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Abstract

The Long-Term Ecological Research (LTER) Network is the largest and longest-lived ecological network in the United States. Designed to provide long-term data from a broad range of key ecosystems, the LTER Network represents a unique national resource to address pressing environmental issues such as climate change, loss of biodiversity, and changes in patterns of land use. LTER is recognized internationally as one of the best organized and most successful large groups conducting research in ecology. With over 1,500 scientists, educators, and students, the network spans 26 sites located in 16 states in the contiguous United States, Alaska in the Arctic, Antarctica, and islands in the Caribbean and the Pacific Ocean (Fig. 1).

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Long-Term Ecological Research Network (LTER)

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Article Outline

Glossary

Biodiversity Variation of life at all levels of biological organization.

Disturbance A relatively discrete event in time and space that alters populations, communities, and ecosystems, including their attendant processes.

Ecology The study of the relationship of organisms or groups of organisms to their environment.

Ecosystem dynamics The observed changes in the characteristics of an ecosystem over time.

Ecosystem The organisms living in a particular area in combination with the physical elements of the environment in which they live.

Episodic Limited in duration or temporary.

Invisible present Relating to an observation whose importance cannot be evaluated for lack of context.

Scale Refers to differences in the spatial or temporal extent of a set of observations or measurements.

Synthesis The creation of new knowledge by combining observations from diverse sources.

Transformative research Scientific investigations whose results lead to radical changes in understanding of fundamental concepts.

Definition of the Subject

The Long-Term Ecological Research (LTER) Network is the largest and longest-lived ecological network in the United States. Designed to provide long-term data from a broad range of key ecosystems, the LTER Network represents a unique national resource to address pressing environmental issues such as climate change, loss of biodiversity, and changes in patterns of land use. LTER is recognized internationally as one of the best organized and most successful large groups conducting research in ecology. With over 1,500 scientists, educators, and students, the network spans 26 sites located in 16 states in the contiguous United States, Alaska in the Arctic, Antarctica, and islands in the Caribbean and the Pacific Ocean (Fig. 1).

The network's formal vision is a society in which long-term ecological knowledge contributes to the advancement of the health, productivity, and welfare of the global environment, thereby advancing human well-being [2]. Within this vision, LTER's mission is to provide the scientific community, policy makers, and society with the knowledge and predictive understanding necessary to conserve, protect, and manage the nation's ecosystems, their biodiversity, and the services they provide. The LTER Network achieves this mission by using long-term observations and experiments to generate and test ecological theory at local to regional scales.

The National Science Foundation (NSF) created the LTER program in 1980. For three decades, the network has generated rigorous, site-based scientific research that has led to important regional and continental syntheses. LTER provides the scientific expertise, research platforms, and long-term datasets necessary to document and analyze environmental change.

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Introduction

Because some of the most interesting and important ecological phenomena take place over long periods, long-term observations or experiments are necessary to truly understand their impacts. Processes such as climate change, recovery after disturbances such as forest fires, and changes in land cover are ecological processes that must be studied over the time scale of their occurrence (see, e.g., [3, 4]). Consequently, studies over sufficiently long time periods and large geographical scales are necessary to permit generalizations and theory about long-term events – such as deforestation, acid deposition, grazing, fire, and changes in trace gas fluxes [5].

In the concluding summary to a special report entitled "Long Term Ecological Research: An International Perspective," Risser [6] noted that long-term ecological studies are especially useful under four conditions: (1) the phenomena being studied are long term in their dynamics; (2) are episodic in nature, rare, complex, or subtle, such that long-term experiments are needed to isolate their dynamics and the control processes; (3) are poorly understood and cannot be predicted from short time scales; or (4) when long-term records are needed to make policy decisions.

Although important, such long-term studies are generally rare, with only a few examples all across the globe (Fig. 2). According to Risser [6] long-term ecological studies are rare because: (1) long-term studies may not be considered innovative science, making their continuous funding difficult; (2) sites where the measurements are taken may change, making the long-term results meaningless or difficult to interpret; (3) experimental designs may be too ambiguous for consistent long-term measurements or may not include adequate auxiliary studies to unravel controlling processes; (4) resources or incentives may be inadequate for dedicated scientists or research leaders to continue the studies; (5) new instrumentation may render the original methodology obsolete, coupled with insufficient attention to calibrating the old and new technologies; (6) new scientific advances may make the original question or hypothesis uninteresting or may provide a definitive answer, making the studies unnecessary.

