Long-Term Ecological Research Program
A Report of the 30 Year Review Committee

I. EXECUTIVE SUMMARY

The National Science Foundation (NSF) convened a small group of experts (Appendix 1) to evaluate the strategic plan for the Long-Term Ecological Research (LTER) program. The charge to this group was to provide a prospective assessment and strategic vision for the next decade of LTER (see Appendix 2). In response to that charge, the committee met twice (June 2010, October 2010) and committee members made site visits to 8 LTER sites and the LTER Network Office. In the review, we evaluated whether the LTER program's plans for moving forward are likely to stimulate a future that is even more successful than its past.

In general, the committee finds that the LTER network has articulated a good strategy for the future that can be improved into a great strategy once several challenges have been addressed. To move forward, the network must clearly delineate its unique value in the complex universe of ecological and environmental science, and must articulate the questions that can only be uniquely addressed with studies on decadal time-scales. It must continue to build its network-level capacities at both the practical level, where data management poses a significant challenge, and at the vision level, where hard questions must be addressed. The network must poise the LTER program very explicitly to meet some grand scientific challenges, and then evolve to provide the critical science that helps address these challenges. The network must become an active participant in new, emerging programs that will also address long time-scales and continental spatial scales – perhaps playing a key role in a network of networks that brings it together with NEON, OOI, Earthscope, ULTRA and other programs with parallel goals in related fields. This is an opportune time for a new level of leadership to emerge, so that the science of LTER is used to inform critical societal decisions on managing landscapes and ecosystems in a time of planetary change.

This Executive Summary presents the major findings of this report. We list four major strengths of the LTER network that we identified, as well as four significant challenges that it faces in the coming decade. We then list eight recommendations for how these challenges can be met. Section II introduces this 30-year review, and Section III provides information on the 20-year review by way of background. Section IV is a detailed analysis of LTER's current strengths and challenges, and provides the context for this committee's recommendations. We note at the outset that the 2011 LTER Strategic and Implementation Plan was not yet available the time that this 30-year review committee received its charge, met as a group, and developed its recommendations. We have independently arrived at many of the same conclusions as those highlighted in the Strategic Plan. However, as will be clear in this report, our perspectives on how to address certain major concerns, and our sense of their relative urgency, are not always congruent with those of LTER itself.

Key Findings: Strengths

- The committee strongly believes that the LTER program is an excellent science program with an immense and expanding value in ecological and conservation science. It is a

critically important program with outstanding accomplishments to its credit, and it is obvious that, at the very least, this level of accomplishment is likely to continue going forward. It is consistently an excellent investment by the NSF.

- The LTER program has leveraged its funding to support a much more extensive research program than would be possible from LTER funds alone.

- The emergence of a fully functioning network across the sites now allows science to be conducted on continental scales, setting the framework for the next generation of big questions that can be addressed by LTER and the emerging observing system networks.

- The richness of the long-term *observational* data gathered across the LTER network makes it uniquely poised to establish cross-site *experimental* studies of the mechanisms whereby factors such as climate change, nutrient loading, loss of biodiversity, and invasive species impact ecosystem functioning and species dynamics.

Key Findings: Challenges

- Internally, there continues to be a tension between the goal of network-level research and the goal of site-based research. This tension can be highly productive if a back-and-forth interplay is established in which discoveries at one scale are compared, contrasted and synthesized with those at the other. With the right opportunities for synthesis, the site versus network tension could become an engine of creativity and more rapid scientific advancement. At present, though, an insufficient proportion of LTER scientists are as engaged in network-level activities as would be optimal.

- Although most LTER sites provide good web access to the data they have gathered, there has been slow progress in making LTER data comparable across sites and thus easily usable by third-party scientists inside and outside the LTER network. Achievement of these network-wide data management goals will be crucial for cross-site analysis and synthesis.

- Network leadership relies upon a bottom-up, egalitarian approach that results in creative within-site research. However, strong network leadership is important when hard choices must be made, such as enforcing data management standards. We see a need for a greater centralized scientific leadership, empowered by the PIs and site scientists. This leadership could position the network to guide a broader scientific community confronting societal challenges that require ecological understanding.

- Many LTER researchers have recognized the dynamic link between humans and ecosystems, and have included social science components in their research program. At some sites, particularly the urban sites, social science has played a central role in shaping the research program. Though there is a real need to increase integrated research across the natural and social sciences to effectively address human-ecosystem interactions, it is not clear that LTER is well suited to contribute to fundamental advances in the social sciences. The central focus of LTER research is ecological, making it difficult to attract social scientists and to integrate social science research in a meaningful way. Some sites have felt pressured to incorporate

social science elements when they are not ideally poised to do so. There is an authentic desire to increase social science participation, but there is not a clear vision for how to achieve scientific excellence in this area.

Summary of Recommendations:

1. Although the LTER network has been highly successful, it is critical for it to clearly articulate for NSF and for the scientific community as a whole its future "value-added" components. It needs to be absolutely clear (a) what challenges long-term data are *uniquely* poised to answer and (b) what the LTER network can offer *beyond* a collection of excellent long-term studies on diverse issues at ecologically distinctive sites. For LTER to better justify significant additions of resources for current activities (and possibly the addition of new sites), it needs to clarify the grand challenges that individual sites and the network as a whole would be able to answer if such expansion took place.

2. The richness of the long-term observational data gathered across the LTER network makes it uniquely and optimally poised to establish *cross-site experimental studies* of the mechanisms whereby factors such as climate change, nutrient loading, loss of biodiversity, shifts in species composition and food web structure, and invasive species impact ecosystem functioning and species dynamics. Although each site is likely suitable for only a subset of these experiments, the network as a whole would add immeasurably to ecological science by pursuing such coordinated multi-site experimental studies. We recommend that the network plan and actively seek funds for a coordinated program of cross-site experiments and related cross-site observations. To ensure success, the LTER sites should actively recruit a new generation of diverse scholars interested in dedicating their careers to experimental and observational studies at the continental scale.

