The Decadal Plan for LTER

Integrative Science for Society and the Environment:

A Plan for Research, Education, and Cyberinfrastructure in the U.S. Long Term Ecological Research Network

The U.S. Long Term Ecological Research Network
October 1, 2007

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I. Executive Summary

The US LTER Network approaches its fourth decade with a remarkable record of scientific achievement in the ecological sciences. At each of the Network's 26 sites we know an extraordinary amount about the organisms and processes important at the site, about the way the site's ecosystems respond to disturbance, and about long-term environmental change. A growing number of cross-site observations and experiments is also revealing much about the way that key processes, organisms, and ecological attributes are organized and behave across major environmental gradients. In total, research in the LTER portfolio is contributing substantially to both our basic knowledge of ecological interactions and our ability to forecast change and to test ecological theory.

Against this backdrop the Network is poised to undertake a new kind of transdisciplinary science – one that ranges from local to global in scope, and that blends ecological and social science theories, methods, and interpretations in order to better understand and forecast environmental change in an era when no ecosystem on Earth is free from human influence. *Integrative Science for Society and the Environment,* prepared by the Network and delivered to NSF in February 2007 (and reprinted below as Section VII), describes a unifying framework in which we seek to understand how humans perceive the critical services provided by ecosystems at multiple human scales, how these perceptions change behavior and institutions, and how these changes in turn feed back to affect ecosystem structure and function and the ability of ecosystems to continue to deliver services over the long term.

Described in our Integrated Research Plan (Section II) are a set of research themes we propose to pursue over the next decade and beyond. Land and water use change; climate change, variability, and extreme events; and nutrient mobilization and species introductions all are considered grand challenges in environmental science and all are important to society. They also affect every site in the Network – indeed, every part of the U.S. – and are intractable without full consideration of social-ecological interactions. These particular themes are also among those that best match the research strengths of the Network. We propose to address them with new long-term datasets, cross-site experiments, and modeling activities described here in general; details will be more fully defined in follow-on workshops.

Underpinning our research plan are a comprehensive summary of existing long-term datasets (Section III) along with detailed blueprints for the education and cyberinfrastructure resources that will be crucial for its success. We also have a new governance structure that will enable the Network to efficiently carry out an undertaking of this magnitude. The education (Section IV) and cyberinfrastructure (Section V) plans are strategic: each identifies a series of 6-8 long-term goals that will position us for new challenges and opportunities. Among our long-term education goals are initiatives to build site- and Network-level capacities for education leadership, to conduct basic research in social-ecological science literacy, to build a more diverse environmental science workforce trained to undertake transdisciplinary research, and to work with K-12 teachers and administrators, undergraduates and professors, and citizens and leaders to influence local and national science learning. Our cyberinfrastructure plans include building capacities to increase data acquisition, management, and curation at the site level; to increase data discovery, access, and integration at the Network level; to increase modeling and analysis activities; and to integrate cyberinfrastructure into social-ecological research, education, and training. Our new Network governance structure (Section VI) vests decision-making authority in a 12-member Executive Board, which reports to the 56-member Science Council. Both are led by the same chair, elected for a 2-year term.

The efforts of hundreds of scientists from the geophysical, biological, and social sciences and many meetings and workshops over the course of three years went into the creation of these plans. Scientists, educators, and specialists in information technology from within and outside the LTER Network participated. All share the common vision that progress in solving environmental problems that today seem intractable depends upon fundamental, long-term, integrated research that will generate a synthetic understanding of highly dynamic social-ecological systems.

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The Decadal Plan for LTER

The U.S. Long-Term Ecological Research Network

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LTER Integrated Research Plan

The U.S. Long-Term Ecological Research Network
October 1, 2007

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1.0 Summary

The need for research that integrates the ecological and social sciences has never been greater. Fundamental questions related to the services that society receives from ecosystems, how these services are perceived, how perceptions affect behavior, and how behavioral change affects ecosystem form and function are central to understanding the sustainability of ecosystems on which society depends. The Long-term Ecological Research (LTER) Network is uniquely poised to address these questions for a variety of reasons related to their long-term nature, the geographic distribution of network sites, the core strength of the Network's biophysical science, the Network's considerable and growing strength in the area of coupled natural-human systems, and its commitment to K-20 education and leadership in environmental cyberinfrastructure.

In this plan, we lay out a program for integrated, network-level research for the next decade of LTER science. Our plan addresses crucial, long-term, social-ecological questions that we are well positioned to address in each of three thematic areas: (1) land and water use change — the dynamics of urban, exurban, and working systems; (2) climate change, variability, and extreme events; and (3) nutrient mobilization and species introductions. Our questions are long-term and transdisciplinary, developed over the past three years by teams of biophysical and social scientists, educators, and information managers. Our questions are also multiscale, requiring observations and experiments at multiple sites to test hypotheses at scales ranging from the regional to the continental. To effectively address these questions requires new long-term social-ecological observations, experiments, and modeling activities. Additionally, advanced environmental cyberinfrastructure will be needed to collect, store, retrieve, visualize, and integrate complex data streams. Partnerships with other environmental observatory networks will be essential to achieve this integration and facilitate synthesis. Also required are educational initiatives to train the next generation of environmental scientists to address transdisciplinary issues, and to inform a public for which environmental literacy is becoming ever more necessary.

This document articulates the important questions and general approaches necessary to address them. More specific details will result from all-site science, education, and cyberinfrastructure workshops designed to identify individual questions, observations, experiments, and modeling activities within thematic areas, and to identify the corresponding education and cyberinfrastructure needs for this new transdisciplinary research initiative.

2.0 Introduction

More than ever before, society is in need of fundamental research that transcends the ecological and social sciences. To meet the need for a sustainable future requires basic knowledge of the ways that human activities affect the ecosystems upon which we depend, of concomitant effects on the delivery of the services that these ecosystems provide, and of how we perceive and respond to alterations in these services. Especially as environmental change approaches tipping points or nonlinear thresholds, the need to anticipate and mitigate future change is acute.

In particular, integrative research is required that is long-term. Many ecological and social processes change over variable time intervals, exhibit transient behaviors that are difficult to predict from recent behavior, and change in subtle but important ways that are hard to detect without long baselines that reveal trends and dynamics. And a decade of short-term research in coupled natural-human systems reveals that ecological and social processes interact in sometimes surprising ways (Liu et al. 2007). Recent advances in sustainability science, and in particular the growing recognition that human vulnerability to change resides in the sensitivity and resilience of coupled natural-human systems (Turner et al. 2003), underscore the need to examine these systems under different environmental stresses over various time periods, and to understand the implications of long-term change, short-term perturbations, and their interactions.

The LTER Network is uniquely positioned to address this need. A 25-year history of place-based ecological research at 26 sites provides a deep understanding of major ecosystems across the North American continent and beyond (Fig. 2.1; Hobbie et al. 2003, and see Appendix B for a list of site science monographs). A demonstrated and growing commitment to the incorporation of social science into basic questions about ecosystem behavior provides fertile ground for transdisciplinary collaborations (e.g. Carpenter et al. 2007) and meets a growing need among a number of science programs and platforms (Vajjhala et al. 2007). An ongoing commitment to long-term observations, experiments, data curation, and modeling (Appendix C) is unparalleled in ecological science. Leadership in environmental cyberinfrastructure (e.g. Porter et al. 2005, Collins et al. 2006) is providing innovative solutions to challenges in environmental information management. The Network's involvement in K-12, undergraduate, and graduate education and public outreach provides a foundation for training the next generation of environmental scientists in transdisciplinary research and for informing a public increasingly asked to make complex environmental decisions.

Figure 2.1. The LTER Network in 2007. The 26 sites are listed in Appendix A and described in detail at www.lternet.edu *Inserts denote Antarctica and the South Pacific.*

We believe the time is right to build on our substantial capacity to investigate important ecological questions to incorporate important, cutting-edge social-ecological research. We describe the basic framework for this research in the Integrative Science for Society and the Environment (ISSE) initiative. ISSE, delivered to NSF in February 2007 and described below, lays out a framework for addressing compelling long-term questions in coupled natural-human systems. It draws heavily on the need to fully engage social scientists in the pursuit of these questions, and provides an integrated, social-ecological framework in which social-ecological questions can be logically and rigorously addressed.

The research plan described here derives directly from the ISSE and builds on our foundational strength in ecology. In this plan we identify major questions and general approaches. In the section that follows we establish the conceptual and theoretical framework for the plan. In Section 4, we lay out the network-level research themes to be addressed. These themes derive from a series of workshops that involved hundreds of scientists: (1) land and water use change — the dynamics of urban, exurban, and working systems (those that provide provisioning services such as food and fiber); (2) climate change, variability, and extreme events; and (3) nutrient mobilization and species introductions. These topics represent well-recognized grand challenges in environmental research (NRC 2001). To address them effectively will require new long-term transdisciplinary observations, experiments, and models across many sites.

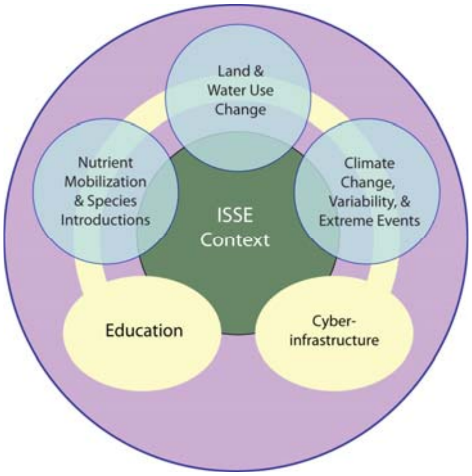

Figure 2.2. Relationship among major components of Network-level science. Integrated research questions within each of three thematic areas are underlain by education and cyberinfrastructure, and all lie within the social-ecological context of Integrated Science for Society and the Environment (ISSE; Collins et al. 2007).

Because education and information flow are integral to the mission of LTER, research, education and cyberinfrastructure are integrated closely in our science plan (Fig. 2.2). Education is both part of our research approach – environmental literacy shapes people's attitudes toward ecosystem services and motivates behaviors that directly and indirectly influence ecosystems – and educating the public, decision makers, and the next generation of environmental scientists is a core Network activity. We describe proposed activities in this domain in Section 5.1.

We additionally propose major improvements in cyberinfrastructure (Section 5.2): the acquisition, delivery, curation, and integration of environmental information, both data and models, are also central to the success of this plan and require separate articulation. Finally, at its core our plan depends on a level of integration across biophysical and social sciences not often proposed and more rarely achieved. Transdisciplinarity at this scale is new, and justified more thoroughly in Section 5.3, followed by a call for capacity building in Section 5.4, and a description of how the LTER Network will interact with other environmental observatories (Section 5.5).

We expect this plan — pending available resources — to stimulate a unique, synthetic, interdisciplinary and multi-site research agenda for the LTER Network during the coming decade and beyond. Detailed plans to carry out this agenda will result from all-site science, education, and cyberinfrastructure workshops (Section 6) that will result in integrated, collaborative research proposals to identify the specific set of observations, experiments, and modeling activities required to address our major thematic questions.

3.0 Conceptual Framework and Theoretical Foundations

As ecology expands from site-based science to regional and global scales, our conceptual scope must also expand to embrace not only climate, geology, hydrology, and soils, but also the increasingly pervasive human dimensions of ecological change. Every ecosystem on earth is influenced by human actions (Palmer et al. 2004), and the rate of change in social and ecological drivers is increasing (Fig 3.1). The environment must now be viewed as a social-ecological system.

Over the past 50 years, people have changed ecosystems more than at any time in human history (Vitousek et al. 1997, Chapin et al. 2000), with substantial consequences for human well-being (MA 2005). Consequences of these ecosystem changes for people have been mixed. Health and wealth have, on average, improved. Yet the geographic distribution of benefits remains extremely uneven and further improvements are often limited by insufficiencies of ecosystem services (MA 2005). Feedbacks between ecosystems and people are thus central for improving human well-being, yet these feedbacks are poorly understood and thus form a challenge for fundamental research in natural and social sciences.

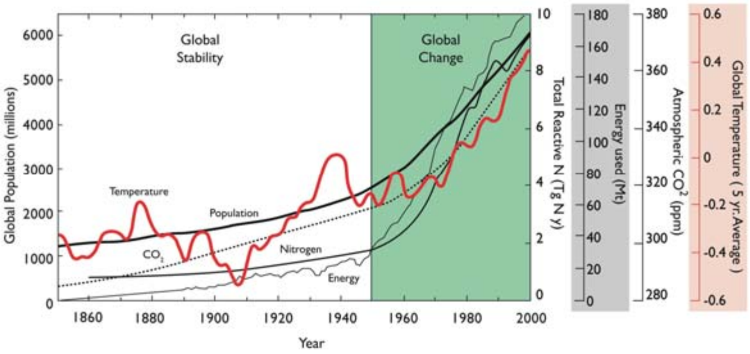

Figure 3.1. Rates of change in major social and ecological drivers: human population, atmospheric CO_2, reactive nitrogen, energy use, and temperature.

As the scope of social-ecological science has expanded, interdisciplinary linkages have evolved. Important advances were initially driven by the International Council of Scientific Unions (ICSU) through the International Geosphere-Biosphere Program (IGBP) and the International Human Dimensions Program (IHDP) (Mooney 1998, Steffen et al. 2004, Schlesinger 2006, Carpenter and Folke 2006). Collaborations among physical scientists and biologists have occurred since the beginnings of regional and global science, whereas collaborations among ecologists and social scientists are more recent and largely confined to applied sciences such as agriculture and forestry. Studies of ecosystem services formed the core of the Millennium Ecosystem Assessment (MA 2005), the first interdisciplinary global assessment of ecosystems requested by the world's decision makers. Meanwhile, in basic research, advances were driven by coalitions in ecology and economics (Mooney and Ehrlich 1997, Goulder and Kennedy 1997), the need to understand how institutions and economies solve common property resource problems (Ostrom 1990, NRC 1999, 2002, Dietz et al. 2003), advances in economic incentive design theory (Hahn 2000), and studies of the resilience of regional social-ecological systems (Gunderson and Holling 2002, Walker and Salt 2006). Liu et al. (2007) illustrate in a new review the diversity of approaches that have been taken to site-based research on social-ecological systems. Yet, they also pointedly note the enormous gaps in social-ecological research, the need for new theory, and the need for a better integration of conceptual and empirical research across a diverse set of approaches.

New research must focus on understanding the long-term dynamic processes that are unique to social-ecological systems versus purely social or purely biophysical systems. Ecosystems self-organize from evolved components; interactions of slow processes with fast ones, and big processes with small ones, create much of the pattern and dynamics that we observe (Levin 1999). Social systems also self-organize, change, and exhibit process scale-dependencies, but human self-awareness allows people to affect and direct system dynamics in ways qualitatively distinct from those that characterize the evolution of ecosystem components (Gibson et al. 2000, Arthur et al. 1997, Westley et al. 2002, Bettencourt et al. 2007). For example, people make forward-looking decisions (they act on expectations of the future), they generate and respond to abstract constructs that shape their world views and expectations, they create feedbacks that act on fast time scales over broad spatial extents, and they develop technology with far-reaching consequences (Westley et al. 2002). These consequences drive feedbacks not only on social systems but on the ecosystems in which they are embedded — in many cases across broad geographic extents and with long-lasting legacies. Because of these complex, nonlinear interactions and feedbacks, a new mechanistic research framework is needed that integrates the internal and interactive dynamics of social and natural systems.

Social and natural systems are deeply interwoven and their dynamics are inherently long-term. Liu et al. (2007) note that social-ecological systems exhibit nonlinear dynamics with thresholds, reciprocal feedback loops, time lags, resilience, heterogeneity, and, above all, surprises. We are now beginning to see some of the emerging trends and surprises that are important for human well-being, but we are a long way from understanding, predicting, and managing them. A combination of theory development and place-based, cross-scale, long-term research that harmonizes diverse disciplinary perspectives is needed to develop understanding and build the capacity to sustainably manage social-ecological systems. Work at regional scales is particularly needed. Ecology has made great strides in understanding place-based change (e.g. Peters et al. 2007), and the field of global ecology is advancing rapidly (MA 2005). Progress has been slower at the intermediate scale of regions, areas larger than most study sites but smaller than continents or oceans. Yet ecosystem change is often most conspicuous at regional scales, and environmental management frequently acts on regions.

Most drivers of social-ecological changes can be characterized as press or pulse events (Ives and Carpenter 2007). *Presses* are environmental impacts driven by constantly increasing pressures on atmospheric, ecological, and social 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. As a consequence, through human actions and decisions, biophysical systems are being decoupled from traditional drivers such as 100-year fire cycles or slow biogeochemical change (Smith et al. *in revision*). This decoupling has important consequences for human social systems. For example, the widespread increase in reactive nitrogen — a key limiting ecological resource — is a press that will dramatically affect ecosystem processes (Schlesinger 2006, Galloway et al. 2003, Liu et al. 2003). Changes in nitrogen loadings coupled with more intense climate pulses could lead to increased leaching of nitrate into groundwater and streams, loss of ecosystem services, and ultimately threats to human health.

Understanding change is the fundamental challenge of social-ecological science. Social-ecological systems can change incrementally and more or less predictably. Some of the most important routine changes (for example, forest succession or the business cycle) are reasonably well understood and incorporated into management practice. Other changes are large in magnitude, spatially extensive, and alter social-ecological systems for long time periods. Examples include evolution or extinction of keystone species, land-use change drivers such as major shifts in food and fuel prices, technological change and land use policy, or the collapse and reorganization of polities such as the former Soviet Union. Although large changes may account for most of the cumulative change we see, they are infrequent events. As a result, observations are few, individual cases may be unique, and our ability to generalize or predict may be severely limited. Understanding extensive, pervasive, and subtle change is therefore one of the most important challenges for social-ecological science.

3.1. An Integrated Research Framework

Scientists have increasingly called for more opportunities for social-ecological collaborations (Grimm et al. 2000, Palmer et al. 2004, Robertson et al. 2004, Newell 2005, Pickett et al. 2005, Kremen and Ostfeld 2005, Balmford and Bond 2005, Farber et al. 2006, Haberl et al. 2006, Liu et al. 2007, Vajjhala et al. 2007). Typically these calls describe case studies and provide general frameworks for why such research is needed, yet rarely do they propose viable, generalizable mechanisms for conducting truly integrated, large-scale, long-term research in human-environment systems. There thus remains a compelling need for a comprehensive conceptual framework that is built on relevant disciplinary research and at the same time emphasizes linkages among disciplines over the time frames and spatial scales at which social-ecological systems operate.

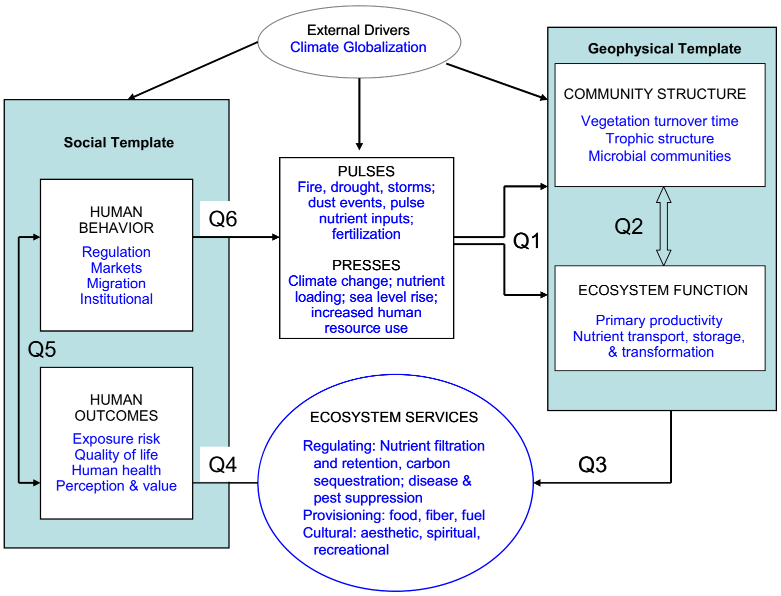

Figure 3.2 The ISSE framework provides the basis for our network-level research questions. The right-hand side represents the domain of traditional ecological research; the left-hand side represents human dimensions of environmental change; the two are linked by the services provided by ecosystems (at bottom), and by pulse and press disturbances influenced or caused by human behavior (at top). Q1-Q5 refer to integrating questions in Figure 3.3. From Collins et al. (2007).

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 alter human outcomes?

Q5: How do perceptions and outcomes affect human behavior?

Q6: Which human actions influence the frequency, magnitude, or form of press and pulse disturbance regimes across ecosystems, and what determines these human actions?

Figure 3.3. Framework questions; see Fig. 3.2.

Figure 3.2 presents the basic components of such a framework and forms the basis for the research we propose. The framework is iterative, with linkages and feedbacks between biophysical and social domains. It allows relevant disciplinary questions (Fig. 3.3) such as "How can biotic structure be both a cause and consequence of ecological fluxes of energy and matter?" as well as crucial integrative questions such as "How do changes in vital ecosystem services feed back to alter human behavior?" Interdisciplinary linkages arise from understanding both the value and importance of ecosystem services, and how human actions and responses affect their provisioning. In sum, the framework provides a set of falsifiable hypotheses on how social-ecological systems interact over time.

To be useful, a unifying framework must also be flexible in order to address questions across relevant scales. Our framework does so: all of the questions in Fig 3.3 can be operationalized locally, regionally, and globally to conduct fundamental research related to biophysical systems, ecosystem services, and human responses and outcomes. Testing the hypotheses embedded in this framework, as well as its further development, will rely on theoretical, empirical, and methodological contributions from the biophysical and social sciences. Application of the framework will contribute substantially to development and testing of theory within these disciplines and, more importantly, will help to build a transdisciplinary science of social-ecological systems.

Many of the essential empirical and methodological building blocks needed to advance such a transdisciplinary science are increasingly emerging, particularly within the LTER Network. Social scientists are employing progressively more biological facts to explain social variation (Grove and Burch 1997, Yabiku et al. 2007). Likewise, ecological and geological scientists are using social facts to understand biophysical variations over the long term (e.g., Hope et al. 2003). Social data are also increasingly spatially explicit (Irwin and Geoghegan, 2001), which permits testing and analysis of novel hypotheses that are spatially explicit, temporally contingent, and multi-scale. Eventually, the use of spatial data may lead to synthetic theories to understand phenomena as social-ecological composites. The inclusion of long-term data and analyses will move theory from correlations and associations to deep probing of multiple causations, simultaneity, slow and fast rates of change, and non-linearities.

A network-level, long-term integrated program based on this framework and emerging empirical and methodological building blocks, with fully shared intellectual partnerships among disciplines, will be unique and transformative for the environmental sciences. Such a program is essential to better understand, predict, and manage the dynamics of human-environmental systems, to generate shared data sets, and to reveal generality through synthesis.

4.0 Network-Level Science

There are many potential axes along which to group compelling questions related to the way that society interacts with the environment. All of the major environmental issues of our day, from climate change to species loss to biosphere eutrophication, influence and are influenced by these interactions, and all are expressed at most — if not all — LTER sites. We have identified three thematic areas that embrace key environmental issues facing society, areas that LTER sites and LTER science seem uniquely positioned to address: (1) land and water use change and, in particular, change that involves urban, exurban, and working systems; (2) climate change, variability, and extreme events; and (3) nutrient mobilization and species introductions. We intend that the plan be as inclusive as possible with respect to sites in the current network, and do not rule out the need to involve additional sites (see Section 5.4). Underlying and integrated with research at all sites are education and cyberinfrastructure support for the transdisciplinary science that forms the basic context for our research (Fig. 3.2).

4.1. Research Theme 1: Land and Water Use Change — the Dynamics of Urban, Exurban, and Working Systems

Human use of land and water systems is pervasive and extends back millennia across most of the globe. Modern scientific interest concerning this use centers on direct and indirect impacts on ecosystem structure and function, human responses to the resulting ecosystem changes, and ensuing consequences for the larger Earth system. Over the next decades, many of the most profound changes and greatest consequences for the global environment are expected to occur in association with urban and working ecosystems, including coastal and marine systems.

Aquatic and terrestrial ecosystems worldwide, including those forming the regional setting for LTER sites, are being reshaped by two major human activities: a) management for subsistence and market products and b) development for residential and commercial use. The underlying causes and ecological consequences of these activities, as well as their interactions and feedbacks, must be understood for society to anticipate, mitigate, and manage the environmental consequences of land and water management and development in the future.

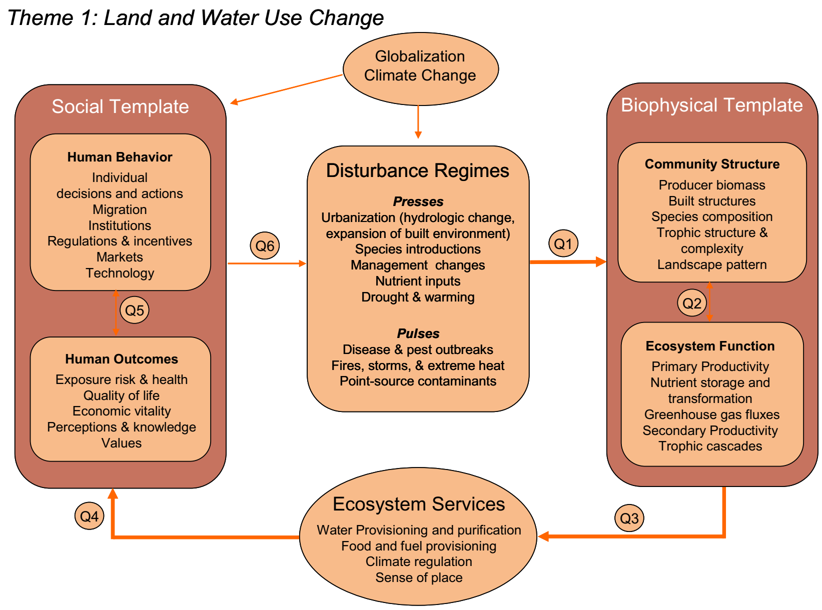

Figure 4.1. Conceptual framework for addressing land and water use change. Questions (Q1-Q6) refer to research questions in text. Q2 and Q5 are the domains of traditional ecological and social science research, respectively; our research concentrates on the feedbacks between ecosystem services and human-influenced press and pulse disturbances as affected by interactions within the social and biophysical templates.

Urban and working ecosystems are coupled social-ecological systems that are intentionally engineered by human activity for human benefit. We seek to investigate land and water dynamics in these ecosystems in relation to the cumulative and synergistic impacts of human–environment drivers (Fig. 4.1). Among working ecosystems we include those dominated by farming, ranching, fishing, and forestry — activities that generate provisioning ecosystem services. Among urban ecosystems we include the range of ecosystems strongly affected by human settlement and migration patterns, in particular, as important patterns in different regions of the US. **Our primary goal is to understand how human settlement patterns in urban ecosystems and their surroundings, and management activities in working systems, relate to and influence critical ecosystem services**. This understanding can then be used to forecast the dynamics and consequences of land and/or water use change at local, regional, and continental scales. Such a predictive capacity is essential for a wide range of social, economic, and environmental policymaking and management efforts at local to national levels.

Central questions guiding this research are adapted from the ISSE (Fig. 3.2) but are specific to urban, exurban, and working systems (Fig. 4.1):

- What is the pattern of land and water use change in urban and working systems: what are the temporal and spatial patterns of human activity and ecosystem dynamics in LTER regions (Q1)?
- How do ecosystems respond to disturbances that affect land and water use change in urban and working systems: how does land–water use change influence ecosystem structure and function and the delivery of ecosystem services at local, regional, and continental scales (Q1, Q2, Q3)?
- How do human activities cause change in working and urban systems and how does this change affect human activities: what are the causes of human activities that are linked to change in urban and working systems, and how do feedbacks from ecosystem change influence future causes (Q4, Q5, Q6)?
- How does effective knowledge exchange occur: how can public policy and private management decisions be informed by knowledge of the impacts of human settlement and management on ecosystem characteristics and services (Q5)?
- What are the causes of change in working and urban systems: by what mechanisms do humans directly or indirectly drive system dynamics (Q6)?

4.1.1. General Approach

The nature, pattern, pace, and ecological and societal consequences of land and water use change will vary on local, regional, and continental scales as a result of spatial variation in human preferences, economic and political pressures, and environmental sensitivities (Carpenter et al. 2007). Thus, we need to determine how variables operate across a range of interacting scales to influence land and water use change and ecosystem properties, and to identify feedbacks to human behavior. Long-term research is needed to understand the ecological and social-ecological dynamics of working and urban systems; but even more importantly, this research must be comparative across relevant climatic, societal, and geographic gradients. We thus propose a combined regional and cross-regional (continental) approach to urban and working systems that takes advantage of the network of LTER sites. Within regions, similar social or ecological constraints may lead to similar patterns of land and water use change, which will contrast with those of other regions having different constraints. Contrasts between Baltimore and Phoenix, locations of the two urban LTERs, most obviously illustrate this difference (Grimm et al. 2000), but numerous other LTER sites are also affected directly or indirectly by urbanization and exurbanization (Fig. 4.2). Well-known gradients such as differences in megapolitan growth rates could be exploited for such comparisons.

Working ecosystems are managed by humans for provisioning ecosystem services, most commonly food, fiber, and/or fuel (Swinton et al, in press). Rising human population, income levels, changing preferences, and changing technologies are major presses that drive demand for the products of working ecosystems (Nelson et al. 2006). In response, these systems have evolved toward increasing intensification. Important pulses from weather and price fluctuations also influence these systems importantly. Across the LTER network (see Appendix A), working systems include managed forests (e.g. HFR, AND, CWT), rangeland (e.g. JRN, SGS, KNZ, SEV), prairie (SGS, KNZ), row crop agriculture (KBS), marine fisheries (e.g. GCE, SBC, CCE, MCR), and subsistence hunting (ARC, BNZ).

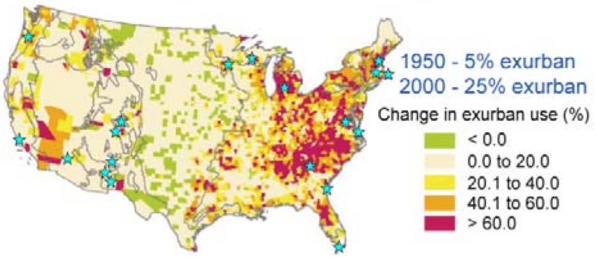

Figure 4.2. Rate of U.S. exurban growth; stars denote LTER sites. Redrawn from Brown et al. (2005).

Our research is question-driven and will take place mainly at existing LTER sites and the regions surrounding them. Research will address various environmental and land and water use change scenarios that are based upon syntheses of existing data, continued long-term measurements (including social science measures, such as interview and survey results), and model development. Scenario development in this theme, as for our other research themes, will require integrated research teams capable of collecting and synthesizing information on human and environmental systems, their interactions, and feedbacks. Teams will be structured as nested hierarchies, with regional teams nested within network-wide teams. Mechanisms such as web-based modeling, distributed graduate seminars, inter-site scientist exchange, and sophisticated visualization will enhance the capacity of teams to construct and analyze scenarios.

4.1.2. Specific Research Questions and Approaches

Question 1: *What are the temporal and spatial patterns of human activity and ecosystem dynamics in LTER regions?*

a. *What are past, current, and anticipated trends and regional patterns of development, urbanization, management, and land cover change?(Q1)*
b. *What are the past, current, and anticipated trends and patterns of freshwater and marine resource use? (Q1)*

Approach. Understanding how ecosystems respond to urbanization and changes in working and urban systems requires accurate long-term tracking of land-use and land-cover change. For each LTER region, spatially explicit data are needed that capture historical and contemporary land cover and land use. The historical depth of the data will be a minimum of 20 years, but may be longer depending on data availability and, more importantly, on the regional importance of specific historical conditions as drivers or constraints of current and future activity. Historical resources are valuable because many current dynamics and future responses are conditioned by ecological legacies (e.g., soil, vegetation, biotic patterns and processes) resulting from past human or natural changes (Foster et al. 1998, Lewis et al. 2006). Acquisition and analysis of historical records, human demographic data, resource consumption and transformation statistics, and imagery will go hand-in-hand with improvements to information management, data access, and data sharing. Future conditions will be projected over the next 30 years in a limited series of scenarios based on existing data and models that are driven by a broad range of alternative assumptions such as status quo, sustained increase in the price of oil, conservation-based land management, smart-growth development, and extreme build-out activity. Land-use information will include constraints on future activity such as conservation overlays (including restrictions), zoning, urban growth boundaries, and land ownership (especially State, Federal, and Indian lands).

Question 2: *By what mechanisms do humans directly or indirectly drive the dynamics of working and urban systems?*

a. *How do historical trajectories of land change and ecosystem management (legacies) constrain future trajectories? (Q1)*
b. *What are the relative influences of human drivers (e.g., population, motives, and rules), and biophysical drivers (e.g., topography, weather, climate) of change in working and urban systems?(Q1)*
c. *How do management decisions of different types vary in their effects on ecosystem structure and function? Which produce the greatest harm or benefit to ecosystems and the services they deliver?(Q2, Q3)*

Approach. Using the spatially explicit and regionally specific data collected to answer Question 1, comparisons will be made within and among regions. For example, to address Q1a, locations with different historical land use and management histories may be compared while controlling for climate, soils, and vegetation. Time-series data on human and biophysical conditions will be analyzed to distinguish the relative temporal and spatial importance of drivers within each domain across regions. Based upon historical restrictions on future trajectories and the relative importance of drivers, the factorial effect of different management decisions on ecosystem structure and function and the delivery of ecosystem services will be assessed. In addition, opportunistic experiments, such as measurement changes in ecosystem structure and function before and after planned development, will be performed in several regions.

Question 3: *What are the causes of human activities that are linked to working and urban system change, and how do feedbacks from ecosystem change influence future causes?*

a. *How are human choices over where to settle and how to shape the local environment to meet their needs and desires constrained or directed by human knowledge, perceptions, values and incentives, and by the contextual characteristics of where such choices are made?(Q5)*
b. *How do the changes in ecosystems brought about by human settlement and management influence future human choices, which in turn, become altered drivers of working and urban system change?(Q5, Q6)*
    - *How are management decisions affected by ability-shaping factors such as knowledge, attitudes, and technology, and attractiveness-shaping factors such as ownership regimes, property rights, market prices, policy inducements, and trade-offs between provisioning services and alternative ecosystem services?*
    - *How do regional to continental scale changes in human or market demand for desired provisioning services affect the management of working systems?*
    - *How do humans evaluate the trade-offs that occur between desired provisioning services and other services, and how do they act on this knowledge?*

Approach. Human choices about where to settle and how to manage working ecosystems can be expected to depend on (1) knowledge and perceptions, (2) personal values (e.g., stewardship), (3) external incentives (e.g., prices, property rights, policies), (4) local ecosystem characteristics, and (5) other relevant demographic variables (e.g., age, race, gender). The relative importance of these variables for driving human choices about urban and working ecosystems will be tested using two broad empirical methods adapted to local LTER vicinities. First, qualitative research using personal interviews and focus groups will be undertaken in order to understand the thought processes of key informant decision makers (Krueger and Casey, 2000). Results from this round of qualitative research will be used to develop testable behavioral hypotheses about the specific knowledge, values, and incentives that drive human decisions about urban and working ecosystems. These hypotheses will be tested in a second round of quantitative research that will include (1) household and business surveys of stated attitudes and willingness to change behavior as well as (2) hedonic land price studies of behavior and relative values revealed by behavior in the land market (Deaton 1997, Dillman 2000, Freeman 2003, Levy and Temeshow 1999, Rosen 1974).