It was this dearth of reliable information on key long-term ecological processes that prompted NSF to create the LTER Network in 1980 (see section "Major Milestones in LTER" in this document for a brief history of LTER's formation). Acting on the recommendations of three working groups comprising members of the ecological community [9–11], the Division of Environmental Biology at NSF constructed a call for proposals designed 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" [12]. Although the early emphasis of the LTER program was on expanding the time scale at which ecological research was conducted, a concomitant expansion of the spatial scale of research was also expected (Fig. 3). This broadening perspective led to the twin concepts of the "invisible present" and the "invisible place."

Time and the Invisible Present

Magnuson [4] coined the term "invisible present" to describe ecological processes that result in significant change over decades but are hidden to the investigator conducting short-term studies. Ecologists working in this "invisible present" are not able to place current conditions in perspective without additional data from a longer span of time. Magnuson noted that short-term observations often could not identify cause and effect relationships because of inherent time lags of a year or longer between cause and effect. For example, changes in biomass accumulation in a forest as a result of disturbance may take years or decades to perceive. In short-term observational studies, it is rare to actually observe infrequent but important events. However, it is common to observe responses of an ecological system to an event that occurred long before observations began. Short-term manipulative studies often observe a system in transition rather than the complete trajectory to a new system state.

A good example of the importance of long-term data on the interpretation of ecological processes is given by observations of the ice cover records of Lake Mendota, WI (Fig. 4, [14]). The duration of ice cover in a single winter (1997–1998 in the example) might seem unremarkable without any other context. However, examination of successively longer segments of the 142-plus years of ice duration data provides the context to see the importance of that single year. A 10-year segment of data reveals that duration of ice cover in 1997–1998 was significantly less than the other 9 years of record [15], and that duration of ice cover varies considerably from year to year. A relationship between ice cover and an important feature of global climate, the southern ocean oscillation index [16, 17], is evident in the 50-year data segment, with 1997–1998 and other El Niño years having shorter durations of ice cover. The general warming trend in the data only becomes apparent within the complete record. What's more, the end of the little ice age about 1890 [18, 19] is reflected in the decrease in the duration of ice cover on Lake Mendota. The single observation from 1997 to 1998, viewed in the context of the complete data set, is revealed to be the year of shortest ice duration in the entire 142-year record. Thus, the long-term nature of this set of observations provides a clear context to interpret patterns at multiple temporal scales.

Space and the Invisible Place

In the same way that a point in time requires long-term temporal context for complete understanding, so a point in space requires a broad-scale spatial context [20]. Interpretation of observations at a single site (the invisible place) requires a spatial context that often spans multiple scales. In the LTER Network, observational or experimental studies are often designed and implemented at the plot scale, where the plot may encompass less than 1 m^2 or an entire watershed. Most LTER site research focuses on plot to landscape scales (Fig. 3), but the use of remote sensing and modeling approaches, the steady development of networked interactions among sites [21], and the growth of the long-term approach internationally provides the means to expand the research focus to regional, continental, and global scales [20].

The study of glacial lakes at the North Temperate Lake's LTER site in northern Wisconsin illustrates a typical approach to linking ecological elements in a broader spatial context. Although lakes in this landscape have many shared characteristics, the relative position of lakes connected along elevation gradients explains much significant dissimilarity, even in areas of slight relief. Lakes that are higher in the landscape are smaller, clearer, more dilute chemically, less diverse, and less affected by human use [22]. This pattern pertains to other lake districts throughout the northern hemisphere.

LTER scientists use two general approaches to extend results from small-scale and short-term studies to regional and broader scales [23]. An empirical approach correlates values of ecological processes with aspects of the physical environment that are measurable at broad spatial scales using specialized tools including remotely sensed imagery. For example, Kratz et al. [24] compared patterns of spatial and temporal variability across 12 LTER sites using normalized difference vegetation indices (NDVI) from Landsat scenes. They found that variability within sites for a given year was considerably greater than variability among sites, indicating that studies of spatial heterogeneity must be coupled with long-term data to achieve an understanding of long-term dynamics at landscape and regional scales.

