1. EXECUTIVE SUMMARY

The National Science Foundation's (NSF) Long Term Ecological Research (LTER) program has the commanding mission of documenting, analyzing and understanding ecological processes, patterns and phenomena that vary over long temporal and large spatial scales. Since its establishment in 1980, the LTER enterprise has evolved from five sites with an annual budget of $1.2 M into a network comprising 24 ecologically diverse sites— including two urban sites— a network office, an annual direct budget of $17.8 M in FY 2002 and some 1,100 scientists and students that generate approximately $44 M in LTER-related research. The LTER program has fostered interdisciplinary, interagency and international scientific collaborations, and 20 nations now have associated International LTER (ILTER) programs.

Achievements of the LTER program in the past 20 years are impressive. Its first decade was devoted to long-term data collection and analysis in five core areas: primary production, nutrient flux, trophic structures, disturbances, and organic matter accumulation and decomposition. In its second decade, the LTER program incorporated the advice of NSF's ten-year review and dealt more with large-scale and cross-site ecological patterns and processes, as well as anthropogenic influences on ecological systems. Twenty years of research at LTER sites have yielded major synthetic and theoretical advances in ecological knowledge, and have served society by informing solutions to environmental problems. New technologies have enabled complex investigations. A legacy of authoritative experimental and observational data has been archived and is being harnessed for deciphering environmental phenomena. And, in the past 20 years, LTER sites have enriched the education of an entire generation of ecologists, as well as thousands of K-12 students through the Schoolyard LTER.

A STRATEGIC PLAN FOR THE DECADE AHEAD

In the decade ahead, the LTER enterprise will inhabit a new scientific landscape. Technology is revolutionizing how research is done and enlarging the scope, scale and complexity of research that can be done. As NSF has recognized, biology in the 21st century is making challenging research problems tractable by being multidisciplinary, multidimensional, scalable, information driven, predictive and model based, education oriented, and virtual and global. Policymakers, funding agencies, organizations, and the public increasingly are asking science to provide solutions to environmental issues and to be more accountable for public investments in research.

This 20-year review is intended to help NSF and the LTER community chart a course for the LTER program on this new scientific landscape— one that will enable it to meet the needs, challenges and opportunities of science and society in the next decade. The LTER community has taken the first step by envisioning the coming decade as one of synthesis science "…in which the data and knowledge gained over the past twenty years, plus current studies, are brought together to reach new levels of understanding of long term ecological patterns and processes,"[1] ultimately for ecological forecasting.

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[1] *LTER White Paper: Priority Setting in the LTER Network, 2001.*

The 20-year review committee strongly concurs with this goal. The LTER program must forge a bold decade of synthesis science that will lead to a better understanding of complex environmental problems and result in knowledge that serves science and society. To realize this ambitious goal, the LTER community, working with NSF, must develop a comprehensive strategic plan for the LTER enterprise. This plan must define the LTER program's vision and mission; scientific priorities, goals and the strategies for achieving them; timelines with outcomes and milestones; governance and organizational structure; and a budget that aligns resources with these elements.

A comprehensive strategic plan for the next decade, jointly crafted in a common forum by the LTER community and NSF, is the principal and organizing recommendation of this report. The LTER enterprise is now a distributed, mid-size organization with enormous research and educational capability. It needs to deploy this capability with creativity, coherence and economy to accomplish synthetic, systems-level ecology. Synthesis science will be a costly, complex undertaking requiring disciplined choices among goals, options and approaches.

A successful strategic plan, formed around these choices, will keep the LTER program innovative, adaptive and nimble and by matching scientific priorities and goals with fiscal resources and by instituting management structures and processes for conducting 21st century biology. Further, joint LTER-NSF planning will produce a common understanding of expectations and strategies, a better fit between desired outcomes and resources, and a satisfactory resolution of historical issues. Joint planning can be accomplished without compromising the independence or NSF's peer review of LTER science.

THE SCIENTIFIC NICHE OF THE LTER PROGRAM

The first order of business in crafting the strategic plan is to establish the scientific niche of the LTER program. What are the scientific priorities of the LTER enterprise? Which complex questions in ecology and environmental biology are best addressed by the network of LTER sites? What larger mission will those questions serve? Establishing these scientific priorities will also entail a critical examination of the LTER core areas— their role, theoretical basis, scope, function and continued usefulness after 20 years. Once determined, LTER's scientific niche and priorities will drive strategic planning and decisions governing LTER research, education, personnel, resources, infrastructure and organization.

In the committee's view, achieving synthesis science requires that biological diversity be designated a new LTER core area or core function at all or selected sites and be funded accordingly. As recognized by NSF workshops and other national and international studies, biodiversity is a pervasive component of long-term ecological patterns and processes. Understanding biodiversity is fundamental to understanding how ecosystems work.

Likewise, the committee recommends that informatics be established as a core function by implementing a systemic informatics infrastructure and architecture to integrate LTER data and tools with those from relevant disciplines. Informatics is the mediating platform for synthesis science, for analyzing and predictive modeling of complex ecological phenomena, and for deploying the LTER program's 20-year data sets.

Strategies for Synthesis Science

The LTER community has identified several strategies for achieving synthesis science[2]. In the committee's view, the first and fundamental strategy must be the organization of LTER research *a priori* by hypotheses and theory, with networked data acquisition, analysis and testing by predictive models across broader and broader phenomena.

Second, LTER synthesis science should adopt and make systemic the components of 21st century biology, including the investigation of complex ecological phenomena using cross-domain approaches and interdisciplinary, collaborative teams. This will entail the aggressive incorporation of powerful new technologies as well as analytical and experimental tools.

Third — and a corollary of incorporating 21st century biology — the LTER program should become a research collaboratory, namely, a seamless, integrated continuum from site-specific to cross-site to network- and systems-level ecological research. The LTER community must recruit scientists, technologists and experts from outside traditional LTER disciplines who will bring a wealth of cross-domain approaches to ecological science. Increasing cross-disciplinary opportunities could occur in the field, the laboratory and at professional meetings, especially the LTER's all-scientists meetings, which should be held more frequently and should invite participation from other scientific communities. For example, by partnering with social scientists, the LTER program could increase understanding of the interrelationships and reciprocal impacts of natural ecosystems and human systems in order to inform environmental policy.

Fourth, the new technologies and interdisciplinary collaborations will foster serendipitous science, which exploits unanticipated events, such as disturbances, and scans multiple databases for emerging, unanticipated patterns and trends. To this end, the LTER program's informatics infrastructure should provide a virtual portal to LTER legacy data for investigators worldwide.

Fifth, the committee recommends that new sites should not be added to the LTER network until such expansion is justified in the strategic plan. If sites are added in the future, such expansion should be strategic and synoptic. The larger ecological community (i.e., LTER and non-LTER scientists) should determine where and how such expansion would provide the greatest benefit to understanding the nation's ecological systems, with competitions for new sites based on these findings. The LTER program should expand internationally by building on its collaborations with the ILTER enterprise.

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[2] *LTER White Paper: Priority Setting in the LTER Network, 2001.*

BROADER IMPACTS: EDUCATION, COMMUNICATION AND PUBLIC POLICY

The LTER program has helped educate a generation of ecological scientists by providing site-based, multidisciplinary training opportunities to undergraduate and graduate students nationwide. Exploiting its unique scientific niche, the LTER program, in partnership with associated universities, should incorporate the characteristics of 21st century biology into its undergraduate and graduate education in field-based ecological research. In doing so, the LTER network can help universities educate a new cadre of ecosystem scientists, ones trained in collaborative teams across disciplinary domains.

At the K-12 level, the Schoolyard LTER should increase its reach and impact by leveraging funds now allocated to individual sites. For example, LTER sites might pool their Schoolyard supplements to develop a suite of modular "suitcase" education programs that target particular biotas, habitats and public issues and that can be used by groups of sites or across the network. The design and outcomes of all Schoolyard LTER programs should be formally evaluated to inform appropriate growth and improvements.

In the arena of public policy, the committee recommends that the LTER program assume a more powerful and pervasive role in informing environmental solutions at local, national and international levels. LTER research can achieve a broader public policy impact by turning its descriptive knowledge— its growing legacy of authoritative science and data— into predictive knowledge of environmental phenomena. Reciprocally, when the LTER program's research and education serve the public good, the science itself will become the most powerful voice for a larger commitment of public resources to the LTER program.

However, communicating complex, scientific knowledge to non-scientific audiences, such as the public, the private sector and government officials, requires special expertise. The committee recommends that the size, scope and potential impact of LTER science warrant a professional scientific communications office in the LTER structure to share the LTER program's research, educational outreach and ecological forecasting with public audiences.

LTER GOVERNANCE AND ORGANIZATION

The extraordinary growth of the LTER program during the past 20 years has brought challenges of management and coordination. For the decade ahead, the comprehensive strategic plan must describe an LTER governance and organizational structure that is as adaptive and unifying as the science it will be asked to enable in the next ten years.

In the committee's view, this LTER structure must provide the intellectual and managerial leadership needed to drive synthesis science, i.e., collaborative research, education, and infrastructure across sites, disciplines and knowledge domains. Planning this structure should be informed by models from other enterprises and by experts from academia, government and the private sector. The LTER governance plan must specify the locus of authority to implement the strategic plan and manage the LTER program, and it must describe a mechanism for developing governance policies.