Question 4*: How does urban and working-system change influence ecosystem structure and function and the delivery of ecosystem services at local, regional, and continental scales?*

- *a. How does the management of working land and water systems for products and amenities affect their capacity to yield these services across time and through space?(Q1 – Q3)*
- *b. How will changes in human population, migration patterns, economy, and land-use activity associated with urbanization alter ecosystem dynamics and the delivery of ecosystem services?(Q1 – Q3)*

Approach. For both urbanization and changes in the management of working systems, ecosystem responses are likely to occur in all of the topical areas identified as grand research challenges in environmental science (NRC 2001): altered biogeochemical cycles, biodiversity change, altered hydrology, infectious disease, and invasive species. More specific questions include: What are the ecosystem consequences of human activities associated with settlement patterns and working ecosystems? How does spatial pattern of land cover matter (across scales)? What are the consequences of local ecosystem management decisions at local to continental scales? What are the relative and interactive effects of land change, ecosystem management, and climate change on social-ecosystems? And how predictable are future rates of change based on current regional attributes? Research methods will include a mixture of field studies adapted to local LTER sites and biophysical modeling.

Question 5: How can public policy and private management decisions be informed by knowledge of how human settlement and management affect ecosystem performance?

- *a. What are the relative benefits and cost of specific land-use systems and ecosystem management strategies under different human-environment conditions?(Q4)*
- *b. What are the likely outcomes and consequences of future scenarios for urbanizing lands and working systems?(Q4, Q5)*
- *c. How do human societies respond to land and water change and alter future use and ecosystem management practices?(Q5, Q6)*

Approach. Research on Question 5 will take retrospective and prospective approaches. The retrospective approaches will draw upon historical records from the areas surrounding LTER sites to infer how human populations have responded to past changes in ecosystem performance. This work will involve qualitative research as well as longitudinal quantitative methods that separate community-level fixed effects from responses to measurable changes in ecosystem services. The prospective approaches revolve around the creation of scenarios and spatially explicit biophysical models for land and water use change in urban and working systems (Hanks and Ritchie 1991, Singh and Frevert 2006). Such models will rely upon parameters developed through long-term field observations and ongoing experiments at LTER sites. Armed with model output, social scientists and ecologists will collaborate to assess the value of ecosystem services and how they change under different scenarios. We will approach Question 5b by developing scenarios, constructing ecosystem change models, and then using visualizations of model scenarios and policy tradeoffs to open a dialog with local, state, and national decision makers (e.g. Antle and Capalbo 1993, Antle et al. 2003). Longitudinal study and repeated iterations of the scenario and model-building exercises show how responses develop and change as ecosystems change. Urban and working systems exhibit ecological conditions and societal feedbacks that are highly variable and regularly changing. Those changing values and relationships, in turn, provide the real basis of interpretations in coupled natural-human systems.

4.1.3. Significance

The combined effects of the human footprint on urban lands and working systems is huge (Kareiva et al. 2007). Urban land area in the U.S. increased from around 15 million acres in 1945 to roughly 60 million acres in 2002, about twice the rate of U.S. population growth. Urban growth during just the latter 10 years of this period was 7.8 million acres or 13 percent (Brown et al. 2005). Rural residential land areas continue to grow as well: from 1997 to 2002, by 21 million acres (29 percent) (Lubowski et al. 2006). The implications of urbanization are broad and span the natural, physical, and social sciences. Land-use dynamics is one of the "grand challenges" defined by the National Research Council (NRC 2001) as the need "to develop a systematic understanding of change in land uses and land covers that are critical to biogeochemical cycling, ecosystem functioning and services, and human welfare." The LTER Network is poised to answer this challenge, as many sites are situated in areas experiencing rapid urbanization (most notably the Southwest and Southeast) or suburbanization (effectively, the area east of the Mississippi river; Fig. 4.2). Working ecosystems to produce food, fuel, and fiber represent the most spatially extensive form of direct human management of ecosystems. Over 50% of the total US land area is used to produce food (Lubowski et al. 2006). Globally, over 30% of the Earth's land area is currently used for agriculture (crops and grazing lands), and of the 26% that is forest (MA 2005), one third is primarily managed for timber production (UN FAO 2006). Working systems are now undergoing dramatic change, as forest harvest continues, marine fisheries collapse, and large tracts of land are being considered for biofuel production. The potential for guiding change in positive ways is strong, but requires fundamental knowledge at the interface of society and the environment.

4.2. Research Theme 2: Climate Change, Variability, and Extreme Events

Revelle and Suess (1957) observed that human society has embarked on a vast, uncontrolled geophysical experiment by altering the millennia-long balance of CO_2 in the atmosphere. We now recognize that the experiment is social and ecological as well as geophysical: it is caused and continues to be influenced by human actions and the complex feedbacks among climate, society and the world's ecosystems (Nelson et al. 2006). Anthropogenic CO_2 in the atmosphere will continue to influence ecosystems and the services they provide to society for centuries, even after CO_2 emissions decline as the global economy restructures its energy sources. In this section we describe the framework we will use to examine how climate change will affect and be affected by social-ecological systems at various temporal and geographic scales. Our social-ecological approach conceptualizes ecosystems as environments driven by complex human and non-human associations, where biophysical and societal elements dynamically and adaptively interact (Berkes and Folke 1998; Redman et al. 2004). We exploit the unique dimensions of the LTER Network to achieve an improved understanding of the interplay between biophysical and societal drivers, an understanding that is crucial for helping to provide achievable mitigation and adaptation options.

Climate change has both short- and long-term components. Changes in the incidence and intensity of extreme weather events — pulses such as droughts, storms, and heat waves — play out on a backdrop of slowly changing presses such as rising air, soil, and water temperatures and changes in ocean salinity and wind and rainfall patterns. Effects on ecosystems and ecosystem services are pervasive and unequivocal (MA 2005).

At LTER sites, presses include documented changes in air temperature, measured both directly and by proxies such as ice cover duration, as well as changes in precipitation. At 21 sites, the slopes of annual mean air temperature, mean maximum air temperature, or mean minimum air temperature are positive over the time periods available; this is the case both for sites with long-term records and short-term records, and is especially pronounced at polar latitudes (Fig. 4.3). Long-term precipitation change is more difficult to extract from existing data, but at least two sites have experienced increases in precipitation over the past 40-70 years (Fig. 4.4). Seventeen of 21 sites have documented significant changes in the duration and frequency of drought: in 10 cases drought severity has increased and in 7 cases it has decreased (e.g. Fig 4.5).

Changes in the cryosphere — that portion of the Earth's surface normally frozen — are also occurring and are particularly notable because of the cryosphere's sensitivity to climate change: a small change in air temperature can cause a change from ice to liquid state, with huge implications for ecological systems and climate feedbacks. In the Northern Hemisphere, snow cover observed by satellite from 1966 to 2005 decreased in every month except November and December (Lemke et al. 2007). Similar observations in the arctic show a 2.7 ± 0.6% per decade decline in annual mean arctic sea ice extent since 1978 (Comiso 2003), with an even larger decline of 7.4 ± 2.4% per decade in the summer minimum (Belchansky et al. 2005). Changes in the cryosphere are well-documented at both northern and high-latitude LTER sites. Average lake ice duration has declined over 30% during the past 150 years at NTL (Magnuson et al. 2000), and a >20% decline in mean sea ice duration has been registered at PAL over just the past 20 years (Fig. 4.6). Warming and thawing permafrost in the far north have profound impacts on terrestrial ecosystem change at BNZ (Fig. 4.7) and ARC.

Global changes in temperature lead to a second kind of press that is critical to many LTER sites, sea level rise (SLR). Sea level change is highly non-uniform spatially, and in some regions rates are up to several times the global mean of 1.8 ± 0.5 mm y^{-1}, while in other regions sea level is falling (Bindoff et al. 2007). At all of our coastal LTER sites there is evidence for some sea level rise, particularly on the East and Gulf coasts, where sea level is rising at a rate of about 2 mm to 2 cm/y due to a combination of true sea level rise and/or land subsidence (Fig. 4.8; Hopkinson et al. 2007). This will place populations and ecosystems vulnerable to coastal storms and storm surges more at risk in the coming decades.

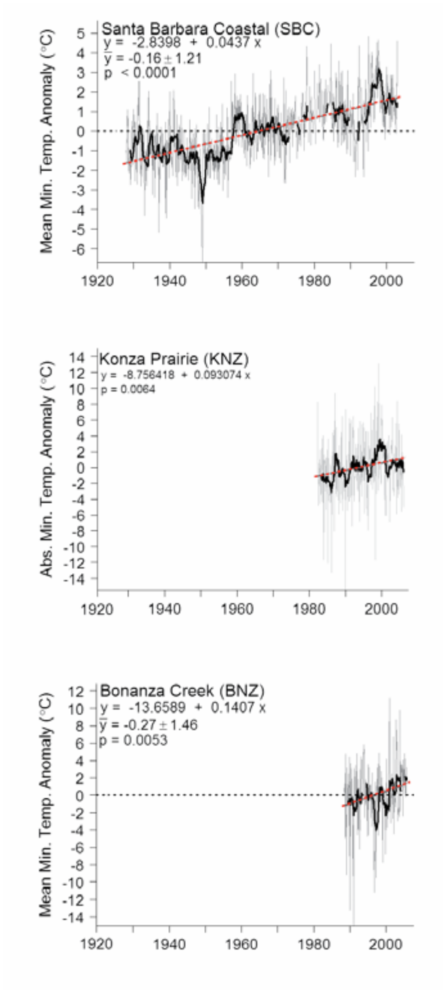

Figure 4.3. Positive temperature trends at Santa Barbara, Konza, and Bonanza Creek LTER sites. From Peters et al., in prep.

In addition to its effects on press disturbances, the longer-term, steady press of warming also has changed the frequency of pulse events such as storms and droughts. Evidence to date also suggests increases in the number of heavy precipitation events within many land regions, even where there has been a reduction in total precipitation amount, consistent with a warming climate and increasing amounts of water vapor in the atmosphere. Storm event frequency is changing at several LTER sites (Fig. 4.9). Globally induced presses (e.g., loss of cryosphere, sea level rise) can amplify the effects of more frequent pulse events for human populations. For example, higher sea levels combined with more frequent storms reduce the habitability of low-lying coastal areas.

Climate change has obvious and well-documented implications for humans. In rural populations dependent upon foraging and hunting, such as those within the Arctic and mountain forests, changes in permafrost will alter species composition and subsequent availability of range animals and result in the resettlement of communities, changes in traditional economic systems and transportation networks, and loss of traditional ecological knowledge (IGOS 2007). Urban populations and the agricultural sector will also be affected by cryosphere loss, particularly in the western U.S., where a majority of water supply derives from snow. Predicted sea-level rise will alter land use and residential patterns throughout the coastal U.S., as well as threaten sources of fresh water. Human vulnerability to storms — due to growing numbers of people living in exposed and marginal areas — is increasing the risks associated with climate change, while human endeavors (such as local governments) try to mitigate possible effects. In many cases, human vulnerability to extreme events is related to historical structural inequalities, producing disproportional impacts among the poor to storms, droughts, and floods, a point harshly illustrated in the aftermath of Hurricane Katrina.

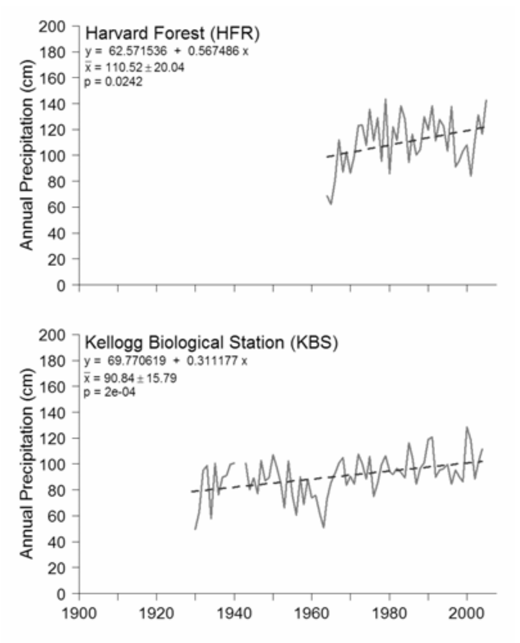

Figure 4.4. Changes in mean annual precipitation at Harvard Forest and Kellogg Biological Station sites. From Peters et al., in prep.

There is, nevertheless, a striking disconnection between our understanding of how ecosystems will be affected by and respond to climate change and our understanding of how humans will be affected and respond: the human dimensions of climate change are vastly understudied, especially the linkage between human perceptions of altered ecosystem services, incentives affecting human responses, and behaviors that affect climate. Unlike the other research foci addressed in this plan, human behaviors that drive climate change have enduring global consequences with local impacts that are often unevenly distributed across environments and societies. Within this context, we need to understand (1) how societies differentially perceive direct climatic events (such as storms) and multivariate, slowly changing processes (such as warming temperatures and sea-level rise), (2) how various forms of social stratification limit social actors' abilities to perceive the consequences of climate change, and (3) what factors shape human responses to perceived risks of climate change. In particular, incentives for the kind of collective action required to affect climate change are believed to vary across scales as well as across environments and societies.

Our research is designed to address this human link in addition to fundamental questions about ecosystem response — a strength of current research in the Network. In particular, our research will explore how alterations in ecosystem structure and function related to climate change will alter critical ecosystem services. These services include provisioning services such as food and fiber, commercial and subsistence fisheries, water quality and supply, and space for commercial and residential uses. Alterations in ecosystem services from climate change will affect people differentially, making some groups and places more vulnerable than others. Vulnerability can lead to mitigation and management strategies that in turn affect ecosystem structure and function. **Our primary goal is to better understand and measure the**

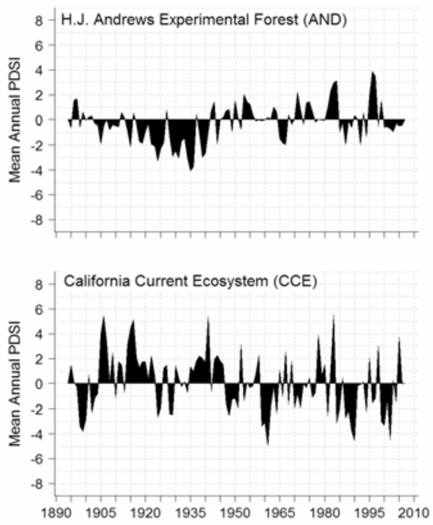

Figure 4.5. Examples of change in the Palmer drought severity index (PDSI) across the network. At 10 sites PDSI has increased (e.g. AND, top), whereas at 7 sites PDSI has decreased (e.g. CCE, bottom). From Peters et al., in prep.

feedback relationships among ecosystem structure and function, ecosystem services, and human perception and behavior in relation to climate change.

Central questions guiding this research are adopted from the ISSE framework (Fig. 3.2) but are specific to climate change and variability (Fig. 4.10):

- How do ecosystems respond to the interactions of climate press (warming, sea level rise) and pulse events (storm, flood, drought frequency, *El Niño–Southern Oscillation [ENSO]*, and fires)? (Q1)
- How are feedbacks between ecosystem structure and function affected by the press and pulse of climate change? (Q2)
- What are the critical ecosystem services provided by these dynamic systems and how will these services be affected by climate-driven changes in ecosystem structure and function? (Q2, Q3)
- To what extent do climate-driven changes in ecosystem services produce risks to both local and regional human populations, and how are these risks distributed within those communities? (Q4)
- What are the critical thresholds of risk and mitigation costs that will change human behavior to mitigate climate change (support for policies and other remedies)? (Q5, Q6)

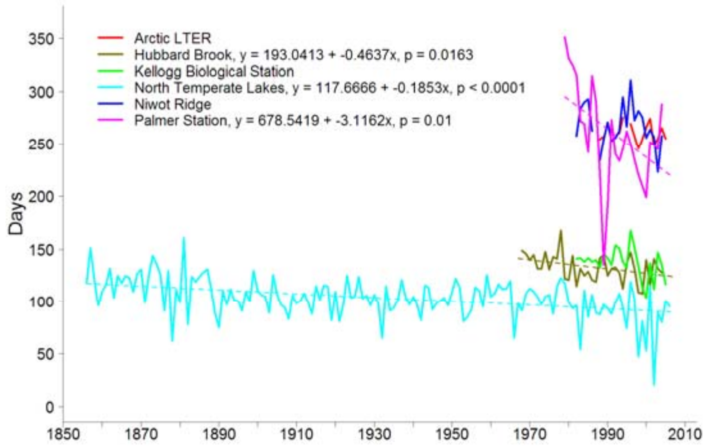

Figure 4.6. Change in ice duration at LTER sites with ice cover records. From Peters et al., in prep.

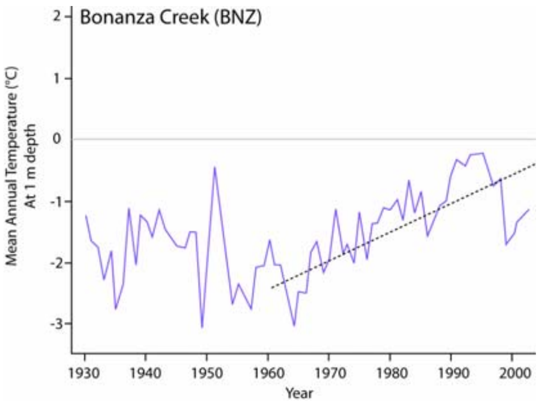

Figure 4.7. Change in 1 m depth soil (permafrost) temperature at BNZ since 1930. From Romanovsky (www.arctic.noaa.gov/detect/land-permafrost.shtml).

4.2.1. General Approach

We will address questions related to climate change and variability by taking full advantage of the diversity of changes occurring at different LTER sites with their accompanying diversity of geophysical and socioeconomic landscapes. For instance, coastal and near-coastal sites (such as FCE, GCE, BES, PIE, SBC, MCR, CCE, LUQ, and VCR) are well positioned to undertake research that seeks to understand systematic alterations in ecosystem services and feedbacks in response to the press of sea-level rise and the pulse of increasing storm frequency. Cross-site comparisons of global climate change impacts on inland sites (such as CAP, SEV, JRN, KBS, KNZ, and SGS) will allow us to effectively address questions related to social-ecological feedbacks that result from ongoing changes in precipitation and temperature patterns. Cross-site comparisons of the effect of climate change on groundwater/surface water interactions and nutrient and solute loading to lakes and streams increases our understanding of land – water interaction (e.g. AND, HFR, CWT, NTL, ARC, KBS). Our polar (PAL, MCM, ARC, BNZ), temperate alpine (NWT), and seasonally cold (e.g. NTL, KBS, CDR, HBR, NTL, HFR, SGS, KNZ) sites provide a variety of landscapes in which to observe and address questions about the retreat of the cryosphere from the planet. With a wide spread of sites ranged across a broad climate gradient, we can both observe different patterns of response and also generalize about responses and feedbacks among closely related and more disparate sites.

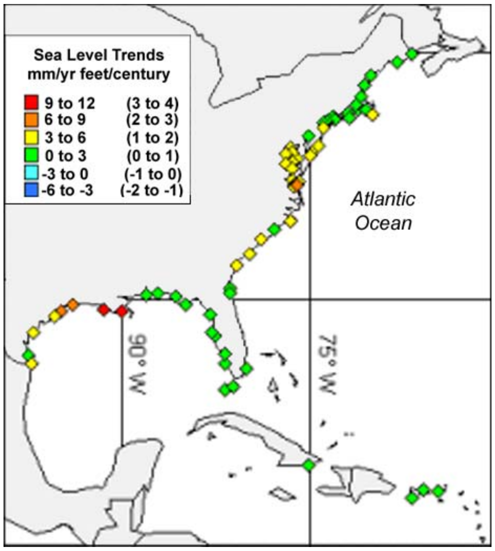

Figure 4.8. Sea level rise along the eastern U.S. coastline. East coast LTER sites include PIE, VCR, GCE, and FCE.

We intend to examine the human dimensions of climate change at a variety of scales. As applicable, our units of analysis will explore human responses to changing ecosystem services at individual, household, institutional, community, and larger regional scales. Moreover, the elements of climate change that we focus on (warming and loss of the cryosphere, sea-level rise, changes in disturbance regime) act relatively slowly over broad areas. People's abilities to perceive subtle changes occurring over the long-term and their capacity to respond effectively to the causes of these changes are additional areas of study. We recognize that there are critical differences in people's ability to respond to climate-induced changes, often based on historical relationships to land and social structures, ethnicity, gender, education, and social class. The LTER Network consists of sites ranged along urbanization gradients and associated land uses (e.g. Fig. 4.2). Urban LTER sites such as those in Baltimore and Phoenix are fully managed landscapes linked to regional and global economies. At the other extreme, antarctic sites such as MCM and PAL have no indigenous population, though they are profoundly influenced by remote anthropogenic effects. Other sites lie along the exurbanization gradient noted earlier in Section 4.1. Our approach seeks to understand the dynamics of these differentials and how these variables feed back into altered perceptions of, and actions toward, a changing environment.

In addition to differential perceptions of climate change across scales, we intend to explore how responses to these perceptions vary. Humans can respond by either adapting to or mitigating the problem. Adaptive strategies need to be understood in the context of the local environment, the culture, and the incentives that shape them. Mitigation strategies are shaped by incentives and organizational constraints. Climate change is a problem of global magnitude, one that is pressing but diffuse, posing major challenges to collective action (Ostrom 1990). In addition, climate is a public good in the sense that it is collectively shared, so from a private perspective, there exist limited incentives to incur costs for mitigating actions. Finally, the complex processes that drive climate change are highly dispersed, so they raise the thorny monitoring and enforcement problems of nonpoint source pollution (Dosi and Tomasi 1994). However, in spite of these incentive problems, there are many local initiatives to address the issue. Hence, mitigation strategies and associated incentives need to be understood from both local "bottom-up" and global "top-down" perspectives, implying multiple scales for the analysis of human responses.

The interplay of these press and pulse events is well illustrated by the Florida Everglades (FCE) LTER. In the Everglades, climate change is most strongly manifest as sea-level rise (a press disturbance) and hurricanes (pulse disturbance). Sea-level rise, coupled with dramatically reduced freshwater inflows to the Everglades in the last century, has led to a landward expansion of mangrove wetlands. Hurricane storm surges accelerate landward transgression across a 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 — a major ecosystem service in the region. To mitigate these problems, the Everglades Restoration Program is attempting 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 Biscayne Aquifer. Yet, rising sea levels also suggest future shifts in land use and cover patterns in coastal south Florida, resulting in increasing pressure on critical buffer lands situated between the Everglades and urban development zones. Risks associated with increasing storm frequency and intensity further complicate regional land use and demographic projections, as well as the sustainability of traditional economic sectors (agriculture and tourism). A transdisciplinary approach that considers these feedbacks (e.g. Fig. 4.10) is necessary for understanding the coupled social-ecological nature of climate change, which in the Everglades requires assessing the complex interactions of Everglades restoration, land-use changes driven by a growing population, and water supply issues.

By undertaking comparative research across the LTER Network, we will better understand the interactions of landscape alterations, such as cryosphere loss, water management systems and development, resultant changes in ecosystem structure and function, coupled with the pulse of extreme climatic events. Moreover, we will be able to examine the role of social institutions, demographic change, and governance in response to and prevention of human vulnerabilities to these extreme events.

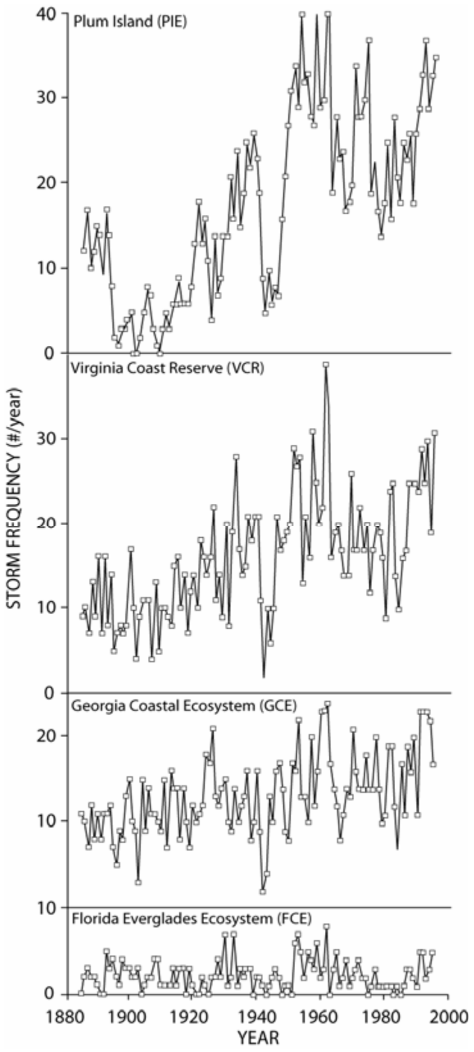

Figure 4.9. Storm frequency trends at PIE, VCR, GCE, and FCE. From Hayden and Hayden (2003).

4.2.2. Specific Research Questions and Approaches

The overarching question driving our climate change and variability research is to what extent can human responses to climate change, manifested as feedbacks within the social-ecological framework, mitigate further long-term change to the social-ecological system while providing adaptive short-term solutions that minimize the loss of important ecosystem services. The LTER Network is particularly well-suited to address the interactions among cryosphere loss, sea level rise, and increases in strength and frequency of major storms, droughts, floods, and fire events. The long-term steady press of climate change is manifested in regional warming that is most intense at high latitudes and other cold regions, resulting in retreat and loss of the cryosphere. As a result of this warming, another press — sea level rise — comes into play, affecting the vulnerability of coastal social-ecological systems to climate pulse phenomena, including temperate and tropical storms (e.g., nor'easters and hurricanes) and extreme events like tsunamis. We seek to understand the relationships, feedbacks, and differential effects of linked press-pulse disturbances on ecosystems and society. Guiding this research are the following five questions.

Question 1: *How do ecosystems respond to the interaction of climate press (e.g., warming, sea level rise) and pulse (e.g., storm frequency, ENSO, fires)?(Q1)* *a. How will regional warming (press) and changes in precipitation patterns, storm frequency, and fire frequency (pulse) affect community structure and net ecosystem productivity (NEP) across the LTER Network?*

b. How will species distributions change in response to climate change-driven migration of vegetation bands to higher latitude? Will this process open opportunities for invasions by exotic species? What is the role of disturbance in climate-change driven alterations in species ranges?

c. What are the effects of climate forcing and its interactions with disturbances and extreme events on the phenology of ecosystem events and processes (synchrony of life cycle processes and seasonal climate events)?

d. Will ENSO frequency and the magnitude of its effects change as the planet warms? How will community structure and nutrient cycling respond to ENSO-scale changes in pulses such as storm events, drought, and ocean circulation?

Approach. Understanding ecosystem response to climate trends and variability requires knowledge of change and ecosystem behavior at specific sites. Climate records are among the longest and most uniformly collected at each LTER site (e.g. Greenland et al. 2003, Peters et al. *in prep*), and thus provide a solid basis upon which to evaluate rates of ecosystem change in response to climate change. In some sites, many aspects of climate forcing will be largely expressed as long-term press (e.g. our inland high latitude sites); in other sites, the frequency and intensity of short-term pulses will likely dominate and possibly be exacerbated by long-term press (e.g., our coastal low latitude sites). But in most sites, climate forcing will be expressed as some combination of pulse vs. press change, and therein lies our ability to effectively address questions about differential climate forcing, ecosystem response, and human perception and behavior. At all sites, specific measurements common to all ecosystems will provide the information needed to address the questions above: net ecosystem productivity, major plant, animal, and microbial communities specific to each site, including key species distributions, and the phenologies of species chosen to represent major trophic groups.

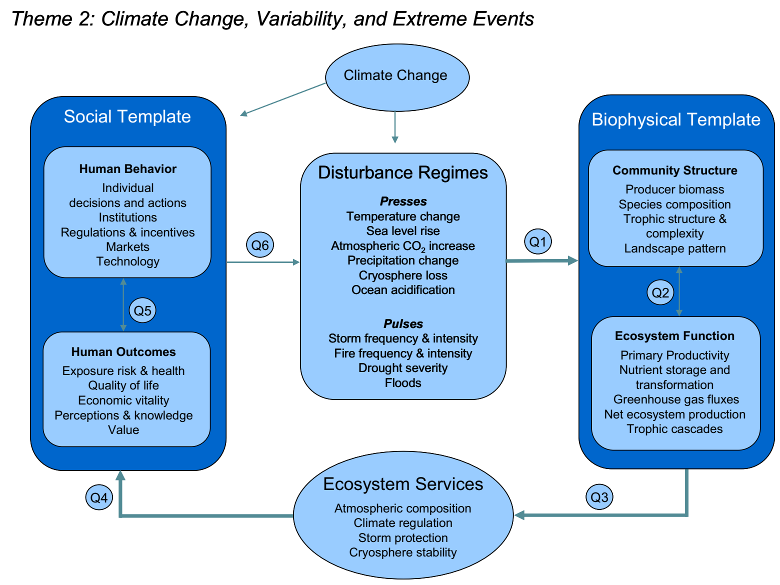

Figure 4.10. Conceptual framework for addressing climate change, variability, and extreme events. See Fig. 4.1 legend for further explanation.

Question 2: *How are feedbacks between ecosystem structure and function affected by the press and pulse of climate change? (Q2)*

a. How have reductions in permafrost, sea and lake ice, and seasonal subfreezing temperatures resulted in changes in plant and animal communities? What are the consequences for NEP, nutrient cycling, and water transport?

b. What are the mechanisms by which sea-level rise impacts the distribution and composition of species and ecotones in coastal ecosystems and how does sea-level rise affect ecosystem *responses to disturbance? How do these impacts affect the availability of organic carbon and phosphorus and other limiting nutrients?*

c. *What is the relative importance of direct (e.g., via the effects of changing CO_2 on plant growth) and indirect (e.g., through changes in community composition) effects of climate change on ecosystem function? How is the interaction between direct and indirect effects modified by changes in the frequency and intensity of pulse disturbances?*

Approach. Interactions between hydrology and climate events influence ecosystem and community structure. Biotic structure in turn affects fluxes, emissions, and storage of nutrients, particulates, and reactive trace gases in and among the atmosphere, land surface, and recipient aquatic, coastal, and groundwater ecosystems. To assess the direction and magnitude of these feedbacks requires both observation and experiments in targeted ecosystems. Patterns of biotic and biogeochemical change documented in pursuit of Question 1, above, will suggest potentials for feedbacks, which will be tested with experimental manipulations in mesocosms or in situ. Soil warming experiments, for example, coupled with isotopic analysis, can address questions related to the differential temperature response of microbial communities attacking different organic matter fractions (Davidson and Janssens 2006), with consequent effects on soil carbon loss, soil food web dynamics, and nutrients available to plants. These changes in nutrient cycling and biotic structures may in turn change the frequency and magnitude of pulse events such as fire.

Question 3: *How does climate change, modulated through alterations of biotic structure and function and disturbance frequency, lead to changes in key ecosystem services?(Q2, Q3)*

a. *What are the critical ecosystem services, their rates of production, and the locations and scales of delivery provided by ecosystems represented at LTER sites? How will they be affected by changes in ecosystem structure and function?*
b. *How do changes in seasonality and loss of the cryosphere affect regulating services such as water purification and pest control? How will they be affected by changes in ecosystem structure and function?*
c. *To what extent are regulating services such as flood control, provisioning services such as adequate water and the sustained productivity of working lands and fisheries, and cultural services such as recreation and tourism affected by more frequent, more intense hurricanes?*
d. *How does sea-level rise affect the availability of the key ecosystem services of clean water, commercial and residential space, regional economies, and coastal protection? Which are most vulnerable to alterations associated with sea-level rise?*
e. *How will changes in drought, rainfall frequency and distribution, and fire frequency alter agriculture, including the choice of crops and animals and the sustainability of these practices?*

Approach. Ecosystem services range from provisioning services such as land access for settlement and subsistence hunting, regulating services such as water purification and pest suppression, and cultural services such as recreational opportunities and visual amenities. Services will vary by region and by the cultural environment in which the ecosystems reside. We will use a scalar approach to assess the delivery of services and in particular to assess changes in services in response to changing climate. Some services (e.g., water provision at NWT) are provided to larger geographic regions, with the services used far from their source of origin. Other services (e.g., subsistence hunting at ARC and BNZ, recreational fishing at NTL and FCE) are valued at smaller scales. To identify the importance of specific ecosystem services to relevant communities, we will conduct economic and social assessments of provisioning, regulating, and cultural services. We will then analyze these data to understand how communities differentially perceive the importance of these services and value them. We will track changes in ecosystem service availability and changes in attitudes toward these services in concert with climate change.

Question 4: *To what extent do changes in climate and ecosystem services alter local, regional, and national communities, and how are these changes distributed within those communities?(Q4)*

a. *What are the costs and benefits associated with changes in ecosystem services? How are these costs and benefits distributed within communities, regions, and the nation?*
b. *Who is most vulnerable to changes in ecosystem services? How do social actors, institutions, and communities differ in their ability to perceive the consequences of these changes and react?*
c. *What scale variables alter human perceptions of extreme climatic events, from the immediate effects of flooding, drought, and storms to evidence of increasing vulnerability to these extreme events on human health, property, livelihoods, and iconic species?*
d. *Does the probability of social action in response to changes in ecosystems or ecosystem services depend on the likelihood that social action will have a short-term effect? Is social action to address changes stemming from local drivers more likely than social action to address changes stemming from global drivers?*
e. *How do the frequency and magnitude of pulse events affect public, private, and institutional responses to sea-level rise across LTER sites? How do awareness and response differ between slow as opposed to rapid change in ecosystem services?*

Approach. For the services identified in Question 3, we will conduct risk assessments and produce risk assessment scenarios to determine how people are differentially at risk to changes in ecosystem services. To understand the social costs and benefits of these changes in ecosystem services, we will use techniques of full-cost accounting (market and non-market variables). Whether a service — and the providing ecosystem — is valued by a particular group may well depend on the group's knowledge of the service and of its connection to ecosystem structure and function. Thus, we will also examine the potential for different educational paths to affect the group's perception of a service and its valuation. This is a long-term activity that requires longitudinal sampling of the same population through time, especially to detect generational changes in attitudes and knowledge.