A second approach uses mechanistic models to simulate interactions among ecological processes measured at sites and predict patterns at broader scales [23]. Data from the LTER Network facilitate construction of mechanistic models in two important ways. Coordination among sites within the network produces consistent, multidisciplinary data sets over a broad geographic range. The existence of data on slow ecosystem processes, which govern long-term ecosystem dynamics, allows estimation of rate constants needed to model these dynamics. One example of the interaction between long-term data and mechanistic models is the photosynthesis and evapotranspiration model (PnET) developed by Aber and colleagues to predict ecosystem processes at regional scales [23]. The PnET models form a nested hierarchy of three models estimating (1) gross and net carbon (C) gain on a daily time step, (2) net C and water fluxes at variable time steps, and (3) biomass, litter fall, decomposition, and nitrogen (N) cycling. Together the three models allow prediction of the integrated function of ecosystems. Predictions from the models have been compared with long-term C, water, and nutrient balance data from the Harvard Forest and Hubbard Brook LTER programs. Discrepancies between predictions and empirical data instruct model improvement and guide site research. The PnET models allow regional scale prediction of integrated ecosystem characteristics over a wide range of future environmental conditions and previous land use histories [23].

Networks of integrated research sites provide the opportunity to examine continental scale ecological patterns and the drivers of those patterns. One multi-site, long-term experiment (the Long Term Intersite Decomposition Experiment or LIDET) manipulated substrate quality across a broad range of vegetation and climate conditions to understand the factors controlling decomposition. Results from standardized measurements at 26 sites (17 LTER sites) indicated that decomposition of low-quality litter across a broad range of environmental conditions was slower than had been previously thought [25] and that significant variability resulted from ecosystem-specific factors such as the composition of the decomposer community. Studies such as these led LTER scientists to develop a conceptual framework for continental-scale research based on connectivity of flows of materials, organisms, and information across scales [26]. This framework emphasizes the importance of coordinated approaches across different research networks at continental and global scales.

Coordination of long-term ecological research at a global scale was initiated in 1993 through the formation of the International Long Term Ecological Research Network [27], which now has research networks in 40 countries. As a founding member of this global network, the US LTER Network continues to play a central role in developing research to address global ecological issues. In addition, many LTER sites perform observations and conduct experiments as part of global networks focused on specific research questions. For example, LTER sites are engaged in global comparisons of forest structure through the Center for Tropical Forest Science at the Smithsonian Tropical Research Institute. This network includes 40 plots in 21 countries encompassing 4.5 million individual trees of 8,500 species.

Major Milestones in LTER

Scientific investigation at and among LTER sites is dynamic and evolves continuously in response to increasing knowledge and new opportunities. The commitment of LTER sites to long-term observations and experiments does not imply rigidity in focus and approach. The ability of LTER researchers to respond nimbly to new opportunities results from a flexible network structure with a minimum of requirements and uniform site activities. This flexibility would not be possible in a more monolithic network design. Thus, during the first decade of LTER (the 1980s), key concepts of long-term ecological research were explored and clarified. In the 1990s, there was an increased emphasis on large spatial scales and multiple interactions of ecological processes, species, and element cycles. In addition, interactions with physical and social scientists also increased. The third decade of the LTER program focused on synthesis. Using data and knowledge gained over the preceding 20 years, the LTER Network sought to reach new levels of understanding of long-term and large-scale ecological patterns and processes. This summary of the intellectual evolution of LTER provides context for a description of the major milestones in the development of LTER research.

Formation of the Network

The seeds of LTER were planted by the National Science Foundation (NSF) when it sponsored three workshops (in 1977, 1978, and 1979) to initiate and maintain close consultation with the ecological sciences community. At these workshops, the philosophy of collaborative research was developed and a centralized working hypothesis approach to collaboration proposed. Five core areas of research (Box 1) were defined to orient long-term ecological research projects toward question/hypothesis formulation and resolution over long time and broad spatial scales.