LTER PROGRAM'S BUDGET AND MANAGEMENT

The comprehensive strategic plan must tie the LTER program's scientific priorities, goals and structure to a realistic budget. The committee recommends that NSF increase funding for the LTER program commensurate with the agreed priorities and expectations for synthesis science in the third decade. The enhanced budget should be invested in the strategies discussed in this report for implementing 21st century biology and achieving systems level science and ecological forecasting.

Specifically, NSF must correct historical inequities by establishing parity baseline funding for all LTER sites as quickly as possible. NSF funding should be sufficient to enable the biodiversity and informatics core activities in an aggressive timeframe. With real incentives—primarily increased funding and competitions—NSF can encourage cross-site and interdisciplinary research, and systems-level collaboration. NSF should provide increased funding for LTER-mediated education and for the communication of LTER science to public audiences and officials.

NSF can also foster LTER synthesis science in programmatic ways: revise LTER proposal guidelines and review criteria to integrate and balance site-specific and cross-site research and education; hold more frequent cross-disciplinary and cross-site competitions that invite participation from outside the LTER community; and increase the importance of data management and informatics in evaluating LTER site activities and proposals.

Finally, the committee recommends that administration of a program of the size, scope and duration of LTER merits two NSF officers; a permanent officer should be in charge to ensure continuity. Because LTER is now funded by several NSF directorates, a formal, cross-directorate committee of program officers should be established to coordinate LTER funding and program management.

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The LTER program is integral to meeting one of the grand challenges for the 21st century—understanding the nation's ecosystems in all their complexity in order to use and preserve them in a sustainable fashion[3]. This knowledge is critical to science and society for managing and maintaining the nation's natural resources, for growing the nation's economy, for improving human health, and for enhancing the quality of human life.

After 20 years, NSF's investment in LTER science, people and infrastructure has paid enormous dividends in advancing knowledge of ecosystem phenomena. NSF has placed the LTER program on the frontier of ecological science, spanning time, terrain, scale and complexity. The need and promise for LTER science in the decade ahead are unparalleled.

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[3] Bloch E., et al. 1995. Impact of Emerging Technologies on the Biological Sciences. National Science Foundation, Arlington, VA 22230

2. INTRODUCTION

Twenty years have passed since the National Science Foundation's (NSF) Directorate for Biological Sciences (BIO) established the Long Term Ecological Research (LTER) program, a visionary enterprise to address the challenge of research and education on long-term ecological phenomena in the United States[4]. The mission of the LTER program, then and today, is documenting, analyzing and understanding ecological processes, patterns and phenomena that vary over long temporal and large spatial scales.

Since its inception, the LTER program has encompassed a network of large, secure, ecologically diverse sites with well-developed support capabilities. Research at these sites has produced a legacy of well-designed and documented long-term experiments and observations for future generations, yielded major synthetic and theoretical studies, and provided service to science and society through authoritative information for the identification and solution of ecological problems. LTER-based research and education combine long-term analysis of site-specific ecological phenomena with general systems theory and cross-site comparisons across diverse ecosystems.

From the outset, the LTER program organized its research around five core areas:

- Pattern and control of primary production
- Spatial and temporal distribution of populations selected to represent trophic structures
- Pattern and control of organic matter accumulation and decomposition in surface layers and sediments
- Patterns of inorganic inputs and movements of nutrients through soils, groundwater and surface waters
- Patterns and frequency of disturbances

A great deal of scientific investigation and knowledge discovery has occurred in these core and related areas; and LTER sites have enriched the education of an entire generation of ecologists. The LTER program has grown, adding sites in different biomes, expanding into the human-dominated urban environment, and harnessing new information technologies and new tools for ecological research and education. From five sites with an annual budget of $1.2 M in 1980, the LTER program has evolved into a network comprising 24 sites, an LTER Network Office, an annual direct budget of $17.8 M in FY 2002 and 1,100 scientists and students that generate approximately $44 M in LTER-related research.

At this 20-year juncture, it is timely to chart a blueprint for the LTER program for the next decade that builds on its accomplishments and targets the opportunities, challenges and technological developments that have emerged since the previous LTER review.

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4 http://LTERnet.edu/

3. TWENTY-YEAR REVIEW

3.1 TWENTY-YEAR REVIEW COMMITTEE AND CHARGE

In July 2001, BIO commissioned an international committee of 17 scientists (*Appendix A*) to conduct a 20-year review of the LTER program. At its first meeting at NSF on August 21, 2001, BIO Assistant Director Mary Clutter charged the committee with conducting a prospective rather than evaluative review, specifically: to describe the opportunities ahead for the LTER program and how it can best incorporate advances in 21st century science.

At its first meeting, the review committee developed nine issue questions (*Appendix B*) to serve as a framework for gathering information from the LTER Executive Committee, the 1,100 scientists in the LTER community, and selected external scientists familiar with the LTER program. The individuals listed in *Appendix C* responded to the nine issue questions in writing or by interview. The committee held its second meeting from October 25 through October 27, 2001 at the LTER Network Office at the University of New Mexico, Albuquerque, and at the Sevilleta LTER site. Between the August and October meetings, individual committee members visited other LTER sites and reported their observations at the October meeting. At both the August and October meetings, the committee received information from and discussed LTER issues with members of the LTER Executive Committee. The LTER Network Office also provided print and Web-based materials documenting the history, scientific products and other accomplishments of the LTER program. Cumulatively, this information forms the basis for this 20-year report, a draft of which was reviewed by the committee at a meeting in Dallas, Texas on January 14, 2002. A complete chronology of the committee's activities appears in *Appendix D*.

4. BACKGROUND: THE *TEN-YEAR REVIEW*

4.1 FINDINGS OF THE *TEN-YEAR REVIEW*

The first comprehensive review of the LTER program was conducted in 1993 by a committee co-chaired by Dr. Paul Risser and Dr. Jane Lubchenko. The resulting *Ten Year Review* documented many of the accomplishments of the LTER program, including: an extensive body of published research; a record of ecological status and trend data; new interactions with foreign LTER programs; and the application of research results in public policy.

The *Ten-Year Review* also raised concerns with the LTER program, particularly the serious discrepancy between expected levels of activity and actual levels of funding for those activities. Although the budget of the LTER program had increased during its first 13 years, the rate of increase was perceived to be inadequate to initiate "…innovative work focusing on current theories and problems in ecology"[5] while also gathering and maintaining core data. The core areas themselves were perceived as too broadly defined. Moreover, the criteria used to select sites had "…not uniformly included specific expectations for

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[5] *Ten-Year Review*, p. 2

developing a comprehensive, representative network of sites."[6] Although NSF's review process for LTER proposals was considered fair, proposals with long-term, interdisciplinary or network-level goals were not valued as highly as they should have been. Moreover, the LTER sites were perceived to lack an emergent power: although "…intersite comparisons have been conducted, …the power of the network of coordinated research sites has not yet been fully realized."[7]

4.2 VISION AND RECOMMENDATIONS OF THE *TEN-YEAR REVIEW*

The *Ten-Year Review* challenged NSF and LTER to do more than strengthen site-based ecological research. It recommended a broader, enhanced LTER research platform that could inform decisions about "… managing the biosphere for long-term sustainability in a political environment."[8] Specifically, it tied "…an integrated ecological research program…" and understanding long-term ecological phenomena to serving "…the nation's need to make defensible environmental decisions and policies; and to implement[ing] practices leading to a sustainable biosphere."[9] The report envisioned the LTER enterprise as a vital, research organism integrated by a common research agenda, experimental framework, and information infrastructure. It saw the breadth of science and research methods at each site expanded and strengthened to encompass all levels of biological organization, from molecular, individual, population, and community to landscape and global. It advised broadening the scope, scale and integrative power of LTER science through collaborative interactions among sites and researchers. It called for LTER to incorporate new technologies and become a forceful network of research networks engaged in developing, aggregating and synthesizing information about the biosphere at regional and global levels. And it asked NSF and LTER to play a larger role in K-16 environmental education.

To implement a broader, more integrated LTER research agenda, the *Ten-Year Review* recognized the need for increased funding from NSF, particularly for research and data management at each site and across sites, research at LTER sites by non-LTER scientists, and coordinated research with other networks and organizations. The report recommended:

- replacing the five LTER core areas with goals that emphasize the breadth, integration and cross-site, comparative potential of the LTER program;
- having the Executive Committee plan and set scientific priorities with NSF, with a new, national advisory board, and with the advice of external *ad hoc* committees;
- designating the LTER Network Office as the "the nexus of communication", disseminating information, coordinating network activities, and implementing specific scientific directions;
- having NSF clarify for reviewers the goals of the LTER network and individual sites, and providing criteria for site selection and network evaluation.

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[6] *Ten-Year Review*, p. 2
[7] *Ten-Year Review*, p. 2
[8] *Ten-Year Review*, p. 34
[9] LTER *White Paper: Priority Setting in the* LTER *Network, 2001.*

4.3 OUTCOMES OF THE *TEN-YEAR REVIEW*

NSF has implemented a number of the recommendations of the *Ten-Year Review*. It added six new LTER sites (four coastal, two urban), held cross-site competitions; relocated the Network Office to the University of New Mexico, Albuquerque; increased the overall LTER budget; and funded the Schoolyard LTER program for K-12 environmental education with supplements to site budgets.