3. Although all LTER sites should incorporate appropriate social-science data into their analyses, we are not convinced that social science research is, in its own right, a central value-added component for the network as a whole, but it may well be so at some individual sites. Before undertaking a major network-wide expansion of social science research, the value of such an expansion must be better articulated and demonstrated.

4. As the goals and spread of long-term science continue to broaden, it is becoming critical to think beyond networked LTER sites, towards networks of networks (including but not restricted to an LTER-NEON network). The LTER network is uniquely poised to seek a leadership role in achieving this goal, and should articulate a concrete vision statement about its leadership opportunities. To ensure success, the LTER program should actively recruit a new generation of diverse scholars pursuing experimental and observational studies at the continental scale.

5. Data management at each LTER site is adequate to excellent in its support of the current science questions at sites, but the LTER network as a whole must invest in making LTER data comparable across sites and more readily available to those interested in network-

wide analyses. This problem can be remedied by either new resources for the network office or by re-directing some existing network office funding towards providing current and future scientists easy access to all LTER data from all sites. In particular, (a) the LTER Network Office must markedly expand its current data activities into a fully functional data management system that serves and archives all LTER data and metadata from all sites in a consistent and easily used manner to third-party users; and (b) each LTER site must fully support this LNO mission by publishing all data sets, in their entirety and with appropriate metadata, in a standard format with the network office and/or some other permanent repository in a timely manner.

6. Citizen science shows increasing promise as an outreach and educational tool to local communities and to audiences with a diversity that reflects the nation. Some LTER sites are encouraging this, among their other educational activities. These efforts should continue and be initiated at other sites. Their success is partially predicated on increasing the diversity of scientists, staff and students at each site as role models to the citizen scientists and each site must enhance its efforts in this area.

7. Cross-site education programs should be a higher priority for funding and effort, both through the spread of the better program models and for education activities that truly leverage the network as a whole. The few cross-site educational programs that have been offered to date have been very promising but funding has been minimal. It is critical to identify funding mechanisms for cross-site education both within and beyond NSF. Such programs should emphasize participation by diverse students and stakeholders.

8. Resources are a key limiting factor for the future of the network. The network should: 1) make realistic prioritizations within the existing resource base to create more science per dollar, and 2) engage with NSF and others to pro-actively develop new resources. Prioritizations will include spending more on data and diversity. The case for new resources could be built around a new level of excellent science that addresses the big science questions that underpin society's grand challenges. In all cases, the best practices and tools for developing new resources could be shared across the network to improve the effectiveness of each site.

II. INTRODUCTION

The Long-Term Ecological Research Program is one of the jewels in the NSF crown. No other program has had such a transformative role on the field of ecology as the LTER. In particular, the older sites, which have existed nearly three decades, now provide data of sufficient depth, breadth and duration to resolve numerous questions of central importance to science and society, and to raise new and testable hypotheses. More typical short-term research programs have often only been able to hint at the resolutions to these issues. The vision to embed manipulative, experimental research into this multi-decadal platform takes a largely observational perspective and gives it more solid connections to theory and more robust predictive capacity for science and society. In the past decade, the emergence of a fully functioning network across the sites now allows science to be conducted on continental scales, establishing a framework for the next generation of big questions that can be addressed by LTER and by the emerging observing system networks. Let there be no question – the LTER program has been an extraordinary success story within the National Science Foundation and one that, if funding continues at the same level, has the ability to produce as much or more in the coming decades.

The challenge, for the LTER network, the NSF and for this review committee, is how to take full advantage of this history and to map a path into the future that builds on LTER's success. No program has the "right" to continue forever just because it asks long-term questions and has a good track record with its past funding. The continuation and particularly the growth of the program must be justified by the quality of the new science yet to be done, the value of that science to the mission of the NSF, and the needs of the people of the United States of America. The LTER has presented a strategy and an implementation plan that reflect its vision of this path. This review committee, comprised of individuals with their own perspectives and biases, has explored both that vision and additional ideas gleaned from its own discussions and interactions with communities beyond the LTER network. In considering the future of the LTER program, we chose to ask some key questions, grouped under five areas, that resulted in eight recommendations:

<u>Defining the Value of Long-Term Ecological Research</u>
What is the essential value of "long-term" ecological research that distinguishes it from more traditional research studies? Is this value of sufficient importance to warrant its own program and unique, long-term funding? What are the key scientific questions that can be addressed by this style of research, and are they among the most important questions in the field? *(Recommendations 1, 2 and 3)*

<u>Reassessing Network Structure</u>
What kinds of partnerships can empower this network to be even more effective in the conduct of its science, in its ability to address key scientific grand challenges, and in reaching larger communities? Who will lead, and how will that leadership express itself as value to the science, network, and society? What is the function of the network, the network office, and the larger management apparatus, and do these structures provide the most cost-effective way to meet these larger needs? *(Recommendation 4)*

Reassessing LTER Data Management Practices
How can LTER and NSF ensure the long-term availability, accessibility, interpretability, and functionality of LTER data, even after LTER sites are no longer funded and part of the network? *(Recommendation 5)*

Extending the Network Reach
How should the LTER network extend its reach beyond its science, how valuable are these activities, and how can they be made most effective? *(Recommendations 6 and 7)*

Looking Forward: Resource Issues
How should financial resources to LTER be allocated in the future, under various realistic growth scenarios? *(Recommendation 8)*

III. BACKGROUND: THE TWENTY-YEAR REVIEW

The second comprehensive review of the LTER program was conducted in 2001-2002 by a committee co-chaired by Dr. Frank Harris and Dr. Leonard (Kris) Krishtalka. The resulting report documented many major achievements that LTER had accomplished since its 10-year review in 1993. The report notes that during its second decade, the LTER program effectively 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. The report also highlighted that LTER's own vision for the coming decade was 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" (LTER White Paper: Priority Setting in the LTER Network, 2001). The 20-year review committee strongly concurred with this goal.