Major Milestones in the First LTER Decade

1980 – NSF selected an initial set of six sites (North Temperate Lakes, H.J. Andrews Experimental Forest, Coweeta Hydrological Laboratory, Konza Prairie, North Inlet Marsh, and Niwot Ridge) funded at $250,000 per year. Lead scientists from each site met in Washington, DC, and constituted a steering committee to begin the tasks of LTER communication, coordination, and accommodation of mutual goals.

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1981 – Dick Marzolf (Konza Prairie) was elected the first Chair of the Steering Committee and NSF awarded a network coordination grant to Kansas State University (with Marzolf as PI). Subsequently, a second competition added five new sites to the network (Central Plains Experimental Range (now called Shortgrass Steppe), Okefenokee, Illinois Rivers, Cedar Creek Natural History Area, and Jornada Basin).

Box 1. Core Research Areas

The core areas are five research themes that are common to research at all sites and thus central to the coordination of network science. Core areas were originally selected by NSF to ensure appropriate breadth in LTER research programs and to guard against divergence among sites over time. Combined, the five core areas describe most of the major structural components of ecosystems. Although discussions about adding new core areas (e.g., biodiversity, social patterns and processes) have taken place within the LTER Network, none of these have been officially adopted.

The core areas are:

1. *Pattern and control of primary production* – Plant growth in most ecosystems forms the base or "primary" component of the food web. Spatial and temporal patterns of production and the controls of these patterns are major factors in structuring ecosystems.
2. *Spatial and temporal distribution of populations selected to represent trophic structure* **–** Populations of organisms are dynamic over space and time, and long-term trends in populations can be important indicators of environmental change.
3. *Movement of organic matter* – The sequestration of carbon by primary producers and its eventual fate in ecosystems have important implications for trophic dynamics, nutrient cycling, and global climate.
4. *Movement of inorganic matter* – Nitrogen, phosphorus, and other mineral nutrients are cycled through the ecosystem by way of decay and disturbances such as fire and flood. Availability of these nutrients exerts important controls over ecosystem structure and function.
5. *Disturbance patterns* – Disturbances often shape ecosystems by periodically reorganizing physical or community structure, resulting in significant changes in ecosystem services available to humans.

1982 – LTER held the first Data Management workshop and the first LTER Meteorological Committee (now Climate Committee) meeting, while the Steering Committee created a policy for workshops supported under the coordination grant.

1983 – NSF conducted the first national review of the LTER Program and the LTER Network Office (Box 2) was established through a coordination grant awarded by NSF to Oregon State University (with Jerry Franklin as PI).

Box 2. The LTER Network Office

The LTER Network Office (LNO) was established in 1983 through a coordination grant awarded by NSF to Oregon State University to support and coordinate network and site activities of the LTER Network. In 1989, NSF awarded another coordination grant to enlarge and establish LNO at the University of Washington-Seattle. The office officially moved to the University of New Mexico in 1997, and added the position of Executive Director. Robert B. Waide, formerly co-principal investigator of the Luquillo LTER program, was the first Executive Director of the LNO. With a core staff of 18 people and an annual budget of $1.5 million, the LNO's current service mandate includes:

- Providing an efficient computational and communication infrastructure for LTER research and education
- Developing and deploying state-of-the-art techniques in information management
- Maintaining a strong public outreach program
- Coordinating interactions with other scientific networks, agencies, and entities
- Providing administrative support
- Contributing to an efficient and effective environment in which site, cross-site, and synthetic research and education can be conducted

1985 – LTER held its first All Scientists Meeting (Box 3) at Lake Itasca, MN.

Box 3. All Scientists Meetings

Triennial All Scientist Meetings are used by the LTER Network to promote team building for cross-site research and synthesis. These 3–4 day meetings focus the LTER scientific community on new challenges, result in the formation of new research collaborations, help to integrate new sites and scientists into the LTER community, and provide the only opportunity for community-wide discussions of the future of the LTER program. In contrast to the usual scientific conference, an All Scientists Meeting focuses less on the presentation of individual research results and more on brainstorming, discussion, and synthesis of results from researchers addressing similar questions in different ecosystems. Moreover, All Scientists Meetings present excellent opportunities to share expertise, to transfer technology among sites, and to generate new scientific concepts, approaches, and experiments.