Question 5: *What are the critical thresholds of risk and mitigation costs that will change human behavior to mitigate climate change (support for policies and other remedies)?(Q5, Q6)*

a. *What institutional forms, including governmental and economic, will most adequately respond to and mitigate the effects of changes in ecosystem services? At what scale will these mitigation measures be most effective (local, national, global)?*
b. *Will changes in public education and awareness alter the human drivers of climate change?*
c. *How effective are climate regulatory policies and what are the feedbacks connecting them into the social-ecological system?*
d. *How will people organize to affect the pace of climate change in response to extreme events, and what sources of motivation (educational, informational, cultural, and economic) will be key to changes in behavior and attitudes?*
e. *Does proximity to the effects of storm events alter environmental literacy about climate change? What is the relative importance of natural disasters, education, iconic species, and changes in economic incentives for altering climate-changing behavior and policy?*

Approach. Institutional responses to cryosphere loss and sea-level rise will be studied using generally similar approaches. As noted earlier, the distribution of LTER sites across climatic regions provides a superb context within which to address questions related to differential ecosystem response to climate press and pulse events. Our approach for the climate-forcing questions will be similar to that used for cryosphere disappearance: a combination of observation, experiments, and scenario-based modeling activities to identify and understand the behavior of key climate-forcing feedbacks in the social-ecological environment. Scenario-building will allow us to construct regional environmental forecasts over 10 to 100 years that engage decision-makers (including the public) in their formulation and use, and that can then be used to inform integrated assessment models, as described below. Regions will be those exemplified by particular LTER sites: How will urban developers and planning groups in Phoenix respond to continued warming if supplies of cooling water from the Colorado River dry up? How will the housing industry in Baltimore and the Chesapeake Bay region (and Miami and the Everglades) respond to increased hurricane frequency and vulnerability associated with sea-level rise? In what similar and different ways will these three different urban ecosystems respond to diverse climate presses and pulses?

Developing regional scenarios, both conceptual and predictive, will require integrating a variety of research methodologies and types of data. In addition to the biophysical measures the LTER Network has traditionally excelled at collecting, sites will collect and analyze data that measure change within social systems in response to alterations in climate-change-induced ecosystem services. This research will include developing land use/land cover change models, analysis of regional and localized demographic data (such as long-term census and economic data), labor and real estate markets, economic indicators of consumption patterns, and water supply and delivery projections. Both qualitative and quantitative research methodologies will be used to develop integrated assessment models (e.g. Sands and Edmonds 2005) such as those used in IPCC greenhouse gas scenarios (IPCC 2007). These large-scale models explore the national and global multi-decade implications of changes in land use, populaton, economic growth, energy supply and demand technologies, and climate change on atmospheric CO_2 stabilization.

Quantitative research will include multi-scale surveys of how people understand climate change and their willingness to pay (or forego income) to mitigate its drivers (Deaton 1997, Dillman 2000, Freeman 2003). The perceived economic value of averting climate change will also be evaluated using hedonic price analysis of real properties facing changed risks due to climate change phenomena (e.g., low elevation coastal property, regions that experience tornadoes and hurricanes) (Rosen 1974). To understand expected effects of climate change on property values, we will include other quantitative measures such as indicators of vulnerability and resilience to alterations in ecosystem services. Qualitative research, such as oral history and other ethnographic techniques, will provide rich in-depth historical information on communities' sense of place and history of environmental and social change.

4.2.3. Significance

Climate research to date has emphasized biophysical approaches, as exemplified by the IPCC Working Group 1 Reports of the Climate Change Assessments, but there have been significant contributions to human dimensions-based climate research as well. The IPCC emissions scenarios (IPCC 2007), for example, represent an important step in predicting how human actions may affect the climate system. The Millennium Assessment (Carpenter et al. 2006) made a seminal contribution by adopting ecosystem services as the key link between the biophysical and social components of the biosphere. However, there has been little effort thus far directed towards an integrated mechanistic analysis of the linked, climate-social-ecological system that our proposed research promises. The LTER Network offers existing organization and infrastructure already engaged in climate-ecosystem research with a growing social sciences component. Network sites are arrayed along latitude, climate, and vegetation gradients, covering the full range of human social development from uninhabited to urban. By joining climatologists, ecologists, oceanographers, economists, and social scientists, working together within a common intellectual framework (e.g., Figure 4.10) and a common research infrastructure (the Network), we can make a unique, powerful, and effective contribution to climate response science.

4.3. Theme 3: Nutrient Mobilization and Species Introductions

Multiple scales and multiple causes present key challenges for understanding regional change (Carpenter et al. 2007). Interacting components at one scale become drivers at other scales, where their effects depend on history, timing of events, and presence or absence of other factors. In most regions, social processes are important in ecological change and ecological processes contribute to social change. Thus, regional systems are both social and ecological, and understanding change requires the perspectives of many disciplines. To make progress we must break problems into components, but traditional disciplinary boundaries are often inappropriately narrow. Instead, the analysis of regional change must be organized into tractable sub-problems that take advantage of synergies across disciplines. Here, we address an important class of problems that have become tractable due to advancing capabilities of interdisciplinary long-term research.

Figure 4.11 The distribution of nitrogen deposition across the continental U.S. in relation to LTER sites (blue stars).

Diffuse drivers (i.e., drivers that have multiple points of entry) of regional change in social-ecological systems raise significant scientific challenges. Unlike drivers that affect an entire region simultaneously (climate, for example) or have a few control points (such as discharge from a river or a sewage treatment plant), diffuse drivers act at many discrete locations. Two important examples are mobilization of critical nutrients (such as nitrogen and phosphorus) from agricultural runoff and confined feed lots scattered across a region, and introductions of non-native species at many locations. Nutrient mobilization and species introductions are among the most important drivers of global ecological change (MA 2005). The topics have similarities that facilitate coordinated research:

- Both nutrient mobilization and species introductions can have natural or human causes. Nutrient mobilization can result from natural processes, such as upwelling in oceans or weathering in watersheds, or from human sources of non-point pollution or atmospheric deposition (e.g., Fig. 4.11). Species introductions can result from natural dispersal processes or human movement of non-native species.
- Both nutrient mobilization and species introductions can have important effects on ecosystem services (MA 2005). Nutrient mobilization enhances production of important living resources, both wild and cultivated, or can impair ecosystems through acidification and eutrophication, both of which have significant consequences for biodiversity (e.g., Fig 4.12). Species introductions can renew ecosystem processes (as in succession) and diversify living resources, or impair resources as in the case of harmful non-native species that become invasive.
- Diffuse drivers are important in social systems as well. New ideas, institutions, or technologies may be introduced to society in scattered pockets and exhibit thresholds or “tipping points” (Gladwell 2000, Fleigel 2001). These may grow and coalesce if the new entity is perceived as successful and may then be adopted (Johnson 2001). Recent innovations such as “viral marketing” are one manifestation of diffuse drivers and tipping points. Nucleation and

emergence of institutions and technologies constitute both a driver of environmental change and a source of innovations for managing the environment.

Because of these similarities, it is logical to study nutrient mobilization and species introductions in an integrated way, together with relevant social processes of cognition, behavior, and institutions. Yet there are important contrasts that are likely to reveal crucial differences in the dynamics of these processes across regions. Nonpoint nutrient mobilization and species introductions have important differences in origins and spatial dynamics (Table 4.1). Origins of nutrient mobilization generally follow a power law where a few sources account for most of the flux (Nowak et al. 2006), whereas species introductions can spread exponentially from a small input of a few propagules (Mooney and Hobbs 2000). Once introduced into a region, nutrient inputs are attenuated by ecological processes, physical diffusion, or downstream transport. In contrast, successful species invasions proliferate across a landscape.

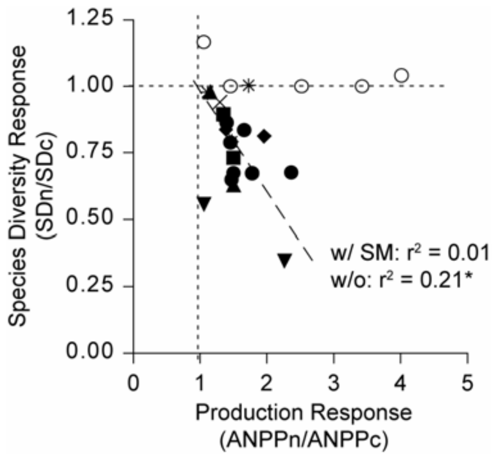

*Figure 4.12. A decline in species richness is related to the magnitude of increased production due to nitrogen fertilization across the LTER Network. Each symbol represents one fertilization experiment. Regression coefficients are given with (w/SM) and without (w/o) salt marshes (open symbols). *P= 0.05. SDn and SDc are species richness and ANPPn and ANPPc are above-ground net primary production in fertilized and control plots, respectively. From Suding et al. (2005).*

Our primary goal is to understand the spatial dynamics of nutrient mobilization and species introductions as drivers of social-ecological change, and to identify and quantify key ways in which changes within ecological and social systems feed back to affect both (1) the perception and delivery of ecosystem services (e.g. clean water, clean air, pest and disease suppression) and (2) the ways that human behavior at various scales affects the functioning of ecosystems that provide these services.

Our research focuses on the interplay between the social origins of nutrient mobilization and species introduction and their social-ecological dynamics in both space and time. As noted above, there are important differences in the origins and dynamics of these phenomena (Table 4.1). The mobilization of nutrients is characterized by disproportionality: a few large sources often account for the majority of the input, and that input is attenuated by processing, diffusion, and downstream transport. In contrast, species introductions tend to be characterized by the weakest link (one event can trigger an invasion) and the growth and diffusion of one event can lead to large-scale expansion. Such differences in origins and dynamics of nutrient mobilization and species introductions are likely to have profound effects on the ability of society to control human-induced changes in these drivers. For example, the distribution and abundance of introduced species can be expected to increase over the next several decades due to the globalization of commerce (products) and transportation (people), and ecological stress associated with climate change. In contrast to species introductions, changes in nutrient inputs are more variable, e.g., changes in nitrogen deposition over the past 10 years have varied markedly among LTER sites (Fig. 4.11). In the face of these global phenomena, social responses through monitoring, regulation, and incentives will be insufficient to prevent the spread of introduced species, and social responses will shift from social-ecological prevention to social-ecological adaptation. In contrast, the proportion of receiving waters impaired more by diffuse than discrete sources of nutrients is likely to increase over the next few decades because it will be easier for society to control and/or mitigate the adverse effects of changes in nutrient mobilization caused by a few large sources.

The overarching questions motivating our proposed research are:

- Under what circumstances is society able to manage the social origins and ecological dynamics of nutrient mobilization and species introductions and under what circumstances does society fail?
- Does society perceive and respond differentially to changes in regulating, provisioning, and cultural ecosystem services caused by human alterations in nutrient mobilization and species introductions?

Table 4.1. Examples of important differences in origins and dynamics of nutrient mobilization and species introductions.

Characteristic	Nutrient mobilization	Species introduction
Origins	Disproportionality: a few large sources account for the majority of the input	Weakest Link: one event can trigger an invasion by a single non-native species, leading to loss of ecological functions and ecosystem services
Spatial dynamics	Attenuation by processing, diffusion, or downstream transport	Growth and diffusion lead to expansion
Temporal	Press processes and pulse events	Primarily press processes

4.3.1. General Approach

Our comparative study explicitly involves two dimensions: (1) a clear contrast in the spatial dynamics of nutrient mobilization and species introductions as drivers of social-ecological change, and (2) regional differences represented by sites in the LTER Network, which vary greatly in their ecological setting and level of human influence. Changes resulting from diffuse drivers are particularly challenging to understand and predict because: (1) synoptic assessment of diffuse drivers over spatially complex regions is difficult, (2) spatial dynamics are frequently complex, involving thresholds and emergent patterns, (3) even the local dynamics of nutrients or non-native species may be complex, and (4) social responses to diffuse environmental change can be spread rapidly, amplifying the complexity of the spatial dynamics. Thus, the design and implementation of a coordinated research approach to understand these processes is an important contribution in itself.

We will take advantage of the wide range of habitat types and varying levels of human influence encompassed by sites in the LTER Network in developing a coordinated research program aimed at answering the overarching questions posed above. Our general approach involves tracking changes in nutrient mobilization and species introductions over time and space with a focus on comparing the nature and spatial distribution of sources, the spatial dynamics of the nutrients or species within the region, the ecological and social consequences, and the ecological and social factors that influence the spatial dynamics. Our focus on gradients in human influence and diffusiveness of two important environmental drivers of ecological change takes advantage of the diverse array of ecological and social systems represented by the LTER Network.

Human actions and behaviors in response to changing ecosystem services will be investigated across the LTER Network at sites where there is a notable human presence. Investigators will track household perceptions and behaviors in and around their site by assembling existing information and by developing new survey and assessment schemes and indices. This effort will involve:

- characterizing ecosystem services and monitoring the risks and impacts on those services due to changes in nutrient flux and species change;

- measuring how government agencies and non-governmental organizations (NGOs) monitor nutrient loading and the spread of non-native species;
- characterizing institutional structures (laws, best management practices (BMPs), enforcement programs, etc.) associated with nutrient mobilization and species introductions; and
- modeling impacts to ecosystem services, and the regulatory and incentive programs instituted to modify household and economic practices associated with nutrient mobilization and species introductions.

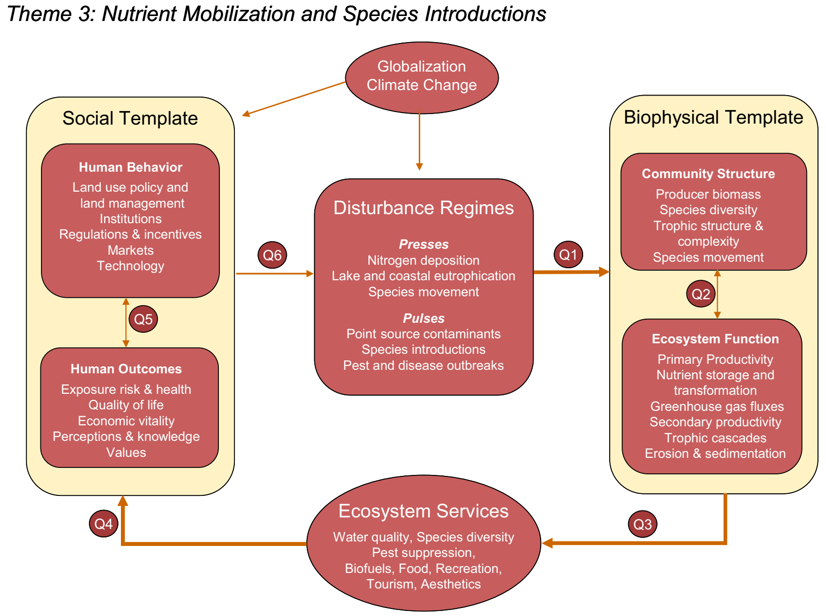

Figure 4.13. Linkages between social and ecological systems with respect to nutrient mobilization and species introductions. See Fig. 4.1 legend for further explanation.

Although the methods for measuring any given structural component or social-ecosystem process will need to be tailored to the system being studied, comparable metrics for each variable measured will be used by all sites to facilitate cross-site comparisons and synthesis. Regression and path analyses and other analytical techniques will be used in network-wide studies of the relative importance of various types of drivers in explaining variation in the ecological and social response variables that we measure. These correlative analyses will be supplemented with: (1) manipulative experiments performed at a subset of sites where it is logistically feasible to demonstrate cause and effect and (2) models designed to increase predictive power and identify critical issues of concern. Importantly, this multi-faceted approach takes advantage of LTER's emphasis on long-term spatial and temporal dynamics, and allows for analyses of spatial dependence, cause-and-effect, and non-linear responses.

4.3.2. Specific Research Questions and Approaches

The mobilization of nutrients and species introductions are caused by a range of human activities and natural processes that may be focused at a single location or at many sources distributed diffusely across a region. Producer biomass, species diversity, and trophic structure/complexity are aspects of biotic structure that are likely to be influenced greatly by alterations in the sources and rates of nutrient mobilization and species introductions (Q1 in Figure 4.13). Changes in these components of biotic structure due to alterations in nutrient loading and species introductions will, in turn, influence important ecosystem processes such as net primary production and nutrient cycling (Q2). Such changes in ecosystems can have dramatic effects on food supplies, water quality, recreation, aesthetics, and other important ecosystem services (Q3), which, in turn, influence the quality of life for humans and the choices that they make (Q4), and the extent to which human outcomes and human behaviors influence one another (Q5). Society frequently enacts policies and regulations to minimize the extent to which humans alter the sources and rates of nutrient mobilization, and to minimize the spread of non-native species in order to protect the ecosystem services that they value most (Q6).

We will exploit variation in the nature and intensity of nutrient loading and species introductions among LTER sites to address specific questions relating to our overarching questions concerning the social-ecological factors determining societal responses to changes in ecosystem services. The boundaries for this effort will vary among sites; however, we will use a standardized approach, much like that taken by the LTER EcoTrends project that compiled U.S. census data for the counties in and around each LTER site (Peters et al. *in prep*). This effort will involve assembly of existing geographic coverages and development of new standard assessment schemes and indices.

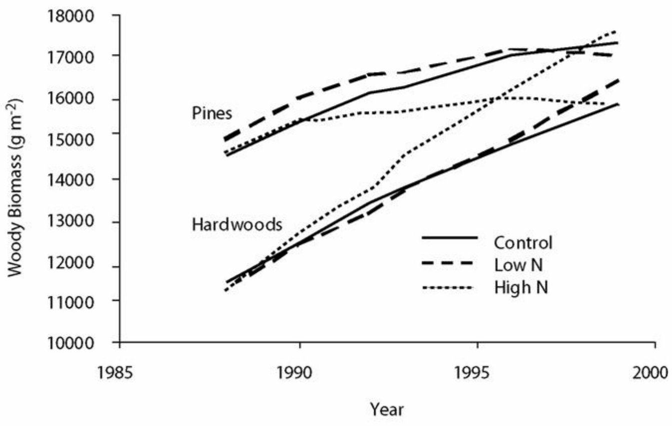

Figure 4.14. Changes in total woody biomass of pines and hardwoods at HFR in response to chronic N addition. From Foster and Aber (2004).

***Question 1**: How do changes in nutrient mobilization and species introductions affect key ecosystem processes?(Q1, Q2)*

a. *How do changes in the mobilization of diffuse and non-diffuse sources of nutrients derived from both human and natural origins interact to influence producer biomass, diversity, net primary production, and nutrient cycling?*
b. *How do changes in the relative abundance of native species alter community structure and ecosystem processes?*

Approach. Nutrients mobilized in terrestrial, aquatic, and marine systems are derived from multiple sources, including atmospheric deposition, microbial decomposition in soils and water, sewage, and human additions of fertilizers (Bennett et al. 2001, Carpenter et al. 1998, Vitousek et al. 1997, 1998, Boyer et al. 2002, Martinelli and Howarth 2006). Isotopic discrimination is an approach well suited to cross-site comparisons and will be used to quantify the proportions of nitrogen derived from these different natural and anthropogenic sources. Phosphorus sources will be assessed using transport measurements and models. Sites will construct nutrient budgets and track proportional changes in the contribution of various sources of nutrients over time to determine the extent to which changes in plant biomass, plant species diversity, net primary production, and nutrient cycling and export are explained by changes in the magnitude and sources of nutrient supply (e.g., Fig. 4.14). Comparable metrics will be used for measuring responses of ecosystem structure and function to facilitate comparisons across sites arranged along gradients in the diffuseness and anthropogenic nature of nutrient supply. Field experiments that alter rates and patterns of nutrient mobilization will be performed at a subset of sites where it is feasible to attribute cause and effect.

We will examine the combined effects of species introductions and extinctions on the ecological traits mentioned above across the LTER Network using correlative large-scale cross-site comparisons to examine generality in pattern, and smaller-scale manipulative experiments where possible to determine cause and effect. Sites will inventory species and classify them according to trophic position (e.g., producers, herbivores, predators, and decomposers). The emphasis placed on any given trophic level will vary among sites due to differences in their natural history. Historical data and existing information from each site will be used to classify each species into one of three categories of indigenousness: (1) indigenous to site, (2) indigenous to region, but rare at site, and (3) non-native (exotic to region). Sites will track changes in species abundance and determine the extent to which the proportions of species in each of the three categories of indigenousness changes over time. The level of indigenousness will be treated as an independent variable used to explain temporal and spatial changes in species diversity (within and across trophic levels), producer biomass and production, and trophic structure.

Question 2*: How do alterations in the sources and rates of nutrient mobilization and species introductions influence the interaction between community structure and ecosystem processes? (Q2)*

Approach. Biomass, species diversity, and trophic structure not only influence fluxes of energy and matter that are central to ecosystem functioning, but they also respond to these fluxes. We will investigate crucial feedbacks between various components of biotic structure and various ecosystem processes using the experimental and correlative data collected to address Questions 1a and 1b. We will synthesize the patterns and compare them across LTER regions using simple empirical models (such as multivariate autoregressions, Ives et al. 2003) as well as various kinds of ecological process models (Canham et al. 2003). We expect to gain insight from the complementary strengths of a variety of models. The complementarity of different types of models has been recognized (Canham et al. 2003), but the development of a set of models for comparing nutrient mobilization and species introductions with respect to ecosystem consequences across the LTER regions is an important new challenge for ecological science. The new research necessary to meet this challenge is an important contribution to theory of this proposed program.

Question 3: *How do changes in nutrient dynamics and species introductions affect the types and amounts of services that ecosystems provide? (Q3)*

Approach. Changes in nutrient mobilization and species introductions may produce a threshold rather than a linear response in biomass, production, species diversity, trophic structure, and nutrient cycling (Groffman et al. 2006). We will examine thresholds of change in these variables across the LTER Network relative to changes in ecosystem services with the specific goal of determining how much a system can be altered before a measurable change in the services it provides to humans can be detected. To quantify various types of ecosystem services, it is necessary to distinguish several distinct types. For example, provisioning services such as food, fiber, and biofuels are typically measured in terms of yields and quality, whereas regulating services such as flood control and maintenance of water quality and biodiversity are valued for their assimilative and transformative capacities and their resistance and resilience to disturbance (Heal et al. 2005). Cultural services such as recreation and aesthetics will be measured to evaluate the economic and societal impacts of changes to ecosystem services; the economic basis might include sales and market values (see Section 4.1).

Question 4*: How do humans perceive, value, and behave in response to changing services associated with nutrient mobilization and species introductions?*

a. *How do cultural and regulating services affected by alterations in the sources and rates of nutrient mobilization and species introductions influence humans as non-consumptive users? How do provisioning services affected by alterations in the sources and rates of nutrient mobilization and species introductions influence humans as consumptive users? How are social groups, individuals, and institutions differentially affected by these changes in cultural, regulating, and provisioning services? (Q4, Q5)*
b. *What determines how society chooses what to protect from among an array of ecosystem services threatened by human-induced changes in nutrient mobilization and species introductions?(Q4, Q5)*

Approach. We will perform repeated cross-site household surveys to determine whether human values, perceptions, and behaviors toward different types of ecosystem services change over time. Surveys will query households for their willingness to pay for a given ecosystem service, their awareness of human impacts on changes in nutrient loading and species introductions, and their knowledge of the degree to which different activities contribute to these impacts. The surveys will also be used to obtain data on demographics and social status (e.g., education level, economic status). Survey data will feed into social /

economic models that predict household location choice, recreational choice, and production/extraction choices at local and regional scales. These models will be compared with hedonic analyses and econometric models of household and firm locational choices to assess the significance of various ecosystem services on a long-term basis.

Actions designed to enhance one type of ecosystem service frequently come with the cost of diminishing other types of services. For example, increased crop and fishery yields often require a change in land use and/or a reduction in natural resources that lead to decreases in aesthetic value and recreational opportunities. To address Question 4b, sites will characterize local and regional government agencies and NGOs' monitoring (cognition) of various sources of nutrient loading and species introductions and their adverse effects on different types of ecosystem services. Administrative and legal records, news articles, editorial opinions, political campaign issues, and election results, coupled with household and organizational surveys and ethnographies, will be used to track public awareness and opinions on the values of competing ecosystem services. These data will be compared to local, regional, and national institutional structures (laws, BMPs, enforcement programs, etc.) to determine how society chooses what to protect from among competing ecosystem services threatened by human-induced changes in nutrient loading and species introductions.

Question 5*: What are the primary mechanisms that humans use to protect consumptive and non-consumptive services influenced by alterations in nutrient mobilization and species introductions?*

a. *Are mechanisms that are employed to reduce human alterations in nutrient mobilization and species introductions effective?(Q6)*
b. *What unintended consequences arise from the use of various mechanisms to reduce human alterations in nutrient mobilization and species introductions?(Q6, Q1)*

Approach. A variety of methods is often used by society to minimize the loss of valued ecosystem services that are threatened by human activities. These methods include regulatory and policy changes, educational and marketing campaigns aimed at increasing public awareness and voluntary changes in behavior, and financial subsidies and incentive programs. Sites will review records of local and regional sales and regulations (e.g., regulatory acts, zoning changes, issuing of permits or citations), and conduct surveys (to assess voluntary mechanisms) to obtain data on the different types of mechanisms enacted to protect consumptive and non-consumptive services diminished by human-induced changes in nutrient mobilization and species introductions. Nutrient budgets will be constructed to determine total nutrient inputs, the relative importance of different sources, and the degree to which the magnitude and sources of nutrient mobilization change over time as a result of mechanisms implemented by society to minimize human-induced changes in nutrient mobilization. Similar determinations will be made to evaluate the effectiveness of mechanisms employed to minimize decreases in levels of endemics and increases in the spread of non-native species. To the extent possible, the effectiveness of different types of mechanisms in managing alterations in nutrient mobilization and species introductions will be tested using manipulative social science experiments that are coordinated with local agencies. In addition, cross-site correlative Before/After Impact/Control Paired (BACIP) studies will be conducted to examine changes in nutrient mobilization and species introductions across a range of human settings before and after the implementation of strategies designed to minimize human effects on these drivers. Ecological and social science data collected as part of other cross-site research activities, as well as ongoing long-term data from LTER sites, will provide valuable information on the extent to which unintended consequences arise from mechanisms employed to reduce human alterations in nutrient mobilization and species introductions.

4.3.3. Significance

Understanding the dynamics of rapidly changing distributions of nutrients and species is a critical challenge in environmental science. The proposed research will make fundamental progress in meeting these challenges by developing a strong conceptual and theoretical transdisciplinary framework and a powerful set of new long-term data collection and experimental activities. This emerging interdisciplinary research requires analysis of coupled social-ecological systems and focuses on space and time scales where ecological change is perceived to be important so that institutions can address these changes. Thus, the proposed research fills a crucial need between traditional, place-based ecological science and global ecology on the one hand, and a bridge among social science disciplines on the other. The scaling challenges of global ecology can be managed by building on a foundation of strong local and regional ecology and the grounding of the social sciences in a long-term, multi-scale, and spatial context (Carpenter et al. 2006, Liu et al. 2007). This research is particularly timely because many of the social sciences have an increased interest in understanding how ecological phenomena explain social variation. The potential to broaden the spatial context of social/ecological interactions has increased immensely because much of the social data that have been used in the past are now spatially explicit. Formally integrating social science research into the LTER Network provides for additional opportunities by adding long-term possibilities, which will substantially contribute to social science theory and methods. Finally, an LTER awareness of and capacity for multi-scale analysis will challenge social scientists to reach out and connect with other social science disciplines.

This research will create a new regional socio-ecology focused on the comparative spatial dynamics of diffuse drivers, specifically nutrient mobilization and species introductions. Contrasting dynamics of these processes will be compared across the regions represented by our sites. Our research explicitly integrates an array of scales, building on the strength of the individual sites, the network of sites, and the global “network of networks” (Peters et al. 2008, *in prep*). Thus, our research will integrate multiple spatial scales from individual research sites to regions to continents, oceans, and the atmosphere. Time scales of the research range from minutes to decades.

This new paradigm is inclusive and explicitly interdisciplinary, integrating physical, biogeochemical, ecological, and social processes. To build a scaleable understanding of human cognition, behavior, and institutions in relation to ecological change, we will focus on the perceptions, behaviors, and changes of individual households and organizations. We will develop and implement research tools that follow household and organizational change in space over decades. This information will allow us to scale social data to the space and time scales needed for integrated social-ecological analyses and the emergence of regional patterns and processes.

5.0 Integration of Education, Cyberinfrastructure, and Transdisciplinary Research

5.1. Education

Education plays a key role in LTER research for a variety of reasons. First, it provides the opportunity to inform and train the next generation of environmental scientists, both biophysical and social. Second, it is an integral part of all of the research themes described above; e.g., people's perceptions of ecosystem services are partly formed via educational activities, whether formal or informal, and this information transfer and resulting behavioral change may be a key driver of social-ecological change. Third, and perhaps most importantly, there is a crucial need to educate the public about our research: our collective future depends on society's ability to understand the coupled natural and human systems on which we depend and to act rationally on that understanding. And it is the public — diverse stakeholders at all levels — who must act.

Our vision of an environmentally literate citizenry able to make informed choices about complex environmental issues includes five parts:

1) a scientific endeavor that continues, builds on, and celebrates its rich history of basic scientific discovery;
2) a society with the environmental science literacy needed for sound environmental citizenship and thereby a society that makes best use of timely, accurate, and unbiased information in decision making, including the capacity to act proactively and with forethought;
3) engagement of the full spectrum of our diverse society in developing and applying understanding of environmental challenges;
4) a scientific community that is receptive and responsive to the knowledge needs of the public and is committed to the delivery of knowledge in a useful form;
5) an environmental research and education enterprise informed by an understanding of the science/society interface — our points of contact, the mechanisms of teaching and learning, the timeframes of information exchange.

Achieving this vision will require strategic initiatives to (1) develop leadership, organization, and cyberinfrastructure, (2) promote research and development around our goals of environmental science literacy and inclusion of diverse people and perspectives, and (3) develop programs for specific constituent groups: K-12 teachers and administrators, undergraduate and graduate students and professors, and active citizens. Background information and greater detail on these activities are presented in the *Strategic Plan for Education in the LTER Network.*

5.1.1. Goal 1. Develop Leadership, Organization, and Cyberinfrastructure

The development of an integrated research and education initiative that focuses on social-ecological research and that reaches all relevant constituent groups requires network-level leadership and cyberinfrastructure as well as sufficient site level personnel.

LTER Network Education Leadership. The Network educational effort to engage learners of all ages (i.e., K-20 students, the public, social-ecological scientists, education researchers) will require leadership to use and learn from LTER research, to coordinate activities led by the education coordinators at the LTER sites, and to coordinate cross-site, regional education, and outreach programs. The Network will need to establish citizen science programming and initiatives that enable formation of collaborative relationships with existing citizen science programs; support the development of novel protocols; engage citizen groups; and organize workshops and other opportunities for sharing best-practices, data exchange, and collaboration.

LTER Network education leaders will also coordinate regular network-wide program evaluation and targeted self-studies and will promote LTER education efforts in regional and national conferences and arenas. These leaders will work closely with a range of LTER staff including scientists, education researchers, constituent groups, education administrators, and cyberinfrastructure and other technical experts.

LTER Education Site Coordinators. The balance between global and local emphases in our programs will demand strong leadership at both site and Network levels. Site coordinators will implement education and outreach activities at the local level; participate in coordinated cross-site and network education programming and assessment; and work closely with site scientists and students, education researchers, local constituencies, education administrators, and site cyberinfrastructure and technical experts.

LTER Education Cyberinfrastructure. Cyberinfrastructure will support the education, outreach, and science components by enabling cross-site collaboration on education research and programs, serving as an active repository for teaching and assessment resources, and enabling network-wide program evaluation. A well-designed, fully integrated cyberinfrastructure will be critical to the success of the Citizen Science program and must be responsive to a wide range of users. Because scientists, citizens, and educators will be supported by a common cyberinfrastructure, the effectiveness of scientific datasets, visualization tools, and other resources in educational programs should be greatly improved.

5.1.2. Goal 2. Conduct Research and Development for Environmental Science Literacy and Inclusion

The LTER Network is uniquely situated to conduct high-quality educational research. LTER sites are geographically dispersed and already working with local populations that include culturally and socioeconomically diverse populations of students. Scientists with expertise in environmental science are working closely with educators. These unique assets will serve as the basis for a program of research and development that focuses on two primary goals: (1) *promoting environmental science literacy* in constituent groups from school-age children through active adult citizens, and (2) *including and learning from diverse people and perspectives* to improve the diversity of LTER research communities, the quality and relevance of LTER research, and the quality of communication between LTER sites and the local communities that they serve.

Activity 1. Develop Learning Progressions Leading toward Environmental Science Literacy

We propose that our work with schools and the public should be informed by a vision of environmentally responsible citizenship. Recognizing that our actions affect the material world — the environmental systems on which we and our descendents depend — we must find ways to use scientific knowledge as a vehicle for considering environmental consequences in the decisions we make as we engage in the various roles of citizens. For these reasons, the LTER Network will support programs with a goal of *environmental science literacy* — the capacity to understand and participate in evidence-based discussions of social-ecological systems. Environmental science-literate citizens should have the capacity to act as environmentally responsible citizens. They should be able:

a. to understand and evaluate experts' arguments about environmental issues, and
b. to recognize social or economic policies and personal actions that are consistent with their environmental values.

Programs developed to promote environmental science literacy at LTER sites will be supported by network-wide educational research and development programs. These network-wide programs will be organized around *learning progressions* in key dimensions of environmental literacy. Learning progressions are descriptions of increasingly sophisticated ways of thinking about or understanding a topic (NRC 2007). Empirically grounded learning progressions in most domains have not yet been developed.

The Network Education Coordinator will work with groups of individual sites to organize research studies leading to the development of learning progressions in key content domains. The results of these studies will include publishable educational research, providing important resources to LTER sites for their local work and helping to establish:

- educational goals for students in elementary, middle, and high schools;
- assessments that enable teachers to monitor their students' progress to ensure that they are meeting the established goals; and
- teaching materials that address fundamental principles and educational goals.

Activity 2. Include and learn from diverse people and perspectives

The social-ecological framework proposed in this plan requires communication between and among actors in the social systems and ecological research communities. These perspectives will be diverse along every axis — political, socioeconomic, ethnic and cultural, age, and gender. We propose implementation of an *LTER Diversity Initiative* that develops new site-based and network-wide programs and coordinates the diversity and training efforts currently in place at sites across the network. This diversity initiative will include:

- an LTER Summer Bridge Program to support minority high school students during the fragile transition period from high school to college;
- coordinated cross-site field trips for undergraduates designed to expose minority college students from 2- and 4-year colleges from across the country to LTER science at several sites; and
- minority graduate and faculty fellowships (including faculty from 2-year colleges and minority-serving institutions) to focus on recruiting new and retaining existing participants in LTER research and education programs.

5.1.3. Goal 3. Develop Programs for Working with Specific Constituent Groups

The general goals and frameworks described above will be designed to support education and outreach programs for work with specific constituent groups at individual sites or collaborative groups of sites. In particular, our programs will focus on work with three constituent groups: K-12 teachers and administrators, undergraduate and graduate students and their professors, and active citizens. Our vision for how these programs will work and will be supported by the LTER Network is described below.

Activity 1. Work with K-12 schools to promote environmental literacy

Work with K-12 schools has been and will continue to be a primary focus of LTER education efforts. Although LTER sites will occasionally have small programs that involve direct work with students, our primary focus at the site level will be on (1) professional development and curricular support for teachers, and (2) work with administrators and policymakers.

LTER sites will continue their engagement in professional development activities for teachers, supported by research and development at the Network level and communicated through the Network cyberinfrastructure. Some of this support will take the form of professional development programs designed to give teachers the knowledge and skills they need to take advantage of LTER resources. LTER sites will also support local schools by creating opportunities for teachers to work directly with LTER scientists through programs such as GK-12 grants that allow graduate students to work in local schools for sustained periods and Research Experiences for Teachers. The LTER Education Coordinator and education cyberinfrastructure will enable the Network to support individual sites in these efforts and to organize collaborative efforts by sites that lack the local resources to develop programs individually.