LTER's responses to the recommendations of the *Ten-Year Review* occurred throughout the network, increasing cross-site and multidisciplinary studies, interaction and collaboration with non-LTER sites, and partnerships with federal agencies including the Forest Service (a unit of the US Department of Agriculture), the US Geological Survey (a unit of the Department of Interior) and various units within the US Department of Energy. The LTER community grew internationally to encompass sites in 21 countries, and regional networks now exist in Central Europe, East Asia, and North America. The LTER Network Office advanced the adoption and use of sensing and information technologies, including remote sensing, geographic information systems, and the application of informatics to LTER data sets, which resulted in an array of shared databases, better communication among sites, and increased accessibility to LTER data.

Individual LTER sites and the Network Office began experimenting with and adopting new technologies that foster cross-site and cross-disciplinary studies and collaboration with scientists outside the LTER network. Efforts to regionalize sites have expanded the scope and scale of LTER research. Educational programs for K-16 and the general public have extended the impact of LTER research beyond the scientific community. Schoolyard LTER was implemented at 20 sites, and many of the resource materials have been made available on the World Wide Web. In the last decade, LTER research has helped inform environmental and public health policy on a range of topics including land use, air quality, climate change, and emerging diseases such as Lyme disease and Hantavirus.

Despite these accomplishments, some of the critical recommendations of the *Ten Year Review* for LTER science have yet to be fully realized. The transition from individual site-based research and science projects to a broader, more integrative research platform has not been sufficient to address large-scale, interdisciplinary environmental issues. Although the LTER network has notable linkages to other agencies, research sites and investigators, the full force of combined resources and interdisciplinary approaches has yet to be exploited.

That said, the LTER program continues to view these recommendations as laudable but "underfunded mandates." Although NSF has supported a number of inter-site and synthesis science activities over the past ten years, the level and nature of this support are perceived by the LTER community as not being sufficient, consistent, or focused enough to meet expectations.

5. FINDINGS AND RECOMMENDATIONS OF THE 20-YEAR REVIEW

The findings and recommendations of the 20-year review committee address issues raised in the *Ten Year Review* as well as new, important ones that have arisen in the course of our review of the LTER enterprise. Our findings and recommendations are discussed in a strategic context that encompasses LTER science, education, management and resources.

5.1 THE SCIENTIFIC VISION

The LTER community has set its vision for the third decade within a 30-year framework[10]. The first LTER decade was devoted to long-term data collection in the five core areas at all sites and analysis of frequencies in system dynamics. The second decade focused more on large-scale ecological patterns and processes, cross-site comparisons, anthropogenic influences on ecological systems, and the deployment of the legacy data sets for integrative studies.

The LTER community envisions the coming decade as one of synthesis, "…in which the data and knowledge gained over the past twenty years, plus current studies, are brought together to reach new levels of understanding of long term ecological patterns and processes,"[11] ultimately for ecological forecasting. Synthesis is expected to occur at both the site and network levels and to incorporate multidisciplinary perspectives on a broad range of research topics.

> **Recommendation 1.** The committee concurs and recommends that the LTER program forge a bold decade of synthesis science, one that will lead to a better understanding of complex environmental problems and result in knowledge that serves science and society.

In order for this vision to be realized, the LTER enterprise will have to adapt its larger size, scope and capability to the new scientific landscape of the 21st century. Technology has revolutionized how research is done and redefined the scope, scale, and complexity of research that can be done. Policymakers, funding agencies, organizations, and the public are increasingly asking science to inform solutions to environmental issues and to be more accountable for public investments in research. The LTER enterprise itself has evolved enormously from a start-up program of five sites to a mid-sized organization of 24 ecologically diverse sites, a Network Office, and some 1,100 scientists and students throughout the United States. Twenty nations now have associated International LTER (ILTER) programs, and government agencies and private organizations are deeply invested in the science that can emerge from the U.S. and international LTER enterprise.

> **Recommendation 2.** In order to achieve the full promise of synthesis science, the LTER program should adopt and make systemic what NSF has informally termed "21st century biology", namely, that LTER science be multidisciplinary,

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10 *LTER White Paper: Priority Setting in the LTER Network, 2001,* p. 5
11 *LTER White Paper. Priority Setting in the LTER Network, 2001,* p.6

multidimensional, scalable, information driven, predictive and model based, education oriented, and increasingly virtual and global.

The rationale for an LTER research agenda that incorporates 21st century biology is well-established[12]. Ecological phenomena result from vastly complex systems processes. Their causes are multiple, diverse and dispersed. Therefore, they cannot be understood, managed or controlled through scientific activity organized on single or traditional disciplinary lines. Further, the data and tools (conceptual, experimental, computational, etc.) required to investigate the causes of complex ecological phenomena are beyond the scope of any single investigator and often beyond the mission, infrastructure and expertise of any single institution. Therefore, such research requires cross-domain approaches involving interdisciplinary, collaborative teams within and across sites and institutions.

At the individual site level, LTER science and proposals from site scientists have already incorporated a number of these characteristics. At the network and systems level, however, the transition to 21st century biology is more difficult and is unfolding much more slowly. Now, at the onset of its third decade, the LTER program has the opportunity, capability and responsibility to fully incorporate collaborative science for large-scale ecological synthesis.

5.2 Scientific Strategies for LTER's Third Decade

5.2.1 Scientific Focus and Priorities

In an attempt to set scientific priorities, the *LTER White Paper*[13] identifies a mission and five major goals for the next decade. However, the five goals are actually *strategies* for doing science— they describe *how* LTER synthesis science should be accomplished— not *what* the major scientific questions to be answered should be. Missing is a clear exposition of what synthesis science LTER should accomplish— what should the scientific focus, niche and priorities of the LTER program be for the next decade?

In setting its scientific priorities, the LTER program needs to determine what larger mission will be served by LTER synthesis science, and which overarching and specific problems are best addressed by the LTER program. Questions fundamental to shaping these scientific priorities are: Where does the LTER program fit into the overall science landscape— what is its niche? How can a small number of LTER sites best contribute to our long-term understanding of the ecology of the country? Which complex questions in ecology and environmental biology is the LTER program best suited to address? Which areas of LTER science will benefit from a networked and systems approach and which won't? The answers, solicited from within and outside the LTER community, will help determine the future foci of LTER synthesis science, its niche within the spectrum of environmental research and the collaborative partnerships to be forged with other research communities.

Recommendation 3. If the third LTER decade is to be one of synthesis science, the LTER program must define its niche, namely, it needs to determine its

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[12] Jasanoff, S. et al. 1998. Conversations with the community. AAAS at the Millenium. *Science*, 278:2066-2067.
[13] *Priority Setting in the LTER Network, 2001.*

priorities for synthesis science and what the scientific focus or foci of such synthesis will be.

5.2.2 Theory

The set of seven LTER research papers submitted to *BioScience* in 2001 represents an important step for synthesis science as it suggests the enormity of the task ahead for LTER and non-LTER scientists alike. Environmental problems, such as global warming or the ecosystem function of biodiversity, are vastly more complex and of a different order of magnitude than the ecological problems addressed in previous decades.

Recommendation 4. Ecological research by LTER scientists involving multiple disciplines, dimensions and scales should be organized *a priori* by hypotheses and theory, and tested by predictive models across broader and broader phenomena.

Ecology, like the other sciences, strives to develop unifying theory, predicting from the general to the particular. Developing comprehensive ecosystem-level theory requires both interdisciplinary and long-term, extensive research programs because of ecosystem complexity and variability in space and time. With its breadth and tenure, LTER holds the greatest promise in the history of ecological research for providing the research platform and data to formulate and test broad, ecosystem-level hypotheses. Theoretical models that will emerge from within and outside the LTER program have the potential to predict the effects of anthropogenic influences on the biosphere, including biodiversity, and on the interface between biological and physical phenomena. Ultimately, then, theory will underpin environmental stewardship.

5.2.3 Core Areas and Biodiversity

Core Areas. Since the beginning of the LTER program, its research has occurred under an umbrella of the five core areas described above. Repeated measurements in these areas constitute the LTER program's long-term datasets that are used to monitor, analyze and predict ecosystem changes. For example, long-term data collected by the Andrews Ecological Research Program helped predict the frequency and occurrence of natural hazards such as landslides in Oregon; core data at the Florida Coastal Everglades LTER are proving integral to restoring aquatic plants and animals in wetlands.[14]

Yet, the expectation to maintain strength in these core areas is frequently cited by the LTER community as a reason for not venturing into new, challenging research domains. A fundamental question emerges from this dilemma: Are the five core areas still fundamental to ecological science and synthesis for the next decade? The answer is equally fundamental in shaping the scientific future of the LTER program.

Examining the core areas will be central to resolving the tensions between old and new science and to charting the LTER's scientific blueprint for the future. It is paramount, therefore, that the LTER program and NSF seek and accept intellectually honest answers to such critical questions as:

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[14] http://www.lternet.edu

- After 20 years, are the five core areas still the right ones? In hindsight, would the ecological community choose these core areas again, or would they choose different ones?
- What are the criteria, theoretical issues or scientific bases for selecting, maintaining, or modifying the core areas?
- What are the accomplishments that justify continued investment in the existing core areas? When should measurements in a core area be reduced or cease?
- Do the existing core areas— or will different core areas— best serve the specific research questions targeted for synthesis in the next decade?
- Do core areas enable or hinder incorporation of new tools, paradigms and concepts?
- Fundamentally, are core areas still a useful, viable principle for organizing LTER research?

> **Recommendation 5.** The LTER community should review the role, theoretical basis, scope, function and continued usefulness of the core areas, especially in formulating its priorities for synthesis science in the next decade.

