TEN-YEAR REVIEW OF THE NATIONAL SCIENCE FOUNDATION'S LONG-TERM ECOLOGICAL RESEARCH PROGRAM

EXECUTIVE SUMMARY

In 1980, the National Science Foundation began the Long-Term Ecological Research (LTER) program with a budget of $1.2 million and five sites selected on the basis of competitive proposals. Subsequently, the LTER program has grown to $11 million and eighteen sites located throughout North America and Antarctica, now involving more than 200 research scientists and about 300 technical personnel and students. The goals of the LTER program are: (1) long-term analysis of site-specific ecological phenomena; (2) comparison of observations across diverse ecosystems and in terms of general systems theory; and (3) provision of large, secure, ecologically diverse sites with well developed support capabilities.

Each participating LTER research site is expected to address five core research topics:

- pattern and control of primary production;
- spatial and temporal distribution of populations selected to represent trophic structure;
- pattern and control of organic matter accumulation in surface layers and sediment;
- pattern of inorganic inputs and movements of nutrients through soils, groundwater, and surface waters; and
- pattern and frequency of disturbance to the research site.

The NSF Biological Sciences Directorate constituted the Ten-Year LTER Review Committee and charged it with appraising the ten-year performance of the LTER program, including activities at the sites and of the entire network. In addition, the Committee was requested to identify those aspects of the current system that could benefit from change and to provide recommendations for the future of the LTER program.

During the ten-year period in which the program has been fully operational, scientists involved in the LTER program have produced a distinguished and extensive literature describing important ecological processes and numerous ecological characteristics from the sites. These long-term research programs have documented the status and trends of key environmental conditions from the eighteen sites. In addition, the LTER program has established interactions with and provided guidance to related programs in several foreign countries. In many instances, research from the LTER program has been instrumental in guiding policies and providing a scientifically credible basis for prudent management decisions about natural resources. For example, a significant portion of the information used to establish the U.S. Forest Service's "New Perspectives in Forestry" originated from studies at three LTER sites: H. J. Andrews Experimental Forest, Coweeta Hydrological Laboratory, and Hubbard Brook Experimental Forest. Similarly, the current re-orientation of most of the federal agencies toward a more comprehensive "ecosystem management" approach is built upon many studies from the LTER sites and program.

Evaluation of the Existing LTER Program

Despite the unquestionable success of the LTER program, there are several issues that need attention if

the program is to improve. For example, the program definition as provided by the NSF Calls for Proposals has purposefully remained flexible to permit as much scientific latitude as possible on the part of the investigators proposing LTER studies. This intentional flexibility has led to some ambiguity in the relative importance of site-specific long-term studies, cross-site comparisons, and furthering ecosystem theory through in-depth studies.

A unique strength of the LTER program is that it specifically studies phenomena that occur over longer time periods, and the funding and research support are designed to recognize these long-term dynamics. At intervals of six years, each site is required to submit a proposal to continue the program. These proposals are expected to have new ideas, but the site is then faced with the need to continue the initial studies while also beginning new ones. The current level of funding is inadequate to meet both continuing and new needs of the research programs at the LTER sites. Thus, there is an obvious and serious discrepancy between the current expectations of the LTER sites and actual funding levels (about $500,000 per site per year). An LTER site is expected to develop an infrastructure for promoting, conducting, and preserving research in all five core areas while also conducting innovative work focusing on current theories and problems in ecology. The expectations of each site increase incrementally as the accumulation of required research increases, as more demands are made on the site from other investigators who want to use the data or work on the site, and as the results of the LTER program become more widely known and receive increased attention and demand. Over the duration of the program, funding has increased, but not at the rate of the increasing demands on the science in the LTER program.

The power of the network approach of the LTER program rests in the ability to compare similar processes (e.g., primary production or decomposition of organic matter) under different ecological conditions. As a result, LTER scientists should be able to understand how fundamental ecological processes operate at different rates and in different ways under different environmental conditions. Some intersite comparisons have been conducted, but the power of the network of coordinated research sites has not yet been fully realized. In addition, the criteria that have been used to select the sites that participate in the program have not uniformly included specific expectations for developing a comprehensive, representative network of sites. Some important ecosystem types are not represented in the current constellation of sites, for example, urban, Great Basin, southern swamps and wetlands, large rivers, and additional marine systems.

The five core research topics were designed to provide guidelines to ensure that sites are selected for broad-based ecological research rather then narrowly focused studies. However, these core areas are defined so broadly that they do not provide significant operational assistance in site selection or evaluation. Moreover, because of the LTER organizational structure within NSF, the research interests of the LTER investigators, and the nature of the core areas themselves, there is some perception of a bias toward ecosystem-level research.

The present LTER review process has been fair. The reliance on peer reviewers for site proposals has ensured that the primary criterion for selection and renewal has been the quality of the science. However, because many reviewers of proposals are accustomed to evaluating hypothesis-driven, single-investigator proposals, some of them have tended to emphasize short-term rather than longer-term and transdisciplinary strengths of LTER proposals. Further, some reviewers tend to focus on individual site achievements rather than on contributions sites make to the overall LTER network.

Suggested Modification to the Current LTER Program

The current LTER program has been highly successful in terms of both research output and provision of a structure for long-term ecosystem research in the United States. The current level of high-quality research has been achieved by involving excellent scientists and rigorous review of individual proposals and by subsequent periodic review of all components of the LTER program. This same level of high expectations must continue, and the current safeguards must remain in place.

Several steps will improve the LTER program in the future. First, on the basis of the experience gained

over the past ten years, the goals should be restated: the goals of the LTER program should be to conduct long-term, continuous measurements and analyses of ecological patterns and processes at specific sites, to integrate and synthesize results both within those sites and among sites, and to seek ways to generalize these results over broader spatial scales.

The five core research topics should not be used as organizing principles per se; rather, the original objective of ensuring breadth, continuity of measurements, and comparability should be accomplished but in a fashion which overcomes the problems with the core areas. Specifically, each site should investigate and document key selected ecological patterns and processes that determine the spatial and temporal ecological characteristics and behavior of the particular ecological systems under study. Moreover, at each LTER site there must be a defined core of site-appropriate observations and measurements that are consistently taken for the duration of the project. All measurements and samples should be collected and analyzed in a manner to be as standardized and comparable as possible with other LTER sites.

The LTER program has focused primarily at the ecosystem level of ecological organization. Because long-term ecological research is also needed at other levels (e.g., population, community, landscape, global), and because understanding of ecological patterns and processes at one level is vastly enhanced by studies at adjacent levels, LTER sites should include more research at these other levels of ecological organization.

The LTER program has developed from an initial constellation of sites, joined only by a common interest in long-term ecological phenomena. More recently, the program has begun to take advantage of the network dimension and to develop and institute comparative intersite studies. Integration and cross-site studies should be question-driven, encouraged, and facilitated within the LTER program.

The LTER program has not been effective in communicating its strengths. Much of the attention of the program seems to have been devoted to site-specific studies, and relatively little effort has been directed toward the future of a powerful set of integrated research sites. As the program continues to mature, more programmatic attention must be applied to developing an ever-expanding vision of the value of the integrated LTER program and to communicating the successes of the program to a wide scientific and non-scientific audience.

The governance of the LTER program needs to evolve as the program develops and matures. The organizational structure needs to disperse the governance process more widely throughout the program, and the Coordinating Committee (which includes the Principal Investigator from each site and the Network Office), through its Executive Committee, must take additional responsibilities. Also, external advisory groups should be established for the LTER program as well as for NSF as it continues to support the program. These changes will facilitate strategic planning and broader participation in decision-making.

Although the NSF review process has been fair, several steps can be taken to improve the review of initial proposals and of proposals produced by continuing sites. These improvements include clarification for the reviewers of the expectations of the LTER program and some consistency of reviewers over the duration of the project.

Recommended Development of the Long-Term Ecological Research Network (LTER): The New Generation Long-Term Ecological Research Network

In the past few years, it has become abundantly clear that managing the earth's resources is not only important but complex. Complications arise for several reasons: economic demands on both renewable and non-renewable resources often damage the long-term productivity necessary to support both the regeneration of renewable resources and the ecological services upon which all life depends; there are

frequently competing demands for the natural resources located on parcels of land; and retaining important natural resources and ecological processes may constrain short-term economic development. These issues are important because: this generation needs to consider the consequences of its actions on the next generation; local actions may affect regional and global processes and vice versa; and management decisions about natural resources affect the political and economic stability of societies.

Decisions concerning the management of natural resources will always be made in the political arena, usually based on the values expressed by many constituencies. These decisions will represent judgments by decision-makers who consider as much evidence as possible. In the past, many such decisions have been made without adequate information about the consequences of the actions as they relate to the near-term and long-term availability and quality of natural resources and vital ecological processes. Frequently, these decisions have resulted in the loss of resources or in the need for expensive recovery actions. Thus, the challenge is to provide the best possible information so that decisions can be based on the most accurate predictions of the consequence of any action.

The most useful information about natural resources for a decision-maker will have

several characteristics:

a. the data will be of sufficient duration that it will be possible to distinguish short-term variations from long-term trends;

b. the data will have been collected over enough different environmental conditions so that researchers and decisionmakers can determine the range of conditions under which the results can be meaningfully extrapolated and applied;

c. the data must measure the important considerations from all the relevant points of view, e.g., physical and biological features, social and economic characteristics; and

d. there must be an understanding of the accuracy or certainty of the data, and the decision-makers must know the extent of the data's credibility within the scientific community.

Any program designed to provide this information must be based on a stable framework so there is both a continuity to the data collections and a convenient methodology for translating the data to the decision-maker in a manner that is most useful.

Currently there is no environmental research program that meets all of these needs. However, the LTER program contains many of the essential elements, particularly a structure for providing long-term measurements, continuity, and an organized framework for collecting, archiving, and making information available.

The LTER program could easily continue its present trajectory as exemplary research, involving excellent scientists who conduct research on important long-term ecological phenomena and questions. In so doing, the program would continue to contribute in very significant ways to the nation's environmental research effort. However, this review has convinced the committee that there is a far broader and more important role for an LTER program. In fact, as just described, many of the challenges of designing and operating a sustainable biosphere can be most effectively and economically confronted with a newly defined LTER program. The present LTER program thus contains the nucleus of a vitally important national effort.

The current constellation of LTER sites and individual research programs can and should be expanded and molded into an operational network including a wider range of ecological organizational levels; a more complete suite of scientific disciplines; research programs designed to address directly topics that are important for the formulation of policies and practices leading to sustainable ecological systems; the

development of technologies to mitigate the adverse environmental effects of human activities; and support for broader ecological education. This new program, building on the strengths of the current LTER program, would involve an expanded and much more integrated network of sites, called the Long-Term Ecological Research Network (LTERN). The ultimate success of the LTERN will, of course, depend on the broad success of the nation's ecological and environmental research program and, therefore, should be developed in concert with related efforts.

Primary goals for this research program are, therefore, to address effectively the long-term ecological, scientific questions of today; to develop an integrated ecological research program that can serve the nation's need to make defensible environmental decisions and policies; and to implement practices leading to a sustainable biosphere. To achieve these goals, the LTERN must accomplish the following:

- Make long-term ecological measurements in order to help understand the dynamics of ecological systems, provide a baseline against which to measure environmental changes, and evaluate and mitigate the adverse impacts of human activities.
- Enhance the spatial dimension of the program so that it will be possible to determine the conditions under which lessons learned in one location can be applied to other locations.
- Expand the network of sites to represent additional important ecosystems that are absent from the existing program.
- Increase the scope of the research program to include a primary emphasis on various levels of biological organization (e.g., genetic to landscape levels) since research has conclusively demonstrated that multiple levels of investigation are required to understand key ecological processes.
- Expand the range of scientific disciplines to include the physical sciences and the social sciences, since understanding ecological phenomena requires the integration of these disciplines and because practical solutions to environmental problems can only be developed and implemented by involving these additional disciplines.
- Institute programs to develop new technologies for measuring and understanding the environment and, as appropriate, for testing the environmental impacts of new technologies.
- Contribute to the nation's educational effort at all levels, particularly by providing educational opportunities and materials directed toward multidisciplinary, field oriented, and problem-solving education and training.