The LTER network and individual LTER sites are also well positioned to affect educational policy and assessment at district, state, and national levels. The network-wide work on learning progressions will enable the Network to influence standards and assessments at the national level, where efforts to make high-quality environmental science available to K-12 schools are a high priority. LTER scientists and educators can also serve on policy-making boards and assessment development committees in states and local school districts.

Activity 2. Work at the undergraduate and graduate levels to improve learning

The nature and scope of social-ecological science requires new models for college teaching and for recruiting and training future scientists at the undergraduate and graduate levels. We must enable the research community to reflect the diverse public that we serve and from whom we seek support. We also must engage students in scientific inquiry that includes an interdisciplinary approach to understanding global issues.

LTER programs at the undergraduate and graduate levels will have two primary goals. First, the Network will support the development of resources that enable professors, including LTER scientists, to develop environmental science literacy in all of the students they teach. At the graduate level, the LTER network will sponsor programs that enable graduate students to communicate across sites and prepare students for careers in interdisciplinary research. Second, LTER programs will introduce minority students to ecological research and seek to recruit diverse students into careers in environmental science.

Activity 3. Engage citizens and leaders in LTER research

The success of a social-ecological research and education plan requires the participation of citizens in the decision-making processes that govern the management of systems that provide ecosystem services. Our program involves a participatory approach — citizen science — in which citizens are active in data collection and communication with researchers and policy makers. The LTER Network Citizen Science Coordinator will serve both to connect LTER research and education programs with existing relevant citizen science programs (e.g. the Cornell Lab of Ornithology, Project BudBurst) and to support the development of protocols that grow out of specific site needs. The Coordinator will also develop and share best practices in communicating the results of citizen science to decision makers. As with any sensor network, citizen science will require its own cyberinfrastructure, which must be fully integrated with the core LTER cyberinfrastructure.

The LTER Network Citizen Science Coordinator will also support local LTER sites in efforts to provide local decision makers with relevant environmental information and to promote environmental literacy in citizens. For example, citizens may want to know about how development plans will affect recharge zones for local aquifers or how various farming practices will affect water quality in local lakes and streams. In some cases, these communications with local citizens may be a part of an LTER research agenda, as LTER sites seek to inform citizens about likely environmental consequences of their actions and investigate the effects of that information on citizens' behavior.

5.2. Cyberinfrastructure (CI)

The network-level science presented in Section 4 involves significant new activities in multi-site comparative analysis and experimentation, modeling, and scenario development, and poses challenges for integrative research and education at multiple scales, across disciplines, and spanning resources, data, and expertise at geographically diverse sites. Meeting these challenges requires investments in cyberinfrastructure and workforce development to support collaboration, scientific integration, and information transfer. To achieve this, we propose three overall goals:

1) enhance high-throughput data services using standardized approaches that provide delivery of high-quality field-based and derived data products;

2) build computational environments using a service-oriented architecture that integrates large amounts of multi-site, multidisciplinary data in conjunction with social-ecological theory, modeling, and experimentation.
3) develop collaborative work environments that house comprehensive tools and algorithms for concept sharing, data mining, and knowledge discovery.

The development, integration, and deployment of the proposed cyberinfrastructure represents significant new investments in people and technology. These investments are crucial steps toward achieving a fully integrated research network capable of transdisciplinary, multivariate, and multi-site advances in social-ecological understanding and prediction at spatially and temporally meaningful scales. To reach those overarching goals requires the six specific activities described below. In some areas, new and growing associations with emerging observatory platforms such as the National Ecological Observatory Network (NEON), the Ocean Observatory Initiative (OOI), and the Water and Environmental Research Systems (WATERS) will provide leveraging opportunities for achieving shared goals. Background information and greater detail on these goals are presented in the *Strategic Plan for Cyberinfrastructure in the LTER Network*.

5.2.1. Activity 1. Build Community-Based Services Through a Service-Oriented Architecture (SOA)

A service-oriented architecture (SOA) is a collection of networked services that provide a common framework for application development without knowledge of the underlying platform implementation of each service. Applications that are built upon an SOA can access both local and distributed services through well-defined web service protocols. As such, a scalable community-based SOA for LTER will provide data and analytical services that ensure secure and efficient access to geographically distributed site data repositories, to computational services for numerically demanding analyses and models, and to data from large-scale, multi-site experiments that may incorporate environmental sensor networks or satellite sensors, or that may require high-performance computing.

Many of the services identified above can take advantage of technology already developed by the grid computing community. An increasing convergence of standards that support service-oriented architectures and those that support grid computing are providing new opportunities for the integration of these two approaches. For example, the use of industry-hardened software products and standards such as Globus, and services for resource monitoring, discovery, and management (including security and file management) could be integrated into the LTER cyberinfrastructure quickly and efficiently. The LTER Network will coordinate activities with other environmental observing networks to assure adoption of standard approaches as technological advances and solutions are implemented.

5.2.2. Activity 2. Build CI Capacity for Increasing Data Acquisition, Management, and Curation

The data collected, managed, archived, and made available online at LTER sites form the foundation for science at the site, regional, and network levels and, coupled with community standards for information access and management, are the key CI strengths of the network. Integrative social-ecological research presents new network challenges that include both the development of system architectures to facilitate the federation of network science data and the development of standard approaches to accommodate multi-site experiments. Large volumes of data provided through sensor network technologies and acquisition of regional collections of spatial and social science data present additional challenges to site information systems for assuring timely access to high-quality data and maintaining system security. Coordination among the sites and the network office and collaboration with emerging environmental observatory networks are essential to leverage resources in developing solutions to the common set of challenges presented by sensor network technologies and multi-site experiments.

Meeting each of the articulated CI challenges requires building capacity at LTER sites to allow information management professionals to participate in site-specific initiatives while maintaining services to allow the throughput of site data into network, national, and global data integration efforts. Building this capacity includes obtaining adequate resources for achieving more robust information systems and developing common approaches and essential services to accommodate this demand for quality data integration. Required resources include:

- site staffing to support information systems that fulfill local requirements for data collection, management, and curation as well as to support the throughput of high-quality data to the network information system;
- site computing technology to implement persistent data services including hardware, mass storage, software, wireless sensor networks, and physical sample archives;
- network office staffing to provide coordination and technical support for sites in implementing standard approaches to assure the federation of site and network science data and to provide development of the network information system; and
- training for site and network staff in advancing technologies such as sensor networks and new approaches to data management and data integration, including technologies and approaches employed by other environmental observatories.

5.2.3. Activity 3. Build CI Capacity for Increasing Data Discovery, Access, and Integration

Expanding research initiatives require more coherent, interoperable systems to discover, access, and integrate information from diverse disciplines and provide information in forms useful to educators and the public. Improving the ability to integrate these multi-disciplinary, multi-site data into consistent, coherent, and usable scientific resources is a primary need. Advances in data discovery, access, and integration will require development of innovative systems utilizing both data warehousing and distributed query systems technologies and adoption of community approaches in applying knowledge representation and semantic mediation. In consideration of planned multi-site experiments, such systems and standardized approaches must assure efficient integration of network science data through a common framework.

A planned framework of tools and expertise will address the integration of heterogeneous data into standard formats and derived data products. The framework is efficient, as it builds on existing investments and experiences, and integrative, as it adopts standard interfaces and approaches. The framework will provide researcher incentives to use standardized protocols such as simplified access to synthetic data products and powerful analytical and visualization tools. The delivery of integrated network data products through this framework will require

- a network-level team of database programmers, software developers, and thematic specialists to design, prototype, and implement common data services for constructing synthetic data products;
- implementation of solutions for interoperability of site data using specified global schemas to allow single point of access architecture for scientists engaged in synthetic multi-site research;
- collaborative working groups focused on mediating data heterogeneity through knowledge representation and ontology development; and
- network-office based computational infrastructure to develop and deploy the network information system.

5.2.4. Activity 4. Build CI Capacity for Increased Modeling and Analysis Activities

Modeling and advanced data analysis are an integral part of network-level science activities. Addressing questions that span the LTER Network and scenario development will require models to be integrated with analytical applications, experimental data, observations, remotely sensed images, and spatial databases. To facilitate and coordinate analysis and modeling activities that significantly improve our ability to understand and forecast changes in regional, continental, and global dynamics of social-ecological systems will require new investment in computing services, software development, and staffing.

In this activity we will organize and direct computational support for analysis- and modeling-related activities and identify and collaborate on the development and integration of new analytical tools. To meet these needs, we foresee a modeling and analysis initiative for the development and implementation of

- scalable computing resources for increased accessibility to new hardware technologies, including high-performance computers, parallel processors for some applications, grid technology, and mass storage and high throughput capacity;
- advanced analytical environments and scientific workflow that provide a framework for application and model development and integration; and
- a community-based repository of archived datasets and models that will provide the persistence, provenance, and methodological detail necessary to recreate published results and enable the synthesis of results across complementary research areas and the investigation of new hypotheses.

Development of advanced modeling and analysis capabilities will be a sequential process, focusing first on community-building through a series of workshops. These workshops will draw on teams of LTER investigators involved in the new science initiatives to generate user specifications for supporting cyberinfrastructure for modeling and analysis.

5.2.5. Activity 5. Build Capacity for Increasing Collaboration

Cyberinfrastructure for collaboration can mitigate distance barriers that inhibit interactions among scientists and educators. Efficient, usable, and persistent infrastructure is key to supporting the collaborations and, ultimately, an integrated research community.

Our approach to facilitating the increased need for research collaboration will be multi-faceted: procuring and deploying video-conferencing and network technology for immediate use, co-developing and deploying a framework for collaborative work environments, developing and deploying analytical tools within that framework, and collaborating with social scientists to build effective frameworks and learn from our efforts. Web-based social software holds promise for community-based collaborative frameworks. Three areas of support are needed to meet this need:

- development of collaborative work environments to allow scientists residing in different locations to analyze, discuss, annotate, and view data to solve scientific problems in an efficient and affordable manner;
- common video-teleconferencing (VTC) capability to support multi-site collaboration and information sharing (we have a modest VTC infrastructure already in place); and
- high-speed network connectivity (e.g. Internet2) at LTER sites to enhance data throughput for both collaborative work environments and data sharing, and for site access to Network and other SOA-based resources.

5.2.6. Activity 6. Integrate Cyberinfrastructure into Social-Ecological Research, Education, and Training

Integration of new cyberinfrastructure including, advanced tools for analysis and synthesis within the research process, will require training students and scientists so that their activities will fully reap the benefits of the new technology. There is also a critical training need for technical staff in the new technology and its applications. There are additional, significant cyberinfrastructure needs associated with our education initiatives (Section 5.1). We will meet these challenges by developing a program of workforce training and education with several goals:

- training in new technologies and methods for information managers and technical professionals who are engaged in data acquisition and management at LTER sites, with an early focus on sensor network management, cybersecurity, and data quality control and assurance;
- training in the use of advanced informatics tools for scientists and students engaged in LTER research, including instruction in traditional informatics areas such metadata and database design, as well as cutting edge technologies such as embedded sensor networks, scientific workflow software, distributed computing and knowledge representation;
- provision of a cross-trained cadre of information managers who can be deployed with standard curricula and training materials for working with LTER colleagues and collaborators; and
- support for K-16 and other educational activities by working closely with the LTER Education and Training Coordinator (Section 5.1).

These programs will 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 such as video-teleconferencing, web-based seminars, and other distance learning modes. Procedures for evaluation of the training workshops and other materials will be developed. Identification of training needs and development of curricula will involve participation of the targeted user groups and will accommodate changing research priorities and tools. This investment in training enables the cross-disciplinary team design and development process that will be a significant feature of our successful cyberinfrastructure creation.

5.3. Transdisciplinary Research

The LTER Network has developed a reputation for excellent disciplinary and interdisciplinary site research. Through a broad set of separate research projects that supplement LTER core funding, site researchers interact in creative and synthetic ways to meld expertise from diverse disciplines. The results of their research are routinely published in top journals of several fields, especially in general science and ecology.

The research we propose will elevate and transform the nature of scientific interaction in the LTER Network in two ways. First, we are re-conceptualizing the scale and scope of our research. Traditional LTER research has focused on specific ecosystems, whereas we are proposing network-scale research designed to address multi-scale environmental concerns. This synergy will allow LTER research to exceed the sum of its respective parts. Second, we propose moving from social science research conducted in parallel with ecological research to social-ecological research that expands the boundaries of both disciplinary and site-level research. This catalytic new approach promises to transform the way that scientific knowledge is created across disciplines and will be truly transdisciplinary.

Transdisciplinary social-ecological research is more than an innovative means to expand the boundaries of science – it is essential if we are to understand the nature of complex dynamic systems where humans so strongly influence the ecological webs in which they are embedded. From understanding and mitigating the impacts of global climate change to investigating the ecological footprint of food production strategies, the research we propose precludes adhering to disciplinary traditions that separate the natural and social worlds. Individual scientific disciplines offer important but incomplete understanding of the complex whole, and many key questions lie in areas that are outside the scope of both disciplinary and interdisciplinary study. Transdisciplinary research is required so that participants come together to formulate new questions and ways to address them.

The LTER Network is poised not only to undertake transdisciplinary research, but also to build the capability for future scientists to do so. The network already creates rich understanding of diverse ecosystems through intensive graduate student involvement in research and cross-fertilization at regular LTER All Scientists meetings. Involving the students directly in social-ecological research at the network level will enhance their understanding of how scientists from other disciplines think, how to communicate with them effectively, and how to appreciate the contributions of disparate bodies of knowledge toward catalytic synergies that create innovative science for an interconnected world. Even larger numbers of undergraduates are involved in LTER research, and many sites also involve K-12 teachers and students. These programs will enable the development of a future generation of scientists equipped to build from the strengths of their individual disciplines to create collaborative efforts without ever realizing that such open-minded engagement might once have seemed challenging to accomplish.

5.4. Capacity Building

Our transdisciplinary research plan builds on strong capabilities that exist at LTER sites. However, the scope and complexity of the research proposed goes well beyond anything ever envisioned for the LTER Network. This new LTER research vision requires additional capabilities that will make possible the level of coordination required to achieve the goals of the proposed program. These enhanced capabilities include new human capital in research, information management, education, updated and expanded cyberinfrastructure at site and network scales, and the expansion of the LTER Network through the addition of new sites and the formation of new partnerships.

Surveys of LTER capabilities undertaken as part of this planning effort, in addition to formal input from our 20-year review (NSF, 2000) have identified four areas where additional human capital is necessary to realize new research goals. (1) LTER sites require additional resources to strengthen social science research at sites. Sites that have received augmented levels of funding to incorporate the social sciences in their research programs (NTL, CWT) have done so successfully, but the majority of sites still lack strong social science components (Gragson et al. 2005). (2) Education programs at LTER sites have made considerable progress in incorporating K-16 programs into their research and education activities. However, further accomplishments are limited by the lack of trained educators to coordinate activities across the spectrum of educational opportunities at sites and within the Network. (3) The proposed research program will increase the capability of LTER sites to collect and integrate large volumes of data from sensor networks and from the acquisition of regional spatial and social science data, but effective management and use of these data require parallel increases in the number and expertise of personnel dedicated to information management. (4) The transition of the LTER program from conventional, individual site-based research to a broader, more integrative, cross-site research plan has been hampered by insufficient funding for cross-site synthesis. Additional human capital is needed to address the large-scale, interdisciplinary environmental issues described in this research plan, a plan that encompasses a broad array of social-ecological domains.

The new vision for LTER science requires that researchers, educators, and technology specialists work together to fully integrate technology, education, and new scientific disciplines across sites and networks, including emerging networks that will provide important opportunities for partnerships. These new kinds of interactions will require the development of new leaders within LTER capable of guiding transdisciplinary research and new training opportunities for LTER scientists.

Enhanced cyberinfrastructure capabilities are a critical need underlying the new science agenda. The envisioned cyberinfrastructure capacity represents a new level of centralization and coordination that will meet both site-based and Network needs and provide the functionality necessary for network-level science. Modern data collection technologies must be acquired and implemented, and the data streams from these new sensor systems will require additional bandwidth, storage, and computing power. An information management architecture needs to be developed and implemented so that LTER data can be integrated with data from other centers and networks and analyzed using tools from multiple sources. Collaborative work environments must be created to support research activities among geographically dispersed investigators. The need for enhanced cyberinfrastructure includes not only hardware and software but also additional human resources at both site and Network levels.

The new LTER science agenda will encourage partnerships at many levels. Individual scientists with long-term projects, field stations, and marine labs with capabilities to participate in new LTER observations and experiments, and emerging networks such as NEON, OOI, and WATERS will all provide important opportunities for cooperation (see below). In addition, the developing LTER research agenda will identify ecosystems and locations where appropriate research capabilities do not now exist. The addition of new sites to the LTER Network is an appropriate means to address the lack of specific research facilities or programs.

5.5. Collaboration and Integration with other Observatory Networks

The topics addressed by our research plan are integral to the NRC's Grand Challenges in Environmental Science (NRC 2001), which are also being addressed by many other agencies and programs. As we develop the specifics of our research program, a major goal will be to complement and collaborate with these other efforts, to learn from them as well as offer our unique capabilities. For example, our work on land and water change will build upon USGS and EPA efforts to characterize and understand land cover change through the National Land Cover Database. Our research plan will require collection of multi-site, long-term data on social-ecological variables and ecosystem services that will be coordinated with other national and international efforts to address the human dimensions of environmental change (e.g. www.nationalacademies.org/hdgc, www.ihdp.uni-bonn.de, http://usgcrp.gov/usgcrp/ProgramElements/human.htm).

There are also many points of potential intersection with the emerging constellation of U.S. environmental observing networks, such as NEON, OOI, and WATERS. These three networks, among others, are infrastructure networks designed as a community resource to permit broad-scale research on ecosystem processes and drivers in an increasingly human-dominated world. The LTER Research Plan would both benefit from these platforms and contribute to the overall network of sites. Where our plan goes well beyond these networks is in the explicit and mechanistic linkages between the biophysical and social sciences in addressing fundamental questions in human-environment interactions and interdependencies.

LTER has strong connections already with NEON: LTER scientists have played and continue to play leading roles in its development, five LTER sites are among the 20 preliminary NEON backbone sites, and several others have been identified as preliminary gradient sites. There is a similar early relationship with the even younger WATERS and OOI networks. In addition, the LTER Network has had a long and productive collaboration with the National Center for Ecological Analysis and Synthesis (NCEAS) and with the San Diego Supercomputer Center (SDSC) on development of cyberinfrastructure tools for synthesis. We have also had productive interactions with a number of other existing and emerging organizations (e.g., the Organization of Biological Field Stations and the National Phenological Network), whose programs will complement and enhance LTER education and citizen science efforts, in particular.

We also have several unique strengths to bring to multi-program and multi-agency efforts to address the environmental grand challenges. Our primary strength is a long history of observations and experimentation in important ecosystems, together with a strong cadre of scientists ready to address network-level social-ecological questions. We also have an established commitment to inclusive, cross-site synthetic research. For instance, the original Lotic Intersite Nitrogen Experiment (LINX) included a mixture of LTER and non-LTER sites (Peterson et al. 2001). The Long-term Intersite Decomposition Experiment (LIDET) included 11 non-LTER sites in addition to those in the Network at the time it started (Parton et al. 2007). An LTER-initiated analysis of ice-out dates for northern lakes and rivers was dominated by non-LTER sites, including many international sites (Magnuson et al. 2000). Two of 9 sites in the Productivity-Diversity Traits Network are not associated with the Network (Suding et al. 2005). And the EcoTrends project currently contains data from about as many USFS and ARS sites as LTER sites (Peters et al. *in prep*).

The development of a family of environmental observatories will provide new opportunities for research, cyberinfrastructure, and education partnerships with LTER, and we are fully committed to exploring and developing new relationships to advance common goals. History suggests that collaborations will be natural and productive. In some cases they will be crucial: for example, it doesn't make sense to create different cyberinfrastructure solutions for each observatory. Early collaboration will be vital for promoting integration and avoiding duplication when developing cyberinfrastructure solutions, in particular – and when designing experiments that will benefit from a larger geographic distribution than that provided by the LTER Network. We fully expect to continue our tradition of working with other sites, networks, and facilities, and look forward to building further collaborations that advance basic social-ecological science.

6.0 Program Management

The LTER Network in 2006 adopted a governance plan well-suited to the coordination and management of network-level science. The lead PI of each site plus a rotating representative from that site and Network committee chairs make up the Network Science Council (Fig. 6.1), led by a chairperson elected for a 2-year term. The chair of the Science Council also leads the 12-member Executive Board, which is authorized to act on the Council's behalf. The Science Council meets once per year in a combination science-business meeting; business is mostly limited to science-related reports and bylaw revisions. Most network business is conducted by the Executive Board, which meets once per month mainly by videoconference. The Executive Director of the LTER Network Office is an ex officio member of the Science Council and Executive Board.

The Executive Board, acting on behalf of the Science Council, will be responsible for the management of our Network research plan. The Board will form a Network-Level Science Committee, which will be charged with organizing all-site workshops in each of our three science theme areas to refine research questions and design the specific set of observations, experiments, and modeling activities required to address them. The Network-Level Science Committee will include site scientists chosen to represent a diversity of research interests and sites as well as members from the Executive Board, the Network Information Advisory Committee (NISAC), and the Education Committee. Workshop participants will include current site scientists as well as others recruited specifically to cover gaps in expertise; for most sites, this would include primarily social scientists, but education and CI specialists would also need to be well-represented.

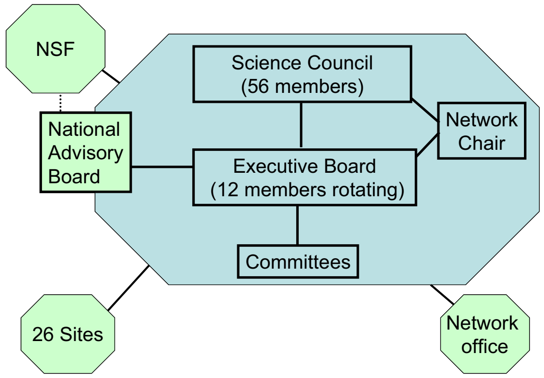

Fig 6.1. LTER Network governance.

We would expect integrated, collaborative research proposals to be developed via workshop activities. Each proposal will identify an organizational structure appropriate to the question, and clear linkage to the Network-Level Science Committee. Proposals will have in common support for Network information management and education at both the network and site levels.

Separate all-site workshops for education and for cyberinfrastructure will also be organized under the auspices of the Network Level Science Committee, and will be led by the Network Education Committee and NISAC, respectively. These committees are also charged with implementing the Network's updated strategic plans for education and cyberinfrastructure, with which research plan objectives are closely aligned.

7.0 Benefits to Society

The dimensions of human well-being valued by every American – health, security, an adequate livelihood, good social relations, and fundamental freedoms – rest on a foundation of ecosystem services. While well-being is generally increasing, many ecosystem services are eroding and further improvements in human well-being are often limited by access to ecosystem services. Thus, we face a challenge of improving human well-being while maintaining current and future ecosystem services. Processes and technologies for using and maintaining ecosystem services depend on fundamental advances in scientific understanding of social-ecological systems. The LTER Network is poised to provide that understanding through the research described in this plan.

First, LTER sites will seek to understand social-ecological dynamics connecting human cognition, attitudes, behaviors, and institutions with ecological structures and processes. This will include understanding variations and similarities influencing human decision making among disparate social groups and under different social and ecological conditions (both in place and time). Second, LTER sites will regionalize in order to understand these social-ecological dynamics in more diverse social-ecological contexts than they traditionally have pursued. For instance, the H.J. Andrews LTER site will likely expand beyond the boundaries of its national forest to include Portland and the entire Willamette Valley. Third, LTER sites will combine a long-term, spatially extensive, and multi-scale approach to understand these social-ecological dynamics in a regional context. This will expose temporal lags, spatial dependencies, and scale mismatches that generate decision-making surprises and sudden shifts. Finally, education will be both an activity and an object of study, engaging students and the public in the generation of ecological knowledge, sharing that knowledge broadly, and learning how to transmit ecological knowledge more effectively. Each of these research challenges is not individually unique. For them to be combined within a site, across sites, and over long time frames is unique and would present a significant opportunity for environmental and social sciences to contribute to society and human well-being.

These contributions to society will take many forms. The foundation starts with data. Decision makers of all types—public, non-profit, and private—need to understand the trends in their system. Rarely, however, can decision makers track trends because it requires long-term, well-documented, and easily accessible data. Long-term data are already a fundamental component of LTER activities.

For instance, research in the Baltimore Ecosystem Study (BES) LTER to understand the ecology of urban riparian areas and nutrients dynamics, a key policy issue for the restoration of the Chesapeake Bay, had two significant outcomes: a theory of urban hydrologic drought (Groffman et al. 2003) and an Urban Tree Canopy (UTC) riparian policy initiative for states in the Chesapeake Bay Watershed. Subsequently, Baltimore was the first urban area in the Chesapeake Bay Watershed to adopt a UTC goal, relying heavily upon data, analyses, and computational capacities of the BES. Methods and software tools were developed through this process, adopted by the USDA Forest Service's Northern Research Station, and applied in partnership with other urban regions including Annapolis, Boston, New York City, Pittsburgh, Washington D.C., and Burlington (Galvin et al. submitted and http://www.unri.org/). In the case of New York City, this analysis has led to a projected increase of $350 – 500 million in new expenditures for urban tree initiatives over the next 10 years. Finally, as a consequence of the BES prototype and wider application by the Forest Service to other cities, these methods and tools have been commercialized by the private sector to address the expanding demand for UTC analysis for a host of issues including storm water runoff, air quality, carbon markets (offsets and credits), and environmental equity (www.ncdcimaging.com/urbanforestry).

These LTER connections between research and decision-making applications — public, non-profit, and private sectors — are likely to increase over time because of the enduring collaborations that are fostered by the long-term nature of LTER sites and the likely changes described previously. The long-term foundation of LTER sites and Network and our forward-looking research plan will also promote research–decision making cycles (Pickett et al. 2007), where new findings and applications prompt decision makers to raise new questions as they implement policies, plans, and management actions. This creates a novel and dynamic cycle of use-inspired basic research and applications that can frame a new compact between social-ecological science and society (Allen and Hoekstra 1992, Stokes 1997, Pickett et al. 2007).

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9.0 Appendices

Appendix A. Sites in the LTER Network in 2007

Site	Location	Principal Biome
Andrews (AND)	Oregon	Northwest forest
Arctic (ARC)	Alaska	Tundra
Baltimore Ecosystem Study (BES)	Maryland	Urban
Bonanza Creek (BNZ)	Alaska	Boreal forest
California Current Ecosystem (CCE)	California	Pacific coast
Cedar Creek (CDR)	Minnesota	Prairie-forest
Central Arizona (CAP)	Arizona	Urban
Coweeta (CWT)	North Carolina	Eastern forest
Florida Coastal Everglades (FCE)	Florida	Coastal Everglades
Georgia Coastal Ecosystems (GCE)	Georgia	Island marshes
Harvard Forest (HFR)	Massachusetts	Northeast forest
Hubbard Brook (HBR)	New Hampshire	Northeast forest
Jornada Basin (JRN)	New Mexico	Southwest desert
Kellogg Biological Station (KBS)	Michigan	Row-crop agriculture
Konza Prairie (KNZ)	Kansas	Prairie
Luquillo (LUQ)	Puerto Rico	Tropical rainforest
McMurdo Dry Valleys (MCM)	Antarctica	Cold desert
Moorea Coral Reef (MCR)	French Polynesia	Coral reefs
Niwot Ridge (NWT)	Colorado	Alpine tundra
North Temperate Lakes (NTL)	Wisconsin	Temperate lakes
Palmer Station (PAL)	Antarctica	Southern Ocean
Plum Island (PIE)	Massachusetts	Northeastern watershed
Santa Barbara Coastal (SBC)	California	Kelp forests, ocean, watersheds
Sevilleta (SEV)	New Mexico	Transition zone for many biomes
Shortgrass Steppe (SGS)	Colorado	Grassland
Virginia Coastal Reserve (VCR)	Virginia	Eastern coastal waters

Appendix B. Site Science Volumes

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Appendix C. Network Vision, Mission, and Goals

The **Vision** of the LTER Network includes a society in which exemplary science contributes to the advancement of the health, productivity, and welfare of the global environment that in turn, advances the health, prosperity, welfare, and security of our nation.

The **Mission** of the LTER Network is to provide the scientific community, policy makers, and society with the knowledge and predictive understanding necessary to conserve, protect, and manage the nation's ecosystems, their biodiversity, and the services they provide.

LTER Network **Goals** are:

- Understanding: to understand a diverse array of ecosystems at multiple spatial and temporal scales.
- Synthesis: to create general knowledge through long-term interdisciplinary research, synthesis of information, and development of theory.
- Outreach: to reach out to the broader scientific community, natural resource managers, policymakers, and the general public by providing decision support information, recommendations, and the knowledge and capability to address complex environmental challenges.
- Education: to promote training, teaching, and learning about long-term ecological research and the Earth's ecosystems and to educate a new generation of scientists.
- Information: to inform the LTER and broader scientific community by creating well-designed and well-documented databases.
- Legacies: to create a legacy of well-designed and documented long-term observations, experiments, and archives of samples and specimens for future generations.

The Decadal Plan for LTER

Integrative Science for Society and the Environment: A Plan for Science, Education, and Cyber-infrastructure in the U.S. Long-Term Ecological Research Network

Section III

Ecotrends: Long-term Ecological Trends in the LTER Network

The U.S. Long-Term Ecological Research Network
October 1, 2007

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The EcoTrends Project was initiated in 2004 by LTER researchers in response to the need for easily accessible data from long term ecological research programs. A wealth of data have been collected since the early 1900s from USDA and LTER sites that represent a wide range of ecosystem types, including forests, grasslands, shrublands, freshwater lakes and streams, coastal and estuarine marine systems, urban areas, and arctic and antarctic systems. A variety of different kinds of data have been collected from these sites through time, ranging from primarily climatic and demographic data since the 1800s to more recent quantitative assessments of plant, animal, and microbial populations and communities, elements of hydrologic and biogeochemical cycles, biodiversity, and disturbance regimes. However, most of these data are investigator-driven with a number of characteristics that limit their usefulness for synthetic analyses. Datasets tend to be very detailed, collected at a fine spatial and temporal resolution, and have limited documentation. EcoTrends was initiated to provide long-term (>10 years) derived datasets in a common format with common documentation (Ecological MetaLanguage) to promote synthesis across these very diverse sites.

The goals of EcoTrends are (1) to create a platform for synthesis by making long-term data accessible, and (2) to illustrate the application of this platform for addressing site and Network-level questions. We concentrate efforts on four major types of data: climate and physical variability, including disturbances; human population and economy; biogeochemistry; and biotic structure, including biodiversity. These data represent priority areas for synthesis within the LTER Network and the decadal research plan, and reflect current and expected future needs of ecologists. To date, the project includes data from all 26 LTER sites, 14 USDA USFS sites, 7 USDA ARS sites, 1 DOE national laboratory, 1 USGS site, and 1 state funded site, for a total of 48 sites. We also collaborate with the National Center for Synthesis and Analysis (NCEAS), and recently received endorsement by the Ecological Society of America. We continue to add data, sites, and collaborators from different state and federal agencies.

Two specific products are underway: (1) a book to be published as part of the LTER Synthesis Series by Oxford University Press on trends in long-term data within and among sites, with examples that illustrate the value of long-term data for addressing important environmental questions; and (2) a web page containing derived data and metadata that will be easily accessible for synthetic analyses and education. The manuscript is scheduled to be delivered to Oxford University Press in January, 2008.

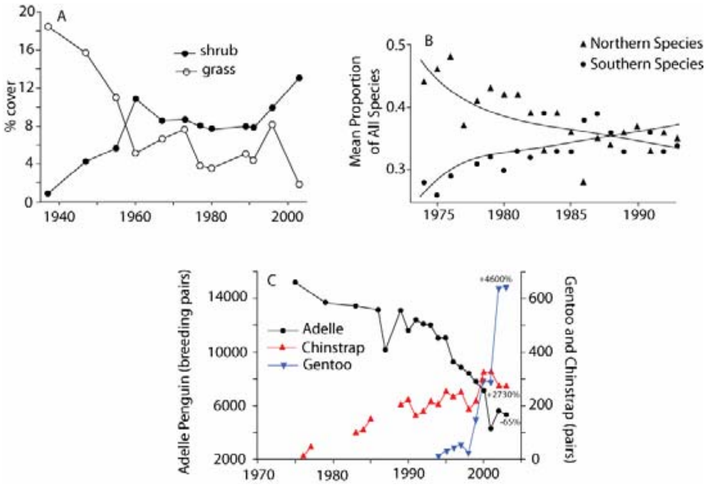

Figure 1. Examples of EcoTrends data products. Long-term changes in (A) shrub vs. grass cover at JRN, in (B) the proportion of northern vs. southern fish species at SBC, and in (C) the distribution of penguin species at PAL. All demonstrate environmental regime shifts only apparent from long-term observations.

The web page will include search and query options, and data will be available for download. The page is being structured as an LTER Network-level resource that will provide a general framework for the expansion of additional datasets and sites through time. The web page is currently under development, to be publicly available in January 2008; it can be presently accessed (and graphs viewed) at www.ecotrends.info using the username “nsf” and password “ecotrends”. Our future plans – pending available funding – include the expansion of sites and data, and the automatic harvesting of data from site-based data catalogs to keep the EcoTrends data up-to-date.

EcoTrends has had broad support

within the LTER Network. In 2005, an 11-member editorial committee and a 9-member committee of technical specialists were formed. Members represent different subdisciplines of ecology from a number of different LTER sites. Both groups meet regularly to provide input on the direction of the project, and to ensure that the project will be of broad utility to researchers, educators, and policy makers. Currently the project is operated jointly by the USDA ARS Jornada Experimental Range and the Jornada Basin LTER site at New Mexico State University (NMSU), in collaboration with the LTER Network Office at the University of New Mexico (UNM). Supplements from NSF in 2006 and 2007 to NMSU and UNM have helped to support the project. We anticipate that the long-term maintenance of the database and its expansion will become an LTER Network-supported activity.

The Decadal Plan for LTER

Integrative Science for Society and the Environment: A Plan for Science, Education, and Cyberinfrastructure in the U.S. Long-Term Ecological Research Network

Section IV

Strategic Plan for Education in the LTER Network

The U.S. Long-Term Ecological Research Network
October 1, 2007

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1.0 Executive Summary for Education

LTER education and outreach efforts can have a significant impact on American education systems and communities if we take advantage of the unique assets of the LTER Network. These include research communities with long histories of interdisciplinary work on environmental issues; a network linking those research communities to one another and to educational systems through both personal contact and information technologies; and place-based, long-term, multi-disciplinary and spatially distributed data sets and resources for acquiring new data and for synthesis and application..

Our vision for LTER education and outreach includes three components:

1. *Develop leadership, organization, and cyberinfrastructure*. Programs that enable LTER research to have a public impact and enable LTER scientists and educators to include and learn from diverse people and perspectives will require an organization with three key parts: a) Network education leaders who coordinate research and development projects and communication among site coordinators, engage in Network-wide program evaluation and targeted self-studies, and connect LTER education efforts to LTER research and to education policymakers; b) education site coordinators who implement education programs at the local level in coordination with LTER scientists and other LTER educators; and c) education cyberinfrastructure that enables cross-site collaboration on education research and programs, serves as an active repository for teaching and assessment resources, and enables Network-wide program evaluation.