The central recommendation of the 20-year review was that a comprehensive strategic plan be developed by the LTER community and the NSF. To quote the 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 by matching scientific priorities and goals with fiscal resources and by instituting management structures and processes for conducting 21st century biology." Twenty-six specific recommendations were offered for ways in which LTER could and should take synthesis science into the next decade.

It is clear that the LTER community was highly responsive to the 20-year review. Consistent with its recommendations, cross-site activities have increased and biodiversity research at individual LTER sites has greatly expanded over the past decade. The role of social science in the LTER network has also gained considerably more prominence, as urged in another recommendation. Finally, consistent with the 20-year review's major directive, a decadal plan was developed in 2007 that has oriented further growth of the network. This committee has closely read that document, as well as the 2007 ISSE (*Integrative Science for Society and*

Environment: A Strategic Research Initiative) report. The present report is offered in the context of what LTER itself proposed to accomplish. Although the 2011 Strategic and Implementation Plan appeared too late to structure our review, we have closely read this document as well.

New challenges have arisen, however, and some of those noted in the 20-year review have not yet been addressed. Three points in particular strongly influenced the context of this 30-year evaluation. First, major fiscal crises within the nation as a whole, and NSF in consequence, precluded funding of some of the LTER's more ambitious ideas. By mid-decade, LTER was faced with the challenge of how to do more (or even the same amount) with less and less. Second, this committee also noted with concern that many problems noted in the 20-year review relating to LTER data management and data-sharing have not been fully addressed. Indeed, they have grown more severe in the past decade, to the point where they risk becoming major constraints on the value of LTER network science. Finally, the increasing speed of anthropogenic change over the past decade made this committee particularly aware of the need to evaluate the current and potential role of LTER in the context of research on human impact on the planet.

IV. FINDINGS AND RECOMMENDATIONS OF THE THIRTY-YEAR REVIEW

Defining the Value of Long-Term Ecological Research

Identifying Value-added Components. We live in a time of rapid and alarming changes in the world around us. The climate system is responding to a mix of natural and anthropogenic influences, some of which are becoming well understood (e.g. El Nino, Pacific Decadal Oscillation), whereas others, like the anthropogenic effects of greenhouse gases, have wide uncertainties about the strength of the signal and the resulting effects on the overall stability of the climate and ecological systems. Human changes to the fluxes of nutrients on all scales are profound and expanding. The re-distribution of biodiversity, including both losses of species and the spread of invasive organisms, are restructuring ecosystems worldwide. The physical footprint of humans is also expanding, encroaching to a greater and greater extent into nearly every ecosystem. At the same time, the potential for renewable energy derived from nature and the value of ecosystem services can play important roles in the socioeconomic processes that drive ecosystem change. These drivers and processes are of huge social concern, and all operate on time-scales of decades to centuries. Managing this planet requires that we understand and can predict the complex dynamics of ecosystems and their emergent properties on the decade to century time-scales. LTER is helping us to do that in a profound way.

The scientific results emerging from the current LTER program illustrate how studying phenomena on these time-scales can successfully address fundamental research questions at the heart of ecology and the needs of society. For instance, LTER research at the Cedar Creek (Minnesota) site uncovered the central roles that biodiversity and species composition can play in determining the stability and functioning of ecosystems. In achieving this goal, this research has inspired scientists in Europe, Asia and South America to determine the importance of these processes in some of the major ecosystems of these continents. The LTER-led example of making data freely available now means that scholars interested in the effects of biodiversity and

composition on ecosystem functioning can do truly global meta-analyses using the data provided by an informal consortium of researchers from around the world. For instance, these results are now allowing economists to determine the economic value of the preservation or restoration of biodiversity based on the values of the ecosystem services that it provides.

Similarly, research at the Everglades (Florida) LTER is revealing the scientific mechanisms whereby nutrient loading impacts species and processes of concern, thus guiding the massive program to restore the Everglades. Work at several LTER sites, including the Konza (Kansas), Jornada (New Mexico), Arctic (Alaska) and Cedar Creek (Minnesota) LTERs, is revealing the mechanisms whereby climate warming impacts species abundances and ecosystem functioning, thus providing insights into the climate-driven environmental change that the Earth may face later this century. Finally, research at the Northern Lakes LTER (Wisconsin) has shown how both the supplies of resources such as phosphorus and nitrogen and the structure of food webs interact to determine the trophic structure of lake ecosystems, and thus water quality in freshwater ecosystems.

Some scientific questions demand not only a broad time scale but a large spatial scale, and the LTER is well set up to do this, especially since some sites have natural affinities.
For instance, three LTER sites form a natural gradient from subtropical Everglades to southeastern coastal marshes to New England salt marshes. Western and Pacific coastal sites differ substantially from the east coast sites in geomorphology and continental shelf bathymetry. Many sites experimentally manipulate nutrient fluxes to elucidate mechanisms that are important to both natural dynamics and anthropogenic impacts. Coordinating research and synthesis activities at related sites could maximize the payoff from the work already being done at these sites.

Long-term science can address profound questions of great importance to the field – questions that cannot be addressed in short-term projects, no matter how comprehensive, experimental and predictive. Every LTER site has one or more of these questions at the heart of its existence and these are tested regularly through the proposal renewal process for their value to the field.

> **Recommendation 1**: It is critical that the LTER network clearly articulates for NSF and for the scientific community as whole its "value-added" components. It needs to be absolutely clear (a) what challenges long-term data are *uniquely* poised to answer and (b) what the LTER network can offer *beyond* a collection of excellent long-term studies on diverse issues at ecologically distinctive sites. For LTER to better justify significant additions of resources for current activities (and possibly the addition of new sites), it needs to clarify the grand challenges that individual sites and the network as a whole would be able to answer if such expansion took place.