The most recent meeting in 2009 was attended by nearly 800 participants including many graduate students and broad representation for the International LTER community. The program included six plenary talks, 75 working group meetings, over 400 posters, four evening mixers, and pre-meetings for information managers, graduate students, education representatives, international attendees, and the LTER Executive Board.

1986 – NSF announced the third call for proposals for long-term ecological research sites; the LTER Intersite Climate Committee (formerly Meteorological Committee) developed standards for meteorological measurements at LTER sites [28, 29].

1987 – Five new sites (Arctic Tundra, Bonanza Creek Experimental Forest, Hubbard Brook Experimental Forest, Kellogg Biological Station, and Virginia Coast Reserve) joined the network; the LTER Intersite Climate Committee summarized climate information at the first 11 LTER sites [30]; and NSF announced the fourth call for long-term ecological research proposals.

1988 – Three new sites (Luquillo Experimental Forest, Sevilleta National Wildlife Refuge, and Harvard Forest) were added to the program, while two (Illinois Rivers and Okefenokee) were withdrawn (Box 4); the NSF Advisory Committee on Scientific and Technological Planning for LTER identified scientific issues addressed by the sites and recommended network-wide capabilities to address them; and the minimum standard installation (MSI) for LTER site data management was developed.

1989 – NSF conducted a second national LTER Program review and awarded a coordination grant to enlarge and establish the LTER Network Office at the University of Washington-Seattle (with Jerry Franklin as PI); an LTER working group developed the "Global Change Research Action Plan"; acquisition of satellite imagery and aerial photography for all sites began; an LTER-Chinese Ecological Research Network (CERN) exchange was developed; and the first LTER Network Strategic Plan resulted from the 1989 LTER Coordinating Committee Meeting at Harvard Forest ("A long-range Strategic Plan for the Long Term Ecological Research Network").

Major Milestones in the Second LTER Decade

Box 4. Evaluation of LTER Sites

NSF funds each LTER site independently for 6-year periods, with renewal of awards based on proposals describing accomplishments and plans for future activities. Renewal proposals are reviewed by special panels of experts convened by NSF. The review panel may recommend continued funding, preparation of an addendum addressing specific points, or probation. An LTER site that is placed on probation receives only 2 years of funding and must write a new proposal addressing shortcomings for the next renewal cycle 2 years later. If the new proposal addresses criticisms successfully, 4 more years of funding are awarded. If not, the site is provided with terminal funding to close operations. The purpose of the probation process is to ensure that NSF's long-term investment is protected from transient problems, such the death or retirement of leading investigators, while still maintaining high standards of rigor in peer review. Four sites have been terminated during the 30-year history of the LTER program.

NSF also conducts mid-term program reviews as an essential part of NSF's ongoing evaluation cycle of the LTER program. Midway through the funding period, external peer review teams visit each site to evaluate the quality of science, education, and outreach as well as how well the site is managed and how integrated the sites are with the entire LTER Network [31]. The site reviews also serve as opportunities for site scientists and staff to get constructive criticism from the review team and to identify potential problems that require correction [32].

1990 – The LTER Coordinating Committee developed site data management policy guidelines; LTER held its second All Scientists Meeting at Estes Park, CO.

1991 – Following an NSF Antarctic research proposal competition, a new site, Palmer Station LTER, Antarctica, was added to the network supported by funds from Polar Programs and Environmental Biology divisions; Geographic Information Systems (GIS) working group analyzed the status of LTER Network technical supplements and assessed future technical needs; and Global Positioning Systems (GPS) units were acquired for shared LTER site use and GPS training provided for representatives from all sites.

1992 – The LTER Coordinating Committee, at the request of NSF, developed an 8-year vision ("LTER 2000") for the creation of a global environmental research network based upon approaches established in the LTER Program.

1993 – A second Antarctic site, McMurdo Dry Valleys, was selected for the LTER Network; the NSF commissioned a 10-year review of the LTER Program; the third LTER All Scientists Meeting was held at Estes Park, CO; an International LTER Summit at the Estes Park meeting led to the establishment of the International LTER (ILTER) Network, with Jerry F. Franklin (U.S. LTER Chair) as Steering Committee Chair; the LTER Network Internet (gopher) server was established at the Network Office; the LTER All-Site Bibliography, Core Data Set Catalog, and Personnel Database were developed and put online in searchable form; and the North Inlet LTER site was withdrawn, leaving 18 sites in the network.

