N., J.D. Aber, J.W. Erisman, S.P.Seitzinger, R.W. Howarth, E.B. Cowling, B.J. Cosby. 2003. The nitrogen cascade. *BioScience* **53**: 341-356.

Golley, F.B. 1993. A history of the ecosystem concept in ecology: more than the sum of the parts. Yale Univ. Press, New Haven, CT.

Green, J.L., A. Hastings, P. Arzberger, F.J. Ayala, K.L. Cottingham, K. Cuddington, F. Davis, J.A. Dunne, M.-J. Fortin, L Gerber and M. Neubert. 2005. Complexity in ecology and conservation: mathematical, statistical and computational challenges. *BioScience* **55**: 501-510.

Grimm, N.B., J.M. Grove, S.T.A. Pickett and C.L. Redman. 2000. Integrated approaches to long-term studies of urban ecological systems. *BioScience* **50**: 571-584.

Haberl, H., V. Winiwarter, K. Andersson, R. U. Ayres, C. Boone, A. Castillo, G. Cunfer, M. Fischer-Kowalski, W. R. Freudenburg, E. Furman, R. Kaufmann, F. Krausmann, E. Langthaler, H. Lotze-Campen, M. Mirtl, C. L. Redman, A. Reenberg, A. Wardell, B. Warr, and H. Zechmeister 2006. From LTER to LTSER: conceptualizing the socioeconomic dimension of long-term socioecological research. *Ecology and Society* **11**: URL: http://www.ecologyandsociety.org/vol11/iss2/art13/ (viewed February 2007).

Hansen, A.J. and D.G. Brown. 2005. Special Feature: Land-use change in rural America: rates, drivers and consequences. *Ecological Applications* **15**: 1849-1850.

Hansen, A.J., R.L. Knight, J.M. Marzluff, S. Powell, K. Brown, P.H. Gude and K. Jones. 2005. Effects of exurban development on biodiversity: patterns, mechanisms and research needs. *Ecological Applications* **15**: 1893-1905.

Houghton, J.T., Y. Ding, D.J. Griggs, N. Nogeur, P.J. van der Linden, X. Dei, K. Maskell and C.A. Johnson. 2001. Climate change 2001: the scientific basis. Cambridge University Press, Cambridge, UK.

Huston, M.A. 2005. The three phases of land-use change: implications for biodiversity. *Ecological Applications* **15**: 1864-1878.

IPCC 2007. Climate change 2007: the physical science basis. Summary for policy makers. IPCC Secretariat, Geneva, Switzerland.

Jansson, A.-M., M. Hammer, C. Folke and R. Costanza, Editors. 1994. Investing in natural capital: the ecological economics approach to sustainability. Island Press, Washington DC.

Jones, M.B., M.P. Schildhauer, O.J. Reichman and S. Bowers. 2006. The new bioinformatics: integrating ecological data from the gene to the biosphere. *Annual Review of Ecology, Evolution and Systematics* **37**: 519-544.

Kardash, C.M. 2000. Evaluation of an undergraduate research experience: perceptions of undergraduate interns and their faculty mentors. *Journal of Educational Psychology* **92**: 191-201.

Kemp, M. 2005. Science in culture: inventing an icon. *Nature* **437**: 1238.

Kremen, C. and R.S. Ostfeld. 2005. A call to ecologists: measuring, analyzing and managing ecosystem services. *Frontiers in Ecology and the Environment* **3**: 540-548.

Krishtalka, L. 2002. Long-term Ecological Research Program twenty-year review. Report to the National Science Foundation.

Liu, J., G.C. Daily, P.R. Ehrlich, and G.W. Luck. 2003. Effects of household dynamics on resource consumption and biodiversity. *Nature* **421**: 530-533.

Lopatto, D. 2004. What undergraduate research can tell us on research on learning. *Project Kaleidoscope* **4**:1-8.

Lubchenco, J., A.M. Olsen, L.B. Brubaker, S.R. Carpenter, M.M. Holland, S.P. Hubbell, S.A. Levin, J.A. MacMahon, P.A. Matson, J.M. Mellilo, H.A. Mooney, C.H. Peterson, H.R. Pulliam, L.A. Real, P.J. Regal and P.G. Risser. 1991. The sustainable biosphere initiative: an ecological research agenda. *Ecology* **72**: 371-412.