Actively Fostering Cross-Site Activities. As a committee, we discussed multiple visions for the strategic added value of the LTER network. We believe that the LTER sites are doing critically important science in their own right that, in a perfect world, would be sufficient justification to expand on this program. The last 30 years of research across the LTER sites have provided a rich foundation upon which to build the "big science" infrastructure essential for addressing the

major anthropogenic challenges that face the planet. Indeed, we know of no other suite of research sites as suitable for this mission as the LTER sites. The LTER network has realized that and has framed its decadal plan around a few of those important questions. However, within-site studies alone will not be sufficient to provide the scientific knowledge needed to address issues related to the impacts of climate change, invasive species, and other human environmental impacts.

The current strategic emphasis takes the work that is done at the existing sites, looks for common activities and questions, and then groups these activities under common titles and science questions. This can lead to synthesis and is extremely worthwhile. However, the goal of synthesizing patterns across sites is not driving the decadal plan, nor does it appear to be articulated as a central goal of the program. For example, almost all LTER sites measure nutrient fluxes, and in every location nutrient fluxes are changing at some level due to human activities. Thus, the decadal plan has identified the study of ecosystem responses to anthropogenic nutrient fluxes as an important goal. The authors of the decadal plan overlay a map of the LTER sites on a map of nitrogen deposition rates across the continental United States (Figure 4.11). In this figure, one can see that the deposition of nitrogen peaks across the upper midwestern United States, the agricultural heartland. Yet, there are no LTER sites in this high-deposition area, and only one site (Kellogg Biological Station, Michigan) has a strong agricultural focus. If cross-site synthesis were a strategic focus of LTER, then the network should be looking for other data to fill in around this gap. Furthermore, a strategic focus on ecosystem dynamics and continent-scale anthropogenic nutrient fluxes would likely lead to a recommendation for specific types of new LTER sites, including additional agricultural sites, across a gradient that incorporates the key high-deposition areas.

This choice between an emphasis on synthesis activities (important under any circumstances) and a real strategic focus that drives the science in new directions and addresses new questions is one that the network must address. This committee was very comfortable with the network's concentration on site-driven scientific questions, where the societal questions provide added value through synthesis. The network can justify its future direction by maximizing the value-added components through partnerships, synthesis and collaboration. The alternative, and probably scientifically riskier, approach would be to really engage these key continental-scale, socially-relevant questions and to chart a path that has these broader questions as the central goals in the science. The committee believes that designing the future expansion of the network to directly address large science questions through cross-site, continental-scale experimentation on decadal scales is required for justifying a dramatically greater scope and role for this program.

One potential mechanism for expanding the capacity of the LTER network to address big, coordinated, experimental science questions across the network could involve NSF competitions targeted to this goal. The LTER decadal plan identifies a number of the big science areas, but, as mentioned above, takes a synthesis approach rather than pushing for the network to directly address each question. The LTER network and the NSF could challenge the LTER and non-LTER communities to submit proposals that directly addressed a key grand challenge. These proposals could involve one or more new sites, specific experimentation at many appropriate sites and even additional measurements across the whole network as appropriate to address the science goals. We are not recommending a broad "supplement" to the program, evenly applied

across the network, rather the converse. Individual big ideas would compete with each other through the proposal process and likely involve a subset of the network and targeted expansions towards a specific goal. We recognize that this is at odds with the very egalitarian culture in the network, but feel that the risks are small compared to the enormous opportunities to let big science questions, each tested by peer-review, drive the needed expansion to address grand challenges. This same network approach could also tie in NEON sites and other resources. With the maturation of the LTER program, the recent successes in synthesis centers and the emerging observing systems, this may be a great time to create a proposal process which can allow the field to achieve the science behind these even greater aspirations.

We also want to emphasize that the synthesis of cross-site long-term ecological research need not and should not be an obligation of LTER researchers alone, nor an opportunity for them alone. Rather, non-LTER scientists interested in synthesis should have the ability to become active users of LTER data, via excellent web availability of all LTER data, partnerships with the new NSF ecology synthesis center in Annapolis, and synthesis workshops and other activities sponsored by the LTER network office. Scientists and students who come from other disciplines and traditions can be an important source of new ideas and insights for the network going forward.

> **Recommendation 2:** The richness of the long-term observational data gathered across the LTER network makes it uniquely and optimally poised to establish *cross-site experimental studies* of the mechanisms whereby factors such as climate change, nutrient loading, loss of biodiversity, shifts in species composition and food web structure, and invasive species impact ecosystem functioning and species dynamics. Although each site is likely suitable for only a subset of these experiments, the network as a whole would add immeasurably to ecological science by pursuing such coordinated multi-site experimental studies. We recommend that the network plan and actively seek funds for a coordinated program of cross-site experiments and related cross-site observations. To ensure success, the LTER sites should actively recruit a new generation of diverse scholars interested in dedicating their careers to experimental and observational studies at the continental scale.

Reassessing the Role of Social Science. Decade-time-scale science is set in the context of the information and prediction needs of people who themselves interact with the rest of the ecosystem. People are an integral part of every biological system on earth and we can only understand the dynamics of the system when people are included in the research. The importance of integrated natural and social science to address human-environmental interactions has led some LTER scientists and other ecological scientists to embrace the value of collaboration with social scientists. In two LTER sites, the ecosystem is urban – the cities of Phoenix and Baltimore. In urban systems, humans and their structures are dominant features of the ecology, and the dynamics of the human population are an overlay on all other elements of the system. Integrated research including social sciences may even lead to a new program for Urban Long-Term Research Areas (ULTRA) defined by social science research questions. Commendably, many LTER sites have added a social science component to study the dynamic link between humans and the ecosystems those sites study. We support these efforts and the value they have brought to the network.