Biodiversity. The importance of biodiversity as an ecological core area has been recognized by numerous NSF workshops and other major national and international studies[15]. Biodiversity is a fundamental, pervasive component of long-term ecological patterns and processes, including the structure, composition and functioning of ecosystems, ecological genomics, restoration ecology and the phenomena encompassed by the five existing LTER core areas. Biodiversity and the healthy ecosystems that underpin it sustain our economy and way of life, providing the nation with "clean air, clean water, food, clothing, shelter, medicines, and aesthetic enjoyment"[16]. Moreover, the need for understanding the relationships between biodiversity and ecosystem function is increasingly urgent as the daily conversion of natural systems to human-managed systems accelerates the decline of biological diversity and its habitats, "disrupting natural ecological processes, and even changing climate patterns on a global scale."[17] Essentially, understanding biodiversity is fundamental to understanding how ecosystems work. A third decade of synthesis for LTER research demands core knowledge of biodiversity.

> **Recommendation 6.** The committee recommends that biological diversity be designated a new core area (or function) for the LTER program at all or selected sites and receive appropriate levels of funding.

Specifically, the committee finds applicable to the LTER program many of the findings of the second NSF BON workshop[18], which dealt with the scope of and research agenda for biodiversity in an ecosystem framework. Briefly, biodiversity is defined as the sum of life on

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[15] Bloch, E. et al. Impact of Emerging Technologies on the Biological Sciences. National Science Foundation, Arlington, VA 22230, 1995; The Darwin Declaration. Australian Biological Resources Study, Department of the Environment, Environment Australia, Canberra, 1998; Final report of the OECD Megascience Forum Working Group on Biological Informatics. OECD Publications, 75775 Paris CEDEX 16 France, 73 pp., 1999 (http://www.oecd.org//ehs/icgb/biodiv8.htm).
[16] Teaming with Life: Investing in science to understand and use America's living capital. President's Committee of Advisors On Science and Technology: Panel on Biodiversity and Ecosystems. 86 pp., 1998.
[17] Ibid.
[18] http://www.vcrlter.virginia.edu/biodwrk99/BON99a.htm

Earth— plants, animals and microbes and their levels of organization from genes to ecosystems. As an LTER core area (or function), research on biodiversity should encompass its composition and spatial distribution; its ecological patterns, processes and functions; and its anthropogenic dimensions. Biodiversity research might involve a core suite of ecologically compelling taxa from terrestrial and aquatic habitats, such as selected vascular plants, fungi, vertebrates, arthropods, mollusks, algae and diatoms, and nematodes, microbes or other appropriate soil biota.

Biodiversity research will have a broader impact beyond helping to elucidate ecosystem phenomena. It will act, effectively, as an early warning system of changes in biodiversity and environments across LTER sites, many of which may have important consequences to human society and well-being. Examples of such early warning biodiversity observations include algal blooms, declining amphibian populations, emerging disease pathogens and vectors, invasive and pest species, genetically engineered taxa, and anthropogenic changes to the environment.[19]

5.2.4 Scientific Collaboration

The *LTER White Paper* recognizes the need for increased cross-disciplinary and cross-site collaboration. The committee concurs, underscores and expands this need. For successful synthesis to occur, the LTER program needs to keep stoking the cauldron of ideas by ensuring a rich, interdisciplinary mixture of scientists who share LTER goals. Although site-specific research should remain strong and focused, the LTER program needs to seize opportunities to develop broader, more network-level experimental frameworks and include other networks and agencies in their design and implementation.

For example, LTER synthesis science would profit from involvement of public health professionals, faculty and students in computer science and mathematics departments at LTER-associated universities, and scientists in private-sector corporations and in other government agencies. By invite them to collaborate, the LTER enterprise can expand its technological base and become a stronger partner in the network of networks.

> **Recommendation 7.** The LTER program should become a research collaboratory— a seamless, integrated continuum from site-specific to cross-site to network-wide and systems-level ecological research. Building on its successes to date, the LTER program should become more collaborative across ecological and other research communities. To do so, it must increase its recruitment of scientists, technologists and expertise from outside traditional LTER disciplines who will help formulate hypotheses and apply technologies that will advance ecological science.

Essentially, the LTER sites and network as a whole need to establish and manage a program that demands broad participation in and a systems-level approach to LTER research. They need to recruit non-LTER scientists— the best in class— to collaborate with LTER researchers, use LTER data, work at LTER sites, and chart synthetic opportunities at the network level. One of many venues for nurturing intellectual collaboration and interdisciplinary relationships among scientists is the all-scientists meetings, which should be

[19] http://www.vcrlter.virginia.edu/biodwrk99/BON99a.htm

held more frequently, perhaps every other year, and feature special-topics sessions or symposia to discuss integrative topics and collaborative research. Along with accelerating cross-disciplinary research, these relationships might become the foundation for educational initiatives, such as cross-site IGERT (Integrative Graduate Education and Research Training) projects, which, in turn, can accomplish two ends: unite scientists from several departments or institutions in highly interdisciplinary collaborations; and train the next generation of ecologists along broader, team-based, technological and multidisciplinary lines.

From the LTER perspective, the limiting factors for this to occur are people, time and resources rather than a reluctance to collaborate across the network and disciplines. But fundamentally, the LTER program is caught in the tensions of a cultural shift from historically independent sites to collaborative systems. For individuals and the network the tensions reside between core areas and new ideas, between site-level and network-level activities, and between resources and expectations. When new collaborative opportunities do emerge, their development is often stymied by the lack of discretionary funds for innovation at the site and network level.

NSF can help the LTER program achieve a healthier balance between systems-level and site-specific research. Historically, LTER science, budgets, peer reviews, and accountabilities have essentially been focused on the individual site. Science outreach — for example, supporting non-LTER scientists on the core budget — has been effectively penalized in site reviews and renewal competitions as being "too unfocused." Without explicit, positive incentives, the LTER sites continue to limit their collaborations and interdisciplinary activities to those non-LTER scientists who have independent funding. Essentially, "outsiders" and "insiders" should not have to encounter "border checks" at each attempt to cross the traditional boundaries separating organization domains and scientific disciplines.

> **Recommendation 8**. NSF should provide real incentives — primarily funding and competitions on a regular basis— to encourage cross-site, interdisciplinary, systems-level collaboration to enhance theory, reveal large-scale ecological phenomena and inform environmental policy.

Specifically, NSF, through its solicitations and competitions, could emphasize, promote and reward a collaborative, systems-level approach in the LTER program — much as it has in special agency-wide competitions such as *Biocomplexity in the Environment* and *Knowledge and Distributed Intelligence*. NSF competitions should encourage and regularize LTER cross-site research, including annual cross-site competitions and sites outside the LTER network, without eroding the core. For site renewals or augmentations, part of the increased budget might be "fenced" for cross-site research, synthesis, and inclusion of collaborators from non-LTER sites. NSF competitions could regularly court best-in-class researchers and graduate students to use the LTER program's rich array of databases, thereby leveraging the infrastructure and talent residing within the LTER program.

The NSF's review criteria for the LTER program may be selecting against network-level science. The current accountabilities and their approximate weighting for LTER site renewal proposals and site visits are:

- site-specific research, 50%;

- site-specific information management, 20%;
- site-specific management and governance, 10%;
- cross-site activities, synthesis, outreach, 10%; and
- network-level activities, 10%.

As such, 80% of the accountabilities are for site-specific activities, and 20% for cross-site and network-level activities. At best, this sends a mixed message about priorities to the LTER community: the accountabilities do not fit the greater expectations for network-level synthesis science.

> **Recommendation 9.** NSF should revise LTER and LTER-related proposal guidelines and review criteria to provide greater balance and synthesis between site-specific and cross-site research and education. In doing so, NSF should consider placing site-specific and cross-site competitions and activities on parallel, complementary tracks.

5.2.5 Informatics: A Core Function for Synthesis Science

The kinds of intense collaborations between scientists that will be needed to achieve synthesis, and the vision of 21st century biology, depend on the existence of a robust, ubiquitous, and easy-to-use information infrastructure. The Internet and World Wide Web have had enormous influence on the practice of collaborative ecological research in the past ten years. But, to date, the kinds of more specialized tools that could respond directly to the needs of ecologists and collaborative research remain largely undeveloped and unimplemented.

Information technology has the potential to revolutionize many aspects of the research enterprise by supporting activities in the field; allowing researchers to search across vast and distributed archives for data meeting specific needs; supporting the interactions of groups of researchers separated by large distances; sharing the use of predictive models and associated data and parameters; visualizing vast data resources; and mining data resources for unexpected patterns and anomalies. The general term *informatics* has emerged as a way of referring to such applications of information technology, and of emphasizing their power in relation to the more traditional aspects of data management.

Despite serious underfunding and a culture of local control of data, the LTER program has made progress in developing informatics capabilities. It has conceived a framework for interoperability, considered standards-based protocols, tested middle-tier technologies to exchange information, and established an Information Management Committee to guide planning and implementation. However, if the LTER program is to meet its goals of synthesis science and ecological forecasting, it must position itself in the vanguard of ecological informatics and become known world-wide as an innovative leader.

> **Recommendation 10**. The LTER program should establish informatics as a *core function* by implementing a systemic informatics infrastructure and architecture that integrates LTER data and tools with those from relevant disciplines.