Lutz, W., W. Sanderson and S. Scherbov. 2001. The end of world population growth. *Nature* **412**: 543-545.

Magnuson, J.J., T.K. Kratz, and B.J. Benson 2006. Long-term dynamics of lakes in the landscape: long-term ecological research on north temperate lakes. Oxford University Press, London, UK.

Mann, M.E., R.S. Bradley and M.K. Hughes. 1998. Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* **392**: 779-787.

Mann, M.E., R.S. Bradley and M.K. Hughes. 1999. Northern hemisphere temperatures during the past Millennium: inferences, uncertainties, and limitations. *Geophysical Research Letters* **26**: 759–762.

Millennium Ecosystem Assessment (MEA). 2003. Ecosystems and human well-being – a framework for assessment. Island Press, Washington DC.

Millennium Ecosystem Assessment (MEA). 2005a. Ecosystems and human well-being: current state and trends. Island Press, Washington DC.

Millennium Ecosystem Assessment (MEA). 2005b. Ecosystems and human well-being: scenarios. Island Press, Washington DC.

Millennium Ecosystem Assessment (MEA). 2005c.Ecosystems and human well-being: synthesis. Island Press, Washington, DC.

McIntosh, R.P. 1985. The background of ecology. Cambridge University Press, Cambridge, UK.

Mooney, H.A 1998. The globalization of ecological thought. Ecology Institute, Oldendorf/Luhe, Germany.

National Academy of Sciences (NAS) 2007.The international geophysical year. http://www7.nationalacademies.org/archives/igyhistory.html. (viewed February 2007).

National Research Council (NRC) 1999. Our common journey. National Academies Press, Washington, DC.

National Research Council (NRC) 2001. Grand challenges in environmental sciences. National Academies Press, Washington, DC.

National Research Council (NRC) 2002. The drama of the commons. National Academies Press, Washington, DC.

National Research Council (NRC) 2003. NEON: addressing the nation's environmental challenges. National Academies Press, Washington, DC.

National Science Foundation (NSF) 2000. Environmental science and engineering for the 21st Century. http://www.nsf.gov/pubs/2000/nsb0022/reports/nsb0022. pdf. (viewed February 2007).

National Science Foundation (NSF) 2003. Complex environmental systems: synthesis for earth, life, and society in the 21st Century. http://www.nsf.gov/geo/ere/ereweb/index.cfm

Ortega, S., A. Flecker, K. Hoffman, L. Jablonski, J. Johnson-White, M. Jurgenson-Armstrong, R. Kimmerer, M. Poston, A. Socha, J. Taylor. 2006. Women and minorities in ecology II (WAMIE II) Report. Ecological Society of America, Washington, DC.

Palmer, M.A., E. Bernhardt, E. Chornesky, S.L. Collins, A. Dobson, C. Duke, B. Gold, R. Jacobson, S. Kingsland, R. Kranz, M. Mappin, F. Micheli, J. Morse, M. Pace, M. Pascual, S. Palumbi, J. Reichman, W.H. Schlesinger, A. Townsend, M. Turner, and M. Vasquez. 2004. Ecology for a crowded planet. *Science* **304**: 1251-1252.

Palmer, M.A., E. Bernhardt, E. Chornesky, S.L. Collins, A. Dobson, C. Duke, B. Gold, R. Jacobson, S. Kingsland, R. Kranz, M. Mappin, F. Micheli, J. Morse, M. Pace, M. Pascual, S. Palumbi, J. Reichman, W.H. Schlesinger, A. Townsend, M. Turner, and M. Vasquez. 2005. Ecology for the 21st Century: An action plan. *Frontiers in Ecology and the Environment* **3**: 4-11.

Pickett, S.T.A., M.L. Cadenasso and J.M. Grove. 2005. Biocomplexity in coupled natural-human systems: a multidimensional framework. *Ecosystems* **8**: 225-232.