However, to date, the LTER network has not articulated issues in ways that social scientists view to be of central importance to their disciplines. Relatively few leading social scientists have shown an interest in embracing the social science issues being addressed by the LTER network and proposed within its decadal plan. With rare exceptions, LTER scientists are untrained in the social sciences and unable to perform social science research of sufficient caliber. Thus, the social science questions posed by the LTER decadal plan and the supply of leading social scholars who choose to collaborate with LTERs are too limited at present for such work to be a central focus of the network. Embedded social science as a component of the ecological science questions should continue and expand. However, without a clear tie to central questions in the social sciences and a broader approach for filling the shortage of excellent social science research capability, we do not think LTER-based social science research will be a central value-added component for the network as a whole.

No matter how difficult it may be to achieve high-quality social-science research at LTER sites, we believe that all LTER sites should incorporate appropriate social-science data in their analyses. For example, we are rapidly entering an era in which the best predictor of future water quality in any ecosystem may be upstream changes in land-use laws.

> **Recommendation 3:** Although all LTER sites should incorporate appropriate social-science data into their analyses, we are not convinced that social science research is, in its own right, a central value-added component for the network as a whole, but it may well be so at individual sites. Before undertaking a major network-wide expansion of social science research, the value of such an expansion must be better articulated and demonstrated.

Reassessing the Network Structure

Over the past two decades, the individually-funded LTER projects have grown to be a well-functioning network. This network provides a range of benefits, including facilitation of communication among sites and of cross-site and multi-site research, and has also helped improve the science conducted at each site. By providing venues and vehicles for cross-site synthesis, a body of science that is larger than the capabilities of individual scientists and LTER sites has begun to emerge. We applaud this, and have a variety of suggestions for how LTER can continue to build this capacity.

The LTER Executive Board and the LTER Network Office play important roles in the functioning of the LTER program. The Executive Board, which was established about 6 years ago, sets network-level policy. The LTER Network Office's most critical role is to facilitate collaboration and synthesis and to support data sharing within the network and data availability to all researchers from outside the network for whom LTER might be useful. Although the LTER Executive Board has streamlined network-level decision-making, we do see that the LTER network still suffers a perhaps unavoidable tension between bottom-up and top-down control. Decision-making in LTER has long been dominated by a bottom-up approach that is very egalitarian and encourages creative within-site research. However, this approach may have compromised the ability of the network to adopt and enforce network-wide policies. We see a

need for a greater centralized scientific leadership, empowered by the PIs, but that retains the dedicated involvement of site scientists. Organizational democracy principles may have great relevance here in helping this group find a path towards an empowered leadership team that fosters scientific creativity throughout the network.

The committee believes that this is a crucial time for the LTER network. It must make important decisions if it is to capitalize on a range of new opportunities and challenges. The emergence of the observing systems provides a new, parallel channel for conducting long-term, continental scale research. NEON is most relevant to the future of LTER, due to their common focus on ecological questions and overlapping science communities. However, other initiatives including the Ocean Observatories Initiative, ULTRA, EarthScope and non-NSF ecological networks like the Smithsonian Center for Tropical Forest Research (which now includes temperate sites), offer exciting opportunities for synergies as well. LTER is already connected to many of these initiatives. The challenge is whether to lead and, if that is the choice, how to do so most effectively.

The choice to engage in the science behind major environmental challenges brings both opportunities and requirements for partnership and collaboration. The LTER network will find itself rubbing elbows with a whole range of other networks and significant communities of scholars, professionals, and stakeholders. Other fields, like limnology, oceanography, climate science, agriculture and economics will have parallel networks that provide critical information and understanding. The stakeholders and decision-makers are themselves organized at a variety of levels, from local to global. If the LTER network wants to both lead the science and lead the use of that science in policy and business, its scientists must develop a new capacity for leadership and organize themselves to take advantage of it. At the very least, they must be key partners in this collection of networks and learn to play synthetic and constructive roles. Isolation within disciplines will no longer be sufficient. Conversely, through leadership, the LTER network can build an even stronger case for the value of its science, for the level of funding that it deserves, and for the role of NSF in helping make positive and concrete contributions to society.

At a more practical level, the emergence of observing system networks and other scientific communities in conservation, sustainability, long-term research and earth system science all require a sea change in the level of collaboration in the network. NEON is the most immediate challenge. This continental-scale observing system provides a unique backbone on which long-term, large-scale ecological research can and will be conducted. It is designed around the needs of a modest number of large science questions with significant overlap and input from a subset of the members of the LTER network. In this overlap, there are considerable existing synergies between some LTER sites and some parts of the NEON network. Some discrete and potentially simple steps could go a long way towards allowing these two entities to have the greatest cross-fertilization and value. Annual over-flights of each NEON site are part of its overall plan and as many as half of the LTER sites will be included because of their spatial co-location with NEON sites. Expanding this single activity to the rest of the LTER sites in the continental US would mean that synthesis activities that employ those data could easily be extended by scientists in either network to draw data from both and extrapolate more broadly in time and space. LTER scientists are now collecting social science data through access to land-use and spending datasets

that are sometimes national in scope. Here too, a simple extension of the geographic range of the analysis could provide NEON scientists the opportunity to gain the same kinds of human-nature interaction insights that have become a valuable part of LTER.

Going further, once created, the NEON sites will be logical locations for many additional kinds of research, made stronger by the great diversity of other measurements that will be routinely collected. LTER scientists have developed one of the strongest academic traditions for how to actually do that kind of science and manage that kind of interdisciplinary knowledge enterprise. We believe that LTER scientists and their students should rise to this challenge and, at a greater level than currently envisioned, grasp this opportunity to use the NEON network for many kinds of research pioneered in the LTER network. In addition, there are great opportunities to take the time-series synthesis skills of LTER scientists and lead the synthesis that will become possible with a combination of LTER and NEON data. While there is already some joint leadership between the two programs, there is also tension at both the network level and among many of the PIs. Much of this was initially created by the opposite worry about the undue influence of LTER on NEON in its formative stages. Those times are past. This opportunity is too great and the benefits to science and to NSF from the synergies are too profound to miss. LTER scientists and NSF must both push strongly for a tighter integration and collaboration between the two groups.