The rationale for an informatics core function is its overarching importance for the entire LTER enterprise, which is data intensive. Informatics is requisite to deploying the 20-year legacy of core and other data sets, and integrating those data with tools and data from other domains for analysis of complex ecological phenomena. Success in implementing such an architecture will have a cascading effect, because informatics is the mediating platform for many of LTER's goals and this committee's recommendations. While reaching horizontally across data domains and science disciplines, LTER informatics can also enable vertical integration of biosphere systems from genomics to ecosystems to global systems.

Central to informatics is the concept of a common *ontology*, based on commonly recognized *objects* or elements of ecological systems. These include such central and ecologically relevant concepts as species, individual, patch, watershed, contour, reach, and plot. By agreeing on the specifications of a common ontology, the LTER sites would achieve a degree of interoperability that would allow one site's data to be understood by other sites, and by other groups outside the network, without requiring each site to adhere to imposed standards.

Candidly, the LTER program is playing serious catch-up in this area, having to deal with an enormous amount of legacy data that have been acquired and archived using a wide range of approaches. In hindsight, and citing a principle recognized by recent NSF-sponsored BON and NEON workshops, the LTER ontology should have been in place *prior to the collection of a single datum*.

At a different level, the development and adoption of a single network approach to metadata would allow researchers to search across the entire set of LTER data holdings, rather than site by site. With a common ontology and metadata format, it would be possible for the network to develop a single *gateway*, allowing users to search across all LTER data holdings by directing a single query to a single site. This would allow a single search of the form "what information does the LTER network have on carbon cycling?" in place of 24 searches of each site's archives.

The LTER program would also benefit from a central and proactive initiative to promote the development and adoption of powerful informatics tools, in areas of data integration, analysis, visualization, and modeling. Significant new advances in informatics have often come about because computer scientists, statisticians, and others have been motivated by problems in specific domains of science, such as the Human Genome Project. To date there are no obvious examples of this process working in the case of ecology. The LTER program could play an important role through partnerships with technical specialists, funded through such programs as NSF's ITR.

> **Recommendation 11.** NSF should: (1) increase the importance of data management and informatics in its evaluations of LTER activities and in its requests for proposals, consistent with the importance of these issues in LTER's coming decade of synthesis; (2) support the informatics core function at a level sufficient to achieve the LTER program's informatics objectives in an aggressive timeframe.

There are several ways in which the second part of this recommendation might be facilitated. First, NSF could make new resources available for distribution among the sites, in the form of a block grant to the Network Office. Second, NSF could hold an open competition for an *informatics hub*, namely, a center that would be a proactive force in developing and promoting new informatics tools and technologies, with strong links to groups such as NPACI. The second NEON workshop report describes many of the functional requirements of an informatics infrastructure designed to serve a diverse and distributed community of scientists[20]. The LTER Network Office might compete for this role, but so could other groups including those from outside the current network. A significant advantage of this second approach is that it would be easier for an independent group to marshal effective expertise in technical areas. Concentration of informatics resources in a single hub would also achieve greater visibility and economies of scale than distribution of resources among existing sites.

5.2.6 Incorporating New Science and Technologies

The incorporation of new science and technologies is essential to achieving interdisciplinary, synthesis science. LTER scientists have begun to explore a variety of new technologies and disciplines, including geographic information systems and remote sensing, computational and communications systems, and ecological informatics. Through partnerships with federal agencies, national laboratories and the private sector, LTER scientists have introduced advanced instruments and information management to LTER projects that have served as testbeds for wider application at the site and network levels. The LTER program recognizes the potential applications and future research payoffs of incorporating smart dust, *in situ* sensors, data mining, new satellite technologies, and other high-technology tools.[21]

However, it is essential that the incorporation of new scientific disciplines, technologies and tools be focused by LTER's scientific priorities for synthesis across knowledge domains. For example, what gaps in technological capability are hindering knowledge discovery in such fundamental areas as the ecosystem function of biodiversity? What kinds of essential LTER research are now not possible because other scientific disciplines, such as genomics or mathematical and computational modeling, have not yet been incorporated? What priority science is not possible because the sensing, experimental or analytical tools are not yet available?

> **Recommendation 12**. The LTER community should aggressively incorporate powerful new scientific approaches, technologies and analytical and experimental tools that can expand the scope and scale of LTER science to systems-level ecological research. In doing so, the LTER program must identify and select the disciplines, approaches and technologies appropriate to achieving its scientific priorities and agenda for its decade of synthesis. For its part, NSF must boost funding levels to enable incorporation of new science and technologies in order to enhance the scale, scope and tractability of LTER's ecological research.

Through collaborative discussions within and outside the LTER community, the LTER program could stimulate the incorporation of new scientific approaches, technologies and tools appropriate to LTER's scientific priorities. In this vein, NSF's National Ecological

[20] http://www.sdsc.edu/NEON/mar2000/index.html
[21] *LTER Response to the 20-Year Review Committee*, p. 10

Observatory Network (NEON) initiative, specifically, NEON's second workshop report, may serve LTER as a valuable guide for incorporating new science and technologies[22].

5.2.7 Social Science

When the NSF established urban LTER sites and charged them with pursuing ecological studies in an urban environment, it also mandated involvement of social scientists in studying the interrelationships of human and natural systems across non-urban LTER sites. Subsequent meetings, workshops, and symposia of ecologists and social scientists revealed the complexities involved in understanding the human dimensions of ecosystem science. What emerged were six social science core areas and a conceptual framework to focus future investigations.[23] What did not emerge was a strong theoretical basis or research agenda for coupling natural systems with human systems across the LTER program to enhance an understanding of both. Instead, the social sciences appear to be an add-on to the non-urban LTER sites.

> **Recommendation 13.** The LTER program should partner with social scientists to increase understanding of the interrelationships and reciprocal impacts of natural ecosystems and human systems in order to inform environmental policy.

For example, greater LTER collaboration with economists could help determine the value of ecosystems services. Anthropologists, sociologists, historians and technology market forecasters could help elucidate how prior land use has affected the landscape, its biodiversity and its ecological properties, and how emerging social and technological systems may alter the landscape in years to come. And demographers could help establish the effects of population dynamics on land use, landscapes, ecosystem function and global change. In turn, for ecologists, knowledge of the human impact on ecosystem structure and function is vital to preventing and restoring disturbed ecosystems. Garnering resources for such collaboration will be iterative: the broader the knowledge gained about the human dimension of ecosystem function and its applicability to solving real-world problems, the more resources will become available for LTER science.

NSF could facilitate studies of the relationship between human and natural systems at long-term ecological settings through LTER-focused competitions that demand collaborative proposals. Targeted workshops for communities of social and natural scientists could reveal: What do social scientists want and need to know that would foster their understanding of the relationship between humans and the environment? What are the indicators of the social forces that drive land-use change? Scientists involved with the Land-Use and Land-Cover Change (LUCC) program, a part of the International Geosphere-Biosphere Program, could contribute to these workshops, because they focus on questions related to the human dimensions of global environmental change[24].

5.2.8 Serendipitous Science

For two decades, LTER data, information and knowledge have been used to address unanticipated questions and to generate unanticipated results. For example, integration of LTER data with those from other sources (e.g., museum biocollections; CDC databanks)

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[22] http://www.sdsc.edu/NEON/mar2000/index.html

[23] LTER Response to the 20-Tear Review Committee, p. 32

[24] *http://www.uni-bonn.de/ihdp/AboutIHDP.htm*

revealed the causes of sudden, episodic events, such as the Hantavirus outbreak in the Southwest U. S. and the effect of the El Niño cycle on the severity of such outbreaks.[25] In Alaska, tree-ring chronologies provided evidence that contradicted the prediction of global climate models and effected a change in the state's forest plan.[26] Clearly, serendipitous applications of LTER data and scientific expertise add value to these 20-year core assets, increase the NSF's return on investment, and demonstrate the unique value of the LTER program to the broader research community and the public.

Whereas synthesis science looks forward and is hypothesis and theory driven, serendipitous science exploits unanticipated events. For example, disturbance events are excellent opportunities for serendipitous science, particularly the application of long-term data to quick responses to natural and/or human disturbances. Using FEMA's plan for emergencies as a model, could the LTER program develop a strategic plan for nimble responses to appropriate disturbance events by a cadre of trained scientists? Armed with long-term data, informatics capabilities, state-of-the-art data collection technologies, and robust predictive models about ecological systems and processes, LTER and non-LTER scientists could rapidly assess the short and long-term impacts of a disturbance event and provide information useful to policymakers.

Serendipitous science also scans multiple databases for emerging, unanticipated patterns and trends, and is fueled by interdisciplinary collaboration. The LTER network should therefore promote the integration of its data with tools and datasets from other disciplines for serendipitous (as well as synthesis) science, which requires informatics capabilities discussed earlier in this report (see Section 5.2.5, Informatics).

> **Recommendation 14.** The LTER program should foster increased opportunities for serendipitous science by providing a virtual portal to its legacy data for investigators worldwide.

5.3 BROADER IMPACT OF LTER SCIENCE

The broader impact of the LTER program derives from its long-term ecological experiments, observations and data sets, and network of scientists and students. LTER program research, featured in many journals, has advanced our understanding of natural and human-induced changes and episodic events in the environment. It has fostered interdisciplinary, interagency, and international collaborations among scientists. It has informed land use and public health policies, wetlands restoration efforts and fisheries, forest harvest, and fire management practices mostly at the local level. And NSF's long-term support for LTER has extended the scale and scope of ecological research into complex questions about the biosphere.