To meet these needs, the committee recommends that the new LTERN include a broader representation of key types of ecological systems by expanding the number of primary sites to no more than double the current number. Spatial resolution of the network should be increased by adding satellite sites to the primary LTERN sites and by taking advantage of the broad range of shorter-term ecological research sites supported by NSF and other agencies. Research programs should be directed specifically toward providing increased understanding of ecological systems, particularly long-term processes, and also toward using that understanding to provide answers to questions of resource management and environmental protection. The LTERN research program must include a broader range of scientific disciplines, and the biological component must involve all levels of organization. Special emphasis must be placed on technologies, both for developing new techniques for measuring environmental processes and for testing the impact of new technologies in a variety of environmental conditions. Moreover, the LTERN program must have formalized ties to the nation's decisionmaking processes and to its educational programs.

To meet these new challenges, the LTERN annual budget must increase by an order of magnitude. This budget must include funds for research and management of the primary and satellite LTERN sites, for intersite coordinated studies, for studies conducted by other scientists on problems and ideas that are related to the LTERN, for conducting collaborative research with other agencies and organizations, and for increasing the network and communication activities of the program.

This new budget represents a significant investment, especially in these times of fiscal constraint. However, this investment will be repaid many times over as the LTERN provides sound scientific information for policy and management decisions that protect our natural resources and that prevent

environmental damage requiring enormously expensive steps to clean up and restore. The LTERN, as described in this report, presents an opportunity for the National Science Foundation, in concert with the scientific community, to meet the sizable and continuing challenge of producing sufficient ecological understanding for sustaining human societies and for providing responsible stewardship of the biosphere.

TEN-YEAR REVIEW OF THE NATIONAL SCIENCE FOUNDATION'S

LONG-TERM ECOLOGICAL RESEARCH PROGRAM

THE REVIEW COMMITTEE

The Long-Term Ecological Research (LTER) program, created in 1980 by the National Science Foundation (NSF) with five initial sites, currently consists of a network of eighteen sites (Appendix A) located across North America and in Antarctica. In 1993, the Biological Sciences Directorate of NSF appointed a ten-member committee (Appendix B) to evaluate the LTER program over the ten-year period of its existence. The committee was charged with appraising the past performance of the LTER program, including activities both at the sites and of the entire network. In addition, the committee was requested to identify those aspects of the current system that need to change as the LTER program continues to evolve and to provide recommendations for the future of the LTER program.

THE REVIEW PROCESS

The committee sought information, ideas, and suggestions from a wide variety of sources in evaluating the past performance, current status, and future directions of the LTER program. At the first meeting of the committee, which took place in Washington, D. C., on February 3-4,1993, a questionnaire (Appendix C) was developed to enable each LTER site, and the Network Office, to respond to several key questions. To enrich the views available for evaluation, the committee requested that many participants at each site and the Network Office assist in completing these questionnaires. Individual questions were designed to solicit information and opinions in four broad areas: (1) the effectiveness of the current program for implementing LTER objectives, (2) products and outcomes of the program in terms of scientific insights and impacts on society, (3) future directions the LTER program should take, and (4) any other information the sites chose to include that was not addressed specifically in the questionnaire.

During the review process, committee members discussed the LTER programs with members of the scientific community. Also, to ensure that the program was well understood by the committee, each member was asked to become especially knowledgeable about particular LTER sites by reviewing NSF-provided materials and by visiting the sites if necessary. Representatives from each site and the Network Office were then invited to attend the second meeting held March 16-18, 1993, at Miami University in Oxford, Ohio.

As a major part of the agenda for the meeting in March, each site representative was

asked to make a brief presentation responding to the following three questions:

1. What are the most important accomplishments from your site?

2. What have been the most serious constraints to your program?

3. What are the most important future directions for your site?

In addition, several panel discussions were conducted which focused on the present status and future directions for the LTER program and on the relationship of the LTER program and its research to societal issues such as biodiversity, global change, and sustainable ecological systems. Dr. James Edwards represented the National Science Foundation and participated during the second half of the meeting.

THE REVIEW COMMITTEE REPORT

In its evaluation of the LTER program, the review committee incorporated information provided by discussions with members of the scientific community, visits to selected LTER sites, literature relating to the LTER program (Appendix D), the questionnaires (Appendix C), and the ideas presented during the March meeting. The following report considers issues at the site and network levels from three interrelated standpoints. Part one focuses on the past performance, successes, and shortcomings of the current LTER program; part two suggests short-term steps that might be taken to improve the LTER program given that it continues to operate with some increase in the level of funding and size in the future; and part three provides recommendations for a more ambitious network of sites which builds on current LTER strengths but also capitalizes on new and emerging technologies and expanded research opportunities and national needs.

Evaluation of the Existing Long-Term Ecological Research

(LTER) Program

The LTER Concept

The Long-Term Ecological Research (LTER) program sponsored by the National Science Foundation has been remarkably successful. From its beginning with just five sites in 1980, the program has grown to include eighteen sites (over the course of the program, two sites have been discontinued) representing a broad array of ecosystems and research emphases. The current network includes participation of more than 200 research scientists and about 300 technical personnel and students.

The mission of the LTER program is to conduct and nurture ecological research by:

- · understanding general ecological phenomena which occur over time periods of a few to many years and over a broad range of spatial scales;
- · creating a legacy of well-designed and documented long-term experiments and observations for use by future generations;
- · conducting major synthesis and theoretical studies; and
- · providing information for the identification and solution of societal problems.

The LTER Network Office, located at the University of Washington in Seattle, has the

responsibility for:

- facilitating communication and data sharing among the LTER sites and between the LTER program and other scientific communities;
- supporting the planning and conduct of collaborative research efforts, including provision of some technical support services;
- leading some intersite scientific activities;
- providing a focal point and collective representation of the LTER program in its external relationships; and
- developing linkages with other relevant long-term research programs, site networks, and science and technology centers.

The Network Office provides direct access to electronic mail on all major networks, online data bases, information bulletin boards, and Internet. An annual personnel directory, a site directory, and a semiannual newsletter as well as specialized reports are also published by the Network Office. The LTER Remote Sensing and GIS Laboratory assists in the acquisition, archiving, and analysis of satellite and GIS data for the network of sites. Among the important products at the Network Office is the Core Dataset Catalog, which provides both LTER and non-LTER scientists with information about data and studies across the entire LTER program.

Although the LTER system was originally conceived as a loose confederation of sites united in their focus on long-term studies, the potential value of coordination of certain data gathering and monitoring activities has become very clear as the program has developed over the past decade. With the establishment of the Network Office in 1988, LTER scientists agreed on protocols for standardization, communication, and analysis of certain basic meteorological data sets referred to as the "minimum standard installation" (MSI). MSI elements include the common hardware and software elements necessary for the computer networking system that links all eighteen sites as well as standardization of other computer applications such as geographic information systems.

During the ten-year period in which the program has been fully operational, scientists involved in the LTER program have produced a distinguished and extensive literature describing important ecological processes and numerous ecological characteristics from the sites. These long-term research programs have documented the status and trends of key environmental conditions from the eighteen sites and have established interactions with several foreign countries. In a number of instances, research from the LTER program has been instrumental in guiding policies and providing a scientifically credible basis for prudent management decisions about natural resources.

The LTER network generates site-based, long-term observations, providing a baseline against which changes can be detected. Such baseline studies will be increasingly important, especially as the scientific community addresses the structure and function of the global system and its interactive physical, chemical, and biological processes in order to understand and predict global change. These comprehensive baseline and process studies have greatly increased the value of long-term ecological research sites. The understanding gained from ecosystem-based studies is one of the essential building blocks for assessments of the contributions of specific ecosystems to global change as well as the effects of global change on ecosystems. Likewise, long-term studies are making significant contributions to our understanding of the importance of biological diversity to ecosystem structure and function, the role of ecosystems in transforming and transporting pollutants, and the effect of human population growth on land cover and use.

The records of atmospheric carbon dioxide concentrations from Mauna Loa, started in 1958, have provided tremendous insight not only into trends over time but also into the role of biological systems in its regulation. The long-term records of soil chemical properties and agricultural yield from Rothamsted Experimental Station in the United Kingdom have provided invaluable information on soil organic dynamics over 150 years of study. In similar ways, the long-term ecological research at these specific LTER sites will prove invaluable, and the importance of these observations will increase rapidly over time.

In the 1960s, several ecosystem projects were initiated which addressed the dynamic behavior of ecosystems and provided the opportunity to study process controls and detailed functions of these ecosystems. The Hubbard Brook Experimental Forest site in New Hampshire is one example where manipulative experiments begun over 30 years ago continue to contribute substantially to the understanding of ecosystem structure and function and to the relationship between ecosystems and human activities. The scientific publication rate from this site has increased rather than decreased over time, showing the power of established experimental sites with long-term commitments. Long-term ecological research will continue to provide an in-depth understanding of the behavior of ecosystems, thereby guiding our use of renewable resources provided by ecosystems and allowing us to assess how our use of non-renewable resources affects ecosystems.

The NSF vision for LTER has proven to be an overall success not only in this country but elsewhere. It has provided internationally recognized leadership in developing long-term ecological studies, and other countries (e.g., the United Kingdom's Environmental Change Network [ECN] and the Chinese Ecological Research Network [CERN] of the Chinese Academy of Sciences) now use the LTER program as a model. Despite these successes, however, the future contributions that the LTER program makes nationally and internationally will depend in part on how it meets the challenges described in this report.

In its original call for LTER proposals, NSF stressed that "environmental biological research may require

more time than allowed by the usual two-to-three-year grant period," and support was made available for long-term ecological research projects. This was a visionary approach taken by NSF that recognized an important set of conditions in ecological research. Many ecological processes are slow and require long-term studies to elucidate their rates, environmental controls, natural fluctuations, and long-term trends. Thus, the LTER program was designed to match the research funding process with these dynamics of ecological processes.

Scientific Successes and Societal Outcomes

As the LTER program has matured, its value as a network of sites has begun to increase. This constellation of eighteen sites represents different types of ecosystems and habitats, each with distinctive ecological conditions. With this diversity of ecological conditions, the network has successfully begun to facilitate the conduct of comparative studies between and among sites. The power of this network approach rests in the ability to compare similar processes (for example, primary production or decomposition of organic matter) under different ecological conditions. As a result, LTER scientists have been able to understand how fundamental ecological processes operate at different speeds and in different ways under different environmental conditions.

Comparative Studies

An example of the power of comparative approaches is provided by studies of landform effects on ecosystem pattern and processes involving four separate LTER sites, the H.J. Andrews Experimental Forest, the Niwot Ridge, the Central Plains Experimental Range, and the North Temperate Lakes. Landforms define the spatial context of specific locations within ecosystems and represent the physical "stage" on which biotic processes are played. Comparisons of forest, lake, alpine, stream, and grassland ecosystems have identified landform controls on energy, nutrient, and sediment budgets as well as controls on disturbance regimes. Because landforms and landscapes are easier to observe than many ecosystem processes, an understanding of these connections provides great power for predicting ecosystem behavior. For example, the position of lakes and streams in drainage basins greatly affects many aspects of water chemistry and biology. LTER research has demonstrated that sensitivity of lakes and streams to acid deposition is highly correlated with landscape position. In terrestrial ecosystems, landforms affect the behavior of disturbances as well as the patterns of post-disturbance ecosystem recovery. The LTER program is now extending these landscape studies to include fifteen LTER sites and, as a consequence, will further increase the power of the predictions between land form and ecosystem behavior.