Beyond NEON, we are entering a golden age of scientific observing systems in NSF and elsewhere. Earthscope and the Ocean Observatories Initiative are being built. Other networks of observing systems for water and the urban environment are being contemplated or designed. The ocean time-series studies from the old Joint Global Ocean Flux Study are many decades old and continue to be a source of new knowledge about the dynamics of the open ocean. Beyond NSF, there are the ongoing NASA satellite platforms that have datasets that now extend for decades. The long-term tropical forest studies started by Steve Hubbell through the Smithsonian in Panama now encompass dozens of sites around the world. There are even many observational platforms that were never designed for science that provide critical data on the same time-scales through measurements of streams, farms, finances, real estate and other data critical to the kids of questions that LTER envisions.

One way to address the shortage of social science expertise within the LTER network is to reach out to environmental social science organizations, such as the American Anthropological Association Section on Anthropology and the Environment, the American Sociological Association Section on Environment and Technology, and the Association of Environmental and Resource Economists, in order to frame joint research initiatives. Doing so is one method, among others, to increase collaboration between the social science and LTER research communities.

The network must create and manage its own future, particularly if it chooses to explore some of these approaches to grand challenges. Leadership will be critical. The network must find within itself and bring in from outside of the network the kinds of people who understand and value the visionary steps that the network chooses to develop. The network may change in its inter-personal character through this evolution from somewhat passive to very pro-active, and the leaders that it chooses must be selected specifically to drive and manage this change. At its heart, this will be a set of personal choices by PIs and by the network leadership. Both the

network and NSF must have a strong sensitivity to this kind of change to retain the strengths of the existing community while still provisioning it for future success.

> **Recommendation 4**: As the goals and spread of long-term science continue to broaden, it is becoming critical to think beyond networked LTER sites, towards networks of networks (including but not restricted to an LTER-NEON network). The LTER network is uniquely poised to seek a leadership role in achieving this goal, and should articulate a concrete vision statement about its leadership opportunities. To ensure success, the LTER program should actively recruit a new generation of diverse scholars pursuing experimental and observational studies at the continental scale.

Reassessing LTER Data Management Practices

The LTER network began with all aspects of data management being solely a site responsibility. Although data acquisition, quality assurance, quality control, extensive metadata, local accessibility and archiving must remain site responsibilities, we commend the network office for recognizing the critical importance of and initiating a network-wide data management system focused on data sharing, exchange, synthesis and preservation. We strongly support the concept that individuals within and outside of the LTER network should be able to access all LTER data easily from a single web site managed by the network office and then straightforwardly compare and synthesize data from numerous sites. The long-term data sets gathered across the network are highly valuable, but this value will be maximized only if all data, from all sites, become comparable, available, locatable, accessible, understandable, usable and full archived and preserved.

The individual data managers at each site provide essential services to the teams of investigators at each site and use data systems that are appropriate to the science questions. The task faced by site data managers is immense. Data gathered on-site by 50 or more investigators, post-docs, graduate students, research interns and technicians must be processed and verified to assure data quality, and then assembled into data sets and data retrieval systems that facilitate site-based research. However, as recognized by the network office, the higher-level network-wide data system that it is developing is also of critical importance to the future of the LTER network. While progress has been made at the network level through recent increases in funding, this transition must be greatly accelerated if science and society are to receive the full benefits of LTER research. Current approaches are not yet adequate.

If LTER is to enable the study of phenomena that occur on a time scale longer than individual research careers, then a substantially greater effort must be made towards developing the information infrastructure necessary to make data sets useful to "third-party scientists" — that is, scientists who had no part in creating the data sets. Furthermore, LTER data must be managed and made available in a manner consistent and interoperable with current and emerging trends in other biological fields. Since technology changes rapidly, the committee believes that LTER data-management will require significant attention and oversight so long as the LTER program is funded. This attention and oversight must occur in the context of a rapidly and continuously changing environment, both in technology and in scientific needs and expectations.

There are two particular data issues that came to the committee's attention during our review. First, it is critical that data are archived and made available from any sites no longer receiving LTER support. It is our impression that data may have been lost when LTER sites are no longer funded. This indicates that merely making data available through each LTER site's own web site is not adequate. LTER sites must annually share data sets by publishing them, in their entirety and with appropriate metadata, with the network office and/or some other permanent repository. NSF must ensure that such repositories are indeed securely and sufficiently backed-up and permanent, since the information they contain is irreplaceable.

Second, the idiosyncratic nature of the data system of each LTER site means that assembling network-wide data sets with which to address a synthesis question can be extraordinarily difficult. For instance, we discovered that it is virtually impossible to search for and locate existing LTER data by the dates when the data were collected (though the full set of dates are available). For a program that is focused on the temporal domain (i.e., long-term), the inability to easily retrieve data by date is a significant problem. More importantly, there are many data sets that cannot be located through the network office's web site, yet are available from individual LTER sites. In addition, the sites differ significantly in their presentation of available data sets. The committee strongly recommends that network-wide data management be used to assure comparability, that network-wide data management become a central responsibility of the network office, and that all sites fully support this new network-wide task.

Because information technology is so dynamic, it is impossible for the 30-year committee to make detailed, specific data-management recommendations for coming decades. Instead, the committee recommends that NSF, LTER, and the wider ecological community engage in an on-going discussion of how to improve LTER network-wide data management.[1]

The committee notes that substantial improvements to LTER data management have been achieved in the last ten years and that the network office has recently been given supplemental ARRA funding to improve further its data-management services. Many of the LNO's planned innovations are intended to address these issues. As this is still a work in progress, however, the review committee cannot determine how successful this effort will be. We do note that NSF should monitor these activities carefully and should be prepared to take steps to maximize the likelihood of a successful outcome.