> **Recommendation 15.** Using the knowledge gained from synthesis and serendipitous science in the coming decade, the LTER program should assume a more powerful and pervasive role in informing environmental solutions and public

[25] *LTER Response to the 20-Year Review Committee*, p. 7-8
[26] *LTER Response to the 20-Year Review Committee,* p. 8

policy at local, national and international levels. The LTER program should increase and regularize efforts to share this wealth of knowledge with public officials, especially at the national level where environmental policies can have significant impact.

This broader impact can be achieved if the LTER program is successful in turning its descriptive knowledge— its growing legacy of authoritative science and data— into ecological forecasting of environmental phenomena. As other nations adopt the LTER model and share LTER knowledge and data through an informatics platform in a network of networks, researchers will be able to study global environmental problems and develop common understandings and integrated solutions to these problems.

Certain issues, such as global warming, carbon sequestration, invasive species, and biohazards are of vital interest to national and local government officials. We think, for example, that the Office of Management and Budget might be interested in learning more about the economic value of ecosystems and the cost of recovery when these systems are perturbed or destroyed. The LTER Network Office, site directors and individual scientists should develop relationships with public officials and invite them to LTER sites and special symposia where they could learn how long-term ecological research is conducted and why it is important to their policy decisions.

Communicating complex, scientific knowledge to non-scientific audiences, such as the public and government officials, requires special expertise. Communications specialists can translate LTER scientific concepts and accomplishments for the public and advertise high-profile research "stories" that have had an economic or policy impact. They can serve as a conduit to science writers in the news media and popular publications (e.g., *Discover, Scientific American*, *National Geographic*, *Natural History*) and see that articles about LTER research appear regularly in the public domain. Although the LTER program has increased its public outreach, e.g., the development of research vignettes, the effort requires a science communicator who can tell the story to lay audiences.

Recommendation 16. The LTER program should establish a professional public communications office to assist LTER scientists in informing the public and policy makers about the importance of LTER science to local, regional and national environmental solutions. NSF should provide a budgetary line item for this function.

Initially, the LTER program might provide sabbaticals for communication experts. The LTER might also follow the lead set by the Hubbard Brook Research Foundation's Science Links ™ program. The program prepares and publishes synthetic reports, written in language accessible to non-scientists, that inform public discussion of critical science-related issues (see Box 1, below). Ultimately, to achieve broad public awareness, the investment in public communication will need to be commensurate with the investment in science— a valuable lesson provided by the Human Genome Project.

Box 1. **The Science Links™ Program**

The Science Links™ program is sponsored by the Hubbard Brook Research Foundation, an independent non-profit organization formed to support the activities of the Hubbard Brook Ecosystem Study at the Hubbard Brook Experimental Forest, one of the original LTER sites. The Science Links™ program is based on two premises:

(1) environmental policy will be more effective and better serve the public if it is grounded in ecosystem science; and
(2) ecosystem science can be enriched by an increased awareness of current environmental questions.

An initial Science Links project that focused on new developments in acid rain research was launched in May 1999. One important output is a report called *Acid Rain Revisited: Advances in Scientific Understanding Since the Passage of the 1970 and 1990 Clean Air Act Amendments*, available at www.hbrook.sr.unh.edu/hbfound/report.pdf.

The report is written in clear language accessible to lawmakers and non-scientists interested in environmental policy; it explains how and why, as of the year 2001, "acid rain is still a problem and has had a greater environmental impact than previously projected." In response to the question: "Will ecosystems in the Northeast recover?," the report says no, citing evidence from an "acidification model," a predictive computer model of ecosystem function over time. The report concludes that "the Clean Air Act has had positive effects, but is not sufficient to fully recover acid-sensitive ecosystems in the Northeast." Importantly, the report, as part of the Science Links™ program, is "not intended to advocate particular policy outcomes, but rather to provide scientific information on the likely consequences of potential actions and to ensure that this information is timely, clear and widely available."

5.4 EDUCATION FOR THE FUTURE

5.4.1 Undergraduate and Graduate Education

The LTER program has played a primary role in training a generation of ecological scientists by combining undergraduate and graduate education with site-based research. LTER sites continue to provide multi-disciplinary research training opportunities for graduate students and take advantage of regular NSF programs for undergraduate education (REU--Research Experience for Undergraduates; UMEB--Undergraduate Mentorships in Environmental Biology.)
Citing a study by the National Academy of Sciences, a recent article in *Science* concludes that:

> More than at any time in the recent past, there is a demand for mechanisms and incentives to foster interdisciplinary research, education and problem

> solving. …[T]oday's young scientists will find their advancement restricted unless they are trained from the start to diversify their expertise…[27]

An NSF workshop report[28] echoed this recommendation for the biological sciences in general and for ecology in particular. Building on its educational accomplishments, the LTER network, in partnership with associated universities, is a natural arena for such interdisciplinary, cross-domain education.

> **Recommendation 17.** The LTER program should expand the scope of its undergraduate and graduate education in field-based ecological research by incorporating the cross-disciplinary, collaborative approaches and characteristics of 21st century biology.

The LTER network can be the platform for helping universities educate a new cadre of ecosystem scientists for the 21st century, ones trained across disciplinary domains— ecology, systematics, conservation biology, population genetics, informatics, environmental economics, geospatial sciences and so on. These students will be better equipped to study and decipher complex ecosystem phenomena, and to work in teams with other biologists, earth systems scientists, engineers, computational scientists and social scientists. One mechanism to achieve this goal is multiple, collaborative NSF IGERT projects involving many of the LTER sites and associated universities. Other mechanisms might involve educational partnerships with natural history museums, field station and marine laboratories, genomics and geospatial facilities, and social and economic research entities that focus on environmental issues.

Broader student education across LTER sites will have collateral impacts. For example, when biodiversity becomes a core area or function of LTER study, students trained in this field will help reverse the loss of taxonomic expertise from the nation's systematics community, especially expertise in poorly known organisms, such as soil biota, that are key to understanding ecosystem processes. Also, LTER-based students who are provided the opportunity to work with policy makers, for example, as AAAS Science and Technology Policy Fellows or as interns with local congressional representatives, will broaden the impact of LTER science and scientists in the policy arena, as recommended earlier in this report.

5.4.2 K-12 and Public Education

The Schoolyard LTER program has become one of the most visible education and outreach activities in the LTER network. Participation in the Schoolyard program is high at many sites, with Web-based documents available to students and teachers worldwide. Yet, this successful initiative is cited by the LTER Executive Committee as an example of an underfunded mandate most sites must add funds from other sources to the annual $15,000 NSF supplements for the Schoolyard activity. NSF and the LTER network need to resolve this issue.

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[27] Jasanoff, S. et al. 1998. Conversations with the community. AAAS at the Millenium. *Science*, 278:2066-2067.
[28] Bloch, E. et al. 1995. Impact of Emerging Technologies on the Biological Sciences. National Science Foundation, Arlington, VA 22230.

Recommendation 18. The implementation and impact of the Schoolyard LTER should be enhanced in three ways. First, the LTER sites should leverage funds provided for this program to achieve economies of scale and increased outreach; second, NSF should increase its support for LTER K-12 educational programs; and third, the design and outcomes of LTER K-12 educational programs should have formal evaluation to inform appropriate growth and improvements.

For example, LTER sites might pool their Schoolyard supplements to develop a cost-effective suite of modular "suitcase" education programs that can be implemented by a group of sites or across the network. Such modular programs might change every two or three years and be tailored to biotas, habitats and public issues specific to single sites, groups of sites or the network. Curricular modules at several educational levels might be developed around the valuation of ecosystem services— the importance to people's lives of healthy ecosystems, the consequences of ecosystem degradation, and other topics that relate to people's economy, health, food and quality of life. Joint Schoolyard and public outreach programs for the next decade might tie these broad educational themes to state environmental objectives, which might prove effective with elected officials in illustrating the importance of a science-based public policy. Finally, with increased funding from NSF, LTER might provide a laboratory for research on K-12 and public informal science education by investigators in schools of education, natural history museums, science museums and other informal science institutions.

6. MANAGEMENT

6.1 THE STRATEGIC PLAN

To realize its bold future, the LTER program, working with NSF, will have to develop a comprehensive strategic plan for accelerating its transition into 21st century science. This plan will be critical to adapting the LTER program to the new science landscape, managing the LTER program for excellence at both the site and network level, and achieving LTER's goal for its third decade of synthesis science, ecological forecasting and informing environmental policy. Synthesis science in the 21st century will be a costly and complex undertaking. It will require disciplined choices among goals, options and the processes to achieve them — choices that will become the framework of the strategic plan.

The strategic plan and planning process should also reflect the size and scope of the LTER program, which is now a mid-size organization with international partners and personnel, data, and activities at multiple locations. The planning needs robust involvement at both site and network levels, with the overall strategic plan clearly recognizing the differences and resolving the tensions between network level goals and those of individual sites and investigators.

The *LTER White Paper*[29] represents a good beginning in this direction. It addresses many of the challenges of 21st century science and articulates particular positions and strategies that this committee has endorsed in this report. But it is not a strategic plan, falling far short of

[29] *LTER White Paper: Priority Setting in the LTER Network, 2001*

identifying scientific goals and priorities for the next decade and tying them to a real budget, timeline or accountabilities— or explicitly justifying the requested doubling of the LTER budget. A successful strategic plan will help the LTER program remain adaptive, nimble and innovative by balancing fiscal resources with research expectations. It will describe LTER program management structures and processes that enable incorporation of 21st century science.