Long-Term Studies and Short-Term Events

In addition to the long-term nature of these comparative studies, LTER research has provided a critical context and perspective for intensive short-term studies. The decades-long environmental records at such sites as the Hubbard Brook Experimental Forest, Coweeta Hydrological Laboratory, and the H.J. Andrews Experimental Forest provide ample proof of the importance of sometimes rare episodic climatologic events on ecosystem processes and energetic and elemental budgets. Studies at the Cedar Creek LTER demonstrate that biological diversity is often most critical to ecosystem function during extreme events such as droughts (see Box 1). The occurrence of Hurricane Hugo provided the Luquillo Experimental Forest LTER with an opportunity to understand the ecological impacts of major natural disturbances on Caribbean tropical forests. Studies such as this would have virtually no meaning if it were not for the long-term records and coordinated research that are the hallmarks of the LTER program.

Box 1 - Ecosystem Function and Extreme Events

Connections between the mechanisms of plant competition and whole ecosystem patterns of nutrient cycling are being explored at the Cedar Creek LTER in collaboration with one of the longest-term studies of ecosystem behavior in the world, the Park Grass Study at Rothamsted Experimental Station in England. The dramatic effects of various nutrient additions on plant species composition and biodiversity as demonstrated by the 140-year records at Rothamsted were a central inspiration for the design of the Cedar Creek long-term experiments. Various nutrient addition experiments at both Rothamsted and the Cedar Creek LTER have led to the development of plots that differ greatly in plant biodiversity. On small spatial scales, plant diversity in unfertilized LTER Cedar Creek grasslands fell by nearly 40% during a severe drought in 1987-88. Rare species were at much greater risk of extinction than relatively common species. After four years, plots have recovered only half of their pre-drought diversity. Moreover, across a range of grassland environments, variation between productivity and diversity is not significantly correlated during years of normal rainfall. However, recent analyses of these long-term data sets provide a very strong warning about how the loss of biodiversity affects the subsequent behavior and productivity of ecosystems. There is a clear relationship between plant biodiversity before a major drought and the impact of the drought on primary production. Regardless of their initial richness of species, plots that had lost biodiversity prior to drought were most susceptible to severe loss of primary production during drought and recovered more slowly from drought.

LTER Sites as Research Catalysts

In addition to research funded through the LTER program, LTER sites and research have served as a platform for the development of a wide range of research programs supported by other funding sources. These collaborative programs enhance the value of LTER research and the importance of the LTER sites themselves, e.g., the extensive collections of arthropods from the H.J. Andrews Experimental Forest LTER provided the basis for the development of the Western Forest Insect Biodiversity Center at Oregon State University (see Box 2).

Box 2 - Facilitation of Non-LTER Research

The accumulated data and long term character of the LTER sites make them ideal for studies in such areas as evolution and systematics. Arthropods, particularly insects, are by far the most diverse group of organisms and also the least known. The extensive collections of arthropods from the H. J. Andrews Experimental Forest LTER provided the basis for the development of the Western Forest Insect Biodiversity Center at Oregon State University. This inventory is probably the most complete for any site in North America. The species diversity is remarkable; an average cubic meter of forest floor soil contains over 250 species of arthropods. This assemblage of organisms is essential to decomposition and mineral cycling in these ecosystems. With such an inventory, investigators from the H. J. Andrews Experimental Forest LTER are beginning to ask key questions concerning the connections between arthropod diversity and ecological processes. For example, would reductions in arthropod diversity have major impacts on decomposition rates? Does isolation and fragmentation of forest patches lead to extinctions of arthropod species? Initiated to understand the role of arthropods in the decomposition of wood in the old growth forests of the Pacific Northwest, these systematic studies have played an important role in identifying potential threats associated with the introduction of non-indigenous insect pests on timber from such areas as Siberia and New Zealand. The results of the arthropod research on the H. J. Andrews Forest have encouraged similar work on other LTER sites and at a number of non-LTER sites and agencies.

Research and Management Policies

In numerous instances, research from the LTER program has been instrumental in guiding policies and providing a basis for prudent management decisions about natural resources. For example, research at the Central Plains Experimental Range and Konza Prairie LTERs has focused on the potential impacts of livestock grazing and fire on the long-term productivity and diversity of public lands (see Box 3) and, as a result, has provided answers to questions about how grasslands should be managed. Population, community, and ecosystem level studies at the Coweeta Hydrological Laboratory, Hubbard Brook Experimental Forest, and H.J. Andrews Experimental Forest LTERs have greatly influenced forestry

practices nationwide and have provided the scientific basis for detailed planning and management guidelines. In fact, much of the information base for the U.S. Forest Service's "New Perspectives in Forestry" originated from these three LTER sites. Moreover, studies from these and other LTER sites have been crucial in developing the more comprehensive "ecosystem management" approach now being adopted by all the land-management federal agencies.

Box 3 - Implications of LTER Research for Rangeland Management

LTER research is making significant contributions to our understanding of the sustainability of a variety of natural resources. Research at the Central Plains Experimental Range LTER has made one of its foci understanding the potential impacts of livestock grazing on the long-term productivity and diversity of public lands. Here, scientists have studied the long-term effects of grazing and cropland abandonment on vegetation successional dynamics. Rather than having a detrimental impact, these researchers have found that heavy levels of grazing in shortgrass steppe plant communities resulted in little change in annual net primary production, increased plant density, and decreased abundance of exotic invading species. Indeed, the removal of grazing from such communities is a form of disturbance. This response probably reflects the importance of native ungulate herbivores in these ecosystems through evolutionary time. However, this particular response to grazing is not generalizable to all grassland ecosystems. Comparison of Central Plains Experimental Range data to grasslands worldwide revealed that variation in sensitivity to grazing among grassland ecosystems varies with gradients of productivity and environmental conditions.

Anthropogenic Influences

During the past decade, anthropogenic impacts on our global environment have become a matter of great concern. Although such issues were not part of the original LTER objectives, LTER research has proven extremely valuable in the study of global processes and the interrelationships between these processes and human activities (see Box 4). Some data for examining changes in ecological systems within the U.S. Global Change Research Program has been collected on the LTER sites. For example, the large NASA-FIFE program designed to examine energy and gas exchange between the biosphere and atmosphere using satellite data was conducted at the Konza Prairie LTER, using the spatial and temporal ecological data bases provided by the LTER program for validation. The Hubbard Brook Experimental Forest LTER site was the source of much of the data and many of the ideas that led to our current understanding of acid precipitation.

Box 4 - Contributions to Global Issues: Heterogeneity and Desertification

Research at nearly all of the LTER sites has provided important, sometimes critical, insights into the causes and consequences of regional and global anthropogenic environmental change. For example, a combination of experimental and modeling studies at the Jornada Experimental Range LTER in southern New Mexico indicates an unexpected positive feedback between heterogeneity and ecosystem impoverishment. Long-term grazing of semiarid grasslands leads to an increase in the spatial and temporal heterogeneity of water, nitrogen, and other soil resources. Such heterogeneity promotes invasion by desert shrubs, which leads to further localization and concentration of soil resources under shrub canopies. The erosion and gaseous losses of elements are accelerated in areas between shrubs, increasing spatial heterogeneity even more. The result is rapid conversion of formerly productive grassland to a desert dominated by shrubs. Researchers from the Jornada Experimental Range LTER have demonstrated that this model of desertification applies to virtually any process (e.g., off road vehicle use, agriculture) that increases spatial heterogeneity. Furthermore, the LTER model is generalizable worldwide to desert regions such as the Sahel and the Mediterranean Basin.

LTER Studies at Many Spatial Scales

To increase the importance of long-term studies, research at individual LTER sites has now begun to expand to larger spatial domains. Such "regionalization and globalization" expansions have become central features at several LTER sites. At the Central Plains Experimental Range, LTER data gathered on the scale of tens to hundreds of meters have been used to develop models of the relationships between ecosystem production and nutrient cycling with gradients of land-use topography, soil characteristics, and moisture. Using a combination of remotely sensed data, soil survey data, climatological data, and topography layered into a geographic information system, these models have been extended to predict patterns of ecosystem response over a four-state region. At the Arctic Lakes and Tundra and the North Temperate Lakes LTER sites, models are being developed to facilitate regional and global extrapolation of trophic interactions and nutrient spiraling in rivers and lakes as well as the importance of these ecosystems in boreal and temperate carbon budgets. Intensive studies at Palmer Station, Antarctica, to understand the importance of spatial and temporal patterns of pack ice development on the dynamics of pelagic marine ecosystems are coupled to a basic 200 x 900 km sampling grid with sample points spaced at 20-km intervals. This combination of intensive and extensive studies will permit generalization of results for the entire margin of the Antarctic continent.

Education

The LTER network has provided valuable educational resources across the curriculum and experiences for many students. At the Harvard Forest LTER, for example, more than 2,000 children, representing elementary schools and clubs of all kinds, view educational slide shows and hike along nature trails at the research site. Field demonstrations, exhibits, and audio-visual presentations of LTER projects are an integral part of this program, which emphasizes the importance of long-term research and scientific understanding of ecosystems. At the undergraduate college level, approximately 25 students work at the Harvard Forest each summer on LTER projects. Many of these activities lead to senior thesis projects and decisions to pursue careers in ecology. Also, Ph.D. students from such varied programs as biology, earth and planetary science, and landscape architecture utilize the Harvard Forest for thesis research. Currently there are eleven students pursuing doctoral research on LTER topics because the accumulated data base and long-term mission of the LTER sites are ideal for doctoral studies. Although these examples are from the Harvard Forest, similar programs are conducted at most LTER sites.

In summary, the LTER program has been successful in bringing together highly competent groups of scientists with broad backgrounds to focus on research that would not have been possible under more conventional research programs. There has been a demonstration of the potential value of a network of sites representing a variety of ecosystem types and dedicated to long-term studies. The program has made major contributions to our understanding of important ecosystem management issues nationally and worldwide. The LTER network has also succeeded in educating many students who have become trained in a multidisciplinary, site-oriented environment with interaction and collaboration among many disciplines.

Success in Meeting LTER Program Goals

NSF Level: The NSF official description of the LTER system is contained in the four Calls for Proposals (proposal deadlines in 1980, 1981, 1986, and 1988) and has in principle remained constant over time.

The goals of the LTER network were originally to "(1) initiate the collection of comparative data at a network of sites representing major biotic regions of North America and (2) evaluate the scientific, technical, and managerial problems associated with such long-term comparative research" (Call for Proposals 1980, 1981). In the 1986 and 1988 Call for Proposals, these goals were changed to: "(l) long-term analysis of site-specific ecological phenomena, (2) comparison of observations across diverse ecosystems and in terms of general systems theory, and (3) provision of large, secure, ecologically diverse sites with well developed support capabilities." These announcements were intended to provide

flexibility in the proposal solicitation process since this was not a directed research program. The first two goals from 1986 and 1988 can be used as guidance in a general way, while the third can be described more accurately as a criterion for proposal review than a goal for the LTER program. Many of the programmatic and administrative recommendations in this report are designed to provide advice on the relative importance of (1) site-specific, long-term studies, (2) cross-site comparisons, and (3) furthering ecological theory through in-depth studies. In some instances, reviewers have emphasized one or more of these components, which has resulted in inconsistent recommendations from the LTER panel reviewing proposals, site review committees for individual sites, and *ad hoc* proposal reviewers.

Site Level: Although the three goals stated by NSF are interconnected, a more proper evaluation at the site level can initially be made by considering them separately.