Pickett, S.T.A., M.L. Cadenasso, J.M. Grove, C.H. Nilon, R.V. Pouyat, W.C. Zipperer, R. Constanza. 2001. Urban ecological systems: linking terrestrial ecological, physical and socioeconomic components of metropolitan areas. *Annual Review of Ecology and Systematics* **32**: 127-157.

Pickett, S.T.A. and P.S. White. 1985. The ecology of natural disturbance and patch dynamics. Academic Press, New York, NY.

Rahm, J., H.C. Miller, L. Hartley and J.C. Moore. 2003. The value of an emergent notion of authenticity: examples from two student/teacher-scientist partnership programs. *Journal of Research in Science Teaching* **40**: 737-756.

Rahm, J., M-P Reny, and J.C. Moore. 2005. The role of after-school and summer science programs in the lives of urban youth. *School Science and Mathematics* **105**: 1-9.

Robertson, G.P., J.C. Broome, E.A. Chornesky, J.R. Frankenberger, P. Johnson, M. Lipson, J.A. Miranowski, E.D. Owens, D. Pimentel, and L.A. Thrupp. 2004. Rethinking the vision for environmental research in U.S. agriculture. *BioScience* **54**: 61-65.

Russell, A. 2005. Strengthening the science and mathematics pipeline for a better America. American Association of State Colleges and Universities 2: Nov./Dec. 2005.

Schiermeier, Q. 2006. The costs of global warming. *Nature* **439**: 374-375.

Seymour, E., A.B. Hunter, S.L. Laursen and T. DeAntoni. 2004. Establishing the benefits of research experiences for undergraduates in the sciences: first findings from a three-year study. *Science Education* **88**: 493-534.

Schlesinger, W.H. 1997. Biogeochemistry: an analysis of global change, 2nd Edition. Academic Press, San Diego, CA.

Schlesinger, W.H. 2006. Global change ecology. *Trends in Ecology and Evolution* **21**: 348-351.

Siegenthaler, U., T.F. Stocker, E. Monnin, D. Lüthi, J. Schwander, B. Stauffer, D. Raynaud, J.-M. Barnola, H. Fischer, V. Masson-Delmotte and J. Jouzel. 2005. Stable carbon cycle-climate relationship during the late Pleistocene. *Science* **310**: 1313 – 1317.

Sills, D.L. and R.K. Merton. 1968. International encyclopedia of the social sciences. Free Press, New York, NY.

Singleton, R.A. and B.C. Straits. 2005. Approaches to social research. Oxford University Press, Oxford, UK.

Smelser, N.J. and P.B. Baltes. 2001. International encyclopedia of social and behavioral sciences. Elsevier, Amsterdam, The Netherlands.

Smith, M.D., A.K. Knapp and S.L. Collins. 2007. Global change and chronic resource alterations: moving beyond disturbance as a primary driver of contemporary ecological dynamics. *Ecology Letters*: submitted.

Steffen, W., A. Sanderson, J. Jäger, P.D. Tyson, B. Moore III, P.A. Matson, K Richardson, F. Oldfield, H.-J.Schellnhuber, B.L. Turner II and R.J. Wasson. 2004. Global change and the Earth system: a planet under pressure. Springer-Verlag, New York, NY.

Spahni, R., J. Chappellaz, T.F. Stocker, L. Loulergue, G. Hausammann, K. Kawamura, J. Flückiger, J. Schwander, D. Raynaud, V. Masson-Delmotte, J. Jouzel. 2005. Atmospheric methane and nitrous oxide of the late Pleistocene from Antarctic ice cores. *Science* **310**: 1317-1321.

Tilman D, J Fargione, B Wolff, C D'Antonio, A Dobson, R Howarth, D Schindler, W Schlesinger, D Simberloff, and D Swackhamer. 2001. Forecasting agriculturally driven global environmental change. *Science* **292**: 281-284.

Vitousek, P.M., H.A. Mooney, J. Lubchenco and J.M. Melillo. 1997. Human domination of Earth's ecosystems. *Science* **277**: 494-499.

Wu, J. and O.L. Loucks. 1995. From balance of nature to hierarchical patch dynamics: a paradigm shift in ecology. *Quarterly Review of Biology* **70**: 439-466.