2. *Conduct ground-breaking programs of research and development leading to shared goals and programs for education and outreach*. We have identified two targeted goal areas in this component. The first of these is environmental science literacy – the capacity to understand and participate in evidence-based discussions of socio-ecological systems – for students and citizens. Network-wide research and development programs in this area will lead to learning progressions that identify appropriate educational goals for children and adults of different backgrounds, teaching materials, and assessment resources. The second goal area is including and learning from diverse people and perspectives within LTER communities. Network-wide research and development programs in this area will enable LTER sites and the LTER Network to include people from diverse backgrounds in LTER research and to learn from local and national communities.

3. *Develop Network-supported programs for working with key constituent groups*. We have identified three constituent groups where LTER education and outreach efforts are particularly important.

    - *Work with K-12 teachers and administrators*. Although LTER sites will have programs that involve direct work with students, their primary focus will be on (a) professional development and curricular support for teachers, and (b) work with administrators and policymakers. These programs will focus on the two goals areas identified above: promoting environmental literacy for all students and engaging diverse people and perspectives in environmental science.

    - *Work with Undergraduate and graduate students and professors*. The nature and scope of social-ecological science requires new models for promoting environmental literacy through college teaching and for recruiting and training future scientists at the undergraduate and graduate levels. We must enable the research community to reflect and to inform the diverse public that we serve and from whom we seek support. 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, and professional training that include components aimed at expanding recruitment and retention of a diverse student body and faculty.

- *Work with active citizens in LTER communities*. The success of a social-ecological research and education plans requires the participation of citizens that govern the management of systems that provide ecosystem services. Our program involves a participatory approach – citizen science – in which citizens are active in data collection and communication between researchers and policy makers.

Education and outreach are central to the LTER Network's mission. Our research cannot be successful unless citizens understand its implications. And the scientific community needs to be receptive and responsive to the views and needs of a diverse array of stakeholders within society while educating those stakeholders about LTER research and its implications. We seek to reap the full benefit of the Network's potential by providing an integrated education plan that fully complements its research portfolio.

2.0 Introduction

Long term ecological research matters intellectually; it contributes to our growing understanding of the social-ecological systems that we study. It also matters in a practical sense, because our collective future depends on our ability to understand the social-ecological systems on which we depend and to act on our understanding. The LTER Integrated Research Plan describes how we can enhance our scientific understanding of these systems. However, it is not scientists or the readers of academic research that will determine how human populations act in social-ecological systems; it is members of the larger public who need to understand and act on our research.

Education and outreach are central to LTER's mission. Our research cannot be successful unless citizens understand its implications. The scientific community needs to be receptive and responsive to the views and needs of a diverse array of stakeholders within society while educating those stakeholders about LTER research and its implications.

We envision:

- a scientific endeavor that continues, builds on, and celebrates the rich history of basic scientific discovery;
- a society with the environmental science literacy needed for sound environmental citizenship. Thereby, a society that makes best use of timely, accurate, and unbiased information in decision making, including the capacity to act proactively and with forethought rather than just reactively and with hindsight;
- engagement of the full spectrum of our diverse society in developing and applying understanding of environmental systems and challenges;
- an environmental science enterprise that both embraces as one of its goals the delivery of useful knowledge for environmental decision making; is committed to the delivery of knowledge in a useful form; and that is receptive and responsive to the knowledge needs of the public; and
- an environmental research and education enterprise informed by an understanding of the science/society interface – the points of contact, the mechanisms of teaching and learning, the timeframes of information exchange.

LTER education and outreach efforts can have a significant impact on American education systems and communities if we take advantage of the unique assets of the Network. These include:

- research communities with long histories of interdisciplinary work on environmental issues;
- a network linking those research communities to one another and to educational systems through both personal contact and information technologies; and
- place-based, long-term, spatially distributed data sets and resources for acquiring data.

In the following pages we present our plan for taking advantage of the LTER Network's unique assets to work toward the goals envisioned above. We begin by describing a vision and an illustrative scenario that embodies our long-term goals. We then describe the results of a self-study conducted by LTER education representatives that lays out our current resources and needs; on-going assessment is an important part of our strategic plan. Finally, we describe strategic initiatives to address each aspect of the programs we envision.

3.0 Education Vision and Illustrative Education Scenario

Our vision for LTER education and outreach includes three key components:

1. *Leadership, organization, and cyberinfrastructure* that will enable the Network to support programs at individual sites and to influence education standards and assessment at state and national levels.
2. *Research and development* leading to shared goals and programs for education and outreach. We have identified two targeted goal areas: a) environmental science literacy for students and citizens and b) including and learning from diverse people and perspectives within LTER communities.
3. *Programs for working with key constituent groups*, including a) K-12 teachers and administrators, b) undergraduate and graduate students and professors, and c) engaged citizens.

In this section we describe each component of the vision, then show how the components can work together with an illustrative scenario focusing on the role of water in environmental systems.

3.1. Leadership, Organization, and Cyberinfrastructure

The LTER Network provides the foundation for an integrated research and education program that focuses on developing two-way communication with several constituent groups, ranging from children in elementary schools to active adult citizens. The key actors in this program will be scientists and education representatives at individual LTER sites, each engaging students and citizens in their localities and states. These local representatives will be supported by Network-wide resources in several forms:

- leadership from Network-wide education and Citizen Science coordinators, working with education coordinators at each site;
- Network-wide education cyberinfrastructure that enables cross-site data sharing and data analysis, sharing of educational resources, and multi-site educational research and development projects;
- research and development activities that enable site representatives to agree on shared education goals and to conduct educational research on how to achieve those goals;
- teaching resources for programs developed by individual sites or networks of sites and shared through Network-wide cyberinfrastructure; and
- assessment resources to evaluate the success of programs at individual sites and for the Network as a whole.

The LTER Network will develop programs for several constituent groups: K-12 students and teachers, undergraduate and graduate students and professors, culturally and racially diverse constituents, and engaged citizens. For each program, the work of scientists and educators at individual sites will be supported by the Network-wide resources suggested above.

3.2. Research and Development: Goals for Education and Outreach

The LTER Network is uniquely situated to conduct high-quality educational research. LTER sites are geographically dispersed and already working with local populations that include a culturally and socioeconomically diverse sample of students and teachers. Scientists with expertise in areas of environmental science where public understanding is critical are already working closely with educators. In our vision these unique assets will serve as the basis for a program of research and development that focuses on two primary goals: a) environmental science literacy for constituent groups from school-age children through active adult citizens, and b) including and learning from diverse people and perspectives to improve the diversity of LTER research communities, the quality and relevance of LTER research, and the quality of communication between LTER sites and the local communities that they serve.

3.2.1. Environmental Science Literacy

The LTER Network research plan considers as an organizing construct the interactions between ecosystems and the humans that occupy, manage, or otherwise affect them. This expansion of the Network's research portfolio poses challenges and opportunities for educators as well as scientists. In particular, it provides the opportunity to reconsider the goals for our collective work with schools and adult citizens.

We propose that our work with schools and the public should be informed by a vision of environmentally responsible citizenship. We must recognize that our actions affect the material world – the environmental systems on which we and our descendents depend – and find ways to use scientific knowledge as a vehicle for considering the environmental implications of the decisions we make as citizens.

For these reasons, the LTER Network needs to focus on the goal of environmental science literacy – the capacity to understand and participate in evidence-based discussions of social-ecological systems. Environmentally literate citizens should have the capacity to act as environmentally responsible citizens. For us that does not imply any particular political position, but it does mean two things:

1) environmentally literate citizens should be able to understand and evaluate experts' arguments about environmental issues; and
2) they should be able to recognize social or economic policies and personal actions that are consistent with their environmental values.

We note that this definition of environmental science literacy does not imply teaching particular values or positions on environmental issues. Rather, it requires helping citizens to be aware that human actions have environmental consequences and to understand arguments from evidence about those consequences. Just as the "integrated and iterative conceptual framework" (Collins et al. 2007) provides a diagrammatic way to represent the LTER Network's science agenda, we suggest that a simplified version of this diagram (Figure 1) can represent our shared education agenda.

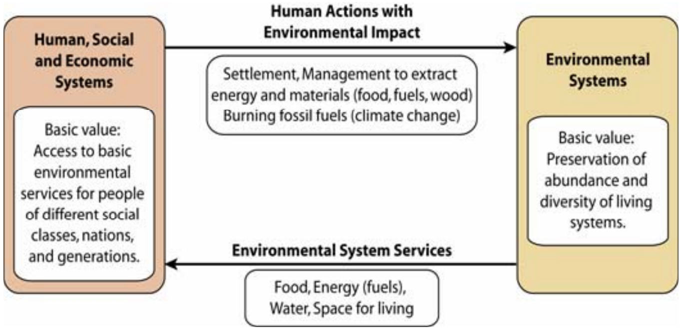

Figure 1. Structures and processes of social-ecological systems (from Anderson 2007; cf Collins et al. 2007).

Figure 1 depicts key relationships in terms of two boxes, representing human and environmental systems, and two arrows, representing the environmental impacts of our actions and the environmental services upon which we depend. Thus citizens need to understand that issues associated with one part of the loop inevitably involve the whole loop. For example, if we want to preserve water quality in environmental systems (the right-hand box), we need to consider how our management affects water quality (the human actions impact arrow) and how we will satisfy our demands for water (the environmental system services arrow).

This implies both different ways of thinking about school subjects – social studies and science – and different ways of living our lives as public and private citizens. Whenever one thinks about any of these issues, one needs to think about the whole loop. For example, the current science curriculum (e.g., NRC 1996, NAGP 2006) is mostly inside the environmental systems box. LTER research and development can lead to programs that enable schools a) to teach what's inside the environmental systems box – traditional science content – in a way that helps students connect environmental systems to actions and services, and b) to help students and citizens see connections between the box and arrows typically not considered.

Figure 1 provides a framework for research and development, not a finished product. Although citizens need to understand general principles associated with this diagram, its most important applications are local and specific. The LTER Network is uniquely positioned to develop resources that balance the general with the local.

3.2.2. Including and learning from diverse people and perspectives

The goal of environmental science literacy seems to imply primarily one-way communication – from LTER sites to local communities. We do not believe, however, that this goal can be achieved unless the communication goes both ways. LTER sites and the LTER Network must both include people from diverse backgrounds and learn from local and national communities.

This goal poses both social and intellectual challenges. Socially, LTER sites and the Network need to support programs that recruit students from diverse backgrounds into careers in environmental science, and that involve citizens of diverse backgrounds – students, teachers, and active adult citizens – in LTER research. Intellectually, LTER sites and the Network need to develop organized ways of learning from diverse people and perspectives to improve the quality and relevance of LTER research and the quality of communication between LTER sites and the local communities in which they reside.

3.3 Programs for Working with Key Constituent Groups

The LTER Network will continue to have limited resources for education and outreach, so our programs will need to focus on specific constituent groups if they are to be effective. Based on current programs and on consideration of where LTER programs are likely to have the greatest impact, we have identified three focus groups for LTER education and outreach programs.

K-12 teachers and administrators. Although LTER sites will continue to have some programs that provide direct services to students, the primary focus of the LTER Network will be on programs for teachers and administrators. The Network leadership and cyberinfrastructure will support professional development for teachers, as well as testing and disseminating instructional materials and assessments that will help teachers develop environmental science literacy in their students. The Network will also work with administrators and policymakers to influence school curricula and assessments by placing LTER scientists and educators on key committees and by providing quality resources for standards and assessments.

Undergraduate and graduate students and professors. LTER programs at the undergraduate and graduate level will have two primary goals. First, the Network will support the development of resources that enable professors, including LTER scientists, to develop environmental science literacy in all of the students they teach. At the graduate level, the LTER Network will sponsor programs that enable graduate students to communicate across sites and prepare them for careers in interdisciplinary research. Second, LTER programs will introduce minority students to ecological research and seek to recruit diverse students into careers in environmental science.

Active citizens. LTER programs will promote engagement of local citizens in Citizen Science activities that a) enable scientists and educators to benefit from the local knowledge of citizens, b) allow citizens to learn about and participate in environmental science research, and c) provide useful data. LTER programs will also provide information and education for citizens who are in decision-making roles and would like to consider the environmental consequences of their actions.

3.3.1. An Example: Education and Outreach for Water in Environmental Systems

To provide an illustration of how this system might work, we choose an important issue: water movement and water quality in social-ecological systems. Processes that affect water movement and quality are studied at every LTER site as a component of the core research questions, and water is critical to both natural and human communities.

The LTER Network education and outreach programs will thus include water systems as an emphasis area. This decision leads to many questions. How do students learn about the water cycle? How do we educate scientists who will conduct research that is relevant to society? What do citizens need to know about that research, and how can we inform them?

An understanding of water in environmental systems is a necessary, though not sufficient, component of environmental science literacy. Without understanding how water moves through environmental systems and interacts with other substances, it is not possible to make informed decisions about water at an individual or societal level. For example, an individual who does not know which substances will dissolve in and move with water underground will be unprepared to participate in a community decision about how to manage an aging municipal landfill.

Specific goals for citizens' understanding of the role of water in socio-ecological systems appear in Figure 2, which illustrates the connected understandings necessary to reason about water in natural and engineered systems. Arrows connecting two boxes representing natural and human engineered systems represent the environmental services that natural systems provide for humans and the impacts that humans have on natural systems. Within both natural and human engineered systems, environmentally literate citizens should understand the structure of systems through which water flows and be able to trace matter (water and other substances) through systems. Tracing matter requires understanding processes that move

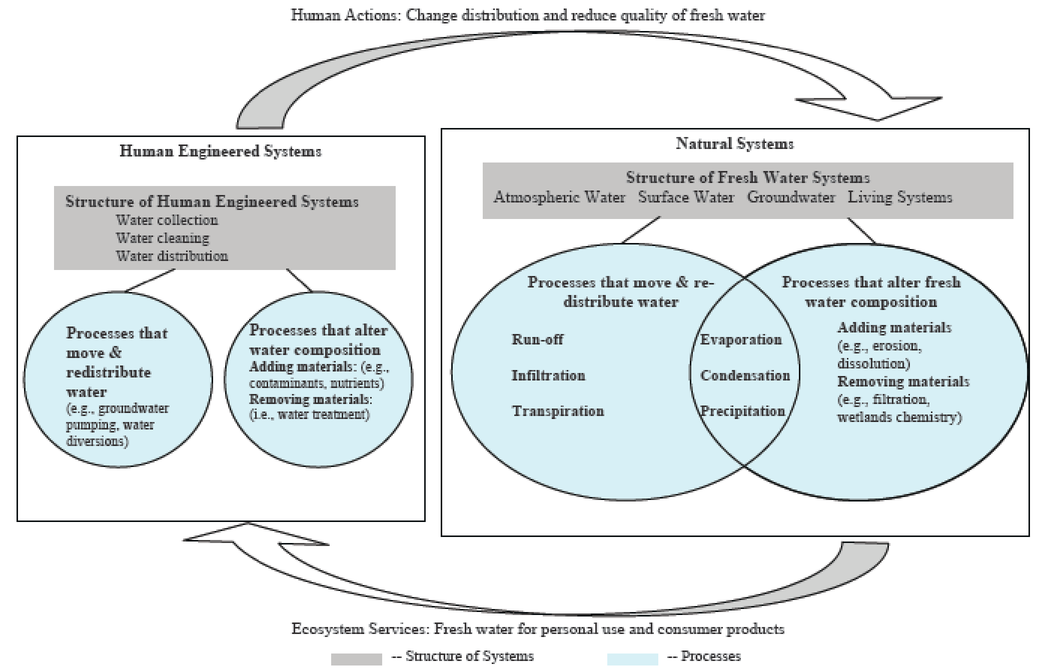

Figure 2. Loop diagram for water literacy. This diagram (from Covitt, Gunckel, and Anderson, in preparation) was developed through a research project that was supported in part by two EdEn supplements to a collaborative group of four LTER sites (KBS, BES, SGS, SBC).

water and substances and processes that change the composition (quality) of water.

Fig. 2 suggests how we can balance general principles with local activities as individual LTER sites engage their constituent groups. The diagram also provides a mechanism to envision an integrated research and education plan for the LTER Network. Imagine K-12 students at the beginning of their studies of the water cycle: their teacher focuses on a lesson plan developed while participating in an LTER education program (e.g. a Research Experience for Teachers or a workshop or other professional development opportunity). The teacher uses assessment resources that focus on environmental literacy for water to evaluate the effectiveness of the lesson. If appropriate, the teacher submits the plan to a program that makes teaching resources available throughout the Network. The plan is peer reviewed and, if appropriate, made available to others through Network cyberinfrastructure.

By the time these students enter high school, a strong foundational understanding of the structure and processes of freshwater systems has been formed, as well as an understanding of local and regional watersheds and human water supply systems. This is possible through the long-term relationship between the LTER site and the K-12 school system. Throughout high school students develop the basis of understanding the social-ecological issues surrounding local and regional water systems. Their understanding includes how science research is conducted and how citizens can use science to inform their decisions.

Some of these high school students will graduate and become a part of the local community, working in diverse fields and engaging in social issues as environmentally literate citizens. Some number of these citizens will maintain an interest in participating in environmental issues, becoming an LTER Citizen Scientist. Those so-engaged will participate in workshops, lectures, and training to collect samples and data relevant to LTER research and their water system.

Other high school students will go on to college. LTER scientists will integrate LTER research into their classrooms using projects such as Teaching Issues and Experiments in Ecology Education (TIEE) and other curriculum efforts. Some students will take the opportunity to participate in undergraduate research through the LTER. These research experiences will provide opportunities for students to engage in social-ecological research. Some undergraduates will become involved in LTER education programs and, ultimately, will choose teaching as a career, bringing their science and research experiences to their K-12 students.

Other undergraduates will be inspired to continue their science education by becoming graduate students in LTER programs. These students will continue their socio-ecological research training under the mentorship of LTER scientists. These students could take advantage of opportunities to work across sites, engage in synthetic research projects with their peers, and engage fully in the socio-ecological framework by participating in discussions between LTER scientists and decision-makers, citizen scientist groups, educators, and all the various constituent groups that interact within this framework. The distinguishing feature of LTER programs, i.e. their long-term nature, provides the opportunity to imagine this scenario. The implementation of an integrated social-ecological research and education program would allow it to be realized.

4.0 Current Status of LTER Education Programs

With support from a pair of NSF EdEn grants, we have contacted education representatives at all of the LTER sites and conducted surveys about current programs and goals for future work. Several findings inform our strategic plan.

Current education and outreach activities. LTER sites are engaged in a wide variety of education programs, including local programs that address all of the goals and constituent groups identified above. In general, LTER sites have been very effective in leveraging schoolyard LTER and EdEn funds to obtain support from many other public and private sources for their programs. These programs are strongest in K-12 and undergraduate education. LTER sites have fewer connections with community colleges and independent schools, or with Citizen Science programs. Although there are graduate students working at all LTER sites, there are few systematic programs to prepare students for cross-site or interdisciplinary work.

Lack of Network-wide coordination and cyberinfrastructure. Although there are extensive site-to-site contacts among education representatives and there are several education and outreach projects that involve cooperation among sites, communication and coordination among education programs at different sites have declined since the Network lost its Education Coordinator in 2004. Aside from a listserve, there is no cyberinfrastructure to support Network-wide education and outreach programs.

Support for goals and constituent groups. Individual sites vary in their emphases, but there is strong support for working towards all of the goals and constituent groups identified above. Moreover, a number of individuals and sites have volunteered to play leadership roles for each of the programs proposed above.

5.0 Strategic Initiatives to Develop LTER Education

Our vision for a Network-wide education program described above balances general principles with local knowledge and also balances Network-wide development of goals, resources, and cyberinfrastructure with implementation of local programs at LTER sites. The LTER Network is uniquely qualified to promote environmental science literacy because of its ability to address both local and global issues while giving multiple constituent groups access to cutting-edge environmental science.

In Section 4 we reported on our assessment of the current capacities and organization of education efforts in the Network. The LTER Schoolyard program has achieved impressive results with limited resources. The LTER education community surveys show that a significant component of the success of the LTER Schoolyard program is a result of leveraging funds for staff and program support and partnering with complementary programs, institutions (e.g., K-12 school districts), and initiatives. Further, while the site programs are robust they are site-specific; cross-site projects rarely occur and, when they do, programs don't expand across the Network.

In this section we propose specific initiatives that will bridge the gap between where we are now and our vision for the future. We follow Section II's outline to describe initiatives to a) develop leadership, organization, and cyberinfrastructure, b) promote research and development around our goals of environmental science literacy and diversity, and c) develop programs for specific constituent groups: K-12 teachers and administrators, undergraduate and graduate students and professors, and active citizens.

5.1. Initiative 1: Develop Leadership, Organization, and Cyberinfrastructure

The development of an integrated research and education initiative that focuses on social-ecological research and that reaches multiple constituent groups requires Network-level leadership and cyberinfrastructure as well as sufficient site level personnel. Each of these requirements we describe below.

Goal 1. Develop LTER Network Education Leadership

The Network educational effort to engage learners of all ages (i.e., K-20 students, the public, social-ecological scientists, education researchers) will require leadership to use and learn from LTER research; to coordinate activities led by education coordinators at individual LTER sites; and to coordinate cross-site, regional education and outreach programs. The Network will also need leadership for the Network-wide effort in Citizen Science programming and initiatives by forming collaborative relationships with existing Citizen Science programs; supporting the development of novel protocols; engaging citizen groups; and organizing workshops and other opportunities for sharing best-practices, data exchange, and collaboration. LTER Network education leaders will also coordinate regular Network-wide program evaluation and targeted self-studies and will promote LTER education efforts in regional and national conferences and arenas. These leaders will work closely with a range of LTER staff including scientists, education researchers, constituent groups, education administrators, and cyberinfrastructure and other technical experts.

Goal 2. Establish LTER Education Site Coordinators

The balance between global and local emphases in our programs will demand strong leadership at the site level as well as the Network level. Site coordinators will implement education and outreach activities at the local level; participate in coordinated cross-site and Network education programming and assessment; and will work closely with site scientists and students, education researchers, local constituencies, education administrators, and site cyberinfrastructure and technical experts.

Goal 3. Develop LTER Education Cyberinfrastructure

Cyberinfrastructure will support education and outreach as well as science by enabling cross-site the collaboration on education research and programs; serving as an active repository for teaching and assessment resources; and enabling Network-wide program evaluation. Because both scientists and educators will be using the same cyberinfrastructure, it will be much easier than it is now to use scientific datasets, visualization tools, and other resources in educational programs.

5.2. Initiative 2: Conduct Research and Development for Environmental Science Literacy and Inclusion

Both of our targeted goal areas, environmental science literacy and including and learning from diverse people and perspectives will require programs of research and development.

Goal 4. Develop Learning Progressions Leading toward Environmental Science Literacy

LTER sites as research institutions are uniquely positioned to develop high-quality education resources combining site-based and Network-wide components. Returning to water systems as an example, each site can develop resources that make use of data about local water systems and the experiences of LTER scientists and educators in their local environments. For example, local networks of schools could engage in stream-monitoring projects that track water quality and flow-rates in local watersheds, supplementing their data with data from other schools and the LTER Network. The LTER education site coordinators can develop materials that support teachers in the classroom and in the field, enable them to communicate with one another, and enable them to assess their students' understanding of local water systems.

These local efforts will be supported by Network-wide educational research and development programs. The Network-wide programs will be organized around *learning progressions* in key dimensions of environmental literacy. Learning progressions are descriptions of increasingly sophisticated ways of thinking about or understanding a topic (NRC 2007). Well-grounded learning progressions can serve as a basis for dialogue among science education researchers, developers of standards documents, assessment developers, and curriculum developers. This approach is endorsed by both the National Research Council (Wilson and Bertenthal 2005, NRC 2007) and the National Assessment Governing Board for their 2009 National Assessment of Educational Progress science assessment (NAGB 2006). The conceptual and methodological foundations for learning progressions appear in Briggs et al. (2004) and Smith et al. (2006).

In most environmental learning domains empirically grounded learning progressions have not yet been developed. With support from two EdEn supplements and other grants, a project that includes four LTER sites (Kellogg Biological Station, Baltimore Ecosystem Study, Shortgrass Steppe, and Santa Barbara Coastal) has made progress toward developing learning progressions in four key domains:

1. *Carbon.* The role of carbon compounds in Earth, living, and engineered systems, including carbon dioxide in the atmosphere, energy flow and carbon cycling in ecosystems, and fossil fuels in human energy and transportation systems.
2. *Water.* The role of water and substances carried by water in Earth, living, and engineered systems, including the atmosphere, surface water, and ice, ground water, human water systems, and water in living systems.
3. *Biodiversity.* The diversity of living systems, including variability among individuals in a population, evolutionary changes in populations, and diversity in natural ecosystems and in human systems that produce food, fiber, and wood.
4. *Citizenship*. Using scientific reasoning for responsible citizenship. Citizens play both private roles (e.g., learner, consumer, worker) and public roles (e.g., voter, volunteer, advocate) in which their actions have environmental consequences.

The LTER Network is uniquely positioned to develop learning progressions in these and other domains. The Network and the individual sites bring scientists performing cutting-edge work together with educators; they have data and experience with a wide variety of local ecosystems, and they have access to teachers and students representing the geographic and cultural diversity of the U.S. as a whole. The LTER Education Coordinator and LTER cyberinfrastructure will make these complex cross-site studies possible.

The Network Education Coordinator will work with groups of individual sites to organize research studies leading to the development of learning progressions for each facet of environmental literacy. The results of these studies will include publishable educational research. They will also provide important resources to LTER sites for their local work, including:

- learning goals for students in elementary, middle, and high schools;
- assessments that enable teachers to monitor their students' progress through the learning progressions – how well they are meeting the learning goals; and
- teaching materials that address fundamental principles for each component of the learning progression.

Goal 5. Include and learn from diverse people and perspectives

The social-ecological framework proposed in the LTER research and education plan requires communication between and among actors in the social systems and ecological research communities. These perspectives will be diverse along every axis – political, socioeconomic, ethnic and cultural, age, and gender – much of which should be represented in all participating groups. Current research suggests that the benefits of diversity within groups include higher system performance and robustness (Johnson and Longmire 1999) and increases in group creativity, information sharing, flexibility, and thoughtfulness (Phillips et al. 2004; Nemeth 1995; Triandis et al. 1965; Maier and Hoffman 1961). We propose implementation of an *LTER Diversity Initiative* that develops new site-based and Network-wide programs and coordinates the diversity and training efforts currently in place at sites across the Network.

Aided by information collected at the LTER Network level on the current status of diversity across the Network, new programs will aim to increase diversity at multiple levels beginning with a focus on recruiting K-12 students to college. An LTER Summer Bridge Program would support minority high school students during the fragile transition from high school to college provides support at a fragile transition point. The program would recruit students from across the Network while they are in high school, providing college readiness training and support during their senior year, and an REU site-like internship for the summer between high school graduation and matriculation to college.

At the undergraduate level, coordinated cross-site field trips designed to expose minority students from 2- and 4-year colleges across the country to LTER science at several sites would aim to recruit diverse students to science teaching and research. This program might include collaboration with the Ecological Society of America's Strategies for Ecology Education, Development, and Sustainability Program (SEEDS; (www.esa.org/seeds/)) or similar programs to assist with student recruitment and professional development activities for faculty.

The development of a robust network to support diversity cannot stop at the undergraduate level. LTER programs would include minority graduate and faculty fellowships (including faculty from 2-year colleges and minority-serving institutions) to focus on recruiting new and retaining existing participants into LTER research and education programs. Successful models include the NSF's Interdisciplinary Graduate Education and Research Traineeship (IGERT) and Department of Education GAANN initiatives. Students and faculty would be recruited from four-year institutions, two-year community colleges, and institutions that serve minority populations (e.g., Tribal colleges and historically black colleges and universities).

5.3. Initiative 3: Develop Programs for Working with Specific Constituent Groups

The general goals and frameworks described above will be designed to support education and outreach programs for work with specific constituent groups at individual sites or collaborative groups of sites. In particular, our programs will focus on work with three constituent groups: K-12 teachers and administrators, undergraduate and graduate students and their professors, and active citizens.

Goal 6. Work with K-12 Schools to promote environmental literacy

Work with K-12 schools has been and will continue to be a primary focus of LTER education efforts. Although LTER's will occasionally have small programs that involve direct work with students, their primary focus will be on (a) professional development and curricular support for teachers, and (b) work with administrators and policymakers. Each of these programs is described below.

Professional development and curriculum support for teachers. Programs of educational research and development can produce resources for teaching and learning, including standards, assessments, and teaching materials. These resources are necessary but not sufficient to support high-quality teaching in K-12 schools. LTER sites will also continue their engagement in professional development activities for teachers, supported by research and development at the Network level and communicated through the Network cyberinfrastructure.

Some of this support will take the form of professional development programs designed to give the teachers the knowledge and skills they need to take advantage of LTER resources. For example, teachers engaged in water quality monitoring projects will need general scientific knowledge about aquatic systems and processes that affect water quality, specific knowledge about local water systems, and techniques and equipment to study water quality in watersheds around their schools and to communicate about their data.

LTER sites will also support local schools by creating opportunities for teachers to work directly with LTER scientists. For example, several LTER sites that are associated with universities have used GK-12 grants to allow graduate students to work in local schools for sustained periods. Similarly, LTER sites have used small grants for Research Experiences for Teachers, bringing teachers on site and engaging them in LTER research projects. The LTER education coordinator and cyberinfrastructure will enable the Network to support individual sites in these efforts and to organize collaborative efforts by sites that lack the local resources to develop programs individually.

Policy and assessment support for administrators and decision makers. The LTER Network and individual LTER sites are well positioned to affect educational policy and assessment at district, state, and national levels. The Network-wide work on learning progressions will enable the Network to influence standards and assessments at the national level, where efforts to make high quality environmental science available to K-12 schools are a high priority. LTER scientists and educators will also be well-positioned to serve on policy-making boards and assessment development committees in states and local school districts.

This kind of work will be especially important for topics like water, which are underrepresented in current standards, assessments, and curriculum materials. For example, although the National Science Education Standards (NRC 1996) mention the water cycle, they do not mention watersheds, water quality, or ground water. Other topics, such as carbon cycling, are well represented in the Standards, but in fragmented ways that work against the kinds of integrated understanding that will enable students to "connect the boxes with the arrows" in Figure 1 when they confront issues such as global climate change. With the support of Network resources, LTER scientists and educators will be able to act as effective advocates for environmental science literacy as a fundamental goal of our science curriculum. They will also be able to supply appropriate language for standards, item pools for assessments, and support materials for teachers.

Goal 7. Work at the undergraduate and graduate levels to improve training

The nature and scope of social-ecological science requires new models for college teaching and for recruiting and training future scientists at the undergraduate and graduate levels. And as highlighted above, we must enable the research community to reflect the diverse public that we serve and from whom we seek support (COSEPUP 2005). 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 2002, 2006).

We recognize these two goals – engaging a more representative student body and improving science education, particularly in the realm of the social-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 and 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 in the report *Using Data in Undergraduate Science Classrooms* (Manduca and Mogk 2002) and teaching methods supported by Teaching Issues and Experiments in Ecology (http://tiee.ecoed.net/), 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 Ecological Society of America's SEEDS program focus on diversity through an inquiry-based approach. These initiatives and programs provide models for some elements of the undergraduate initiative proposed here. We propose expanding those models via an integrative approach to diversity and curriculum through efforts such as 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 IGERT program concludes that students trained in these programs receive different experiences from those in traditional disciplinary degree programs, and that these experiences better prepare them for the interdisciplinary science of the future (Abt. Associates 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. 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 in the LTER Integrated Research Plan 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 (ASLO) has actively promoted improving interdisciplinary education through two prominent graduate programs: Dissertations Initiative for the Advancement of Limnology and Oceanography (DIALOG), which integrates across the full range of aquatic sciences; and Dissertations Initiative for the Advancement of Climate Change Research (DISCCRS), 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 our initiatives, particularly when coupled with goals related to broadening participation of underrepresented groups.

Goal 8. Engage citizens and leaders with LTER research

The success of a social-ecological research and education plan also requires the participation of citizens in the decision-making processes that govern the management of those systems that provide ecosystem services. Our program involves a participatory approach – Citizen Science – in which citizens are active in data collection and communicate with researchers and policy makers. Citizen Science is a participatory process for including all sectors of society – the general public, government, and industry – in the development and conduct of public-interest research in order to bridge gaps between science and the community and between scientific research and policy, decision-making and planning. Bridging these gaps involves a process of social learning through sound environmental research, full public participation, the adoption of adaptive management practices, and the development of democratic values, skills and institutions for an active civil society (CRC 2007).

There are many existing Citizen Science projects that have generated peer-reviewed publications focused on the distribution and patterns of occurrence of organisms in the landscape. For example, the reproductive success of Wood Thrush populations with acid deposition in the Northeastern United States has been clearly related (Hames et al. 2002). A robust LTER Citizen Science program will provide both the potential for enhancing the scope of the science program as well as the potential for increasing public engagement in science.

The LTER Network Citizen Science Coordinator will serve both to connect LTER research and education programs with existing relevant Citizen Science programs (e.g., Cornell Lab of Ornithology, Project BudBurst) and will support the development of protocols that grow out of specific site needs. The Coordinator will also develop and share best practices in communicating the results of Citizen Science to decision-makers. As with any sensor network, Citizen Science will require its own cyberinfrastructure, which must be fully integrated with the core LTER cyberinfrastructure. A well-designed, fully integrated cyberinfrastructure will be critical to the success of the Citizen Science program and must be responsive to a wide range of users.

The LTER Network Citizen Science Coordinator will also support local LTER sites in their efforts to provide local decision makers with relevant environmental information and to promote environmental literacy in citizens. For example, citizens may want to know about how development plans will affect recharge zones for local aquifers or how different farming practices will affect water quality in local lakes and streams. In some cases these communications with local citizens may be a part on an LTER research agenda, as LTER sites seek to inform citizens about likely environmental consequences of their actions and investigate the effects of that information on citizens' behavior.

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The Decadal Plan for LTER

Integrative Science for Society and the Environment: A Plan for Science, Education, and Cyberinfrastructure in the U.S. Long-Term Ecological Research Network

Section V

Strategic Plan for Cyberinfrastructure in the LTER Network

The U.S. Long-Term Ecological Research Network
October 1, 2007

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1.0 Executive Summary for Cyberinfrastructure

The LTER Network has articulated new visions for research that seeks understanding of human-natural systems through advances in collaborative, synthetic social-ecological science at multiple scales. This report defines improvements in cyberinfrastructure (CI) that are necessary to facilitate this research and to support other ongoing LTER research activities. As defined by Atkins et al. (2003), "In scientific usage, cyberinfrastructure 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." In our context cyberinfrastructure embodies both the people and the technologies that allow collaborative activities and technological solutions for data collection, discovery, access, integration and analysis across disciplinary and scale boundaries.