1. Long-term analysis of site-specific ecological phenomena.

Many of the sites have initiated important observational and experimental studies that could not have been performed without the assurance of long-term support. Long-term studies depend not only on long-term funding but also on a stable infrastructure, secured site management, and a base-line data collection system. It is clear that long-term analysis of ecological processes has been the guiding theme for the research teams submitting proposals for LTER funding. Potential LTER scientists have been offered opportunities for conducting long-term research, and they have been eager to accept the challenges. The first goal stated by NSF in the Calls for Proposals has thus been met by the proposals and funded projects at the LTER sites.

Competing pressures to test new and challenging hypotheses while also providing consistent long-term science are cited as problems by investigators at nearly all LTER sites. At current levels of funding, these pressures cannot be reconciled because there are insufficient funds for accomplishing both responsibilities. Also, there is the expectation that the research program at each site will grow and evolve, but at the same time, sites are expected to continue research programs presented in the initial proposal. Long-term studies will inevitably be based on the scientific questions or ideas identified when the work began, but such research questions and ideas are likely to change or be modified over the life of a ten-twenty year project, although these long time periods may be necessary to answer the original questions. Thus, the current funding levels are inadequate for research expectations for both new ideas and for the continuity required to answer the questions posed earlier in the beginning of the LTER studies. However, the concept of the LTER program was never intended to support all the studies on a given site. Rather, the LTER program was developed to provide an infrastructure and to fund selected investigations of key ecological conditions and processes that are long-term in nature.

2. Comparisons across ecosystems.

During the first ten years, the LTER program has not been as successful in advancing ecological knowledge through cross-site comparisons as compared to site-specific research. Nevertheless, several initiatives for cross-site comparisons have been developed by individual investigators as well as the LTER Network Office (e.g., comparative decomposition rates, landform control of ecological processes). The increased attention by NSF toward cross-site comparisons has encouraged and facilitated this development of a stronger intersite comparison component of the LTER program. Reviewers of the LTER program, however, have not always placed consistent emphasis or value on cross-site comparisons. As a result, mixed messages have been received by the LTER scientists when the programs are evaluated and when proposals are reviewed. In the future, it will need to be clear that in addition to site-specific scientific questions, proposals may also address critical questions and hypotheses that can best be addressed through multi-site LTER comparisons.

In its original 1980 Call for Proposals, representation of "major biotic regions of North America" was a stated LTER priority. This explicit specification was dropped from the subsequent 1981 Call for Proposals. Little guidance was provided relative to the meaning of comparisons "across diverse ecosystems," and the selection of proposals was made based on site-specific scientific criteria and the quality of the proposal, without any major attention toward representation of major ecosystem types. In

the third Call for Proposals in 1986, NSF expressed special interest in proposals including the following ecosystem types: (1) high latitude (i.e., Arctic or subarctic), (2) tropical moist forest, and (3) agroecosystems (especially those combining conventional and innovative practices). In the latest Call for Proposals in 1988, emphasis was given to (1) tropical forest ecosystems, and (2) land margin ecosystems representing the interface of continental land masses and coastal oceans. With the exception of these suggestions, NSF has provided limited direction to the type of sites to be selected, leaving the selection process largely to the decision of the scientific community. Future site selection should retain an emphasis on the quality of science; but now that much of the network is in place, increased attention should be given to potential sites representing important gaps in the program.

Although the rationale for site selection has not always been entirely clear, the LTER sites successfully represent a diverse array of ecosystems. It is also necessary to emphasize the value of including non-LTER sites in comparative studies, and this has occurred in some instances. The power of spatial resolution of ecological phenomena would be severely limited if the current LTER network were considered to contain all the sites necessary for insightful cross-ecosystem comparisons.

3. Provision of large, secure, and diverse sites.

The range of size of LTER sites is large (100 to 100,000 ha). However, even the smallest sites appear to be sufficiently large to address the long-term questions being addressed by the LTER program studies.

Security of the sites has been achieved largely by establishing them on federal land (approximately 75% of the sites are on federal land), and all sites seem to be relatively secure from the perspective of the land being available for a long-term commitment of resources and research investment. LTER funding has in many instances provided more secure support for the site and its research program than was available from the institution responsible for managing the site. However, in several instances, the institution has reallocated the administrative overhead reimbursement of the LTER grant back to the site and thus provided further support for long-term stability.

In addition to attracting considerable support from the host institution, the LTER projects have been successful in establishing groups of scientists who have a corporate responsibility for site management and scientific guidance. The sites have thus avoided the danger of relying on one Principal Investigator whose departure could jeopardize the strength and continuation of the site. Thus, NSF and the LTER program have been successful in providing "secure" sites, and over time the value of these sites and their associated data will markedly increase to potential users; this will also increase the security of the sites because of the large user constituency.

The goal to have well-developed support capabilities has in general been successful. Most sites have adequate support, partly provided by the NSF LTER grants and partly from other sources. However, investigators from many sites have expressed concern that site management now demands an increasing share of NSF funding, and the sites have been successful in meeting this need only by attracting considerable external funding (frequently external support is six to seven times greater than the basic LTER support). The demands on limited funds for site support and for research projects will become an increasing problem. Successful renewal proposals to NSF must include new and exciting science, but at the current funding level, much of the support must be used for maintaining the site. It should also be noted that, although sites have different costs for general maintenance (e.g., plot management or travel costs to) from the site), with the exception of the sites in Alaska and Puerto Rico, equal funding is provided to all sites within one cohort of awards.

Network level: The Network Office has been important in fostering cross-site comparisons. A number of strategies have been used, for example, including calling separate meetings to address specific issues, developing an efficient communication network, implementing a minimum standard computer configuration at all sites, and organizing all-scientists meetings. The Network Office and these activities are essential in order to achieve the goal of cross-site comparisons. A central coordinating function within the LTER program is required to achieve the value added through cross-system comparisons. Such cross-system comparisons will increase the scientific value of the program as a whole and of the

site-specific studies and will contribute to the development of ecosystem theory.

Core Research Topics

In addition to the aforementioned goals, the NSF Calls for Proposals have consistently

stated that the research at the sites should address five core research topics:

1. pattern and control of primary production;
2. spatial and temporal distribution of populations selected to represent trophic structure;
3. pattern and control of organic matter accumulation in surface layers and sediments;
4. pattern of inorganic inputs and movements of nutrients through soils, groundwater, and surface waters; and
5. pattern and frequency of disturbance to the research site.

The core areas were originally designed to promote some degree of topical consistency, while at the same time allowing flexibility and choice at the project level. These core topics have provided guidelines to ensure that sites are selected for broad-based ecological research rather than narrowly focused studies. The five core areas are defined broadly, and no standard methodology is stipulated. Thus, these core areas have not provided strict operational assistance in site selection or evaluation.

No single site investigates all five topics in depth, but all of the sites devote attention to some important aspects of all five topics. The breadth of ecological studies conducted at a site has been maintained, and the research groups have not been constrained by undue pressure regarding how the balance is divided among specific core topics.

At the organizational level of the network, the five research topics could have been important for developing a minimum data set. However, standardization of measurements and agreement of a minimum data set have not been fully developed, and there are legitimate questions about just how such an effort should be addressed. A minimum meteorological data set exists, but otherwise the collection of data is not standardized. Although strict standardization of methodology is difficult and perhaps undesirable to achieve, the possibility for cross-site comparisons addressing the five topics has been limited by the lack of comparable data sets.

Network Governance

The LTER program has developed a Coordinating Committee that represents each of the sites. There is an Executive Committee that conducts the more routine activities of the program and works closely with the Network Office and its Principal Investigator, who also chairs the Executive Committee. The Network Office and the Coordinating Committee interact with NSF concerning general program directions. All LTER sites are led by one or more Principal Investigator(s), frequently with an advisory committee composed of investigators at the site. Each site also has an external advisory committee that meets occasionally with the site investigators and provides a review of the research.

Network Office

As described previously in the report, the Network Office assists in the achievement of the overall goals of the LTER program, provides leadership, and coordinates and facilitates communication within the program and with organizations outside the LTER program. The assessment from the sites of the role of the Network Office has varied from enthusiastic to critical. Part of the necessary support capabilities mentioned in the third goal of the LTER program is provided by the Network Office. For some functions, such as electronic networking, the Network Office has performed an essential function as these systems have been developed, but the need for a continued high level of involvement in this network is not clear. The program should decide whether the Network Office should continue as a central manager or acquirer of remotely sensed data.

The Foundation has put emphasis on the need for appropriate data management at both site and network levels. Many sites have effectively addressed this issue, but significant financial resources are needed to develop and maintain an effective site data management protocol. The participating scientists must recognize the value of a site data base and the necessity of timely inclusion of all relevant data in a manner that makes it accessible to scientists at the site, in the network, and outside of LTER. The Network Office has proven effective in providing a focal point for site data managers to consider data issues and develop common approaches to data problems.

It is also important that the Network Office represents the view and values of the LTER network to the outside world and encourages external links. Such outreach activities should involve the collective abilities and contributions of the entire LTER program scientific community.

Review Process

The present LTER review process has been fair, although as noted previously, some of the directives to panels and review teams have been less than precise. Because some reviewers are frequently accustomed to evaluating hypothesis-driven, single-investigator proposals, they may tend to emphasize short-term rather than long-term perspectives and disciplinary rather than transdisciplinary strengths of proposals and LTER research programs. Further, a few reviewers tend to focus on individual site achievements rather than on contributions of the sites to the overall LTER network. Thus, there is a need for better, written briefing of reviewers on the unique nature of LTER expectations and on the appropriate criteria for proposal evaluation.

Continuity of research expectations is of particular importance in the evaluation of long-term research; as a consequence, each evaluation must draw on knowledge of the original hypothesis that motivated the initial collection of long-term data sets. Although the LTER program will adjust the specifics of its program as research issues evolve, the review process must not apply shifting demands on a site without due consideration of the site history and of the long-term research goals of the site studies. The necessary institutional memory can be instilled in the review process by overlapping memberships in review panels and by briefing new reviewers with full site histories and providing copies of previous reviews. As discussed previously, one unique characteristic of the LTER program is the requirement that each site conduct long-term research activities in all five core areas. Unfortunately, in the proposal review process, the required focus on core areas is often lost on reviewers, so better briefing of the evaluators is necessary.

In many cases, the reviewers best acquainted with the unique objectives and constraints of the LTER program are the LTER scientists themselves. To reduce the possibility of conflicts of interest, LTER scientists are sometimes appointed to review panels but never constitute a majority. This practice is entirely appropriate.

A procedure exists for giving currently funded sites that do not meet NSF standards during the renewal process a probationary trial period to address the Foundation's concerns. Some sites have been successful in obtaining continued funding after such a trial period whereas others have not, but the criteria used for discontinuing sites are not clear to all program participants. It is critical that this process be well explained and that the sites which continue to be funded have a clear understanding of what is expected from them.

Funding

The number of sites actually funded has increased from five in 1980 to eighteen in 1993 (Table 1). The current average grant per site is slightly less than $500,000. However, the total funding for LTER (primarily from the NSF Division of Environmental Biology, but, since 1990, also from the Division of Polar Programs) has grown more rapidly due to increased allocation to network coordination and other supplementary grants.

TABLE 1 - HISTORICAL SUPPORT PROFILE FOR LTER ACTIVITIES						
FISCAL YEAR	NUMBER OF SITES	FUNDING OF SITES $M	FUNDING PER SITE $M	FUNDING[1] OF COORD. $M	FUNDING[2] OF OTHER $M	TOTAL FUNDING $M
80	5	1.2	0.24			1.2
81	5	1.4	0.28	0.1		1.5
82	5	1.1	0.22	0.1		1.2
83	11	2.7	0.25	0.1		2.8
84	11	3.2	0.29	0.2		3.4
85	11	3.4	0.31	0.2		3.6
86	11	3.5	0.32	0.2		3.7
87	15	5.1	0.34	0.3		5.4
88	15	5.2	0.35	0.3	0.7	6.2
89	17	6.7	0.39	0.4	1.6	8.7
90	18[3]	7.2	0.40	0.4	1.6	9.2
91	18	7.4	0.41	0.5	1.6	9.5
92	18	7.6	0.42	0.5	1.6	9.7
93	18[4]	8.8	0.49	0.8	1.4	11.0

1) Funding for the Network Office.