> **Recommendation 19.** The LTER community and NSF, using the findings and recommendations of this report, should jointly craft and implement a comprehensive strategic plan for the LTER program, i.e., its science, funding, outcomes, governance and organization for the next decade. The comprehensive strategic plan should contain all the components basic to any strategic plan: vision and mission; goals, priorities, objectives and actions; deliverables, timelines and milestones; and a budget that aligns resources with these elements.

The committee recognizes that NSF and LTER jointly formulating a strategic plan might be a radical departure from past practice and NSF's organizational culture with respect to grantees. However, given LTER program's long-term importance, scale and funding, NSF needs to accommodate such joint planning without short-circuiting or compromising its peer review of the LTER scientific enterprise. Successful planning protocols of other NSF science enterprises, such as the Science and Technology Centers, Engineering Research Centers, and NPACI, might provide useful models and lessons learned for joint LTER-NSF planning.

Joint LTER-NSF planning is critical because it is more likely to produce: a shared vision and mutual understanding of expectations; satisfactory resolution of lingering, historical issues so that new issues can be addressed; and a better fit between desired outcomes and resources, resulting in fewer perceived underfunded mandates or unmet expectations. Joint planning in a common forum with a common agenda will be most effective for reaching agreement on the goals, objectives, strategies, timelines, and milestones of the strategic plan; on the resources required to achieve these ends; and on the range of sources for such resources.

In short, it is time for all the players involved in the science and support of the LTER enterprise to gather at the same table, develop a common agenda, and determine how resources can be garnered, leveraged and redeployed to attain the promise of 21st century ecological science.

6.1.1 Planning Scientific Goals and Priorities

The first order of business in crafting the strategic planning is to address and establish the scientific goals for the LTER program, which, in turn, will drive strategic decisions governing LTER research, personnel, resources, infrastructure and organization. The strategic plan must tie society's need for scientific knowledge to long-term investments in scientific research. The science itself will become the most powerful voice for a comprehensive commitment of public resources when the ultimate goals of LTER's research and education serve the public good— for example, understanding the roles of ecosystems in cleaning the planet's air, water and soils; the dimensions and effects of environmental change; and the role of biodiversity in sustaining ecosystem health and worldwide food production. Many of the scientific issues critical to LTER's next decade of synthesis have been discussed in Section 5 above and should be addressed in the strategic plan. The results will help the LTER community and NSF circumscribe and set the LTER science agenda, recognize constraints, and develop a realistic budget and implementation plan.

6.2 BUDGETARY ISSUES

6.2.1 Matching Resources with Goals

The current LTER budget has not kept pace with inflation and has reached the limits of elasticity. It cannot accommodate a changing research landscape and new opportunities, activities or technologies, much less many of the recommendations in this report. The discrepancy between fiscal resources and research expectations creates a tension that, if not corrected, will keep the LTER program from embracing 21st century biology as fully as it should. As part of a realistic strategic plan, NSF and the LTER program need to examine research mandates and deliverables, set their priorities and, as appropriate, either shore-up funding or trim unfounded items from the agenda.

> **Recommendation 20.** In crafting the strategic plan, NSF and LTER program must tie the scientific goals and objectives to a realistic budget. NSF should increase funding for the LTER program commensurate with the agreed goals and priorities for synthesis science and ecological forecasting in the third decade.

The committee is not specifying the level of increased funding; rather, as we recommend, strategic planning should precede and dictate appropriate budgetary decisions. However, throughout this report the committee has specified strategies that require increased NSF investment in order to accelerate LTER's incorporation of 21st century biology. Again, these strategies include: collaborating across sites, systems and disciplines; incorporating new science and technologies; implementing informatics as a core function; establishing biodiversity as a new core area or function; and making social science systemic.

> **Recommendation 21.** The enhanced budget for the LTER program should be invested in the LTER's scientific priorities and in implementing the strategies discussed in this report for achieving 21st century biology and synthesis science.

A number of specific activities are common to these strategies and merit increased funding, including, regular and more frequent cross-site competitions and all-scientists meetings; and post-doctoral fellowships in collaborative disciplines at LTER sites and the Network Office. NSF and LTER might consider a block-grant to the Network Office to implement selected activities, as well as fencing a portion of the budget as incentives for collaborative and interdisciplinary activities at the cross-site and network level.

6.2.2 Enabling Informatics

Increased NSF investment in the LTER informatics infrastructure is a particularly critical need. In addition to fostering synthesis science, it will help reverse the perception that informatics is an "add-on" rather than a fundamental component of ecological research. According to statistics from NSF's Division of Biological Infrastructure, research projects in biology allocate an average of 5% of resources to informatics when the actual need is between 35%-40% of total project costs. LTER science, which is data intensive, exceeds this average, allocating approximately 10%-20% of total project costs to informatics depending on the site. Still, this short-changes informatics, which has diminishing returns in the long run, resulting in information that is less capable of integration, analysis, synthesis and prediction by LTER and other scientists.

An appropriate level of investment in an informatics infrastructure for the entire LTER community will be cost-effective and achieve economies of scale for NSF and the LTER program. Part of the increased investment in informatics should target the management and maintenance of LTER data, an irreplaceable asset for current and future research and applications. LTER data are no different in this respect from federal census data, remote sensing and genomic data, taxonomic and culture collections, and other national archives.

6.2.3 Achieving Parity

A serious, long-standing shortcoming in LTER's current budget is the large discrepancy in base funding among cohorts of LTER sites, which resulted from the cycle of competitions and renewals during the past 20 years as well as a series of supplements and budget adjustments. Older cohorts of LTER sites receive approximately half the annual base budget of the newest cohort. For example, current annual base funding for Konza, Andrews and Shortgrass Steppe is $560K, whereas that for Coweeta and North Temperate Lakes is about $1M. NSF's current plan for correcting this imbalance is a step in the right direction but will raise the underfunded cohort sites to only $820K in five years.

> **Recommendation 22.** The NSF should establish parity funding for all LTER sites as quickly as possible commensurate with the scientific goals and activities called for by individual sites and the network in the strategic plan.

6.2.4 Growing the Base

This report documents the need for increased funding across the LTER enterprise. The challenging task for NSF and LTER is to work together to develop a stronger support base, which the committee thinks is achievable. As LTER science becomes more predictive— and therefore more useful to policymakers— the value of the LTER program and its benefits to society will justify and generate increased allocations and expenditures. Legislators, policymakers and federal agencies, increasingly faced with environmental problems that affect the health and economy of the nation, seek solutions that are based on sound ecological theory, data and knowledge. The promise and delivery of such solutions, embodied in LTER's goal of ecological forecasting, should help NSF grow its environmental budget. Such growth could occur over several years, in phase with a suite of ecological deliverables. By sharing its science, data, tools and infrastructure with other agencies, the LTER could leverage interagency funding for complementary research. Critical here, as recommended earlier in this report, is NSF and LTER investment in public communications expertise that can tell the stories to legislators, policymakers and the public of how LTER science serves society.

6.3 Governance and Organization

During the past 20 years, the LTER program has experienced extraordinary growth in budgets, personnel, sites, scientific disciplines and activities. Not unexpectedly, this kind of growth has generated challenges in managing and coordinating LTER science. A Network Office and various committees and advisory groups were added to help grapple with these challenges. However, important issues of growth, structure and management need to be resolved if LTER is to stay on the frontier of long-term ecological research.

6.3.1 Scale and Growth

Before expansion is considered, the LTER program and NSF need to establish: (1) a unifying, intellectual focus for LTER systems science and ecological forecasting, and (2) an adequate resource base, infrastructure and management plan for such an intellectual mission to succeed. Clearly, expansion should not occur while the current network is still too diffuse for synthesis and systems science, and while the gaps between resources and expectations are wide enough to be termed unfunded or underfunded mandates.

> **Recommendation 23.** New sites should not be added to the LTER network until such potential expansion is justified in the strategic plan.

That said, the committee thinks there is a clear need for expansion in LTER coverage and scale to produce accurate synthesis. Fundamental questions here for the LTER community are: Will synthesis science be limited by the ecosystems represented by the 24 current LTER sites? Are there critical habitats and ecosystems not represented by current LTER sites? For example, are eastern forest ecosystems or urban ecosystems adequately represented by only two LTER sites? In some locations, new, intensive sites may be called for, whereas in others, extensive satellite sites might be most appropriate and cost-effective.

> **Recommendation 24.** Should sites be added to the LTER program in the future, such expansion must be strategic and synoptic. The larger ecological community (i.e., LTER and non-LTER ecological communities) should determine where and how such expansion would provide the greatest benefit to understanding the nation's ecological systems, with competitions for new sites based on these findings. The LTER program should expand internationally by building on its collaborations with the ILTER enterprise.

6.3.2 Structure

The strategic plan for LTER science must describe a governance and organizational structure that can encompass and facilitate the program's projected goals, scope and scale. The structure will have to be as innovative and nimble as the synthesis science it will be asked to enable for the next ten years. Also, the LTER program is a unique beast— a distributed organization of 24 units that are loosely coupled, scientifically diverse and independently funded. For this reason, designing and implementing the LTER structure will be as challenging as designing the LTER scientific blueprint. The answers from within and outside the LTER community to the questions raised by the committee in Section 5 regarding scientific priorities, core areas and foci for collaboration will be critical in formulating LTER's governance and organizational structure.