To identify cyberinfrastructure challenges and consider potential solutions, LTER CI planners convened a diverse group of information technology (IT) professionals from science and technology centers, large IT development projects, and national observatory initiatives in a series of meetings that addressed (1) Multi-site Experiments, (2) Data Integration, (3) Modeling, and (4) System Architecture and Human Resources. These groups identified areas where improvements in cyberinfrastructure are necessary, including data acquisition, management, and curation; data discovery, access, and integration; modeling, analysis, and synthesis; and large-scale collaboration. Crosscutting issues that span cyberinfrastructure improvement areas include development of a service-oriented architecture on which to build collaborative environments, strategic CI partnerships, programs for workforce training, and support for education and outreach activities.

The current LTER program has significant strengths that will contribute to meeting these new cyberinfrastructure challenges. These strengths include the availability of existing long-term data and Network-level products, use of community standards for metadata, policies for sharing data, broad experience in ecoinformatics, a history of informatics research, and an LTER Network Office to serve as the focal point for development efforts. Existing partnerships with the National Center for Ecological Analysis and Synthesis (NCEAS), the San Diego Supercomputer Center (SDSC), and the National Center for Supercomputer Applications (NCSA) are positive collaborative strengths, as are new and growing associations with emerging observatory platforms such as the National Ecological Observatory Network (NEON), the Ocean Observatory Initiative (OOI), and the Water and Environmental Research Systems (WATERS) Network. At the same time, however, a survey of LTER sites also identified impediments. Critical issues that require attention include uneven information management and information technology expertise among Network sites; diverse forms of data and methods for collecting and managing data; wide variations in Network connectivity (particularly at field sites); and inconsistent access to collaboration technologies.

We propose six strategic CI initiatives to support new and existing science activities in LTER:

1. *Build community-based services and a service-oriented architecture (SOA)* - A scalable, community-based, service-oriented architecture will provide data services to ensure secure and efficient access to data stored in site data repositories, as well as provide computational services for numerically demanding analyses and models and for large-scale multi-site experiments that include sensor networks, satellite sensors, and high performance computing.
2. *Build CI capacity to increase data acquisition, management, and curation at the site level* - Near-term goals for increasing LTER sites' capacity for collecting high-quality data and participating in Network-wide experiments, integration, modeling, and synthesis activities will require significant enhancements to staffing and technology.
3. *Build CI capacity to increase data discovery, access, and integration* - Advances in data integration require the development of innovative prototype systems utilizing data warehousing

and distributed query systems technologies, linked to research in applying knowledge representation and semantic mediation approaches to harmonize heterogeneous data.

4. *Build CI capacity to increase modeling and analysis activities* - Facilitating and coordinating LTER Network-wide analysis and modeling activities aimed at understanding and forecasting changes in regional, continental and global dynamics of social-ecological systems will require significant investment in computing services, software development, and staffing. This effort will require developing scalable computing resources, advanced analytical environments such as scientific workflow systems, and a community-based repository for archiving model code.
5. *Build capacity to increase collaboration* - Collaborative work environments allow scientists residing in different locations to analyze, discuss, annotate, and view data using collaborative analytical tools and video teleconferencing. LTER researchers need access to these tools at both central and remote locations.
6. *Integrate cyberinfrastructure into social-ecological research, education, and training* - Integration of new cyberinfrastructure including advanced tools for analysis and synthesis within the LTER research process will require linking centrally-developed training, education and outreach programs to other training resources that can be remotely accessed by scientists, students, and technicians.

Undertaking these initiatives will require significant new investments in people and technology. These investments are the first step towards achieving a fully integrated research network capable of interdisciplinary, multivariate, and multi-site advances in social-ecological understanding and prediction at spatially and temporally meaningful scales.

2.0 Introduction

The CI Strategic Plan is designed to support the research agenda of the LTER Network, and in particular the new agenda for social-ecological research described in the Network's Integrated Research Plan. The new vision for integrated science is inextricably intertwined with developments in cyberinfrastructure (CI).

Cyberinfrastructure is the term coined by an NSF blue-ribbon committee (Atkins et al. 2003) to describe new 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, cyberinfrastructure 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."* Cyberinfrastructure also includes people and organizations that operate and maintain equipment, develop and support software, create standards and best practices, and provide other key services such as security and user support.

Advancing the practice of collaborative science is the major motivation for advancing cyberinfrastructure. In this document we describe a new era of LTER cyberinfrastructure and expound a vision of facilitating and promoting advances in collaborative and synthetic social-ecological science at multiple temporal and spatial scales by maximizing data flows, information synthesis, and knowledge generation. Key cyberinfrastructure will be needed by the Network to achieve its science mission. The required cyberinfrastructure entails building a significant new capacity (Figure 1) within LTER and demands significant new investments in people and technology:

- People - staffing to meet data management and integration needs to match the foreseen increases in data volume and demand for integrated products, to develop applications and services that will accelerate the pace of synthesis, and to develop and conduct education and training to produce a new cadre of IT-adept ecological scientists and cross-trained informatics specialists.
- Technology - for collaboration; communication; data acquisition and generation; data management and curation; data discovery; data integration; knowledge representation; analysis; synthesis; and modeling.

These investments are required to take the next crucial step towards achieving a fully integrated research network capable of advances in social-ecological understanding and prediction at multiple scales. LTER cyberinfrastructure planning and development must be forward looking not only to address existing needs but also to address as yet unanticipated synthetic science over the next ten years. Research that is interdisciplinary, multivariate, and multi-site at these scales will face many challenges and will require significant enhancements to existing cyberinfrastructure. The successful specification and implementation of this cyberinfrastructure will depend on domain scientists and information specialists and will both rely upon and contribute to informatics expertise and CI systems outside of LTER.

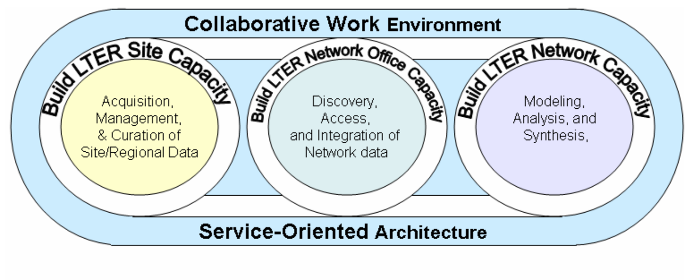

Figure 1. An integrated vision of a new era of LTER cyberinfrastructure.

To identify and be better prepared to address these CI challenges, we engaged a diverse group of IT professionals from science and technology centers, large IT development projects, and observatory initiatives to broaden the expertise base for the planning process, facilitate the integration of efforts across programs, and catalyze future partnerships. Interactions focused on four critical function areas that the planners felt would require well-supported cyberinfrastructure:

- Multi-site/Network Experiments,
- Data Integration,
- Modeling, and
- Architecture and Human Resources.

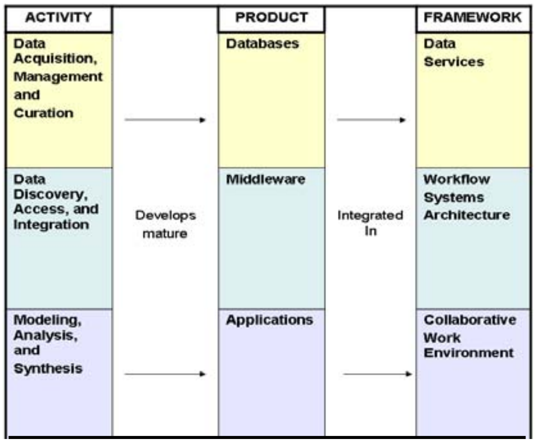

Figure 2. Diagram of envisioned CI activities, products, and frameworks.

This plan draws from documents produced for each functional area and subsequent interactions with the LTER National Advisory Board and Network Information System Advisory Committee. In the sections below we first (Section 2) present the CI necessary to support a science scenario taken from the LTER science planning effort in order to set the stage for a generalized vision for LTER CI. In Section 3, we present a summary of the current status of CI in the Network based on a detailed inventory and discussion groups. In Section 4 we identify key CI challenges for facilitating Network science. In Section 5, we present a series of 6 strategic initiatives that draw on the strengths of the LTER Network and the IT community to address the challenges identified. Finally in Section 6, we recognize the importance of collaboration with emerging environmental observatories in developing solutions for common challenges.

3.0 Cyberinfrastructure Vision and Illustrative Science Scenario

The cyberinfrastructure vision for LTER anticipates integrated activities at the site and network levels to develop critical products that are integrated as key framework components (Figure 2): (1) high-throughput data services that provide high-quality delivery of field-based data products, (2) a service-oriented architecture for a computational environment that allows for the integration of large amounts of multi-site, multidisciplinary data, and (3) collaborative work environments that house comprehensive tools and algorithms for knowledge discovery and data mining, with comprehensive user interfaces that provide tools for easy access, navigation, visualization, and annotation of biological information.

Three major activities feed into this framework:

1. *Data acquisition, management, and curation.* A framework of data services, tools and expertise that leverages network architecture could potentially support all multi-site studies and experiments. In addition to creating economies of scale, the framework could also provide incentives to researchers to conform to standardized protocols and provide experiment metadata in return for powerful analytical tools and secure data storage. Network personnel could provide design and development support for multi-site experiments such as generating customizable data entry software, designing and curating databases, and creating tools for data quality screening and data query. CI components and personnel at the sites will increase their capacity for collecting high-quality data and for participating in Network-wide automated and semi-automated information processing, integration, and synthesis. Information management professionals at the site will participate in both site-specific initiatives and in Network, national, and global information systems.
2. *Data discovery, access, and integration.* We envision support for data federation through traditional data warehousing approaches as well as through the implementation of emergent techniques relying on knowledge representation and semantic mediation. A typical Network project will involve data sources and users distributed among various institutions. Such projects require a mature infrastructure that allows seamless integration, analysis, storage, and delivery of information to a distributed community of users.
3. *Modeling, analysis, and synthesis.* We envision the establishment of a modeling and analysis support activity that will 1) promote the synthesis of data across the LTER Network, 2) promote the improvement and development of analysis tools and models to answer questions fundamental to the LTER mission, and 3) archive and document data and models and their output for the use by the larger community.

To be carried to fruition, these activities require the development of intermediate products (databases, middleware, and applications) integrated within a framework that provides high throughput data services, a service oriented computational environment, and a collaborative work environment.

The following simple study scenario illustrates these needs:

> Chronic nitrogen deposition removes nitrogen limitation on biotic activity, resulting in diverse unintended consequences to terrestrial, freshwater, and marine ecosystems including changes in plant community composition. To test the hypothesis that changes in N deposition, night-time warming, and precipitation drive long-term changes in plant community composition, and to forecast future continental scale patterns of change, an integrated program of multi-site experimental manipulations and modeling is designed. Changes in N deposition and night-time warming are characterized as "presses." Changes in precipitation are considered "pulses."
>
> To pursue a program of experimentation linked to modeling, background information is needed on precipitation quantities and patterns, N deposition, and temperature regimes to determine the magnitude of treatments for the study. In experimental plots, data to be collected by technicians

include plant community composition, N composition of plant species, and soil nutrients. A network of sensors will collect light flux, soil and air temperatures, soil moisture, and relative humidity. New plant community composition data will be integrated with existing long-term community composition data to evaluate how the community change trajectory in the experimental plots compares to the trajectory of the overall site. Thus, the first-level synthesis in this scenario is the integration of new and long-term data from multiple sites.

The ECOTONE simulation model will be used to synthesize process-based understanding gained from experimental manipulations. The model predicts community composition and will simulate the dispersal, establishment, growth, and mortality of individual plants on a small plot (1 to 5 m^2) at variable time steps from daily to annually. Soil water content by depth is simulated daily and effects on plant processes are aggregated to one year. Feedbacks among the vegetation, soil water, and soil structure are included in the current formulation of the model. Validation tests of the model at all sites will serve as a test of the overall hypothesis about the role of climate and N deposition in controlling changes in plant community composition.

To extend the generality of study results and forecast the effects of future changes in climate and N-deposition across N. America, a spatially explicit model (10 x 10 km) of plant community composition must be developed. This requires scaling of mechanisms operating at the scale of individual plants to entire communities. Calibration will be based on reconstruction of temporal and spatial patterns observed at individual LTER sites, while validation will be based on reconstructing historic regional patterns of community change. Linkage with global climate models (GCM) and predictions of future rates of N-deposition will drive forecasts of potential future patterns of plant community composition.

Vast acreages of land are exposed to low levels of atmospheric deposition, and hotspots of nitrogen deposition occur downwind of expanding urban centers or large agricultural operations, resulting in regional effects of impaired visibility and haze in exurban areas and national parks. From a social science standpoint there is the further need for an integrated, multi-site experimental manipulation and modeling effort that might include field testing of potential land management practices to reduce the emission and impact of nitrogen deposition. For example, in what ways can prescribed fire, mechanical thinning, or different harvesting regimes reduce decadal nitrogen accumulation? How are the effects of this accumulation and its potential abatement perceived by the public? How do perceptions translate to behavior? Such an experiment suggests several data needs. For example, a compilation of the geography of existing and potential sources and sinks of nitrogen deposition should include prevailing wind patterns, air shed boundaries, and point sources along with knowledge about the current intensity of land use and historical changes in this intensity since 1960 (e.g., animal processing, transportation corridors). Spatially attributed, high categorical resolution land management, land use history, and attitudinal and perceptual data to differentiate among social groups is needed, as well as parcel data (attributes and geography) and high resolution, multi-spectral imagery for the study area.

Cyberinfrastructure requirements. This study scenario begins with synthesis of site-based information that will require more resources at the site level for data acquisition and management, and quickly grows to a scope and complexity that will require integrated CI across all involved sites to be successful. Most obvious of the CI drivers for this scenario are 1) the coordination and collaboration that will be necessary to do the science, and 2) the integration of vast amounts of data derived from historic data collection efforts; from new data collections, including sensor networks; and from multiple distributed sources. In addition, support is needed for multi-site experimental data acquisition including the implementation and management of a complex array of sensors.

The second phase will require the development and parameterization of an integrative model from distributed data sources. The validation of the model will also require multi-site data collection and integration capabilities. The final phase represents new model development to extend the scale of predictive results. New algorithms may be required to extract plant community composition from satellite data. New tools may also be required to validate land use histories and practices and explicit patterns of plant community change. The collection and integration of social science data with ecological data poses additional challenges and relies heavily on spatially explicit GIS and remote sensing data. The multi-site science coordination from design to analysis would be greatly enhanced by the use of collaboration technology.

As it increases in scale, this study requires support for a substantial and integrated cyberinfrastructure. Using the capabilities provided by existing cyberinfrastructure, this study would proceed slowly, requiring months to years to accomplish, if it could be done at all. Enhancements to cyberinfrastructure would greatly facilitate this effort and perhaps even make it possible. A community-based, service-oriented architecture will provide secure and efficient access to site data repositories and satellite data, and provide access to computational services and high performance computing for running models. This architecture would provide a seamless and fault-tolerant environment to allow linkage with global climate models and allow access to predictions of future rates of N-deposition and forecasts of future plant community composition.

4.0 Current Status of LTER Cyberinfrastructure

In developing a strategic plan for new LTER CI we took into consideration the existing status and strengths of the Network. The LTER Network is particularly well-suited to take on the challenges presented by the Network's new science agenda because of its many existing CI strengths that are absent or nascent in similar networks. These include:

- Long-term site data that are rich, extensive, well-documented, and online.
- Network-level products that have been developed to facilitate integrative, cross-site research include a Network-wide database catalog; Network-wide databases for climate and hydrology (ClimDB/HydroDB), for site descriptions (SiteDB), and for bibliographic references; and substantial collections of LTER-wide remotely-sensed imagery.
- Community standards that have been developed and adopted for metadata (Ecological Metadata Language, EML) and site information management; the LTER Network has been the first and largest adopter of metadata standards in the ecological community, and has set standards for site information management systems that have been peer-reviewed and vetted by the ecological community.
- Open data policies have been developed and adopted for release, access, and use of LTER data that clearly define user and provider requirements.
- Wireless sensor networks at a number of sites are providing test beds for the development and deployment of environmental sensor technologies.
- A Network office is funded and charged with support and leadership in informatics and in computing and communication infrastructure.
- The diversity of knowledge and approaches in the LTER IT community has generated diverse, innovative informatics solutions.
- Informatics research includes scientists committed to Network-level ecological research.

4.1. Strategic Partnerships

LTER's history of interaction and cooperation has helped to keep LTER IT efforts community-oriented and informed. This strength derives in part from strategic partnerships with national centers and collaborative efforts with ecoinformatics partners:

- The National Center for Ecological Analysis and Synthesis (NCEAS) has been very productive in advancing informatics capabilities for the ecological community and will play a critical role in developing and supporting cyberinfrastructure for synthesis. In particular, NCEAS has been involved in developing tools for generic access to ecological data and will play an increasing role in training and improving technical capabilities of users engaged in synthesis and analysis at NCEAS.
- The San Diego Super Computer Center (SDSC) has established collaborations with the LTER community and provides expertise on information management technologies relevant to observatory networks. SDSC has sponsored training workshops in technical areas of interest such as web services.
- The National Center for Super Computer Applications (NCSA) has been a key collaborator in the development of proposals addressing cyberinfrastructure needs of the LTER Network. In particular NCSA provides critical expertise in Grid architecture and related technologies.
- The LTER Network has strong connections with the emerging National Ecological Observatory Network (NEON), which will provide new partnerships and leveraging

opportunities for co-developing and sharing cyberinfrastructure solutions; five LTER sites are among the 20 preliminary NEON backbone sites, and several others are preliminary gradient sites.

4.2. The LTER Network Information System

For the past several years the LTER Network has been developing a Network Information System (NIS) to accelerate the generation and use of data and synthesis products resulting from cross-site research. Modules of the NIS, as it exists currently, include the ClimDB/HydroDB climate and hydrology database, the LTER Personnel and Bibliographic Databases, the site description database SiteDB, and the LTER Data Catalog. The NIS strategic plan provides a number of information management strategies that are aligned with the strategies outlined in this CI strategic plan. The primary focus of the NIS strategic plan is on the use of existing data, improving the quality of data and data discovery through the adoption of the Ecological Metadata Language, increasing the quantity of data available through federated architecture, and facilitating synthesis via applications that use the data and infrastructure. NIS will support standardization in the development and management of information content at the sites through guidance, resources, training, and support. NIS includes the development and deployment of applications that accommodate LTER information content, including an on-line data catalog and applications to exploit these data for discovery of information. NIS will support the creation of Network-based synthetic information products through the use of relational database technology, shared middleware, community-based applications, and scientific collaboration.

The Network Information System Advisory Committee (NISAC) is charged by the Network Executive Board to provide guidance for Network CI priorities and policies, and thus guidance to the LTER Network Office team responsible for the development and deployment of the NIS. NISAC also sets site-level requirements for NIS participation. The involvement of NISAC assures that NIS development is driven by current LTER science issues and needs. NISAC is composed of LTER scientists, information managers, and members of the LTER Network Office, and provides a forum for interaction and communication among these groups. NISAC will also assume a critical advisory role for the implementation of this CI strategic plan.

The LTER Network team responsible for the design and development of the Network Information System (NIS) has designed and prototyped a data warehouse framework that builds on the successful deployment of Ecological Metadata Language, the Metacat repository, and Metacat Harvester. This framework, code-named PASTA for Provenance Aware SynThesis Architecture (Figure 3), is efficient because it builds on existing investments and experiences, integrative because it adopts standard interfaces and approaches, and innovative because it incorporates data provenance and data quality into the design. PASTA is currently being tested as the underlying architecture for the EcoTrends project.

This effort will initially serve the LTER scientific community and collaborators, but it is also seen as a "portal" to the LTER Network for the broader scientific community, students, natural resource managers, policymakers, and the general public. This effort will be continued and strengthened as part of the new LTER science agenda.

4.3. LTER CI Survey

As part of the CI planning we assessed the current status of LTER site cyberinfrastructure. Surveys of LTER sites conducted in June 2005 and February 2007 revealed a very wide range of cyberinfrastructure capabilities among LTER sites (http://lternet.edu/technology). Some of the critical trends are summarized here:

- There is enormous diversity in the available expertise for information management and information technology at the sites, ranging from a quarter to more than 3 FTE supported by LTER funding with as much as an additional 7 FTE from external sources. Most sites receive institutional support for their computational infrastructure, although this varies from email support to more "data center" like operations. Information management tasks range from system administration and user support to software development and web design with the majority of time spent on general site data management activities. Additional information management personnel and training were seen as the most important need for sites to allow them to participate fully in Network-level science.

- LTER site data span a wide variety of forms, from remote sensing data, streaming sensor data, and automated shipboard systems to manually recorded field data. All sites have embraced standards for information management, particularly the implementation of structured metadata in the form of Ecological Metadata Language (EML), although complete metadata documentation and methods for online data access are highly variable across the Network.
- LTER host institutions are generally well-connected to the internet but field sites are highly diverse in their bandwidth and service quality. Fewer than half of LTER field sites have high speed internet connections and wireless infrastructure to support sensor networks.
- Several sites are actively developing and deploying wireless sensor networks to routinely sample and communicate information on measures as diverse as trace gas fluxes, animal movement, and water column chemistry.
- LTER site scientists collaborate on IT issues with domain science centers, and some sites are collaborating internally or externally with computer scientists on IT issues.
- LTER researchers at host institutions generally have access to shared video teleconferencing capabilities but access on individual desktops, in conference rooms and at field sites is sparse: only one third of LTER sites have video conferencing capability of any form at the site. Other collaboration tools are generally not used, and email is almost exclusively the electronic collaboration tool of choice.
- Conventional statistical and analytical software are in use as the norm across the Network, but few sites use advanced remote sensing, visualization, or project management tools.

Diverse is the term that best describes the level of functionality across sites. Survey results convincingly demonstrate the need for significantly expanded technology infrastructure and staffing at LTER sites to support a Network-wide scientific effort. The LTER Network Office employs several computer scientists and maintains a focus on computing and communication infrastructure, but is not staffed or equipped to address the large project throughput, integration, and data management support required in the coming decade. The LTER Network as a whole will require adequate resources and expertise dedicated to cyberinfrastructure to successfully meet a number of critical challenges in transforming the science of ecology to a more highly collaborative and interdisciplinary social-ecological science.

5.0 Specific CI Challenges to Facilitating Network Science

There are challenges to exploiting the enormous scientific value of social-ecological data for understanding and predicting the responses of living systems. Collaboration among large groups of distributed scientists is in itself challenging (Hara et al. 2003). Many of the challenges faced by LTER and the social-ecological community are shared by a multitude of other domains attempting to conduct integrative, large scale, computationally intensive science (Maltsev 2006). The challenges in producing high-quality, integrated datasets for synthetic science are immense and long term (Meyer 2006, Stevens 2006). Although the LTER has strengths that provide its scientists an advantage in meeting these challenges, the CI planning process has identified and elaborated specific challenges that include:

1. Acquiring, managing, and curating increasing quantities of data from the Network science agenda despite significant diversity in site cyberinfrastructure functionality.
2. Supporting the integration and delivery of increasing quantities of multidisciplinary, multivariate, and multi-site data that will result from new multi-site and interdisciplinary studies, and mediating unavoidable data heterogeneity in site-based ecological studies, including differences in content, format, precision, scale, semantics, and QA/QC. This effort includes explicitly addressing the unique data problems and challenges in using historical social science data and the challenges in using and integrating data from sources outside the Network, such as high-volume geophysical data.
3. Facilitating increasing scientific collaboration organized at multiple geographic scales with dispersed research teams is often not straightforward and requires careful planning to integrate technology (e.g., collaborative work environments, community software tools, conferencing technologies) into scientific practice and to avoid duplication of effort. Integration includes:
    a. Facilitation and coordination of CI for LTER Network-wide modeling and analysis activities to significantly improve our ability to understand and forecast changes in regional, continental, and global ecosystem dynamics.
    b. Developing community-based computing and data services without duplicating efforts elsewhere; and without re-inventing commercial solutions already in the marketplace.
4. Meeting the demand for trained personnel, including cross-trained informatics experts and informatics-adept students and scientists. The high rate of technological change means that training at all levels, from the informatics expert to the individual researcher, will need to be continuously pursued.
5. Ensuring that priorities for CI development and implementation are science-driven, squarely addressing researcher needs. As described in Section 3, the Network Information System Advisory Committee (NISAC) is currently charged with this task and will continue in this role as part of this plan.

6.0 Strategic Initiatives to Develop LTER Cyberinfrastructure

We propose to undertake six strategic initiatives in CI to support the major science activities in LTER. These include building Network capacity in the critical function areas of data management, data integration, and data analysis, and developing capacity in the crosscutting areas of collaborative work environments, training, and the development of service-oriented architectures. How these strategic initiatives apply to the challenges presented by the LTER science planning effort is readily apparent in some initiatives (e.g., the workforce training initiative), while others leverage the organizational strength of the Network to bring a number of applications under a single heading (e.g. data integration capacity).

6.1. Initiative 1: Build community-based services and a service-oriented architecture (SOA)

A service-based architecture serves as the "glue" that holds all the other components together. A scalable community-based service-oriented architecture (Figure 4) can meet the challenges of providing data services that ensure secure and efficient access to data stored in site data repositories, to computational services for numerically demanding analyses and models, and to data from large-scale, multi-site experiments that incorporate sensor networks, satellite sensors, and high performance computing.

Developing and implementing this architecture will require resources and the development of strategic partnerships, including:

- Supporting collaboration with key partners such as NCEAS and NEON to advance the development and deployment of community-based services;
- Supporting integrative software developers and programmers at the LTER Network Office;
- Supporting LTER site participation in the development, deployment, and use of community services.

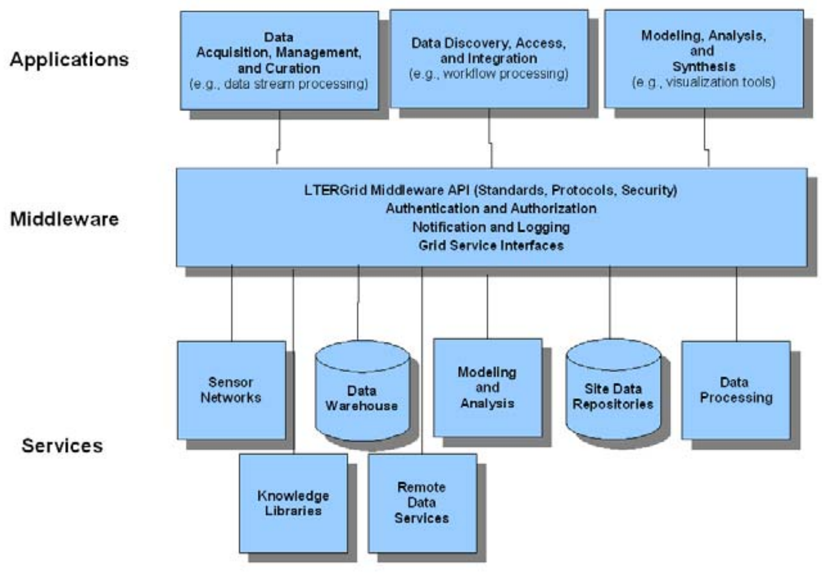

Figure 4. Schematic of Service-Oriented Architecture (SOA). Communication and security are standardized to present common interfaces to all data for service providers and consumers.

Achieving a cyberinfrastructure that enables researchers to easily share and exploit current and historical observations depends upon a foundation on which users can discover and access (1) local and remote data, (2) distributed computational resources, including storage and high-performance computational systems, and (3) other collaborators or institutions conducting similar research, all through a secure, fault-tolerant, and seamless process. The framework provided within many of the grid software stacks, including Globus, can be incorporated to implement this vision.

6.1.1. Rationale.

A service-oriented architecture provides a way to expose the functionality of underlying information systems and analytical resources, without needing to implement a centralized system (Alonso et al. 2004). Just as object-oriented programming promotes software reusability by separating essential functionality from the details of implementation, services encapsulate computational and data resources, allowing access

6.1.2. Approach

Architecture overview. The grid-based services envisioned for LTER CI will support distributed research sites, sensor arrays, collaborations, and other community services of the Network. To do so will require prototyping community integration through a grid "Point-of-Presence" (PoP) model (Figure 5). Each PoP will provide an interface between the LTER resource and other resources interconnected to the LTER Grid via an Internet2/National Lambda Rail connection. The Site PoP is a combination of networked hardware (server, local disk, and Gigabit network interface) and a software stack consisting of industry standard protocols and applications that provide secure and seamless connectivity from the site to other sites and external resources.

Software stack. The PoP software stack (Figure 5) must provide a full complement of services that allow bi-directional connectivity from site resources to any other site or external resources, but at the same time ensure security, fault-tolerance, and an acceptable level of application performance. A crucial service voiced by LTER researchers is security – all access to site data must comply with local authentication and authorization rules, and with the LTER Network Data Access Policy. For this reason, the PoP software services must collect audit information regarding resource usage and the transfer of data.

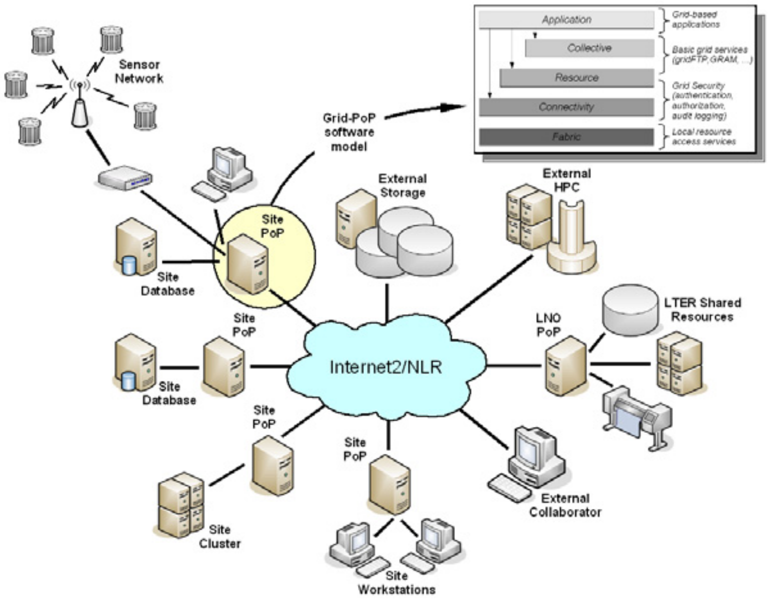

Figure 5. Schematic of a grid point-of-presence (POP) model architecture for the LTER Network

6.1.3 Implementation

First, we will continue developing strategic relationships with supercomputer institutions (e.g., the National Center for Supercomputing Applications and the San Diego Supercomputer Center) in order to leverage their expertise and knowledge in designing and deploying community-based applications and services. As part of this strategic relationship, the LTER Network Office Informatics team will work closely to tailor applications to meet LTER Network and research site needs. We will take advantage of already deployed grid applications that are tested and proven in a production environment as a basis for our design model. Fortunately, many examples are available for scrutiny, such as NEESGrid, BIRN, and TeraGrid. Together with these experienced partners, new partners in NEON and other observatory networks, and a select group of LTER sites that demonstrate their desire to become early adopters, we will prototype a software model to begin connecting and sharing LTER distributed resources.

Second, once the prototype is tested and accepted by the early adopting sites, we will utilize it as a template to deploy to the remaining sites. Following this process will allow us to scale while keeping the site integration time reasonable. In addition, we will strive to bring into the Network additional grid-connected resources that are outside the immediate circle of LTER sites such as high-performance computing clusters, visualization tools, and additional off-site storage.

In support of this CI strategic initiative, the LTER Network Office will require additional staff for software development, integration, deployment, and maintenance. It is expected that individual LTER sites will require technical assistance and resources in the initial deployment of necessary software, and also for regular maintenance and system updates as well as some site level staffing resources for enacting the template locally.

6.2. Initiative 2: Build CI capacity to increase data acquisition, management, and curation at the site level

The challenge of acquiring, managing, and curating increasing quantities of data to support research in coupled human-natural systems requires building capacity at sites by staffing and equipping site information management systems to support data quality, maximum sustainable throughput, and federation of Network science data, including data from multi-site experiments. LTER sites need to increase their capacity for collecting high-quality data and for participating in Network-wide automated and semi-automated information processing, integration, and synthesis. LTER sites need to assure that information management professionals at the site can materially participate in both site-specific initiatives and in Network, national and global information systems. This includes:

- site staffing to support a Network information system and maximize throughput of high quality data; this may include Network administrators, information managers, programmers, sensor technicians, cross-trained specialists in satellite, sensor, and spatial data, and physical sample archive specialists for maintenance of archive facilities and databases;
- site computing technology to implement persistent data services such as hardware, mass-storage, software, sensors, and physical sample archives;
- LTER Network Office staffing to coordinate development and deployment of standards and web services for site data delivery and site staffing for implementation of services and standards; and
- training Network staff in new technology.

6.2.1. Rationale

The data collected and managed at LTER sites form the foundation for science at the site, region, multi-site, and Network levels, and hence, meeting each of the articulated CI challenges relies in large part on the capacity at individual sites and coordination among them. New integrative science will demand ready access to online, fully documented data across sites, and LTER site information systems and expertise will likely be leveraged to provide cyberinfrastructure for other research partners within the broader region and in the context of multi-site experiments. Even when data are online and well documented, data integration across sites can be a daunting task. Data management for multi-site experiments has often suffered from a lack of resources and limited and highly variable expertise among experimentalists. Network level experiments will challenge researchers to design and implement functionality both centrally and at the sites to assure data integration.

Increasing volumes of data and new data collection efforts present additional staffing and training issues. Maximizing the throughput of high quality data from field collection to secure storage to centralized access portals is a necessary requirement for supporting synthetic and integrative science. Embedded sensor networks using wireless technologies provide data at new temporal and spatial scales and constitute a new capacity for generating standardized data in multi-site experiments. Maintaining these sensor networks and processing the large volumes of data that can be produced at expanded scales, including automated data screening for quality, will require an increase in staffing at sites. Broader regional representation will require the acquisition of satellite imagery and other spatial data, and coupling human and natural systems will involve collection of new social science data sets such as land use or economics.

The development of properly archived physical samples of specimen collections and reference samples including organisms (plankton, birds, insects, fish, plants, etc.), soils, sediments, and water will demand construction of remotely queryable digital databases of specimen and sample holdings. Voucher collections will allow taxonomic identifications to be verified at a later date and permit documentation of genetic changes in species over time. Reference samples for trace metal, stable isotope, and other analytical methodologies will be similarly important. The advent of new technologies will allow retrospective consideration of samples in order to reconstruct temporal changes in organisms and associated ecosystems, and resources will be required for cross-site comparative analysis of specimen-based materials. Training of site and Network staff will be necessary to accommodate new technologies presented by these sensor networks, sample archives, and new data collections.

6.2.2. Approach

Building this capacity includes obtaining adequate hardware and staffing resources to accommodate the demand for the robust site information systems that are required to collect, manage, and curate data. In order to function as a fully integrated network, the sites must enact Network-wide standards and interface with the LTER Network Information System (NIS). This will require sites to develop solutions for exposing site information systems in interoperable ways within the context of a service-oriented architecture. Economies of scale favor the development of tools that can be used across sites to support data acquisition, discovery, access, and integration. Investing in the training of site personnel involved in data collection, information management, and data analysis will provide critical enhancements to the capacity at LTER sites. Funding will need to be available at the sites to support sufficient information management personnel to guarantee that site data meet these requirements so that scientific activities are not constrained by access to data and the metadata necessary to make the data interpretable.