2) Funding for computer hardware and software, intersite data analyses and experiments, expanded research opportunities, and undergraduates and faculty members from smaller colleges.

3) From this point, Polar Programs supported one project (Palmer) in addition to BIO/DRB funds.

4) From this point, Polar Programs supported two projects (Palmer and McMurdo). Direct costs of research were approximately $1.0M Polar in addition to BIO/DRB funds.

Since 1987, the Network Office has received an amount similar to that of a single site, except for 1993, when the funding increased to $800,000. This budget item also includes funding for a major all-scientists meeting in 1993. Whereas the sites receive funding for six years, the Network Office must submit proposals every second year.

The amount allocated to supplement other activities has represented 10-20% of the total since 1989. The supplementary funding has been used primarily for minimum standard computer hardware and software installations at the sites. It has also been possible for groups of sites to request additional funding for intersite comparisons (both data analyses and experimental studies). Individual sites have also had the opportunity to request funds for "expanded research opportunities" within a funding cycle. In addition, this budget category for other activities includes funding for undergraduates and faculty members from small colleges.

There is an obvious and serious discrepancy between the current LTER expectations and actual funding levels at the sites. An LTER site is expected to develop an infrastructure for promoting, conducting, and preserving long-term research in all five core areas while also conducting innovative work focusing on current theories and problems in ecology. The breadth of these responsibilities cannot be met without seeking support from sources outside the LTER program. There is certainly a strong logic for NSF to encourage this pursuit of outside support and promote the LTER program as a catalyst of research. Some of this research may be supported through other agencies, but much of it is most closely aligned with the mission of NSF. The current funding is clearly inadequate. The expectations of each site increase incrementally as the accumulation of required research increases, as more demands are made on the site from other investigators who want to use the data or work on the site, and as the results of the LTER program become more widely known and receive increased attention and demands. Over the duration of the program, funding has not increased at the rate of the increasing demands on the science of the LTER program.

The NSF Vision for the LTER Program

In the middle 1970s, the NSF Division of Environmental Biology supported three workshops to begin the development of the concept of long-term ecological research. During these discussions, there were many divergent views about how such a program should be organized, how much uniformity should be imposed on common measurements to be made at the sites, how the sites should be selected, and what the funding level should be if the program were to be successful. During the late 1970s, a consensus began slowly to build around the concept of long-term ecological research, and in 1980, the formal program was inaugurated.

Throughout the planning process, NSF retained its traditional approach of providing as much flexibility as possible and of allowing the scientific community to decide upon the quality of the proposed research. The Foundation decided against specifying representative sites, but rather let each proposal stand on its own individual merits. Once established, the LTER program has continued to demand that the quality of the research meets the standards of the scientific community.

In retrospect, it is obvious that the NSF Division of Environmental Biology was patient in its development of the LTER program and, as described in the preceding section of the report, was successful in building an important and visionary program.

Suggested Modification to the Current LTER Program

The current LTER program has been successful in terms of both research output as well as providing a structure for long-term ecosystem research in the United States. As it has evolved and matured, it has changed from a small set of relatively independent sites to a larger and more integrated network. This evolution has not been without challenges. However, these challenges can be met within the current LTER structure with relatively simple changes and small increments of funding to the whole program. In this section, proposals are outlined to meet these challenges.

LTER Goals and Guidelines

Although this part of the report will focus on organizational changes recommended for the LTER program, the most important recommendation is that the individual sites, the Network Office, and NSF all continue to expect the highest quality of science. The current level of high-quality research has been

achieved by involving excellent scientists, rigorous review of individual proposals, and subsequent periodic review of all components of the LTER program. As a result, many of the nation's best ecological scientists participate in the program, and the products clearly meet the highest standards. This same level of high expectations must continue, and the current safeguards must remain in place. As the program now must move from a collection of sites to a coherent program, new standards for integration must be developed and used to evaluate the coordinated and integrated components of the LTER program.

Balancing the needs of long-term research and monitoring with short-term research continues to represent a challenge for nearly all LTER sites. This dilemma is evident in the review process, in network interactions, and in the presentation and evolution of the site objectives. A restatement of the goals of the LTER program in its current configuration may help clarify for reviewers and proposers the need for commitment to the long-term, integrative nature of the research program.

> **The goals of the LTER program should be to conduct long-term, continuous measurements and analyses of ecological patterns and processes at specific sites, to integrate and synthesize results both within those sites and among sites, and to seek ways to generalize these results over broader spatial scales.**

Core Areas

In the current LTER documents, five "core areas" of research are prescribed and are intended to structure LTER research by outlining elements to be included in all LTER research. Although these core areas provide a list of the kinds of measurements to be made at LTER sites and also encourage some commonality in a range of variables measured across the sites, they do not provide a unified organizing structure for long-term ecological research. Indeed, slavish adherence to these core areas might actually fragment research and reduce integration.

> **The five core areas should not be used as organizing principles for the LTER system. They should be replaced with (1) a succinct statement of NSF's goals for the long-term program (above), and (2) guidelines emphasizing the need for scientific breadth and integration in the LTER framework. Those guidelines call for each site to investigate and document key ecological processes, species, and trophic interactions that determine the spatial and temporal patterns of the ecological systems under study. Moreover, at each LTER site there must be a defined core of site-appropriate observations and measurements that are consistently taken for the duration of the project. All measurements and samples should be collected and analyzed as comparably as possible with other LTER sites. Within this context, the LTER sites should test scientific hypotheses or questions most appropriate for each site or group of sites.**

Integration and Linkages

One of the goals of the current LTER program is to conduct integration and cross-system comparisons among sites within the network. At the current time, this goal has been only partially met by the development of selected comparisons. However, an integrated LTER network was not part of the original LTER concept, and the original sites were not selected nor research programs defined to facilitate cross-site comparisons. Nevertheless, as the network has evolved, NSF has encouraged (and provided priority funding for) integration and cross-site comparisons among the LTER sites; these activities should be encouraged and facilitated. Indeed, participation in integrated and cross-site studies should be one of the clear expectations of each LTER site. However, because of the individualistic process for identifying the LTER sites, there are limitations to what can be reasonably accomplished by the set of sites now in the LTER program.

> **Integration and cross-site comparisons should be question driven, encouraged and facilitated within the LTER program. All important questions will not be answerable**

solely within the LTER network. Therefore, researchers within and outside the LTER network should be encouraged to use LTER data in conjunction with short- and long-term data from other sites and programs to test hypotheses that can be based on such integrated comparisons. In some cases, this will be a first step toward "regionalization," taking advantage of controlling gradients or spatial variability within a region to broaden the perspective on the processes under study at individual LTER sites. Given current LTER site funding levels, such studies should be funded by the non-LTER NSF programs or funds from other agencies. However, with substantially increased funding, regionalization should become an important LTER priority.

Although the LTER Executive Committee recently completed a document recommending future directions and aspirations (LTER 2000), and the network considered its possible role of long-term ecological studies in global processes (1990s Global Change Action Plan), the LTER constellation of sites has not yet achieved its potential. Much of the attention of the sites seems to have been devoted to site-specific studies, and too little effort has been directed toward the future of a powerful set of integrated research sites. The LTER has been only partially effective in conveying its successes to the scientific community (with a strong scientific publication record) and to the public and to decision-makers. As the program continues to mature, more programmatic attention must be applied to developing an ever-expanding vision of the value of the integrated LTER program and to communicating the successes of the program to a wide scientific and non-scientific audience.

The LTER program, largely through the Network Office, has begun to build linkages with some other relevant programs, but much more interaction could be developed. Among the possibilities are closer links with the Land-Margin Ecological Research (LMER) program, the U.S. Global Change Research Program, the proposed Freshwater Imperative and Center for Synthesis in Environmental Biology, and the Nature Conservancy's Natural Heritage Programs. The LTER program should consider interaction with the National Biological Survey as it develops as well as with other federal, regional, and state programs, and private organizations.

Network Governance

The current LTER decision-making structure has not kept pace with the evolution from a loosely tied consortium of sites to an integrated network. The Coordinating Committee, composed of the Principal Investigators from each LTER site, was originally the sole decision-making team. Many decisions are now made by the LTER Executive Committee or its chairperson, who is also the Principal Investigator of the Network Office. The result has been a feeling of some disenfranchisement on the part of some of the investigators. The organization should clarify the governance of the LTER program and construct a delineation of the roles of NSF, Executive and Coordinating Committees, advisory committees, and the Network Office in planning new directions and implementing new initiatives and directions.

The Coordinating and Executive Committees

The Coordinating Committee, which includes the Principal Investigator from each site and the Principal Investigator from the Network Office, should be the primary governing body of the LTER. To facilitate decision-making, the Executive Committee should be composed of approximately five rotating elected members (as is currently done), led by a rotating chairperson also elected from one of the primary sites by the Coordinating Committee. The Principal Investigator of the Network Office should be a voting *ex officio* member of the Executive Committee. The Executive Committee should have responsibility for network-level decisions regarding network scientific activities and interactions with extra-LTER activities. With NSF, it should also carry out long-term strategic planning and the setting of priorities. Finally, the Executive Committee should direct the Network Office in the implementation of activities approved by the Coordinating Committee.

Advisory Groups

The Executive Committee may have need for advice from experts outside the LTER system with regard to both long-term activities and evolution of goals (e.g., to address interactions with international networks, roles in major U.S. initiatives, etc.) and to short-term specific requirements (e.g., to address methods comparisons, data comparability issues). The Coordinating Committee and Executive Committee should appoint *ad hoc* committees as required, using funding from the Network Office or from special requests to NSF.

It is also likely that NSF program managers could benefit from an external advisory committee to help set priorities for the LTER program in the context of its role in other national and international programs. At the present time, it is not clear who within NSF is evaluating the emerging role and needs of the LTER, taking responsibility for initiating interactions, or making commitments for LTER collaborations, nor is it clear how decisions are made regarding the extent of the involvement or which sites in the Network should participate in such outside interactions. NSF should consider utilizing an LTER advisory board to provide advice on the role of a more visible LTER system. This board should include LTER and non-LTER scientists and should meet on an annual basis.

Network Office

The Network Office fulfills a number of vital roles in the LTER program. It should not be perceived as the primary seat of management or decision-making but as the nexus of communication, dissemination of information, coordination of network activities, and implementation of specific Coordinating Committee direction. For example, the Network Office should implement Executive Committee directives related to strategic planning and setting of priorities and facilitate intersite communication, data synthesis and exchange, and synthesis among sites.

The Network Office must be responsive to the evolving needs of the LTER program. For example, with the electronic network in place, more focus should now be directed toward data comparability and standardization, archiving, and dissemination of data (see below). It should also facilitate interactions among LTER investigators through data workshops, methods comparisons, and synthesis workshops.

Even under current funding levels, the network should begin to develop method and measurement comparability. Moreover, common data sets acquired with standard or comparable methods must be made available to the scientific community for basic site variables such as microclimate, precipitation chemistry, soil chemistry, and population, community, and ecosystem characteristics. It is not expected that these common data bases will be in a central archive or data base but rather a common, electronically accessible, distributed data base. The Network Office should structure a common data base with formal quality assurance and quality control procedures as well as specific time requirements for submission of measurements to the data base. It should also facilitate access to LTER data by the scientific community.

Review Process

While the peer-review process for LTER proposals has been fair and broadly successful, the LTER site and network review process could be altered to function more smoothly and consistently. The issues that need attention include: (1) a lack of understanding or appreciation of the long-term objectives of the site proposals on the part of the reviewers, (2) markedly different advice from site review teams, renewal proposal reviewers, and LTER review panels, in part due to limited continuity in team membership, and (3) vagueness in criteria for evaluating site progress (new versus original objectives) and for decisions on continuation of individual projects.