We also note that the problems we have detected in long-term, third-party data availability seem to have occurred for lack of resources, rather than for lack of effort. Within a fixed budget, increasing support for future, third-party science means decreasing resources available for other activities. Deciding to forego some activities to invest more heavily in others is a tough decision

[1] A member of the 30-year committee, Robert Robbins, has prepared a position paper, *"Data Management for LTER: 1980 – 2010,"* intended to stimulate discussion. This position paper is not submitted as part of the 30-year review, because it is a personal position paper, not a consensus committee report. The committee is making his paper available because in-depth discussion of these issues is needed and his paper may provide a useful stimulus for such discussion.

and not one to be taken lightly. However, if support for future third-party science is declared a formal part of the LTER mission, then enough resources must be allocated to make it possible.

> **Recommendation 5**: Data management at each LTER site is adequate to excellent in its support of the current science questions at sites, but the LTER network as a whole must invest in making LTER data comparable across sites and more readily available to those interested in network-wide analyses. This problem can be remedied by either new resources for the network office or by re-directing some existing network office funding towards providing current and future scientists easy access to all LTER data from all sites. In particular, (a) the LTER Network Office must markedly expand its current data activities into a fully functional data management system that serves and archives all LTER data and metadata from all sites in a consistent and easily used manner to third-party users; and (b) each LTER site must fully support this LNO mission by publishing all data sets, in their entirety and with appropriate metadata, in a standard format with the network office and/or some other permanent repository in a timely manner.

Extending the Network Reach

The committee concurs with the NSF Advisory Committee for Environmental Research and Education on the importance of promoting "new and participatory approaches to environmental education and public engagement through formal and informal venues" and on the need to "help policy-makers develop a better understanding of complex environmental systems" (Transitions and Tipping Points in Complex Environmental Systems). These efforts are critical in the 21st century because American society is confronting problems that can only be addressed using environmental science. At the present time, though, the science of climate change is poorly known, the threat of invasive species is widely ignored, and fundamental biological processes, such as evolution, are misunderstood. Policy makers and managers need solid information on which they can base decisions and promote management strategies, and teachers need help in devising hands-on activities that help learners of all ages understand how science is done and how science can solve problems. However, scientific information alone is usually not sufficient for building a meaningful educational program or for designing and executing a management plan that is satisfactory to a variety of stakeholders. Social scientists, communicators, and citizen-advocates are often necessary to formulate and broadcast important messages and strategies. Citizen scientists who participate in LTER research are well poised to learn more about how science is conducted and to help LTER scientists establish additional contacts in local and regional communities. These participatory approaches can provide important opportunities to increase diversity in the field as well as help build ecosystem literacy in a diverse society.

Encouraging Outreach through Science Educators. Schoolyard projects and other K-12 education efforts are being carried out at all LTER sites. Just as the success of collaboration with a social scientist depends a lot on serendipity, i.e., finding the right person and the right focus, so do the education efforts. Many talented individuals have created effective and imaginative

programs throughout the LTER network. Frequent meetings among the people involved in education, along with regular attendance at all-scientist meetings, are necessary to spread good concepts and spotlight new ideas. Additional support should be actively sought to encourage communication and coordination among LTER science educators and to get effective ideas into the science education literature for use by teachers distant from LTER sites.

Encouraging Participation. Every young person visiting an LTER site or participating in an LTER education program should perceive that he or she can be a scientist too, regardless of gender or ethnicity. Nothing says this better than diversity in the LTER work force. Diversity considerations should permeate every hiring decision on an LTER site, including the development of special programs for neighbor minority groups such as Native Americans and enclaves of second-generation immigrants, such as Vietnamese and Micronesians. Summer internships are a good mechanism for introducing minority students; even if interns do not go on to become scientists, they are likely to become educated and concerned citizens. The committee was encouraged by efforts to increase diversity at the sites visited, and we encourage LTER scientists to make sure that outreach continues to be a priority as new scientists and support personnel are hired into a project. The LNO may be able to play a centralized role in attracting minority students with local experience and assigning them to REU sites elsewhere in the country.

Communicating Research Results to Policy Makers and Managers. Every LTER site has a mechanism for extending its research results and their implications to the broader public, and it is probably not realistic to try to coordinate or standardize efforts across sites. Nevertheless, bringing relevant information to managers, policy makers, and the general public is so critical to our society, that coordination with professional communicators should be mandatory. LTER sites can often partner with state and federal agencies to coordinate outreach programs with related messages. Regional Sea Grant offices, for instance, may have an effective communication system that could easily absorb research results from nearby LTER projects. Extension programs in land grant institutions may be able to assist similarly with inland projects. We urge that opportunities to engage with managers, social scientists, and others not directly involved in ecological research in order to extend the process and results of ecosystem research to a larger public be given special resources. Finding and collaborating with non-traditional colleagues require some serendipity, so we feel the details cannot be mandated, and we do not have an associated recommendation. However, sizable "carrots" to foster such interactions should be available in both ecological and social science offerings in the NSF. Perhaps interagency cooperation with USDA NIFA grant opportunities in the Environment and Natural Resources emphasis area could also be developed to address management issues.

Recommendation 6: Citizen science shows increasing promise as an outreach and educational tool to local communities and to audiences with a diversity that reflects the nation. Some LTER sites are encouraging this, among their other educational activities. These efforts should continue and be initiated at other sites. Their success is partially predicated on increasing the diversity of scientists, staff

and students at each site as role models to the citizen scientists and each site must enhance its efforts in this area.

Recommendation 7: Cross-site education programs should be a higher priority for funding and effort, both through the spread of the better program models and for education activities that truly leverage the network as a whole. The few cross-site educational programs that have been offered to date have been very promising but funding has been minimal. It is critical to identify funding mechanisms for cross-site education both within and beyond NSF. Such programs should emphasize participation by diverse students and stakeholders.