6.2.3. Implementation

Near-term goals for increasing the sites’ capacity to participate fully in the research on coupled human/natural systems will require staffing and technology to:

- enhance data collection methodologies (field data entry systems, sensor network, spatial data capture, sample archive databases, automated QA/QC, automated metadata generation) and train site personnel in the use of new technology;
- improve Ecological Metadata Language documents generated by sites to support interoperability (more content; improved standardization of metadata content across sites, e.g.

consistent keywords, units, etc; controlled vocabulary for keywords to permit browser interface to metadata); and

- develop automated access to site data that provides sites with use information (secure web services interface with cross-site authentication; standards for web services content; additional training of site IM personnel to generate site web services).

Mitigating the diversity of current site CI will require developing a critical set of functionality needed at all LTER sites to implement the strategic plan along with a budget estimate for the hardware, software, and staffing needed by the sites to provide this functionality.

6.3. Initiative 3: Build CI capacity to increase data discovery, access, and integration

To gain ecological knowledge from the anticipated increasing quantity and diversity of data, data must first be curated (evaluated for data quality, linked to ontologies and metadata), integrated (finding and constructing correspondences between elements), and delivered (made available in a form for scientific use).

The challenge of supporting the informed delivery of integrated Network data products based on multidisciplinary, multivariate, and multi-site data requires a focused but broad agenda of software development, technical and analytical support, and persistent infrastructure, including:

- LNO staffing to design, prototype, and implement a Network information system to integrate site data services; this would include programmers, software developers, and data integration specialists;
- site resources to implement wrappers for site data to conform to specified global schemas necessary for single point of access architecture to LTER site data for specified sets of queries designed by scientists engaged in synthetic multi-site research;
- LNO staffing to provide analytical and technical support for sites in implementing Network standards and for the Network in utilizing the Network information system for synthesis; this may include data and systems analysts;
- funding for collaborative research and working groups focused on mediating data heterogeneity through knowledge representation and ontology development; and
- equipping the LNO to develop and deploy the Network information system; which may require adding persistent computation infrastructure in the form of mass storage and computing resources.

6.3.1. Rationale

Data integration, in the sense in which it is typically used by ecological scientists, is the process of discovering, accessing, interpreting, and integrating data. This process is generally motivated by a scientific question that is not directly addressable by any analyzable data object within our possession. The data integration need arises because we suspect that the data and information necessary to inform our research question exists, and needs only to be assembled into an analyzable object. In the eyes of the ecological scientist, data integration is more a holistic (and currently, largely manual) process involving major unsolved challenges in each area – discovery, access, and interpretation – typically in succession.

Increased capability across the entire scope of the data integration process, including standards for collection, documentation, and communication as well as tools for data discovery and interpretation, involves continued work that addresses the issue at two levels - those associated with data product providers (developing data warehousing, distributed query, and knowledge services for scientific products) and those associated with data consumers (providing easy discovery, access and interpretation of extant data sets).

6.3.2 Approach

Data integration herein refers to the entire process of creating a consistent, coherent, and usable scientific resource, a Network information system, rather than simply the step of "merging" the data values of independent data sources. Making this process comprehensive and seamless are critical aspects of our data integration agenda.

Prototyping. Data integration at the service provider level is defined broadly as combining heterogeneous data sources into a single, unified source and presenting them seamlessly to the user or to applications as a service. Provider-level data integration is complicated by the complexity of the source data and the relationships among them. Data integration at this level is a functional component of either a process known as data warehousing or a part of a distributed query system. Data warehousing involves acquisition, extraction, transformation, and loading of data into an accessible framework. Decisions are made in advance about the relevancy of data sources, the integration approach, attribute mapping, and data quality measures. Although data warehousing is a valuable, presently irreplaceable tool, the process will not be sufficient for the needs of ecology in the future. Distributed query systems differ in that they do not house the data centrally but provide a federated view of the data and always return to the source. Distributed query systems require that mapping decisions be made automatically and therefore rely heavily on knowledge management systems to mediate the queries. We consider prototyping work in both of these aspects of data integration – data warehousing and distributed query systems – to be critical to implementing this strategic plan.

Research. Mediating data heterogeneity requires a major investment in applied research and application in knowledge representation and semantic mediation. This includes meetings of strategic focus groups on knowledge management and the addition of software development and data integration expertise to develop ontologies and knowledge services. However, the development of these ontologies still depends on social consensus among scientists – a challenge that involves both social and scientific complexity (Maltsev 2006). The development of new tools and algorithms for mining and clustering existing scientific concepts and terms may provide significant assistance to this process. In exploring possibilities for how heterogeneous data can be discovered, accessed, interpreted, and integrated, the value of developing and promoting standardized approaches to data throughout the LTER cannot be overlooked. Enhanced communication is needed to develop standards so that arbitrary data heterogeneity can be significantly reduced (e.g. in multi-site experimentation, to be sure that there is thorough discussion about methodologies – scale of sampling, methods of treatment application and other aspects of the experiment design). Communication should also lead to common data storage methods, consistent data typing, consistent naming and semantics of variables, minimization of data incompatibility due to spatial and temporal scaling differences, etc.

6.3.3. Implementation

To gain economies of scale within the new science agenda, the LTER Network Office will play a coordinating role in the integration of research data that requires Network-level management by providing data management services that include quality assurance, analysis, and curation. Coordination will involve communication with sites and potentially with data centers for multi-site experiments, and is intended to standardize approaches to data integration by reducing the heterogeneity in data collection methodologies and handling as well as the development of data services within a federated system. The LTER Network Office is particularly well-suited to support this endeavor, but CI investment will have to be substantially increased. In addition, the LTER Network will need to leverage investments in this area that will be made by emerging networks such as NEON.

The implementation of these efforts will be by a small team of developers in collaboration with LTER Information Managers and key informatics partners. This approach has been successfully used in the development of a comprehensive Network-wide metadata catalog and tools and support for implementing the Ecological Metadata Language standard across the Network. This team recently completed a successful pilot project with NCSA to demonstrate the effectiveness of grid technologies on a particular informatics challenge in the Network. These efforts will have oversight by a Network level advisory committee (the Network Information System Advisory Committee) consisting of LTER Network Office staff, LTER scientists, and information managers, as described earlier for the Network Information System in Section 3.2.

We will adopt a strategic framework for data integration around the concept of a ‘dataspace’ (see Franklin et al. 2005), an alternative to creating one giant integrated database. The participants in an organization manage a dataspace that encompasses all of the data and information in the organization regardless of its format or location. The dataspace concept structure will allow the LTER organization to model and make available its entire data holdings without exclusion while focusing integration efforts in particular areas of need.

While the LTER Dataspace will provide the conceptual framework, it is necessary to apply a heterogeneous but complementary set of approaches (including application of global schema, automated and manual data warehousing, and knowledge networking) to focus data integration efforts on the highest priority research situations being addressed:

- experimental data where the experiment is designed a priori will benefit from working from a global schema approach;
- post-collection data integration efforts where an ongoing value-added data product is expected should be federated in a data warehouse workflow process, if feasible;
- post-collection data integration efforts where a one-time value-added data product is expected would use manual data warehousing techniques;
- for all data holdings, structural and ontological metadata should continue to be defined and developed to make it possible to do semi-automated data integration for ad hoc analysis; and
- tools for registration and integration of existing databases should be made available, similar to the GEON Portal approach for accessing online resources and the SEEK EcoGrid approach for incorporating semantic mediation and knowledge representation.

6.4. Initiative 4: Build CI capacity to increase modeling and analysis activities

To facilitate and coordinate Network-wide analysis and modeling activities in order to improve our ability to understand and forecast change in social-ecological systems will require significant investment in computing services, software development, and staffing:

- staffing (e.g., programmers, software developers) and increased funding for scientists both at individual sites and at a centralized location that focuses on Network-level analysis and modeling activities;
- access to computing services including new hardware technologies, high performance computers, parallel processors, and high storage and high throughput capacity;
- funding for collaboration on software development, including visualization tools, software to link models with different programming languages and the multiple control of linked models, data- and model-based management tools, and Network-wide site licenses; and
- equipping the LNO to develop and deploy a persistent archive of data and models which may require adding persistent computation infrastructure in the form of mass storage and computing resources.

This initiative will include support for resources needed by researchers, computational support for analysis and collaborative modeling, and support for an archive for models.

6.4.1. Rationale

Modeling and advanced data analysis provide critical functions in understanding problems such as ecosystem structure, function and dynamics, responses to climate change, biogeochemical cycling, introduction of exotic species, and changes in human cognition, behaviors, and institutions in response to changes in ecosystem services. Process-based models are an integral part of Network-level science activities. Addressing questions that span the variety of ecosystem types across the LTER Network will require models to be integrated with analytical applications, experimental data, observations, remotely sensed images, and spatial databases.

Advanced Analytical Applications. The new science agenda will require significant changes in our analytical approaches over the next 10-20 years. These changes will require improved analytical tools, including visualization software, software to take advantage of distributed computing resources, software to link models in different programming languages and the multiple controls of linked models, data- and model-based management tools. The prohibitive costs of "hardening" research software for production-level use makes it necessary to develop robust and scalable tools that can be quickly reconfigured and re-used. Scientific workflows will be needed to document each step in complex analyses so that they can be replicated. Data harmonization and integration will require a host of new analytical tools that will provide semi-automated aggregation and unit conversions, statistical tests for evaluating the effectiveness of integration, and computationally intensive tools that evaluate the impact of decisions in the integration process on the final results of the analysis.

Modeling. As the LTER program embarks on questions related to Network-level science, models will play an increasingly larger role in the future success of research. Integrated ecosystem, hydrologic, climate, and social science models will be essential for generalizing experimental results and examining interactions between human and natural systems. The nature of new integrated science research questions will likely require the development of a new generation of models to examine non-linear responses, emergent properties, connectivity, and other ecosystem properties, and to couple human and natural systems such as land use prediction models. For example, models can be used to expand the press-pulse dichotomy of drivers to include a continuum of potentially interacting temporal scales. Exploring the importance of spatial variability to ecosystem dynamics across a range of scales, from within-sites to regions and across the continent, is cost-prohibitive through experimentation and best addressed through modeling. Under conditions where transport processes at intermediate scales are important, the extrapolation of fine-scale dynamics to broader spatial extents and longer time periods can only be conducted by spatially-explicit process-based models. Although models are powerful exploratory and predictive tools, the development and use of models for Network-level science is currently limited by local technology constraints and resources, the lack of centralized staff and resources dedicated to modeling, and the lack of a formally structured modeling framework.

6.4.2. Approach

This initiative will organize and direct computational support of analysis and modeling related activities and identify and collaborate on the development and integration of new analytical tools. A computational framework and collaboration infrastructure are needed to encourage and persistently support modeling and analysis activities. To meet these needs, we foresee a modeling and analysis initiative for the development and implementation of:

Scalable computing resources. This initiative will require increased accessibility to new hardware technologies, including high performance computers, parallel processors for some applications, grid technology, and high storage and high throughput capacity.

Advanced analytical environments. The use of scientific workflow systems as analytical tools and as a framework around which application and model development and integration can take place is the most promising emerging technology in this area. Scientific workflows are pipelines or networks of analytical steps that may involve, for example, database access and querying steps, data analysis and mining steps, and many other steps including computationally intensive jobs on high performance computing clusters (Ludaescher et al. 2005). The SEEK project is developing an Analysis and Modeling System (AMS) that allows ecologists to design and execute scientific workflows that seamlessly access data sources and services including models, and put them together into reusable workflows. The system is based on Kepler, a scientific workflow system that is community-based and cross-project. This activity will exploit this work and collaborate on specific improvements that will meet the needs of the new LTER science agenda.

Public-private partnerships are also important. For instance, BES researchers are increasingly working to characterize the social and ecological characteristics of all property parcels in the metropolitan region and to link these data to other scales. These analyses are data intensive, often exceeding the computational capacity of existing commercial software. Because many LTER analyses represent the cutting edge of consumer needs, this creates opportunities for commercial vendors to anticipate future market needs and develop products in anticipation of those consumer needs. As a result, commercial partnerships may be valuable for addressing LTER modeling needs.

Community-based repository. Archiving environmental data products has become recognized as a vital research practice: it improves our ability to perform new unanticipated analyses and to reproduce results while saving the cost of redundant data collection activities. The same rationale applies to archiving numerical models (Thornton et al., 2005). Archived datasets and models will provide the persistence, provenance, and methodological detail necessary to recreate published results, enabling the synthesis of results across multiple studies and the investigation of new hypotheses. In addition, archived models will allow determination of uncertainties for comparison with results from other models in assessment / policy studies. The model source code will also allow others to see how models treat individual processes.

6.4.3. Implementation

Development of advanced modeling and analysis capabilities will be a sequential process, focusing first on community-building through a series of workshops. The workshops should draw on both LTER investigators and non-LTER investigators who have relevant synthesis and modeling expertise. The workshop should address questions such as what processes can LTER empirically address across sites now, what modeling capability can be used in the synthesis, and what are the challenges, opportunities, and strategies available for the next 10 years for synthesis and modeling? To sustain synthesis and modeling activities into the future, an ambitious investment is needed to support and train the next generation of modelers. Support for students is needed in the form of targeted graduate student fellowships for synthesis and modeling that includes tuition, competitive stipends, travel allowance for work at multiple sites, and modest research budgets.

Ultimately, we believe that achieving our goals will require the development of a Modeling and Analysis Center that would provide a central location for synthesis and modeling activities and include computational infrastructure, support staff, a director/coordinator, space for visiting scientists (students, staff, researchers), and a venue for synthesis workshops. The center should also be networked to provide year-round accessibility to off-site personnel and include video-conferencing capabilities.

6.5. Initiative 5: Build capacity to increase collaboration

Cyberinfrastructure for collaboration can mitigate distance barriers as research activities increase across multiple scales of geographic distribution and across multiple scientific domains. Efficient, usable, and persistent infrastructure is key to supporting the collaborations and ultimately an integrated research community. By this we mean immediate and continued access to

- staffing for software development and programming of collaborative work environments;

- funding for procurement of video-conferencing technology;
- staffing for software development of integrated analytical tools; and
- funding for procurement of enhanced Network infrastructures.

6.5.1. Rationale

Research activities integrated with CI will enable researchers to work routinely with colleagues at distributed locations (Atkins 2003). To realize this increased capacity demands an understanding of how collaborative work using web-based tools differs from traditional work. It has been shown that geographic distribution can undermine research performance if researchers have not been well-prepared to use collaborative technologies productively. Collaborations that have deliberate social structures, management practices, and frequent contact are more successful (Cummings and Kiesler 2003). Unless the benefits are obvious there will be low tolerance for complicated designs and steep learning curves. The quality of the user-interface, the latency of the network, and the availability of tools are all critical to successful collaboration.

6.5.2. Approach

Our approach to meeting the increased need for research collaboration will be multi-faceted: procuring and deploying video-conferencing and Network technology for immediate use, co-developing and deploying a framework for collaborative work environments, the development and deployment of analytical tools within that framework, and collaboration with socio-technical scientists in order to build effective frameworks and learn from our efforts. Web-based social software holds promise for community-based collaborative frameworks (Figure 6). It is essential that socio-technical expertise in organizational informatics be integrated with this effort to ensure success in meeting this challenge.

Collaborative work environments. The development of collaborative work environments will allow scientists residing in different locations to analyze, discuss, annotate, and view data. Access to video-teleconferencing, shared interfaces, community services, and other collaborative tools will allow groups to identify, discuss, and solve scientific problems efficiently. Portal technologies will facilitate

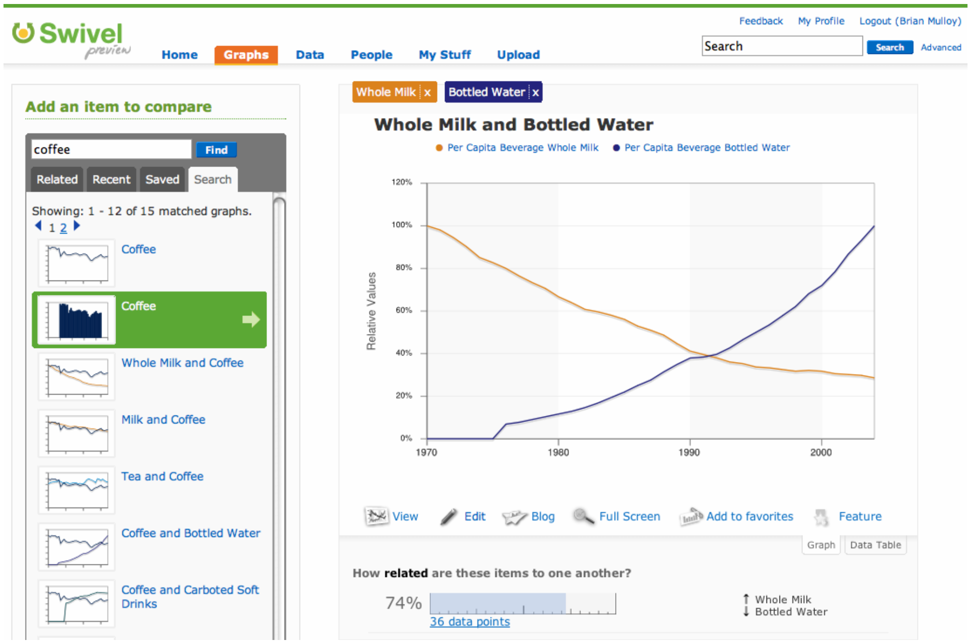

Figure 6. Web-based social software like Swivel (http://www.swivel.com) can facilitate collaboration.

communication and common understanding of project tasks and goals through access to data, text, images, etc., among data collectors, managers, analysts, and investigators as well as provide a web content management solution enabling parallel document development (joint authorship). There are, in development, best-practices that take into account the social and technical aspects of collaboration that can help meet these challenge successfully. To develop and implement a CI-based collaborative environment for ecological science requires the integration of ecology with information technology and with expertise in organizational learning. Strategic partnerships and design and programming expertise are required to make this collaborative environment possible.

Analytical tools. We must deliver immediate gains through tool deployment while allowing the potential of collaborative work environments to become integrated into normal practice. The researchers must have useful tools, even low-level visualization and analytical tools, to "play with" in order to gain confidence in the use and persistence of the system. Researcher co-design opportunities and programming time are required to further this effort.

Video teleconferencing. Common video-teleconferencing (VTC) capability will support multi-site collaboration and information sharing. The LNO has already installed a 48 channel shared VTC facility that provides a basis for support of scheduled and ad hoc meetings from one-on-one communication to large group meetings. Additional hardware and connectivity at the LTER host institutions and sites are needed so that they can use this facility and similar infrastructure to enhance communication across the Network.

Network connectivity. Internet2/NLR connectivity at LTER sites will enhance data throughput in the Network and provide site access to Network and other GRID-based resources. To maximize sustained throughput of data and information, a high-level of end-to-end network connectivity from the field sensor network to the investigator desktop, to local and remote data centers will be beneficial. The majority of LTER host institutions, particularly universities, are already linked by Internet2 connections. However, this level of connectivity is not consistent across the Network. For some institutions support is needed to make the link of the last few feet to the local gigaPOP, but for others, collaborative support will be needed to link to a commercial gigaPOP or similar connection in the city center. For the LTER field sites themselves, more than half of the sites have T1 level or slower data throughput. Similar to the needs of the LTER host institutions, additional hardware and network traffic support costs must be met to enhance Network connectivity beyond the current level.

6.6. Initiative 6: Integrate cyberinfrastructure into social-ecological research, education, and training

Integration of new cyberinfrastructure, including advanced tools for analysis and synthesis within the research process, will require training of students and scientists so that their activities will 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. These challenges can be met by developing a program of workforce training and education with multiple goals:

- provide training in new technologies and methods to information managers and technical professionals engaged in data acquisition and management at LTER sites;
- provide training in the use of advanced informatics tools to natural and social science students and scientists who are engaged in LTER research;
- maintain a cross-trained cadre of information managers who can be quickly deployed with a standard curricula and training materials for working with LTER colleagues and collaborators; and
- develop educational materials tailored to video-teleconferencing, web-based seminars, distance learning, and other paths by which informatics training for educators, students, scientists, and technical professionals can be conducted remotely.

In addition to technological training to support research activities, social-ecological education and outreach will be integrated components of the new Network science. Programs will include science education research, engagement of K-16 students in inquiry-based science that integrates social-ecological disciplines and focuses on working with data, opportunities for graduate students to conduct collaborative research within the context of long temporal and broad spatial scales, and efforts to engage the public with broad participation representing our diverse society. In this section we discuss the unique CI needs of training and education and outreach beyond those supporting research activities in general.

6.6.1. Rationale

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. As the LTER Network is engaged in implementing cutting-edge, enabling CI, the vision of many researchers productively engaging in integrative, interdisciplinary science by easily accessing and analyzing diverse data will only occur with organizational and cultural change that promotes new approaches for designing and conducting science. These new approaches are conceptual (e.g. how do we effectively engage in interdisciplinary research), technological (e.g. what tools can we use to accomplish that research), and social (e.g. how can we convey our findings to other disciplines, policymakers, and the public accurately, appropriately, and with demonstrated relevance).

The new LTER science agenda will produce a tremendous volume of data and information in the not-so-distant future. The societal expectation that we will make good use of that investment argues that a decades-long process of workforce development is not acceptable. Institutional programs designed to train domain scientists in informatics are currently non-existent. These challenges will be addressed by the development and implementation of a training curriculum for graduate students and research scientists. This will result in a generation of students and professional scientists from multiple disciplines engaged in research on complex environmental questions who are able to bring the latest technologies and cyberinfrastructure to bear on the problem of design, conduct, and communication of interdisciplinary research.

Effective use of new technology and the development of innovative, Network-wide CI solutions also demands that training be provided to keep the technical and informatics professionals competent in current and developing technology. This training program is another arena in which partnerships with computer scientists engaged in cutting-edge development can be fostered to facilitate technology transfer. The LTER Network will need to operate at a new level of coordination in order to provide CI for the expanded science agenda, and it is critical that site information managers be involved in the training that such coordination and optimal use of new technology requires. Other technical personnel may benefit from centralized training programs as more LTER sites develop sensor networks and confront the challenges in scaling up the data volumes produced.

Training graduate students, researchers, and technology professionals will support the goals of the Network level science program. However, additional training and developments will need to be made to translate technologies and data products into K-16 classrooms and to the public. For example, technology will support the dissemination of diverse (e.g., ecological, sociological, geophysical) data in multiple formats (e.g., real-time, historical, data visualizations). However, achieving educational goals using this new integrated social-ecological research program will require a deeper understanding of what constitutes data literacy within and across disciplines at all levels of education. Similarly we will need to develop effective mechanisms to communicate with and respond to a diverse public.

6.6.2. Approach

Centrally developed training programs can address the need for cross-trained informatics experts and informatics-adept students and scientists. 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. To meet some more targeted needs, a cross-trained cadre of information managers will be quickly deployed with training materials. Remote learning environments will be constructed for certain needs that use video-teleconferencing, web-based seminars, and other methods for distance learning. Procedures for evaluation of the training workshops and other materials will be developed. Identification of training needs and development of curricula will involve participation of the targeted user groups.

Training program for domain-scientists and students. Training workshops will be provided to graduate students, teaching or research faculty, and research professionals engaged in research on environmental problems. The development of a community of scientists who can use relevant technologies in ecological research can be addressed by 1) providing training in methods and technologies that emphasize information and knowledge management, integration, analysis, synthesis, and dissemination; 2) exposure to example applications where these have been effectively and appropriately applied; and 3) mentoring individuals as they attempt to bring these new approaches into practice. The training program will provide instruction on traditional informatics areas such metadata and database design as well as cutting edge technologies such as embedded sensor networks, scientific workflow software, distributed computing and knowledge representation. The workshops will be structured to provide students with background in fundamental topics before introducing cutting edge technology.

Training program for technical staff. Training workshops will be developed for informatics topics identified by both the LTER information management community (for example topics, see Table 1) and IT partners. Each course will include lectures, hands-on labs, and examples of cases where these approaches have been used in environmental studies.

Special CI developments for education and outreach. Our CI initiative will address the unique challenges presented in the K-16 educational setting. Approaches such as distance learning technology (e.g., webcasts, linking classrooms, etc.), which are used routinely in undergraduate and research settings must address issues of insufficient infrastructure and technical expertise in the K-12 environment. Some challenges are common to K-12 and undergraduate education. For example, research databases must be tailored to achieve pedagogical goals and must work with educational technology infrastructure. Embedded resources, such as guides to support student inquiry, interactive learning components, and more engaging graphic interfaces would support the learning community. In short, dissemination of scientific products to educational settings entails dealing creatively with the mismatch between the infrastructures available at K-12 institutions vs. institutions of higher education. In practice, there is a wide continuum of resource availability in schools, and therefore it is necessary to have products and communication available in multiple modes to accommodate this diversity. Finally, research tools (e.g.,

Table 1. Potential near-term training needs for technical staff based on a recent survey of LTER sites and Information Managers. Listed tools are examples of relevant tools.

Category	Needs
Web services	Tools and techniques for participating in Network SOA
Spatial data systems	Remote Sensing / GIS / Spatial Data Engines
Ecoinformatics	Data management, archiving, and curation; includes EML
Data quality	Quality assurance, quality control, quality management

online or embedded assessment tools) and databases developed for educational research purposes would help to integrate the science education research community.

7.0 Collaboration and Integration with other Observatory Networks

Noted throughout this plan are specific instances of potential collaboration with emerging environmental observing networks such as NEON, OOI, and WATERS, and key areas where integration will be crucial in order to leverage synergies and avoid duplication. As a network we are fully committed to participating in the development, testing, and distribution of solutions to the common challenges faced by all environmental observatories.

As detailed in Section 3, many years of CI development both at the site and Network levels has provided a rich body of experience and insight with respect to CI deployment. This experience ranges from the development of community-led site-based data standards to Network-wide data integration and harvesting technology to the deployment of wireless sensor networks. Wherever possible we will leverage resources, funding opportunities, and education and training activities to further CI needs within the entire family of observatories. At the same time, however, a number of needs will likely remain specific to LTER, at least in the near term, and we will actively pursue meeting these needs in concert with those that are more commonly shared. An example of a more specific LTER issue is the crucial need to integrate and make accessible a rich body of legacy data sets such as those illustrated in the EcoTrends project.

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The Decadal Plan for LTER

Integrative Science for Society and the Environment:
A Plan for Science, Education, and Cyber-infrastructure
in the U.S. Long-Term Ecological Research Network

System VI

Network Governance for LTER

The U.S. Long-Term Ecological Research Network
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Network Governance for LTER

The LTER Network in May 2006 adopted a governance structure designed to streamline Network operations and allow for more coordination and collaboration among member sites. In short: to promote Network-level science while bolstering the ability of sites to meet site-level science needs. The basic structure is outlined in Figure 1; Network Bylaws, adopted in May 2006 and reprinted below, provide detail. The Science Council is the basic unit of authority in the Network; it is made up of the lead PI of each site plus a rotating representative from that site; the Science Council Chair, elected for a 2-year term; the Executive Director of the Network Office; and chairs of standing and targeted committees. The Chair of the Science Council also leads the 12-member Executive Board, which is authorized to act on the Council's behalf. The Science Council meets once per year in a combination science-business meeting; business is mostly limited to science-related reports and bylaw revisions. Most Network business is conducted by the Executive Board, which meets once per month mainly by videoconference. The Executive Director of the LTER Network Office is an ex officio member of the Science Council and Executive Board.

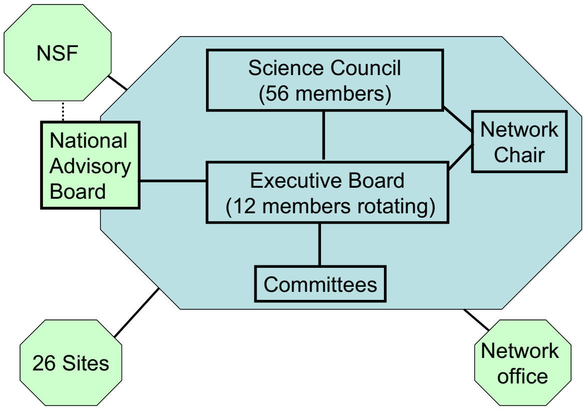

Figure 1 Organizational chart for LTER Network governance.

LTER Network Bylaws

Article I
Name

Article I, Section 1. Name: The name of the network is the Long Term Ecological Research Network (LTER Network).

Article I, Section 2. Purpose: The purpose of the LTER Network is to promote the advancement and applications of long-term ecological research in the United States and internationally. This is accomplished through communication and coordination of research, education, and information management activities, and through synthesis activities across sites and ecosystems and among other related national and international research programs.

Article II
Membership Affiliation

Section 1. Membership: The LTER Network consists of Sites funded under the LTER program by Directorates of the National Science Foundation (NSF), or by other agencies in conjunction with the NSF, and an LTER Network Office (hereafter called the Office) designated specifically by the National Science Foundation. Any person affiliated with a Site can be part of the LTER scientific community.

Article III
Meetings of Membership

Section 1. Periodic All Scientists Meetings: At approximately three (3) year intervals, the Office, with guidance from the Executive Board and Science Council, will organize an All Scientists Meeting to facilitate synthesis activities and collaborative research efforts in the LTER Network. The scientific theme(s) for the meeting will be determined by the Science Council. The Office will seek additional funding from NSF for these meetings. The Office will evaluate options for meeting locations to present to the Executive Board at least two (2) years before the scheduled meeting, and meeting locations will then be determined by majority vote of the Executive Board.

Article IV
LTER Science Council

Article IV, Section 1. Powers: The scientific direction and vision of the LTER Network is established by the Science Council. The Science Council reserves ultimate authority for decisions affecting the Network, and may address any issue that arises from the Executive Board, the Network Office, or the participating LTER sites. The Science Council has the responsibility to provide leadership and planning for cross-site research and education, to develop proposals for the conduct of network-level science, to interact with existing and emerging networks, to develop products that synthesize network-level data and information, and to otherwise manage the science affairs of the LTER Network. As needed, the Science Council shall appoint subcommittees to help carry out its responsibilities. The Science Council elects the Chair, approves Bylaws changes, and recommends candidates for the National Advisory Board to the Executive Board. With the exception of the Chair, the Science Council receives no compensation other than reasonable expenses.

Article IV, Section 2. Composition: The Science Council shall be composed of a Chairperson, a Chair-Elect (as needed), the Chair of each network-wide and Targeted Standing Committee, the Executive Director of the Office, and the Principal Investigator and an additional participant from each LTER Site. The Principal Investigator serves as the Voting Representative of his or her Site; the other participant will be a rotating, non-voting member (hereinafter referred to as the Second Representative).

IV, 2.1 Chairperson

The Chair of the Science Council shall be elected by the Science Council from within the scientific community of the LTER Network. Nominations for Chair will be accepted from the LTER scientific community by the Executive Director of the Office. The Office will distribute resumes of each nominee to the Science Council and thereby to the scientific communities at all LTER Sites at least 30 days prior to the election. Election of a Chair will be by majority vote of the Science Council. The election will be held at the Science Council meeting at least one (1) year prior to the expiration of the current Chair's term (i.e. every other year). The individual elected shall serve as Chair-Elect for one (1) year prior to assuming office as Chair and during this time shall be an ex-officio, non-voting member of the Executive Board. The term of office for the Chair will be two (2) years. The Chair may stand for re-election for one consecutive two (2) year term.

IV, 2.2 Chairperson-Elect

If, for any reason, the Chair shall be unable to carry out the duties of that office, he/she shall be succeeded immediately by the Chair-Elect for the remainder of the term. The Chair-Elect shall succeed to fill his/her term at the end of the substitution.

IV, 2.3 Principal Investigator

The Principal Investigator of the NSF award to that LTER Site will serve as the Site's *de facto* Voting Representative to the Science Council and shall represent that LTER Site in all actions performed by the Science Council. It is expected that the Principal Investigator will attend all meetings of the Science Council. In the rare instance that the Principal Investigator must be absent from a Science Council meeting, he or she shall appoint from among Site members, an Acting Voting Representative.

IV, 2.4 Second Representative

For every scheduled meeting of the Science Council, each LTER Network Site will select an individual to serve as the Second Representative for the Site. The role of the Second Representative is to provide expertise related to the annual meeting science theme(s). The Second Representative shall be selected by the Site and shall serve for a minimum of one (1) year. The Second Representative may be selected from within or outside the LTER scientific community. It is expected that a Second Representative, along with the Site Principal Investigator, will attend all meetings of the Science Council. If a Second Representative vacancy occurs, the Site will select a new Representative..

IV, 2.5 Chairs of the Standing Committees

The Chair of each network-wide and Targeted Standing Committee shall serve as a non-voting member of the Science Council.

IV, 2.6 Executive Director of the Office

The Executive Director of the Office shall serve as an ex-officio, non-voting member of the Science Council.

Article IV, Section 3. Meetings: The Science Council will meet annually on dates mutually agreed upon by the Executive Board, the Principal Investigator of the LTER Site hosting the meeting, and the Executive Director of the Office. Notice of such meetings shall be given to the Science Council by the Chair at the previous annual meeting or by electronic mail not less than six months before the date fixed for the meeting. The Science Council will determine the science themes(s) and scientific program for the meeting. The Chair, in consultation with the Executive Director, will prepare the agenda for the business portion of the meeting. Locations of Science Council meetings will be determined at least two years in advance by majority vote of the Science Council based on nominations from the floor. An attempt will be made to rotate meetings among the LTER sites to allow LTER Network scientists to become familiar with the science programs at each site. The Science Council may use teleconferencing or other electronic methods as an alternative to meeting in person, but in no instance shall it meet in person less than once per year. Meeting minutes shall be archived and made available to all Sites no more than four (4) weeks after any meeting.

Article IV, Section 4. Quorum: Except as may be otherwise expressly required by these Bylaws, two-thirds (2/3) of the Voting Representatives of the Science Council shall constitute a quorum at a meeting in which a vote occurs.

Article IV, Section 5. Voting: Voting requires a quorum. Except as otherwise expressly required by these Bylaws, all matters shall be decided by the affirmative vote of a majority of the Science Council members present. Each Voting Representative of the Science Council attending the meeting shall be entitled to one vote.

Article IV, Section 6. Chair Resignation or Removal: The Chair may resign by giving written notice to the Science Council, Executive Board, and Executive Director of the Office. Such resignation shall take effect at the time of receipt of the notice, or at any later time specified therein. The Chair can be removed by a two-thirds (2/3) vote of the Science Council. In the event of a vacancy in the Chair, the Chair-Elect shall assume office immediately, for the remainder of the term. He/she shall succeed to fill his/her term at the end of the substitution. If no Chair-Elect exists the procedure described in Section 2.1 above shall be followed to elect an interim Chair to serve out the remainder of the term. In the period between the vacancy and the election of an interim Chair (no more than 45 days), the Executive Board shall elect one its Members to fill the duties of the Chair.

Article V
LTER Executive Board

Article V, Section 1. Powers: Full power in the management of the affairs of the LTER Network is vested in the Science Council. To this end and without limitation of the foregoing or of its powers expressly conferred by these Bylaws, the Executive Board shall have power to authorize such action on behalf of the LTER Network; make such rules or regulations for its management; create, evaluate, and dissolve such additional offices or special committee; and select, employ or remove such of its officers or agents as it shall deem best. The Executive Board shall have the power to fill vacancies in, and change the membership of, such duly constituted committees. The Executive Board shall have the responsibility for developing and updating the LTER Strategic Plan for the Network and for developing and recommending Bylaws changes. If a site objects to a decision of the executive board, it can seek redress of the issue with the Executive Board, and with the support of at least 5 sites, with the Science Council. With the exception of the Chair, the Executive Board receives no compensation other than reasonable expenses.