NSF Functions

NSF can take specific actions to deal with the perceived and real problems of the review process. First, NSF can reduce confusion about goals and increase uniformity and consistency in the review process by providing written instructions to all LTER review teams, emphasizing long-term objectives and criteria for evaluation. To ensure continuity, a common subset of the reviewers should take part in site reviews and renewal proposal reviews.

Criteria for Site Evaluation

One important basis for uniformity in the review process should be a clearly and simply stated set of criteria against which proposals can be evaluated. For the site proposals, reviews should evaluate (1) progress toward original and/or evolved goals and hypotheses, (2) synthesis and integration of long-term data at the site level, (3) importance of the site in the network, (4) value of the long-term archival data and collections (e.g., evaluation of standardization, comparability, accessibility of the data), (5) relevance of continued data collection, (6) participation in intersite integration and comparisons, (7) response to extra-network interactions, (8) innovation and evolution in intersite research (e.g., regionalization), and (9) encouragement and facilitation by other scientists to use and benefit from LTER sites and research.

The first of these criteria is the most important. Progress on the original and evolving LTER site objectives should be presented and evaluated at the six-year renewal stage; new objectives may be added but should not be expected or required for continued funding. In the current system, renewal proposals appear to strive to include new research areas and objectives in addition to the treatment of long-term objectives proposed at the outset. Review of these proposals often emphasizes these new areas rather than the progress made on, or evolution of, the long-term goals originally proposed. When funding is renewed, there are frequently insufficient funds to address the proposed new research and still maintain and support the LTER infrastructure and the original long-term research. To reduce this problem, sufficient funds should be available to support short-term (three-five year) objectives that relate closely to the long-term objectives of the LTER program.

It is critical that the review process, and especially the process for discontinuation of a site, be explicitly defined.

Criteria for Network Evaluation

The LTER structure clearly has evolved from a loose confederation of sites to a more or less integrated network, and as a consequence, the Network Office has assumed and should continue to assume broader responsibilities. The Network Office should continue to be evaluated frequently, and evaluation criteria should include the success of the network in (1) providing leadership and facilitation of intersite studies, (2) providing leadership in the development of comparability information, uniform data base formats, and quality assurance and quality control protocols, (3) assisting in providing access to LTER data for the scientific community, and (4) supporting communication between the LTER system and other national and international programs.

Funding

The problems identified with the current organization and operation of LTER in this n of the report can be

remedied by an increase in funding levels of approximately 25-50%. It is imperative, however, that if the sites are to reach their potential, increases s magnitude should be directed solely to fixing the existing program rather than to ting any new studies or sites. There will remain a significant obligation on the part sites to attract funding from other sources to continue the research program.

Recommended Development of the Long-Term Ecological Research Network (LTERN): The New Generation Long-Term Ecological Research Network

In the past few years, it has become abundantly clear that managing the earth's resources is not only important but complex. Complications arise for several reasons: economic demands on both renewable and non-renewable resources damage the long-term productivity necessary to support both the regeneration of renewable resources and the ecological services upon which all life depends; there are frequently competing demands for the natural resources located on parcels of land; and retaining important natural resources and ecological processes may constrain short-term economic development. These issues are important because of the need to consider the consequences of our current actions on future generations, of local actions on regional and global processes and vice versa, and of management decisions about natural resources on the political and economic stability of societies.

Decisions concerning the management of natural resources will always be made in the political arena, usually based on the values expressed by many constituencies. These decisions will represent judgments by decision-makers who consider as much evidence as possible. In the past, many such decisions have been made without adequate information about the consequences of the actions as they relate to the near-term and long-term availability and quality of natural resources and vital ecological processes. Frequently, these decisions have resulted in the loss of resources or in the need for expensive recovery actions. Thus, the challenge is to provide the best possible information so that decisions can be based on the most accurate predictions of the consequence of any action.

The most useful information about natural resources for a decision-maker will have several characteristics:

a. the data will be of sufficient duration that it will be possible to distinguish short-term variation from long-term trends;

a. the data will have been collected over enough different environmental conditions so that researchers and decisionmakers can determine the range of conditions under which the results can be meaningfully extrapolated and applied;
b. the data must measure the important considerations from all the relevant points of view, *e. g.*, physical and biological features, social and economic characteristics; and

d. there must be an understanding of the accuracy or certainty of the data, and the decision-makers must know the extent of the data's credibility within the scientific community.

Any program designed to provide this information must be based on a stable framework so there is both a continuity to the data collections and a convenient methodology for translating the data to the decision-maker in a manner that is most useful.

Currently there is no environmental research program that meets all of these needs. However, the LTER program contains many of the essential elements, particularly a structure for providing long-term measurements, continuity, scientific rigor, a close coupling between ecological patterns and studies of the processes determining these patterns, and an organized framework for collecting, archiving, and making information available.

From its beginning ten years ago with five sites, the NSF LTER program has developed into a strong and widely recognized science project consisting of eighteen sites, each with an excellent research record. Thus, the LTER program could easily continue its present trajectory as exemplary research, involving excellent scientists conducting research on important long-term ecological research questions. In so doing, the program would contribute in very significant ways to the nation's environmental research effort.

This review of the LTER program, however, convinced the committee that there is a far broader and more important role for an LTER program. In fact, as just described, many of the challenges of designing and operating a sustainable biosphere can be most effectively and economically confronted with a newly defined LTER program. Thus, the present LTER program contains the nucleus of a vitally important national effort.

The current constellation of LTER sites and their individual research programs can and should be molded into an operational network including: a wider range of ecological organizational levels; a more complete suite of scientific disciplines; research programs designed to address directly topics that are important for the formulation of policies and practices leading to sustainable ecological systems; development of technologies to mitigate the adverse environmental effects of human activities; and support for broader ecological education. This expanded LTER program, building on the strengths of the current program and the myriad associated research programs within the U.S. research community, would involve an expanded and much more integrated network of sites, called the Long-Term Ecological Research Network (LTERN). The following paragraphs describe the rationale for the LTERN and recommend its structure and function. Although significant new monetary and human resources will be required to implement the LTERN, having such a network will repay the investment many times over in increased efficiency and effectiveness of conducting environmental research for formulating environmental policy, developing environmental management procedures, testing new technologies, and increasing the quality and scope of environmental education.

The greatest challenge facing the world today is the need to manage the biosphere in ways that it can be sustained over the long term, thus ensuring that this and subsequent human populations have an opportunity to achieve as high-quality life as possible. To meet this challenge, it is necessary to understand how ecosystems operate and how they respond to human impacts and management practices. Although many types of ecological research will be necessary to develop the techniques for managing sustainable ecological systems, among the most powerful approaches will be an integrated network of sites, each with a long-term record of environmental conditions and where investigators with different types of expertise can focus on common problems, share knowledge and equipment, and integrate research results.

By virtually any measure, the first ten years of the LTER program have been successful and have begun to achieve the maturity and strength to address these issues of environmental sustainability. However, as is true with any dynamic program, changes must be made if the program is to meet new and growing expectations. Long-term ecological research is now facing new challenges. As described by examples in the early part of this report, resolution of many of the most vexing problems in natural resource management depends upon the information that can be produced only by long-term ecological studies.

Vision for the Next Generation of the LTERN

To meet these challenges, the LTER network must undergo significant broadening and enhancement.

Continue Long-Term Measurements

Many of the long-term measurements currently being made at the LTER sites must be continued, since they will be the basis for sound management of natural resources. These records are essential if we are to understand the dynamics of ecological systems and if we are to be able to measure the impacts of human activities on ecological processes such as plant and animal production and the distribution of chemicals and nutrients. In many instances, especially where these processes are driven by climatic conditions, long-term measurements are necessary for understanding the relationships between the

controlling factors and the ecological processes. Much of the strength of the current program will come from the comparisons of these long-term data from different sites. For the future, even more attention must be directed toward making comparable measurements at the sites in the network.

Network Expansion

The current LTER network contains sites representative of many important ecosystems and habitats; however, some significant ecosystem types are not included. It would be impossible to represent all ecosystem types in the network because one could define ecosystem types very narrowly and create an almost infinite list of potential sites. Nevertheless, there are several major ecosystems that are not now represented, e.g., wetlands, non-estuarine rocky and soft-bottom intertidal and subtidal regions, northwest Great Basin, large rivers, and some examples of human-dominated systems. Additional sites must continue to be selected on the basis of the quality of the site, the proposed science, and the investigators.

The network of sites would be expanded by including some key ecological systems that are not in the current constellation of sites. These additional sites, selected by the National Science Foundation using the same rigorous peer-review system used to select the current sites, will provide additional coverage of important major ecosystems and will also strengthen the ability of the network to study comparisons of sites and changes along spatial gradients. The expanded network would be reviewed periodically for performance, just as the current sites are reviewed.

Expanded Spatial Dimension

Although the LTER program has demonstrated the strength and importance of long-term measurements over time, it is now apparent that the spatial dimension is becoming increasingly important. This means that though we may understand ecological processes that occur in one place (the site), frequently we do not understand how those processes change over the landscape or across regions of the country. As a result, management prescriptions developed in one place may or may not be useful in other areas. Therefore, the LTER program needs to be expanded to address the spatial dimension as well as the time dimension. Emphasis on small networks of satellite sites and intersite comparisons, analysis along environmental gradients, and synthesis of data from LTER-site and off-site investigations of key ecological processes would extend the spatial understanding and thereby help specify the applicability of LTER results elsewhere.

The spatial power of the network would be enhanced by identifying a series of regional or satellite sites associated with each of the primary LTER sites. These satellite sites would be used to support measurements and experiments that permit the spatial expansion of results from the primary LTER site. For example, management techniques developed in forests of the primary LTER site can be tested in different types of forests in the region at these satellite sites. The latter sites would not be fully developed in terms of facilities but will depend upon the development at the primary LTER sites. This structure would maintain the efficiencies and economies of one central site but would support the power of smaller-scale regional networks and transacts. Not all satellite sites would be continuously supported since some of them would be developed and used for particular experiments or for monitoring specific conditions or processes.

Expansion of the Experimental Framework

The LTER network has focused on ecosystem-level processes, although many sites include some studies at other levels of biological organization. It is now obvious that long-term studies of ecological processes must occur at many levels of biological organization, from molecular, individual, population, and community to landscape and global levels. Long-term studies at these levels of organization address important questions; even more significantly, many answers at one level depend upon information from other organizational levels. For example, ecosystem-level responses to management techniques may depend upon ecological processes operating at the community or genetic levels of organization. Thus, the range of scientific investigations must be expanded to include integrated studies across this entire

spectrum of biological organization.

As humans are increasingly impacted by the loss of biological diversity as a consequence of massive environmental change, expanded efforts could be devoted to those research areas most directly concerned with the persistence and extinction of species. These areas must include community ecology, population biology, and systematic disciplines that have so far received relatively little emphasis at most LTER sites but that could be readily integrated with current research programs. Species inventories at many sites would provide invaluable baseline data for many long-term studies aimed at understanding persistence versus extinction of species. These data would be doubly valuable in the context of the LTER since they would be accompanied by long-term environmental measurements. This expansion into more specifically organism-focused research should incorporate the full array of modern techniques, e. g., molecular methods for analyzing genetic variation, computer methods for managing species inventory data, and techniques for studying physiological stress of organisms in the field.

Although some LTER sites have begun to include social science as well as the physical sciences, many natural resource questions and policy recommendations which will lead to sustainable ecological systems depend on an expanded scope of research that includes these and other disciplines. Therefore, in addition to basic research on ecological processes, the next generation of the LTER network must also focus directly on policy implications of the research and must include a broader array of the necessary disciplines.