> **Recommendation 25.** The comprehensive strategic plan should describe a governance and organizational structure appropriate to the goals, scope and scale of the LTER program in the next decade of synthesis science. Planning this structure should be informed by models from other enterprises and by experts in academia, government and the private sector.

Drawing from our recommendations in this report for LTER science strategies, the committee envisions that the LTER governance and organizational structure will provide the kind of intellectual and managerial leadership that will drive synthesis science, i.e., collaborative research, education, and infrastructure across sites, disciplines and knowledge domains.

In designing this structure, NSF and LTER should not be prisoners of history— they should not feel constrained by the current LTER governance and organizational structure in developing the strategic plan. The structure that has evolved during the past 20 years might no longer be adaptive for LTER's third decade of ecological forecasting. The organizational challenge is both intellectual and allometric— LTER's structure has to fit the new shape, size and mode of synthesis science.

For example, one structural model used by some organizations to cultivate intellectual and multidisciplinary innovation is the "adhocracy"[30]. Adhocracies focus on ideas, organize themselves horizontally into "ad hoc" multidisciplinary project teams to address those ideas, and rely on expertise, communication and coordination to accomplish the goals derived from those ideas. Adhocracies are decentralized, nimble, innovative and dynamic— as ideas, landscapes and opportunities change, so does the organization.

6.3.3 Management Functions

Whatever structural entities are retained or created, the LTER program must have a suite of components and mechanisms to perform the basic management functions of the enterprise. These management functions are:

- Guide implementation of the strategic plan
- Provide for regular review of the strategic plan by the LTER community to adapt to changing ideas, opportunities, technologies and science landscapes
- Foster a seamless continuum of ideas, people and tools— to use NSF's mantra— across the LTER enterprise
- Coordinate LTER collaborative activities and resources
- Provide intellectual leadership for LTER science and education
- Monitor resources, milestones, timelines and deliverables
- Enforce accountabilities established in the strategic plan
- Guide development and implementation of policies, procedures and standards
- Communicate on behalf of the LTER enterprise as a whole

[30] coined by Alvin Toffler in *Future Shock*

6.3.4 Authority, Responsibility and Policy

It is not clear which entity (or entities) in LTER's existing governance and organizational structure has the authority, responsibility, mandate and resources to implement the strategic plan and manage the LTER program. Although the Network Office, Executive Committee and Committee on Scientific Initiatives each perform some management functions at the network level, none of these entities alone or in combination perform all of the basic functions necessary to implement the strategic plan and manage the LTER program.

> **Recommendation 26.** The strategic plan should specify the entity or entities that will implement the strategic plan and manage the LTER program, as well as a process for developing policies to govern implementation, LTER management and other issues.

For example, such powers might be centralized in the Network Office; or distributed among LTER committees, individual sites or clusters of sites; or assigned to new governance structures created in the strategic plan. Policies might define how authority, responsibility and decisions are concentrated or shared from the network level to individual sites. Clearly, these policies should serve the scientific goals and objectives of the strategic plan.

6.3.5 Intellectual Leadership

In this decade of synthesis science, strong intellectual leadership must become a core management function. This leadership must be rooted in ideas, i.e., it must be nourished by ideas from within and outside the LTER program and enable research and education based on those ideas. To reiterate the committee's recommendations for collaborative science, such intellectual leadership must

- foster broad participation by individual sites in systems-level LTER science
- enlist expertise from outside the LTER and ecological communities in LTER science and education
- leverage the LTER infrastructure in recruiting people, data, tools and resources from other organizations
- facilitate technological innovation, anticipate research opportunities, promote research themes, and formulate theoretical questions
- incorporate bold and innovative research ideas in LTER science

6.3.6 NSF's Administration of the LTER program

The joint strategic plan will inform NSF's administration of the LTER program for the next decade. Elsewhere in this report, the committee has recommended that NSF participate in joint strategic planning and that it foster the goal of synthesis science by adjusting the LTER review criteria, holding more frequent cross-disciplinary and cross-site competitions, and matching goals with resources.

Another issue is staffing. The sheer size and scope of the LTER program merits two NSF officers, with a permanent one in charge of the program to ensure continuity. Officers who are "rotators" can and do manage NSF programs. However, with only one or two years of service to learn NSF protocols and LTER's institutional history, a rotator might be at a disadvantage heading, advising and speaking for the LTER program.

Recommendation 27. NSF should allocate two program officers to administer the LTER program, with a permanent one in charge of the program. Because LTER is now funded by several NSF directorates, a formal, cross-directorate committee of program officers should be established to coordinate LTER funding and program management.

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The LTER program is integral to meeting a grand challenge for the 21st century understanding the nation's ecosystems in all their complexity in order to use and preserve them in a sustainable fashion[31]. This knowledge is critical to science and society for maintaining the nation's natural resources, for growing its economy, for improving human health, and for enhancing the quality of human life.

After 20 years, NSF's investment in LTER science, people and infrastructure has paid enormous dividends in advancing knowledge of ecosystem phenomena. NSF has placed the LTER program on the frontier of ecological science, spanning time, terrain, scale and complexity. The need and promise for LTER science in the decade ahead are unparalleled.

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[31] Bloch E., et al. 1995. Impact of Emerging Technologies on the Biological Sciences. National Science Foundation, Arlington, VA 22230

APPENDIX A. 20-YEAR REVIEW COMMITTEE

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APPENDIX B: ISSUES FOR 20-YEAR LTER REVIEW

Issue 1: *Advancing ecological science*

To what extent does the LTER program feel it has been successful in advancing ecological theories, insights and knowledge? What problems has the LTER network encountered in achieving this goal? How can the LTER program best advance ecological knowledge in the future?

Issue 2: *Fostering serendipity science*

How can LTER expand the use of its data, information and knowledge to address unanticipated questions and foster unanticipated knowledge discovery? Benchmark past performance in this area and project new, future opportunities.

Issue 3: *Incorporating new science and technologies*

How can the LTER enterprise (LTER sites individually and collectively) capitalize on new scientific advances (e.g., comparative genomics, molecular biology, microbiology) and emerging technologies (e.g., nanotechnology, GIS technology, sensor technology) to address critical questions at different ecological scales?

How can the LTER network (LTER sites individually and collectively) contribute to predictive modeling across ecological scales (micro to landscape scale) and to the use/advance of computational biology and informatics in this predictive modeling?

Issue 4: *Informatics for knowledge discovery*

How well do the LTER informatics infrastructure and architecture serve/fulfill the LTER program's mission? What should the informatics infrastructure and architecture be, especially if use of the LTER data and information archives are to take advantage of and contribute to revolutions in technology and theory?

Issue 5: *Intellectual adaptability, priority and evolution*

After 20 years, how can the LTER program remain sufficiently nimble and flexible in vision, direction, and management to move into new research areas and take advantage of new, unanticipated revolutions in technology and theory?

After 20 years, how can the LTER program recognize when a research question—for example, one or more of the five core areas--has been answered? What criteria have been formulated and/or implemented to determine when a project or research theme has been completed or sufficiently investigated?

Issue 6: ***Impact on science and society***

What has been the broader impact of the LTER program on science and society, i.e., on other sciences, on formal and informal education and on informing public policy? Looking ahead, what more could/should the LTER program be doing in these areas?

How well is the LTER network (LTER sites individually and collectively) configured to inform public policy and to interact with the non-profit and private sectors?

Issue 7: ***Networking and collaboration***

How can LTER contribute to and draw from a network of all networks (local, regional, national and international)? How can the LTER network fill gaps in current spatial and temporal coverage? If opportunities arise to expand the LTER network, what criteria should govern the nature and scope such an expansion? What if the number of sites were doubled? Quadrupled?

Issue 8: ***Integration of human systems***

How successful have the efforts been to involve the social sciences across the entire LTER enterprise in order to understand the relationship of human systems and ecosystems. Looking ahead, what more could/should be done in this area?

Issue 9: ***Infrastructure and organization***

Based on your views of issues 1-8, what is your overall vision for the LTER program? How should the LTER enterprise adjust its organization to accommodate this vision? How can NSF foster this organizational adjustment?

APPENDIX C: RESPONDENTS TO ISSUE QUESTIONS

Response Date	*Respondent*
11/19/01	**Laura Huenneke** New Mexico State University Jornada Basin LTER
11/16/01	**Dave Coleman** University of Georgia Coweeta LTER
11/12/01	**Mark E. Harmon** Oregon State University Andrews LTER
11/07/01	**Scott Collins** (Interview) Program Director, NSF/BIO Division of Environmental Biology
11/06/01	**Tim Seastedt** University of Colorado Niwot Ridge LTER
11/01/01	**Roger A Pielke Sr.** Colorado State University
11/02/01	**Mark M. Brinson** Biology Department East Carolina University
10/31/01	**Bruce Hayden** University of Virginia Virginia Coast Reserve LTER
10/31/01	**John Porter** University of Virginia Virginia Coast Reserve LTER
10/29/01	**Paul Risser** (Interview) President, Oregon State University
10/24/01	**Peter Arzberger** San Diego Supercomputer Center University of California, San Diego
10/22/01	**Bill Heal** The Scottish Agricultural College United Kingdom
10/19/01	**LTER Executive Committee** University of New Mexico
10/18/01	**Gary S. Hartshorn** Duke University Organization for Tropical Studies
10/16/01	**Orie Loucks** Miami University of Ohio
11/30/01	**G. Philip Robertson** Professor, Michigan State University, and PI, KBS LTER Program