1994 – In response to the 10-year review of the LTER Program, NSF conducted a special competition for cross-site and international comparisons and synthesis; nine grants ranging from $109,353 to $200,000 were made to LTER and non-LTER sites in the United States, Ireland, Scotland, Costa Rica, Argentina, and Russia; NSF announced a special competition for augmentation of LTER projects (Box 5) for regionalization, comprehensive site histories, and increased disciplinary breadth; LTER established a World Wide Web site at the Network Office; the first International LTER (ILTER) Steering Committee meeting was held at Rothamsted, U.K.; and NSF signed Memoranda of Agreement with the U.S. Forest Service and the National Biological Survey to cooperate/collaborate in LTER Program research.

1995 – Jerry Franklin retired after 12 years of service as Chair of the Coordinating Committee and was replaced by James Gosz; LTER established a National Advisory Board; NSF announced 13 new awards for cross-site comparisons and synthesis at LTER and non-LTER sites; the LTER Publications Committee developed a plan for publication of Network research synthesis volumes; and NSF/DOE/NASA/USDA Joint Program Awards, Terrestrial Ecology and Global Change (TECO), were awarded to seven LTER recipients, including researchers at Bonanza Creek, Cedar Creek, Central Plains, Harvard Forest, H.J. Andrews, and Jornada.

1996 – The first LTER site synthesis volume (Palmer LTER) was published by the American Geophysical Union (AGU).

Box 5. Augmented LTER Sites

In 1996, NSF began an experiment that involved augmenting two LTER sites at a funding level that was double the network standard. The two sites, North Temperate Lakes in Wisconsin and Coweeta in the southern Appalachian mountains, were selected based on competitive proposals [33]. The successful proposals contained significant commitments to involve social and economic sciences and plans for developing regional-scale research.

The increased funding gave these sites the opportunity to focus on complex interactions between humans and ecological processes across a range of scales and to make significant advances in understanding the spatial, temporal, and decision-making components of land use and land-use change, and to build regional, national, and international collaborations.

The site augmentation experiment led to several significant findings by the participating sites. For example, North Temperate Lake researchers found that the economically optimal phosphorus input to lakes is often far less than estimates based on assumptions that lakes are linear, equilibrium systems with no stochastic factors and no time delays. By calculating the net economic value of water quality (based on the economics of farming, value of housing near the lake, and the recreational economy derived from boating, fishing, etc.), the researchers showed that the economically optimal phosphorus loading (which maximizes net costs and benefits to society as a whole) was about one third the current loading rate of the lake. These analyses show that the total economic value (i.e., the net benefit from all uses of the watershed, including agriculture, lakeshore property values, fishing, and other recreation) generated by the Lake Mendota watershed would increase substantially if less fertilizer were used.

At Coweeta, a spatially explicit model of land-use change over a 40-year period (1950–1990) identifying physical and human factors and determining land-use patterns for representative areas across the region showed that land-cover changes were more frequent at lower elevations and near roads. Bird diversity declined with forest patch size, which in turn influenced plant community composition. Some plant groups (e.g., *Liliaceae* and *myrmecochores*) with diaspores dispersed by ants were scarce or absent in patches subjected to intensive past land use. Land-use history was more important than patch size in explaining variation in abundance and composition of seed-dispersing ants. Fish density and diversity, in particular, were more affected by upstream than streamside deforestation. The "legacy effect" and the relative importance of upstream process pointed the way toward large-scale and long-term restoration given the implication that localized efforts often had little effect.

The discovery of these dramatic effects of land-use patterns and environmental heterogeneity on populations and communities led the Coweeta LTER to begin a new 30-year study in 2000 of stream regions forecast to differ over time in type and risk of development.

1997 – A special competition resulted in addition of two new urban LTER sites (Central Arizona Phoenix and Baltimore Ecosystem Study); the Network Office officially began operation from the University of New Mexico.