In summary, the research teams at LTER sites may be expanded to address four important components. First, the range of biological investigation can be increased to include investigators from the levels of genetic systems, to populations and communities, to ecosystems. Second, the range of disciplines may be expanded to include physical and social sciences (including economics). Third, each site can be charged specifically with the responsibility to apply, whenever possible, research results to developing resource and management policies. As a result, the research teams at the sites will involve interactions with policy-makers. Finally, the individual sites and the LTERN as a whole may increase interaction with the private sector. This expansion should be a cooperative effort to minimize environmental degradation and to arrive at policies and practices that relieve adverse environmental impacts. Not all sites will include all of these expanded components since site development will depend on the strength of the sites themselves. Each site would have the opportunity to be developed as fully as possible; however, it seems likely that clusters of sites with special competencies will emerge.

Integrate the Network and Address New Technologies

Although the LTER network currently addresses various management approaches in some types of ecosystems, relatively small amounts of attention have been devoted to testing new technologies that can be used for evaluating and protecting the environment. Since new technologies will be necessary in the future, and the practical feasibility as well as the potential long-term impacts of these techniques on ecological systems must be evaluated, the LTER network could serve as an ideal testbed for evaluating these technologies.

The sites would be used as testbeds to evaluate new technologies, particularly where the impacts of these technologies might not be obvious immediately or where the impacts should be investigated in a variety of different ecological conditions. These new technologies would include new techniques for measuring and understanding the behavior of ecological systems as well as techniques for mitigating the adverse effects of human activities.

Educational Programs

The LTER Network currently participates in a variety of educational programs which involve the public as well as formalized school programs from elementary to the graduate levels. However, the next generation of environmental scientists will require an education directed toward the multidisciplinary, field-oriented, problem-solving training that is possible from the integrated LTER network. Because the process of ecological science can best be understood by observing and participating in environmental

science in action, sites like those in the LTER network have a strong potential to provide unique educational experiences. Thus, the new LTER network must assume a broader role in environmental education.

The future directions of environmental research may lead to changes in this country's formal education structure. More and more, educators at all levels are discovering that the "discovery" process itself is a very powerful learning approach for students at all academic levels. The LTERN, with its structure across a variety of ecosystems, can serve as a testbed for the development of curricular materials, as an environment in which students of all ages can learn, and as a classroom in which teachers can learn about science in ways that make the applicability of the derived information immediately relevant to the classroom. Moreover, at a time when the role and importance of "research" is being questioned in the pervasive scrutiny of higher education, the LTERN is an ideal vehicle for demonstrating the fruitful (necessary) interplay between teaching and research.

The next generation of the LTER Network will expand its contribution to educational programs. In some cases, this will result in new, independent initiatives, but close collaboration with existing centers and systems will be emphasized. The primary focus of these LTER-based educational programs will be on the field sites themselves, with an emphasis on the interdisciplinary nature of ecological sciences.

LTERN-Related Studies

In addition to the NSF-funded LTER Network, there would be a large but informal community of researchers with hypotheses and data to share and with which to examine long-term ecological phenomena. A portion of the LTERN funding from NSF would be used to support these LTERN-related studies and for communication and networking of these scientists. In addition to initiating and supporting new long-term studies conducted within or outside the new-generation LTER network, funding would be used to archive comparable data and to integrate and synthesize data collected outside the LTERN but relevant to long-term ecological research.

Characteristics of the New Generation of the LTERN

Research in the LTERN program would be directed primarily at those ecological processes and phenomena that are long-term in nature. The investigations would have two foci. The first focus would be directed toward measuring the status and trends in key ecological conditions and processes. These status and trend data would be used as baselines to determine when and how environmental conditions change. This baseline is necessary to determine if changes in ecological systems are caused by human or natural processes. Moreover, the long-term character of these measures would assist in determining whether the changes are significant and require mitigation steps or whether the changes are the result of natural processes and do not require expensive responses. As a result, the nation will have a comprehensive set of biological inventories and regional histories of ecological, social, and physical conditions.

The second focus of the LTERN program would be the study of ecological processes that control the behavior of ecological systems. This research program, while emphasizing long-term processes, would employ a wide array of analytical, experimental, and theoretical approaches. In these research projects, many fields of biology would be involved as would a wide range of other disciplines. Moreover, this research effort would include basic research on ecological processes, but a portion of the research would also be directed specifically at policy and management questions. Indeed, the LTERN program would operate as a model for combining fundamental research with the development of policies and practices for managing natural resources, especially in the context of sustainable ecological systems.

Because the new LTERN program would consist of a set of integrated primary research sites, each with a smaller-scale network of satellite sites, several new and important research capabilities would be available. It would be possible to conduct large-scale experiments where the results can be compared not only at one site but among sites in the network and along transacts. Experiments and ecological models can be built and tested at spatial scales ranging from single sites, to the sites within one set of

satellite sites, to the primary and satellite sites throughout the network. This structure of sites available at multiple scales and spatial patterns is unprecedented and would allow the testing of ideas which heretofore have been untestable. Moreover, this integrated network of sites can be used in conjunction with many other investigations and formal programs such as the Land-Margin Ecosystem Research Program, Global Change Research Program, International Geosphere-Biosphere Program, the proposed Center for Synthesis in Environmental Biology, and the evolving National Biological Survey. Thus, the LTERN would serve as part of a "network of networks."

Since the network will include a spectrum of environmental conditions, research would be particularly valuable in designing ecological and engineering approaches to environmental remediation and reconstruction, including techniques using biologically engineered organisms. And, the network would be in continual readiness to respond to unusual research opportunities or bio-environmental crises.

The new LTERN network would present a powerful opportunity to develop and evaluate a wide array of new technologies. Some of the new technologies would be developed for research purposes, e.g., measuring ecological processes and conditions at many scales, from genetic probes to hand-held biosensors to integrated images from remote sensing methods. Other technologies would be directed toward collecting and managing large amounts of data and incorporating these data into models that can be used to understand better the ecological systems or to convey the results to decisionmakers. Technologies would also be developed to mitigate environmental damage or to restore damaged ecosystems.

A major challenge encountered when formulating policies, devising management strategies, or testing the impact of new technologies is that different types of ecosystems and regions of the country behave in different ways. As a consequence, answers obtained at one location may or may not be applicable elsewhere. It becomes costly to install tests or experiments at different locations, especially where these locations lack research support services, local expertise, or records of past and current environmental conditions. The LTERN offers a new and powerful model for meeting this challenge. Within the network, research support services, local expertise, and environmental records are already in place at many sites. Moreover, with this network of primary LTERN sites and the associated satellite sites, it will be possible to develop efficient and comparable tests of ideas, management approaches, and technologies over a wide range of environmental conditions. The LTERN thus becomes a "technology of transfer," that is, a technology itself by which information from experiments and tests within many environmental conditions can be economically transferred to decision-makers across the country.

Making Data Available to Decision-Makers

The existing LTER program has collected an enormous amount of very useful information. Some of the data have already been used for making policy and management decisions; however, with an explicit program-wide process for transferring data and information, the LTER could have been used more fully. The LTERN would be much more powerful than the existing LTER in collecting, analyzing, transferring, and translating data and information to vast numbers of decision-makers. A primary role of the design of the studies in the LTERN would be to collect and translate data directly applicable to environmental management. In fact, this role would be placed on parity with research designed to understand ecological processes.

Structure of the Integrated LTERN

This new vision of the expanded LTERN builds heavily on the success and even greater potential of the current long-term ecological research sites. The expanded scope of research within the sites requires more integration among the sites and adds three new components to the system-satellite sites, associated long-term evolution of, the LTERN-related studies, and coordinated research with other organizations (see Figure 1). As described in the following sections, each of these three components contributes to the expanded scope of the LTERN.

LTER Primary Sites

The backbone of the LTERN system would remain the current LTER sites plus the additional LTERN sites selected to increase the coverage of the important other ecosystems. Thus, a total of no more than double the current number of primary sites would support sustained long-term analysis of ecological patterns and processes across a range of ecological conditions. While the current LTER sites serve as models for these sites (and are expected to evolve to become such sites), the sites in the LTERN would need to be much more integrated, both within and among sites. Within sites, research would integrate ecological processes across the landscape, defining the connections among physical, biological, and social systems, among terrestrial and aquatic systems, and with the atmosphere as these integrated systems are influenced by and influence human activity.

Annual funding for these primary LTERN sites would be approximately $1.5 million for each site. In many sites, about half of the funding would be required for infrastructure, data management, and technology development for ecological analysis; the remainder would be focused on ecological studies within sites, integration between and among sites, research interactions with satellite sites, and education. But there must continue to be flexibility to pursue site-specific research, too. This is vital if the program is to maintain the interests of the best scientists.

Satellite Sites

For many of the LTER sites, information developed within the sites provides hypotheses about the factors that control ecological processes and answers to specific management questions. Until these hypotheses and answers can be tested beyond the site level, the information cannot be generalized and therefore is not as useful as possible. Separate funding is proposed for a component within the LTERN specifically to allow generalization of LTERN site-based information through the use of studies in satellite sites. The proposed research in satellite sites would be specifically carried out in conjunction with LTERN research. The organization of research through the satellite network would encourage expansion of LTERN studies and the involvement of other scientists as Principal Investigators.

Two examples of satellite-site functions are described here. First, satellite sites may be necessary for short-term (two-three year) studies to test specific hypotheses or answer questions arising from LTERN results. For example, if an LTERN site is positioned on a soil of a certain fertility or texture, and the experimental results suggest that soil factors control certain aspects of the ecology of the site (e.g., net primary production or losses of greenhouse gases following a disturbance or a management practice), it may be necessary to select several satellite sites that span a range of soil fertilities or textures in the same region, to test the environmental controls of the ecological process or to determine the range of soil conditions where a management practice can be applied.

Another example of the value of satellite sites is based on the need for long-term measurements of controlling variables such as climate variation, stream water chemistry, atmospheric concentration, frequency or intensity of disturbance, or soil moisture. Before an idea or management approach can be tested, these long-term data sets may be needed to define the space and time scales where the results can be reasonably extrapolated.

Although "satellite sites" would frequently provide regional context to research conducted at the LTERN, proximal location to the primary LTERN site would not be a requirement. Many environmental gradients can be spatially broad, and in some cases it may be useful to select satellite sites at great distances from the primary LTERN site.

To summarize, satellite sites should focus on selected short-term research objectives or specific longer-

term measurements or monitoring that explicitly address a question or hypothesis originating in a single or group of primary LTERN sites. Satellite site proposals may be proposed by non-LTERN Principal Investigators, but the project must demonstrate explicit connections to and coordination with the LTERN sites. Satellite sites would be considered a formal part of the network during the time that they are actively involved in these studies.

LTER-Related Studies

Numerous research sites currently existing in the U. S. and in other countries, but not part of the current LTER program, have been involved in long-term research on a range of ecological and resource management issues. Many of these sites may provide an excellent opportunity for comparative or associated research without the requirement for the large infrastructure costs that are necessary for the primary LTERN sites. Funding should be provided for short-term (five years, but renewable) research for scientists at these sites to address specific objectives related to or associated with issues under study in the core LTERN sites or associated with goals of the LTERN system. These LTERN-related studies provide a cost-effective vehicle for considerable expansion of the knowledge base required for application of scientific knowledge to ecological management and to enhancement of our understanding of these complex biological/ physical/ social ecological systems.

Research proposals for these LTERN-related studies would be initiated by non-LTERN Principal Investigators. Direct collaboration with LTERN Principal Investigators would not be required (although it would be encouraged). Proposals should explicitly demonstrate the importance of the long-term context that these sites provide to the proposed studies and should focus on objectives that meet LTERN system goals. Scientists leading funded LTERN-related studies should participate within the LTERN network and adhere to network requirements concerning data, compatibility, management, and access.