Article V, Section 2. Composition: The Executive Board shall be composed of the elected Chair of the Science Council serving as Chair of the Executive Board; nine Members selected by individual Sites on a rotating basis; an Information Manager; the Executive Director of the Office, and, as needed, a Chair-Elect. All members of the Executive Board shall act in behalf of and are accountable to the membership of the LTER Network. Members will serve as liaisons to LTER Network committees and perform other functions as delegated by the Chair.

V, 2.1 Chair

The Chair of the Science Council serves as Chair of the Executive Board and shall be elected by the Voting Members of the Science Council and be subject to the term lengths described in Article IV, Section 2.1.

V, 2.2 Chair-Elect

The Chair-Elect of the Science Council serves as Chair-Elect of the Executive Board and shall be elected by the Voting Members of the Science Council as described in Article IV, Section 2.2. The Chair-Elect is a non-voting member of the Executive Board.

V, 2.3 Site Representatives

Nine members of the Executive Board shall be selected from among the LTER Sites on a rotation that includes all LTER Sites. The rotation is designed to optimize representation by the Sites in Network governance, and each Site is expected to participate in the Executive Board at the time determined by the rotation scheme. Each Site will choose its Representative in a matter to be determined by the Site. Site Representatives shall have a single term of three (3) years or until a successor is duly selected or elected. In the event that a Site Representative is removed or is not able to fulfill his or her term, the Site will choose a replacement to complete the term. Terms of the Site Representatives will be staggered, so that terms of one-third of the members expire each year.

V, 2.4 Information Management Representative

The LTER Information Management (IM) Committee shall select one member from among them to serve as the Information Management Representative to the Executive Board. The IM Committee shall determine the method by which the Representative is selected. The Information Management Representative is a non-voting member of the Executive Board and shall serve a single three (3) year term. In addition to the responsibilities shared by all Executive Board members, the Information Management Representative shall serve as the liaison between the Executive Board and the Information Management Committee providing insight on informatics, technology implementation, and human-technology infrastructure issues as well as on design and implementation of federated information system activities. In the event that an Information Management Representative is removed or not able to fulfill his or her term, the IM Committee will choose a replacement to complete the term.

V, 2.5 Executive Director of the Office

The Executive Director of the Office shall serve as an ex officio, non-voting member of the Executive Board

Article V, Section 3. Meetings: The Executive Board for the LTER Network will meet a minimum of two times per year on dates designated by the Chair. The Executive Board may use teleconferencing or other electronic methods as an alternative to meeting in person, but in no instance shall it meet in person less than once per year. The Chair shall have the authority to call special meetings of the Executive Board to address urgent governance issues. Except in situations that require immediate action, notice of all meetings must be distributed to Network Sites at least two (2) weeks in advance of the meeting, so that Network members have the opportunity to bring forward business for the Executive Board to consider. Meeting minutes will be archived and made available to all Sites no more than two (2) weeks after any meeting.

Article V, Section 4. Quorum: Except as may be otherwise expressly required by these Bylaws, two-thirds (2/3) of the Voting Representatives of the Executive Board shall constitute a quorum at a meeting in which a vote occurs.

Article V, Section 5. Voting: Voting requires a quorum of the 9 voting members. The IM member and the Executive Director of the LTER Network Office are non-voting members. The Chair only votes to break a tie. Except as otherwise expressly required by these Bylaws, all matters shall be decided by the affirmative vote of a majority of the voting Members of Executive Board members present. Each Voting Representative of the Executive Board attending the meeting shall be entitled to one vote.

Article V, Section 6. Resignation, termination, and absences: Resignation from the board must be in writing and received by the Executive Director of the Office. A Executive Board member may be removed by a two-thirds (2/3) vote of the Executive Board.

Article VI
Officers and Duties

Article VI, Section 1. Chair: The Chair shall preside at all meetings of the Science Council and the Executive Board and, along with the Executive Board, generally oversee and supervise the governance of the LTER Network. The Chair shall facilitate communication to Network Sites regarding decisions of the Executive Board; provide a receptive ear for any Network member who wishes to raise an issue of concern; and serve as or appoint liaisons to NSF, other agencies, associations, networks, the public, and to Network committees. The Chair, with assistance from the Executive Director and Office, is responsible for preparing meeting agendas and overseeing the taking of minutes at all Science Council and Executive Board meetings and for ensuring that such minutes are available to Sites within the time frames specified in these Bylaws. The Chair will orient the Chair-Elect to the duties of the office.

Article VI, Section 2. Chair-Elect: The Chair-Elect shall, in the absence of the Chair, preside over meetings of the Science Council and Executive Board and otherwise exercise all powers and duties of the Chair. The Executive Board, in the absence of the Chair and Chair-Elect, may appoint from among its members, an Acting Chairperson.

Article VI, Section 3. Compensation: The Chair-Elect receives no compensation other than reasonable expenses. The position of Chair requires a substantial level of effort, equal to one-third (1/3) to one-half (1/2) of an FTE. In recognition of the time and effort required of the Chair, the Executive Director of the Office, in consultation with NSF, shall negotiate the mechanism for compensation appropriate to the situation no later than 6 months after the Chair's election.

Article VII
Other Committees

Article VII, Section 1. General: Other committees, consisting of Network-wide Standing, Targeted Standing, or Ad Hoc, may be created by resolution adopted by the Executive Board. Each committee shall have only the lawful powers specifically delegated to it through the charge to the committee approved by the Executive Board. The Executive Board shall evaluate all committees on an annual basis. Any committee may be dissolved by a vote of the Executive Board. Committees may have representation at Executive Board meetings at the discretion of the Executive Board. Committee Chairs shall report on their work at least annually to the Executive Board and at such other times as directed by the Chair. Chairs and members of committees receive no compensation except for reasonable expenses.

Article VII, Section 2. Network-Wide Standing Committees: One or more Network-wide standing committees may be formed by the Executive Board for each major scientific, educational, or research program identified by the LTER Network. Members shall include one Representative from each Site. Network-wide Standing Committees, once formed, shall elect their own Chairs. The Chairs of each Network-wide Standing Committee are non-voting members of the Science Council.

Article VII, Section 3. Targeted Standing Committees: One or more Targeted Standing Committees may be formed by the Executive Board. A Targeted Standing Committee shall be formed to address specific, long-term scientific or administrative issues that require particular kinds or combinations of expertise. Targeted Standing Committees do not require representation from all sites to meet their charge. Targeted Standing Committees, once formed, shall elect their own Chairs. An individual from any of the LTER Sites may be a member of a Targeted Standing Committee. The Chairs of each Targeted Standing Committee are non-voting members of the Science Council.

Article VII, Section 4. Ad hoc Committees: The Executive Board may create such ad hoc committees as may be deemed desirable, the members of which shall be appointed by the Executive Board. Each such committee shall have only the lawful powers and term of operation/existence specifically delegated to it by the Executive Board. Ad hoc committees may have representation at Executive Board and/or Science Council meetings at the discretion of the Executive Board.

Article VIII
National Advisory Board

Section 1. National Advisory Board: A National Advisory Board (NAB) of no more than 15 members representing diverse areas of expertise will provide independent review and advice to the LTER Network, the Office, and appropriate funding agencies. The Chair of the NAB shall be recommended by the Executive Board and invited to perform this service by the Chair. The Chair of the NAB will select approximately one-half of the NAB members from a list provided by the Science Council. The remainder of the NAB will be chosen by the NAB Chair to ensure outside, independent review. NAB membership will be for 3 years with a replacement of at least 1/3 of the membership each year. The NAB will meet in person a minimum of once each calendar year and shall provide a written report after each meeting. The report will be provided to the Executive Board, reviewed by the Science Council, and forwarded to the NSF.

Article IX
Network Office

Article IX, Section 1. Tasks and Duties: The Office exists as the result of a Cooperative Agreement between the National Science Foundation and a contracting institution that hosts the Office. Tasks that the Office performs in support of the LTER Network are defined in the Cooperative Agreement, in the LTER Strategic Plan for the Network and the Office, and by the Executive Board.

Article IX, Section 2. Review of Network Office Performance: An annual review of Office performance shall be conducted by the Executive Board at its first meeting of the year. The review will be based on 1) the annual report of the Office, which will be circulated to LTER Sites on January 1 of each year, 2) a survey of Sites administered by the Office in October of each year, and 3) goals set in the LTER Strategic Plan. The Executive Board will recommend modifications to Office tasks. Those recommendations approved by the Executive Board will be submitted by the Office to the NSF for possible incorporation into the Cooperative Agreement.

Article IX, Section 3. Renewal Proposals: Proposals to renew the Cooperative Agreement for the Office will be developed by the Executive Director of the Office (as Principal Investigator) working with the Executive Board.

Article IX, Section 4. Executive Director: The Executive Director of the Office is the Principal Investigator and scientific leader of the Cooperative Agreement. The Executive Director is an employee of the contracting institution, and operational supervision of the Executive Director resides with the contracting institution. The Executive Director is responsible for the day-to-day operation of the Office. The Executive Director will implement programmatic recommendations of the Executive Board, consistent with the Cooperative Agreement with the NSF. The Executive Director will assist in the orientation of new Chairs and Executive Board members and will work with the Chair to ensure that meeting notices, agendas, and minutes are distributed according to time-frames indicated in these Bylaws. Should the position of Executive Director become vacant, or the Cooperative Agreement be awarded to a different institution, the Executive Board will provide information on the desired qualifications of a new director to the contracting institution. The Executive Board will review applications for the position and recommend one or more candidates to the contracting institution or recommend a continuation of the search.

Article X

Amendments to the Bylaws

Section 1. Amendments: All Bylaws of the LTER Network shall be subject to amendment or repeal and new amendments may be made by vote of two-thirds (2/3) of the Voting Representatives of the Science Council at any annual or special meeting. A notice that has specified or summarized the proposed amendment, repeal or new Bylaws must be circulated to the Science Council at least 30 days before the vote.

The Decadal Plan for LTER

Integrative Science for Society and the Environment:
A Plan for Science, Education, and Cyberinfrastructure
in the U.S. Long-Term Ecological Research Network

Section VII

Integrative Science for Society and Environment: A Strategic Research Initiative

The U.S. Long-Term Ecological Research Network
October 1, 2007

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

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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.

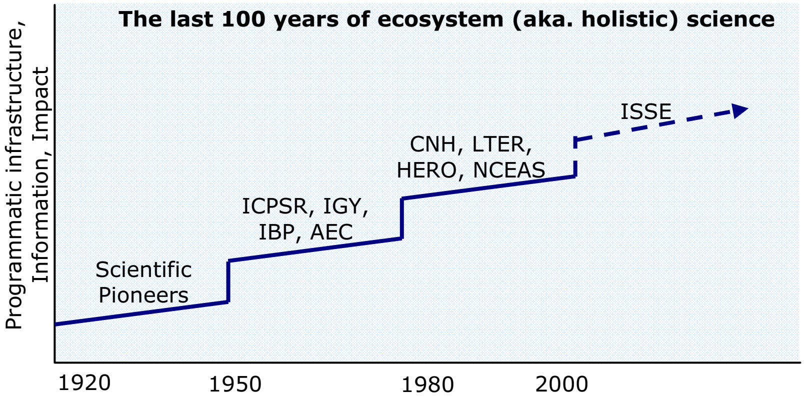


Figure 1. Evolution of the socio-ecological sciences to increasing holism through funding opportunities that led to greater integration within and among disciplines. We envision that the development of the Integrative Science for Society and Environment (ISSE) will be transformative because it will move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

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.

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).

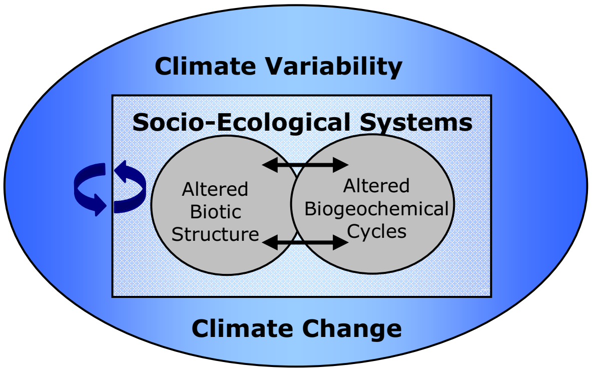


Figure 2. Hierarchical relationships and attendant feedbacks between climate variability and climate change, socio-ecological systems, and altered biogeochemical cycles and biotic structure. These research domains and their interactions, built around Environmental Grand Research Challenges (NRC 2003) 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

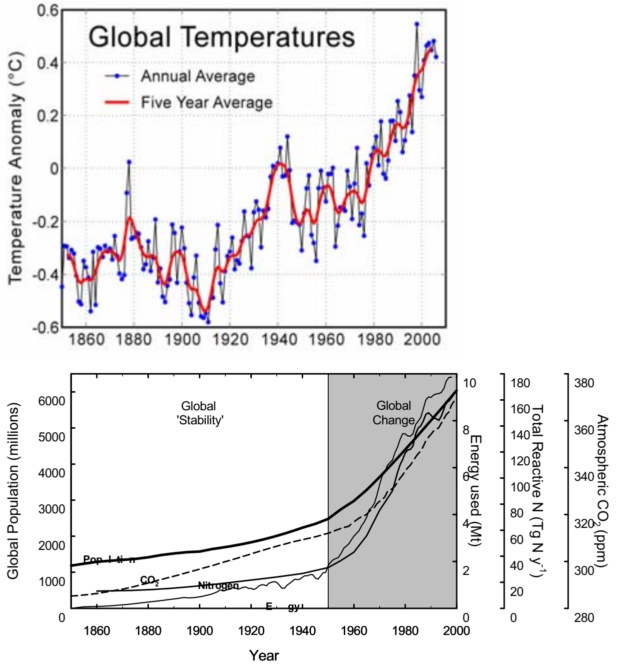


Figure 3. Changes in key ecological and sociological drivers over the last 150+ years. (Top) A plot of changes in global mean temperature based on instrumental records compiled by the Climatic Research Unit of the University of East Anglia and the Hadley Centre of the UK Meteorological Office (Brohan 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).

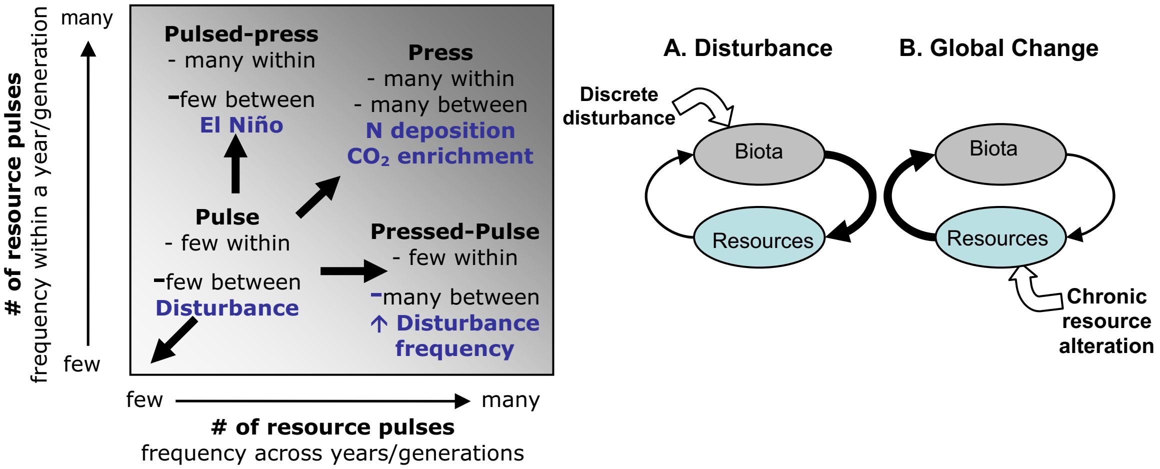


Figure 4. Changes in the nature of press and pulse perturbations in ecosystems in response to environmental change. Historically, natural disturbance regimes altered biotic structure and directly or indirectly altered resources for subordinate species. Environmental change (e.g., N deposition) is increasing 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.

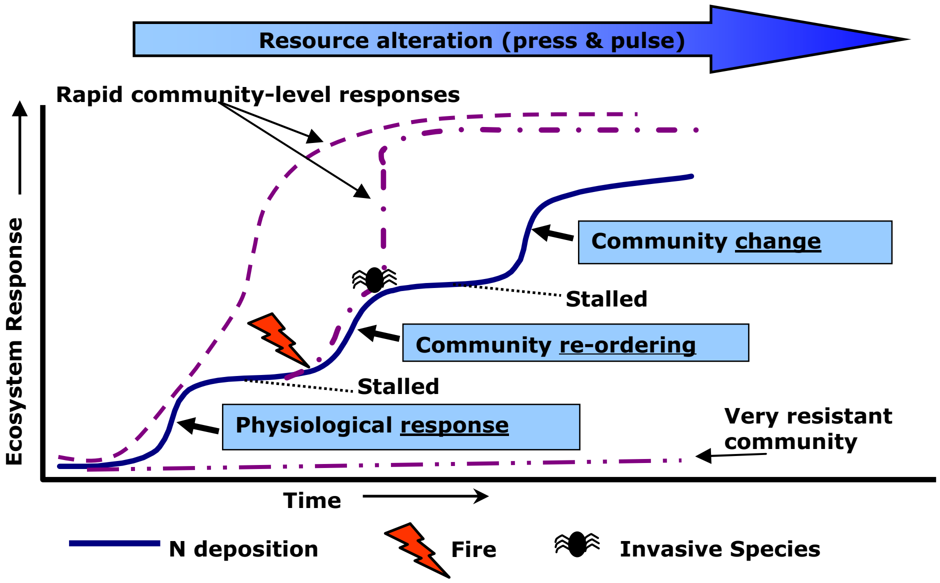


Figure 5. The interaction of press (e.g., N deposition) and pulse (e.g., intense fire) perturbations on organismal, community and ecosystem processes. The rate of change among sites is a function of system stability. The interaction of press and pulse disturbances may rapidly drive an ecosystem into 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.

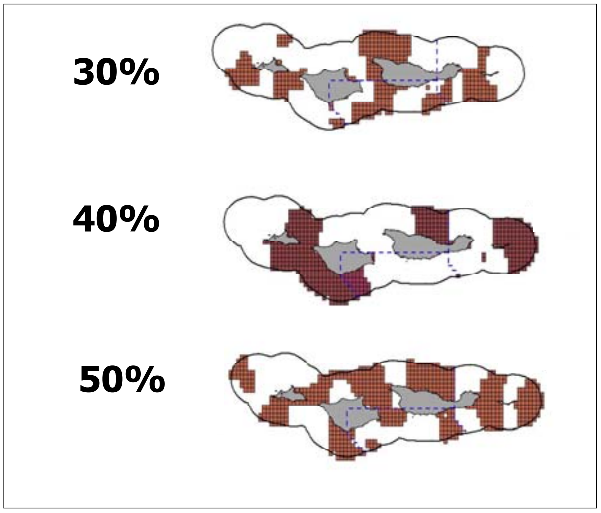
The mangrove forest at Florida Coastal Everglades LTER Program (SRS-6 site about 2 km from the Gulf of Mexico) before (top) and after Hurricane Wilma's landfall in October 2005 (see http:// fcelter.fiu.edu for details).

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.

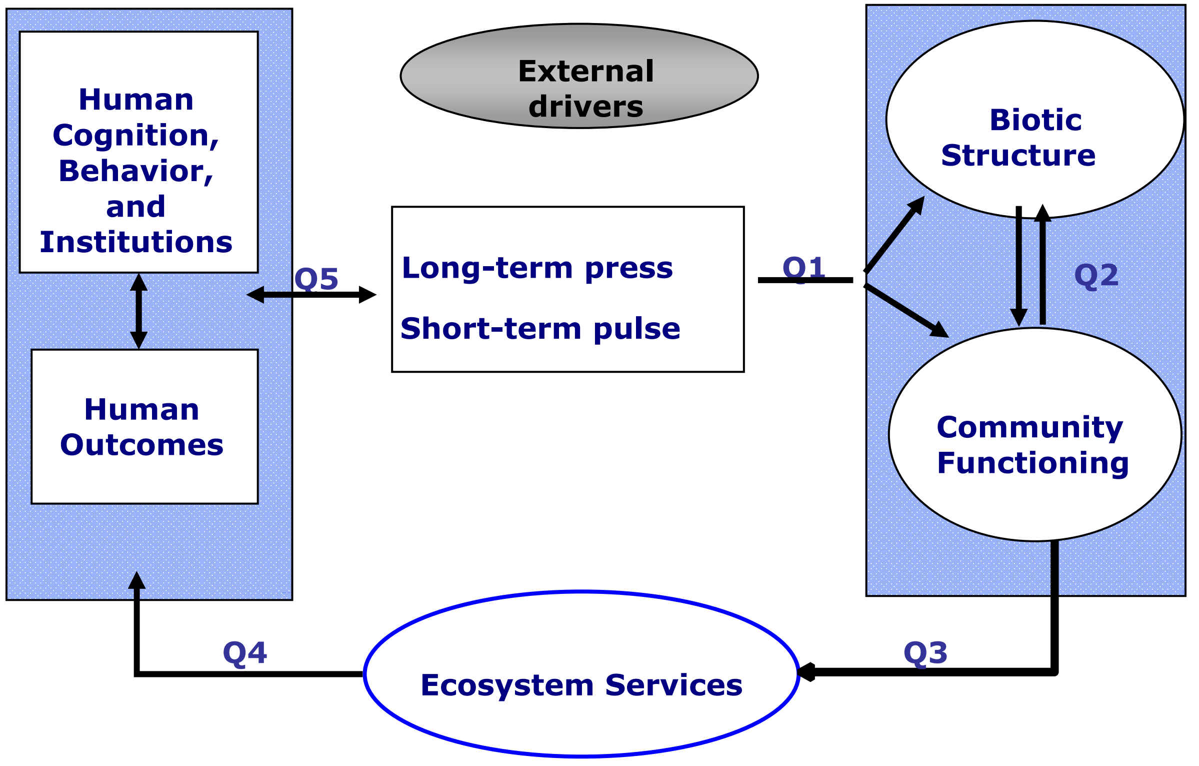


Figure 7. An integrative and iterative conceptual framework for socio-ecological research. Interactions within this framework are driven by a set of general questions (Q1-Q5, see Box 8) that create information pathways for linking the ecological, geological and social sciences. This very general framework 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.

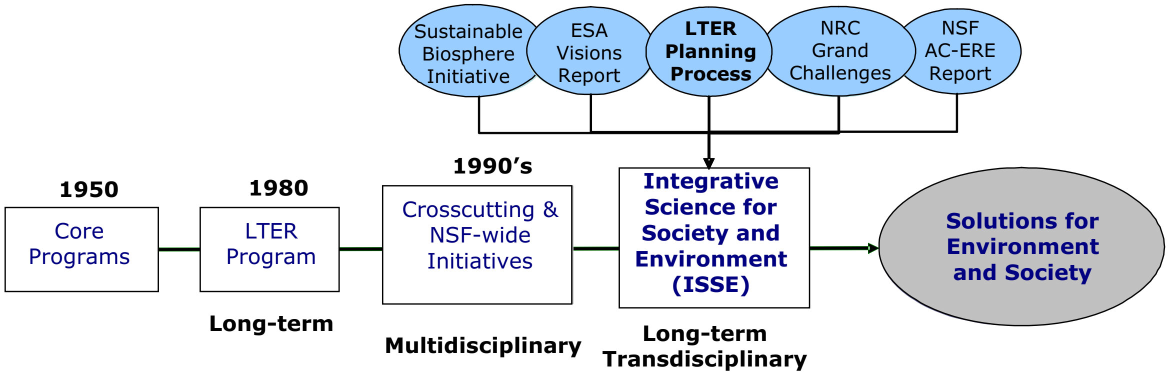


Figure 8. Trajectory of NSF programs supporting socio-ecological research and a proposed new cross-directorate research initiative: Integrative Science for Society and Environment. Historically, NSF core programs have funded individual investigators to conduct short-term disciplinary research. In recognition 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.

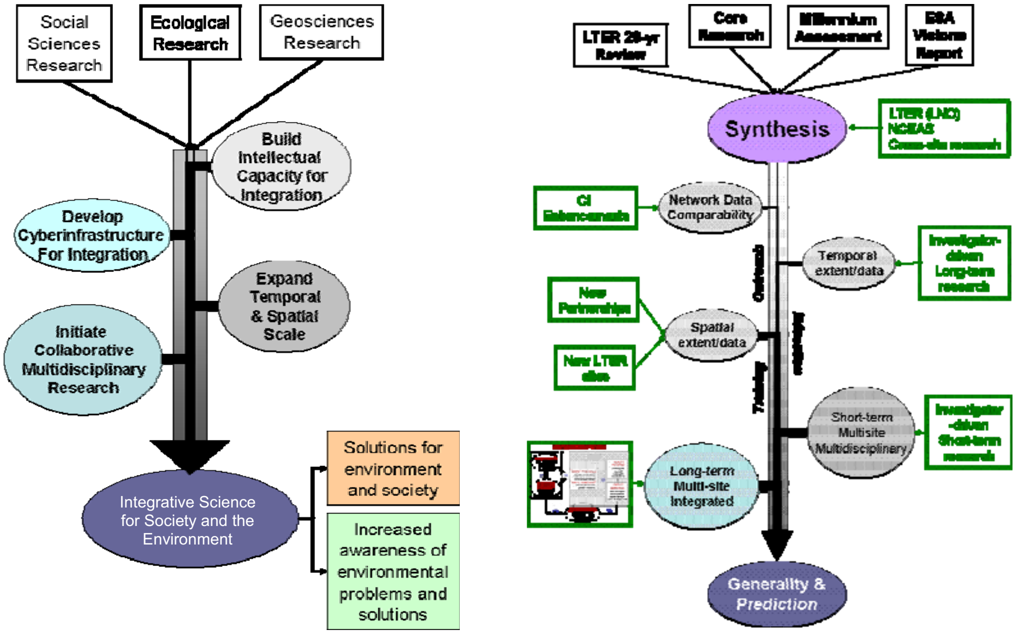


Figure 9. General and specific components of Integrative Science for Society and the Environment. Reports such as the LTER 20-yr review (Krishtalka et al. 2002) and ESA Visions (Palmer et al. 2005) identified critical barriers to creating knowledge that can provide the generality and predictive capabilities 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.

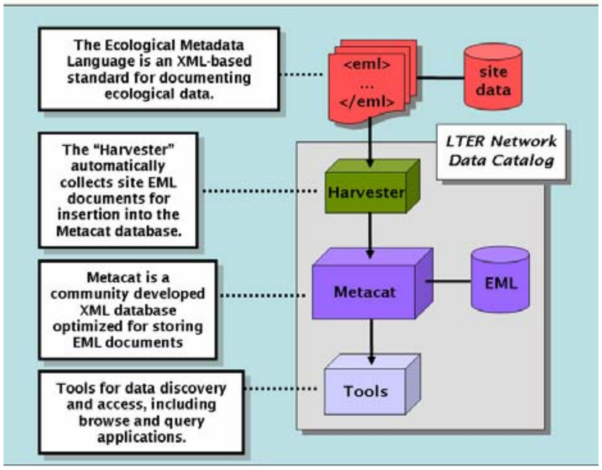
Increasing the capacity for ***data acquisition, management, and curation*** can provide the foundation for integrative science. Existing online data and documentation are valuable resources for integrative, synthetic research, but new data volumes and data types create challenges for data throughput 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

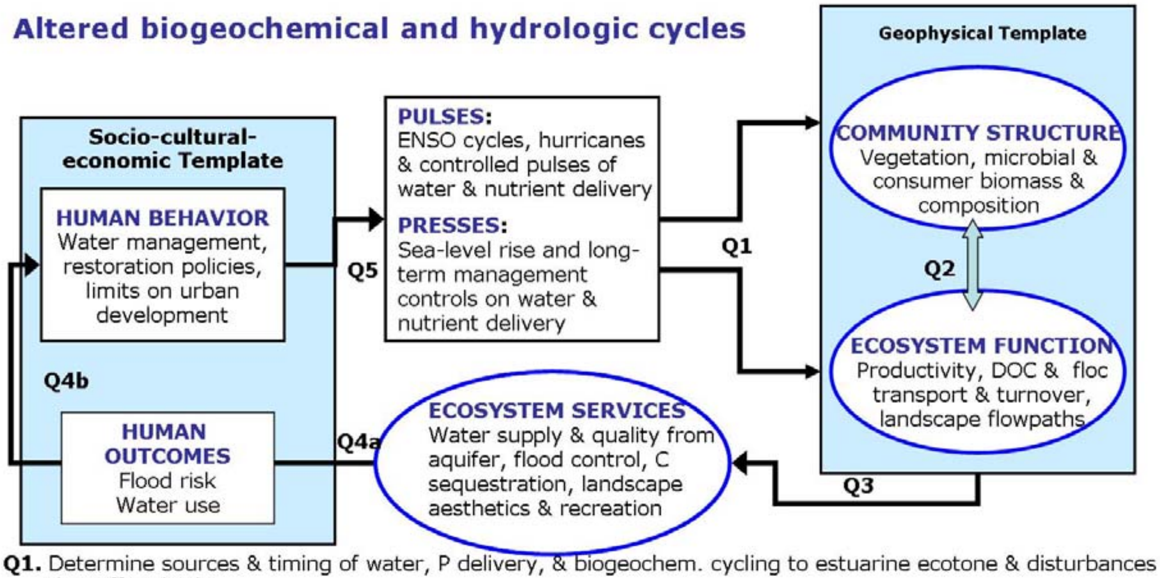
SBE – NSF Directorate for Social, Behavioral, and Economic Sciences

USDA – United States Department of Agriculture

USFS – United States Forest Service

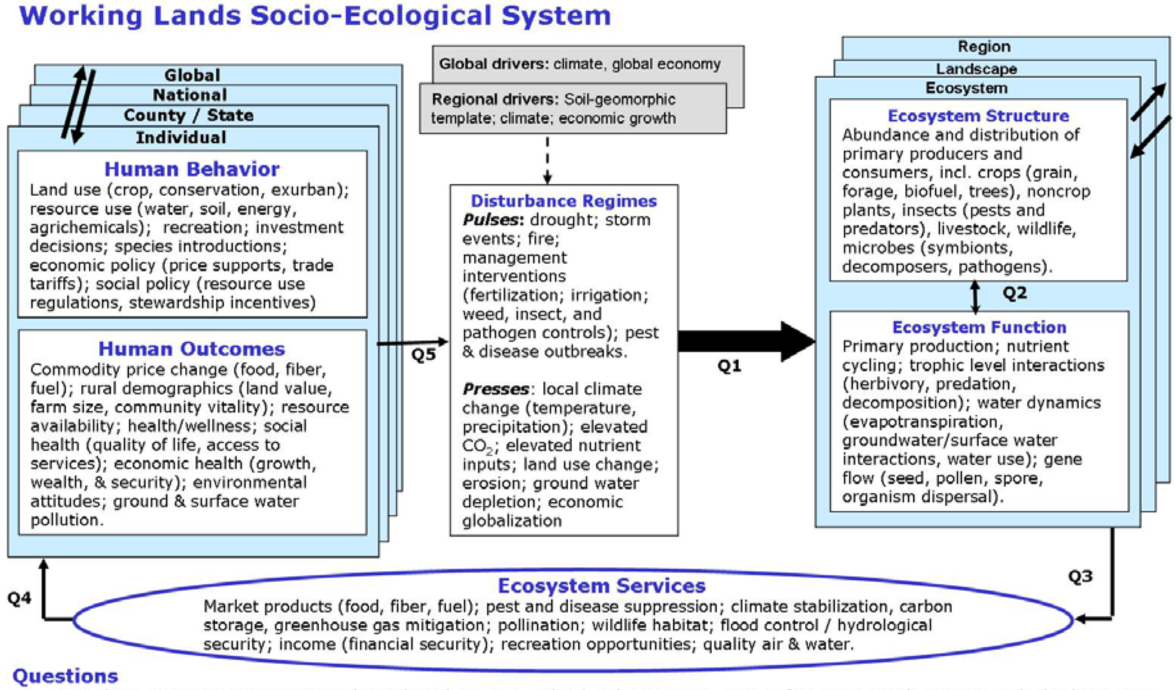
Appendix 2: Examples of Feedback Loops

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.


Altered biogeochemical and hydrologic cycles

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?

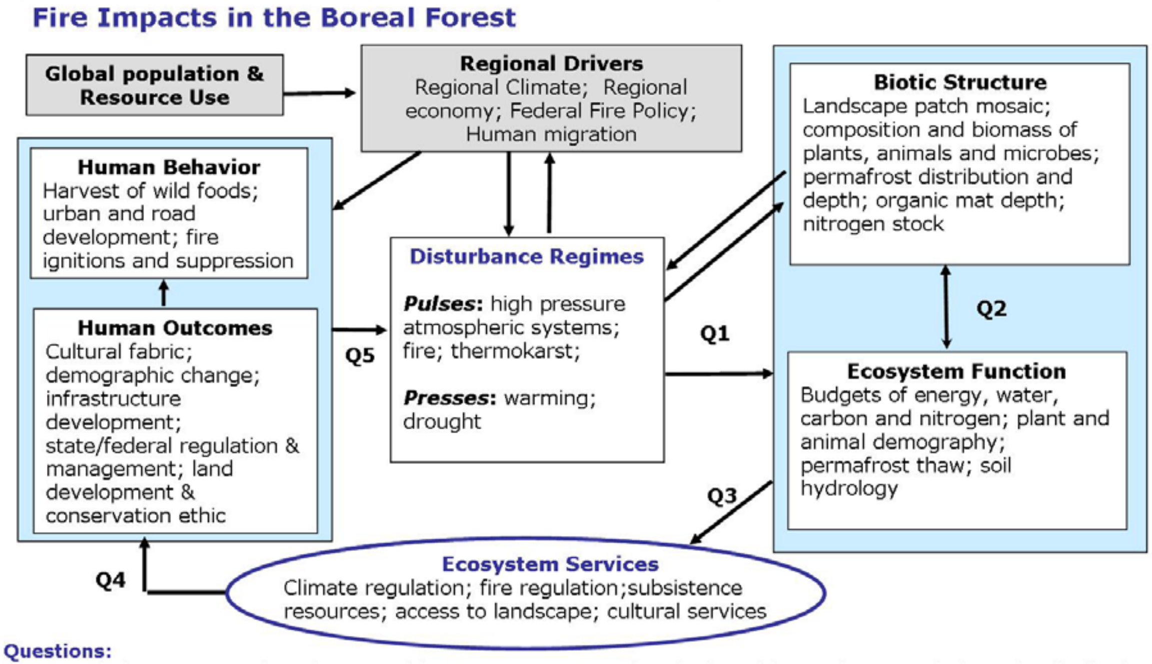
Q2. What are the indirect effects of intentional management (e.g. introduced species and accelerated decomposition and biomass removal) on plant, microbial, insect, and vertebrate populations and the ecosystem functions that they mediate?

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?

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