Looking Forward: Resource Issues

We conclude with a few thoughts on resources. First, we feel that the existing network is of incredible value and represents one of the highest scientific values for the science dollar. In that regard, we feel that modest funding increases should be the minimum trajectory moving forward. Within that context, the continued periodic review process and the ability to add and terminate sites according to the review process is fully appropriate. However, there are a few areas where, even within the existing funding levels, we recommend some changes in emphasis that likely require redistribution of funds. The network office must place more effort on making all network data public and available, even if this could only be achieved at the expense of curtailing other network office activities. In addition, the diversity outcomes are not uniformly adequate and programs that are lacking must prioritize some funding towards new efforts or adopt models from more successful sites. Neither of these re-distributes the bulk of the funding, but some of these choices have to be made and enforced by the network and the NSF.

Second, if new resources for long-term ecological science become available, we recommend that NSF look at a cross-network proposal process that addresses big questions rather than just a simple expansion of the network. Having an open competition for proposals on big ideas that use both the LTER and NEON networks, as well as resources beyond the networks, is likely to result in the best new science for the investment. Such a competition would leverage the enormous capacity of these communities and infrastructure, but be firmly focused on big questions vetted through peer-review. The questions themselves must come from the community rather than through a massive central planning exercise. In this way, excellent "big science" can be done as reasonable "marginal costs" on these two great investments. Further, since many of the big questions are of significant societal concern, they can heighten the value of LTER science to society, particularly when combined with the outreach, stakeholder involvement and citizen science that some LTER sites have pioneered so well.

Third, the network is primed to develop additional resources beyond NSF. LTER sites have a great track record for finding additional resources, both by attracting other investigators with their own NSF funding or by finding funding and investigators from other agencies. The network should expand this effort, encouraging PIs to learn from each other the approaches that have led to success. The network can develop business models for gaining infrastructure funding from new groups that use LTER infrastructure and undertake cooperative research. LTER

scientists can look to the value they provide to stakeholders and develop resources from these sources. As the LTER research meets society's needs, LTER scientists can engage the development offices at their institutions to find private and corporate support. Every site has some mix of these approaches and, together, they could learn how to be even more effective in the approaches that they have yet to try.

> **Recommendation 8:** Resources are a key limiting factor for the future of the network. The network should: 1) make realistic prioritizations within the existing resource base to create more science per dollar, and 2) engage with NSF and others to pro-actively develop new resources. Prioritizations will include spending more on data and diversity. The case for new resources could be built around a new level of excellent science that addresses the big science questions that underpin society's grand challenges. In all cases, the best practices and tools for developing new resources could be shared across the network to improve the effectiveness of each site.

APPENDIX 1

The members of the LTER 30 Year Review Committee were:

Judith Bronstein
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Robert J. Robbins
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APPENDIX 2

Charge: 30 Year Review of the LTER Program

The committee is charged with providing a review of the Long-term Ecological Research program at its 30-year mark. This review is intended to be prospective, rather than retrospective, articulating a strategic vision that will strengthen the core science agenda for the LTER network over the coming decade. The committee should review the program broadly, not the individual sites and their accomplishments.

The recent Integrative Science for Society and Environment (ISSE) report provides a research plan for the inclusion of more rigorous social sciences in the LTER program. We ask the committee to consider how the LTER program should respond to future challenges and needs in ecology, ecosystem science, and environmental biology as well as to the integration of social and environmental science and to education.

Questions to direct the evaluation include but are not limited to the following:

1. What are the key elements of a strategic plan for LTER over the next decade? In particular, what new conceptual areas could or should the program address?

    Issues that might be addressed include the balance of disciplinary and interdisciplinary research; the balance among site types (e.g. urban, agricultural, rural); the scope and role of international LTER investments by the U.S.; other models for long-term research; and limitations of the present network in addressing important research questions.

2. What can a network of long-term study sites accomplish that cannot be accomplished through other funding mechanisms? That is, what unique research contributions can LTER provide?

    Issues might include the value of research funding at a site for more than 30 years; the important questions that have emerged as a result of three decades of data collection; and how a long-term research program can be structured to respond dynamically to complex environmental changes.

3. What role should LTER play in data synthesis, management and analysis, particularly with respect to NSF investments (Table 1)? How should LTER interface with these other investments?

    Issues might include long-lived data access and interoperability; the types of questions that NEON and other observatories will allow LTER to address; and LTER cyberinfrastructure considerations.

Table 1. Current NSF investments in research platforms and synthesis activities.

LTER -	http://www.lternet.edu
NEON -	http://www.neoninc.org
GLEON -	http://www.gleonrcn.org/index.php?pr=Home_Page
ULTRA -	http://www.nsf.gov/pubs/2009/nsf09551/nsf09551.htm
GEOBON -	http://www.earthobservations.org/geobon.shtml
ILTER -	http://www.ilternet.edu/
CZO -	http://www.nsf.gov/pubs/2006/nsf06588/nsf06588.htm

http://www.czen.org/
NESCENT - http://www.nescent.org/index.php
NCEAS - http://www.nceas.ucsb.edu/
NIMBIOS - http://www.nimbios.org/

4. What processes should be considered to determine optimal resource allocation for the LTER? In particular, what criteria should be used to prioritize new investments and shift existing resources?

> Issues might include optimizing coordination among sites (including the role of the LTER Network Office); the relative importance of site-based versus cross-site research; and the tradeoff between continuing existing sites versus establishing new sites.

We thank you in advance for the time and energy you will spend on this important review. Just as you are reviewing the LTER program and will provide us with a vision and guidance toward the future, we are also examining how LTER is managed within NSF, including the efficiency and appropriateness of our funding models. This is an important time for programs such as LTER as we move toward greater integration across the Foundation as well as increased cooperation among funding and governmental agencies nationally. We very much anticipate your forward-looking advice on and insights into the LTER program.