Collaborative Research

Much of the power of the LTERN would derive from coordinating research with other networks and organizations where related long-term ecological research is supported and conducted. As an illustration, the Department of Energy currently funds research at several national laboratories, such as Los Alamos National Laboratory, where there is a focus on pinon-juniper vegetation. At least one LTER site also contains this vegetation type, so a collaborative effort would be much stronger than two independent efforts. Therefore, some funding through the LTERN would be made available for matching and other enhancements of this coordinated research. This coordinated research would magnify the returns from the dollars invested in the LTERN and would provide additional cohesion to the nation's ecological research on long-term processes. In addition, these coordinated research programs would help ensure that long-term ecological research results are available to all federal agencies as they meet their mandated management responsibilities.

Budget for the LTERN

The proposed annual budget for the new LTERN is presented below. As described above, the funding for each of the primary LTERN sites would be used to support research at the site, to make the site available to other scientists, and to manage the resulting information. Much of the research from the primary LTERN sites would require further elaboration from satellite sites. Additional funds for this purpose are placed in a separate budget line and would be made available on a competitive basis since the need for satellite studies will not be the same for all primary sites. As discussed earlier in this report, there has always been tension between the need for strong site-based research and participation in intersite comparative research. Since the intersite comparisons have lagged far behind their potential, a separate budget line has been established for intersite coordinated studies. These funds would be allocated in response to competitive proposals.

The effectiveness of the LTERN can be increased significantly by providing support for smaller studies that are related to the objectives of the LTERN but that are conducted at other sites and by scientists not otherwise involved with the LTERN. Funding of these LTERN-related studies, which can be on a

schedule similar to LTERN primary sites, would be decided from the evaluation of competitive proposals.

As described here, funding for the LTERN would be provided by the National Science Foundation. However, other agencies and organizations support and conduct research which would be even more valuable if it became collaborative with the LTERN. Therefore, a relatively small amount of funding would be provided so that NSF can construct collaborative arrangements with other organizations, thereby enhancing the value of the nation's long-term ecological research.

As the network expands from the current LTER program to the more expansive LTERN, some additional coordination would be required. Moreover, as discussed earlier, the LTERN would require more communication with a much broader audience about the potential and the products of the network. Therefore, funding for the LTERN office would be increased in the budget (see Table 2).

TABLE 2 - BUDGET		
1.	**LTERN Primary Sites (approximately $1.5M per site)**	**$45M**
2.	**Satellite Sites (approximately $0.3M per site)**	**$13M**
3.	**Inter-Site Coordinated Studies**	**$15M**
4.	**LTERN-Related Studies**	**$20M**
5.	**Matching and Enhancement Funds for Collaborative Research**	**$5M**
6.	**Network Office (including communication and public relations)**	**$2M**
Total		**$100m**

This budget represents a significant investment, especially in these times of fiscal constraint. However, this investment would be repaid many times over as the LTERN provides sound scientific information for policy and management decisions that protect our natural resources and that prevent environmental damage requiring enormously expensive steps to clean up and restore. The LTERN, as described in this document, presents an opportunity for the National Science Foundation, in concert with the scientific community, to meet the sizable and continuing challenge of producing sufficient ecological understanding for sustaining human societies and for providing responsible stewardship of the biosphere.

APPENDIX A

The Current LTER Research Sites*

H. J. Andrews Experimental Forest Temperate coniferous forests

Blue River, Oregon

Arctic Lakes and Tundra Arctic tundra, lakes, streams

Brooks Range, Alaska

Bonanza Creek Experimental Forest Taiga

Fairbanks, Alaska

Cedar Creek Natural History Area Eastern deciduous forest and tallgrass prairie

Minneapolis, Minnesota

Central Plains Experimental Range Shortgrass prairie

Nunn, Colorado

Coweeta Hydrologic Laboratory Eastern deciduous forest

Otto, North Carolina

Harvard Forest Eastern deciduous forest

Petersham, Massachusetts

Hubbard Brook Experimental Forest Eastern deciduous forest

West Thornton, New Hampshire

Jornada Experimental Range Hot desert

Las Cruces, New Mexico

Kellogg Biological Station Row-crop agriculture

Hickory Corners, Michigan

Konza Prairie Tallgrass prairie

Manhattan, Kansas

Luquillo Experimental Forest Tropical rainforest

San Juan, Puerto Rico

Niwot Ridge/ Green Lakes Valley Alpine tundra

Boulder, Colorado

North Inlet Marsh Estuarine System** Coastal estuary

Georgetown, South Carolina

North Temperate Lakes Northern temperate lakes

Madison, Wisconsin

Palmer Station Polar marine

Antarctica

Sevilleta National Wildlife Refuge Intersection of dry mountain land, grassland

Albuquerque, New Mexico and cold desert

Virginia Coast Reserve Coastal barrier islands

Oyster, Virginia

*The McMurdo Dry Valleys, Antarctica, site is being added to the program but was not included in this report because its approval occurred during the review process.

**The North Inlet Marsh Estuarine System site will not be continued after this year.

APPENDIX B

The LTER Ten-Year Review Committee

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APPENDIX C

The 10-Year Review Questionnaire

I. IMPLEMENTATION

1. Have the LTER proposal review criteria and process (as described in OMB No. 3145-0058) been consistent with the stated program objectives and been fairly implemented? Specifically:

    a. Does the NSF formal review proposal review process reflect the stated objectives of the program? If not, how should the process be changed?

    b. Is the evaluation process thorough and timely?

    c. To what extent does the review process facilitate or constrain scientific innovation?

2. What mechanisms have been used to attract additional investigators and projects to your site? Please indicate those that have become a part of the LTER team and those who are on-site collaborators but not funded by the LTER project.

3. In consideration of the Network Office:

    a. Describe the functions of the Network Office that you believe to be essential and those that are useful but not essential.

b. Describe additional ways in which the Network Office could augment the LTER program for individual sites and for the LTER network as a whole.

c. Do you believe the current level of investment in the Network Office is appropriate to meeting the existing LTER objectives? If not, what should be increased or decreased?

4. How specifically has the organizational emphasis on computer networking among LTER scientists and projects contributed to the LTER research program?

5. What synergisms and conflicts have developed at your LTER site between the acquisition of general baseline, long-term data sets and the conduct of specific research projects?

6. With respect to the international dimensions of the LTER program:

a. Briefly describe current international collaborative efforts, including the objectives of these collaborations and the involvement of foreign scientists (e.g., number, disciplines, professional status).

b. What specific and tangible results have been produced by these collaborations?

c. Do you plan new or additional international collaboration, and, if so, what do you seek to accomplish?

II. OUTCOMES ASSESSMENT

7. What significant research has been conducted at your site with LTER support that addresses the five core (see OMB No. 3145-0058) research topics? Please submit references to the one or two most important papers from your site addressing each of the above core topical areas. Provide a brief paragraph for each research topic explaining the rationale for the selection. Also, please submit a complete list of publications produced from your site.

8. What significant other research topics (i.e., in addition to the five core topics) have been addressed at your site with LTER financial support? List the two or three most significant publications and give the rationale for deciding that these topics should be studied at the site.

9. In what ways has the LTER framework been important for your research? Address briefly the three following possible reasons and add any others that you feel have been crucial:

a. the existence of a network for comparative purposes;
b. the possibility of conducting multidisciplinary, site-specific research; and
c. the insured six-year financial support.

Give specific examples to illustrate your points.

10. In what ways have you designed a conceptual framework of research at the site, and what specific examples can you give for documenting such integration activities? Please also provide any specific examples of across-LTER site integration and syntheses.

11. A stated rationale of the LTER program is to "augment the progress of ecological science." What are specific LTER contributions to the advancement of ecology as a

science?.

12. If the NSF-supplied financial resources have been adequate for meeting the LTER objectives at your site, what have been the most significant consequences?

13. Beyond activities funded directly by the LTER program, to what extent have the LTER network and your individual site attracted, stimulated, or facilitated other research programs or projects?

a. Provide a list of research projects (with Principal Investigators, funding agencies, and amounts) carried out using your site. Please indicate which of these projects contribute to the LTER objectives.

b. Describe the actual role of your LTER activities in facilitating these adjunct activities.

c. Describe the actual role of your LTER activities in facilitating these adjunct activities.

14. There is considerable public concern about the nature and value of publicly supported research and the ways in which this research might or should benefit society. How might you answer the following question: In what specific ways have or will LTER results from your site or the network contribute to societal issues?

15. In what specific ways has the work of the LTER sites and the network influenced the policies and practices of the following potential constituencies:

a. other research institutions

b. governmental and non-governmental agencies

c. local and regional communities

16. How has the LTER program contributed to:

a. pre-college education

b. undergraduate education in science

c. graduate-level education

d. education of the general public

e. education of those involved in environmental policy-making

III. FUTURE DIRECTIONS

17. Has the LTER program an adequate planning process in place for revising the objectives of the program? In what directions should the program objectives change? Do the five core areas need to be re-evaluated, and, if so, how should this be done?

18. a. If additional funds were available, should priority be given to adding additional sites or for increasing funding of the existing sites?

18. b. If additional funds were available and the choice were to add sites to the network, what criteria should be used for additional sites and what would be your recommendations for high-priority additions to the network?

18. c. If approximately $3M were available as annual funding for your site, how would you propose that the funds be invested?

19. Should more resources be directed toward:

a. network functions

b. international participation, such as IGBP, MAB, and LAI/START
c. refining and augmenting Minimum Site Installation capabilities

d. expanding the number of participating scientists and broadening the range of disciplines

e. use of the research results in a social context

f. education of students and/or the public

g. other activities

IV. OTHER

20. Should the LTER program further standardize a basic core data monitoring program at each site to ensure a long-term data base?

21. Should there be a formal archival system for data and key samples?

22. What other data or opinions would you like to provide that were not requested in the above questions?

23. Please provide a brief description about the process your site used to respond to this questionnaire.

APPENDIX D

LTER Publications Reviewed By The Committee

Long-term Ecological Research. James T. Callahan. *Bioscience*, 1984

The Climate of the Long-Term Ecological Research Sites. University of Colorado, Institute of Arctic and Alpine Research (INSTARR). Occasional Paper 44, 1987

Standardized Meteorological Measurements for Long-Term Ecological Research Sites. Bulletin of the Ecological Society of America, 1987

1990s Global Change Action Plan. LTER Network Office, 1990

Long-Term Ecological Research Network Core Data Set Catalog. Belle W. Baruch Institute and LTER Network Office, 1990

Climate Variability and Ecosystem Response. USDA Forest Service Southeast Experimental Station and LTER Network Office, 1990

Internet Connectivity in the Long-Term Ecological Research Network. LTER Network Office, 1990

Contributions of the Long-Term Ecological Research Network. *Bioscience* July/August, 1990

Long-Term Ecological Research and the Invisible Present. *Bioscience* July/August, 1990

Long-Term Ecological Research and the Invisible Place. *Bioscience* July/August, 1990

Proceedings of the 1990 LTER Data Management Workshop, Snowbird, Utah. Network Office, 1990

Long-Term Ecological Research in the United States: A Network of Research Sites 1991. LTER Network Office, 1991

Technology Development in the Long-Term Ecological Research Network: Status of Geographic Information Systems, Remote Sensing, Internet Connectivity, Archival Storage & Global Positioning Systems. LTER Network Office, 1991

Proceedings of the 1991 LTER Data Management Workshop, San Antonio, Texas. Network Office, 1991

Guidelines and Sample Protocol for Sampling Forest Gaps. USDA Forest Service Pacific Northwest Research Station and LTER Network Office. PNW-GTR-283, 1992

LTER 2000: Creating a Global Environmental Research Network. Network Office, 1992

This material is based upon work supported by the National Science Foundation under Cooperative Agreement #DEB-0236154. Any opinions, findings, conclusions, or recommendations expressed in the material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.