1998 – An NSF competition resulted in a former Land Margin Ecological Research (LMER) site (Plum Island Ecosystem) joining the network; the LTER Network signed a contract to produce a Science Synthesis Series with Oxford University Press; Schoolyard LTER Supplements ($15,000 per year to each site) were added to LTER grants.

1999 – NSF provided funding supplements to enhance Internet connectivity at LTER sites; the LTER Social Science Committee was created; the LTER Network Office, the National Center for Ecological Analysis and Synthesis, the San Diego Supercomputer Center, and University of Kansas collaborated on the "Knowledge Network for Biocomplexity"; and a synthesis volume, "Standard Soil Methods for Long Term Ecological Research," was published by Oxford University Press.

Major Milestones in the Third LTER Decade

2000 – Three new coastal sites joined the network (Georgia Coastal Ecosystem, Florida Coastal Everglades, and Santa Barbara Coastal); the fourth LTER (and first ILTER) All Scientists Meeting was held in Snowbird, Utah, in association with the annual meeting of the Ecological Society of America; and LTER entered into a collaborative relationship with the Organization of Biological Field Stations.

2001 – NSF conducted a 20-year review of the LTER Network; LTER celebrated its twentieth Anniversary; and the LTER Education Strategic Plan was published.

2002 – The first of what became an annual series of NSF-LTER Mini Symposia was held in Washington, DC; the LTER Network Information System Advisory Committee (NISAC) was formed; and the LTER Strategic Plan ("LTER 2000–2010: A Decade of Synthesis") was published.

2003 – The Cooperative Agreement for the LTER Network Office at the University of New Mexico was renewed; the fifth LTER All Scientists' Meeting was held in Seattle, Washington, in association with the Estuarine Research Federation; a Special Issue of *BioScience* focused on the Long-Term Ecological Research Network; the LTER Coordinating Committee approved a formal set of bylaws for the LTER Network; and the U.S. International Committee was formed.

2004 – The first LTER children's book, "My Water Comes from the Mountains," was published; two new sites (California Current Ecosystem and Moorea Coral Reef) joined the LTER Network; and the LTER Network received a grant from NSF to conduct network-level strategic planning.

2005 – The first LTER Graduate Student Collaborative Research Symposium took place at Andrews Experimental Forest; and the LTER Network Office "Strategic Plan" and "Implementation Plan" were published.

2006 – Jim Gosz stepped down after 10 years as Chair of the LTER Coordinating Committee and was replaced by John Magnuson; the Sixth LTER All Scientists' Meeting was held at Estes Park, CO; and the LTER Coordinating Committee approved a new LTER governance structure consisting of a Science Council and an Executive Board (Box 6).

2007 – Phil Robertson was elected Chair of the LTER Executive Board and Science Council; the "Decadal Plan for LTER," incorporating an integrated research plan, a description of the EcoTrends project, a Strategic Plan for Education, a Strategic Plan for Cyberinfrastructure, a new governance plan, and the "Integrative Science for Society and the Environment" document, was published; and "Principles and Standards for Measuring Primary Production" was published as part of the LTER series by Oxford University Press.

2008 – The LTER Network and the National Phenological Network signed a MOU for cooperation in phenological monitoring and assessment.

2009 – The seventh LTER All Scientists Meeting was held at Estes Park, CO; the LTER Network Office core funding was renewed and a separate award was made by NSF to facilitate synthesis and the development of network cyberinfrastructure.

2010 – The LTER Network received the Distinguished Scientist Award from the American Institute of Biological Sciences (AIBS); NSF initiated a 30-year review of the LTER Program; and LTER created a Communications Committee and a Networks Coordination Committee.

2011 – Scott Collins was elected Chair of the LTER Executive Board and Science Council.

Box 6. Governance Structure

The Network is governed by bylaws enacted in 2003 by the *Coordinating Committee*, at that time the governing body of the LTER Network. The bylaws established a new governance structure consisting of an elected *Chair* and an *Executive Board* comprising nine rotating site representatives and one non-voting member selected to provide expertise on information management. Site representatives are the lead principal investigators of each LTER site. The Chair and the *Executive Director* of the LTER Network Office are ex officio members of the Executive Board. The *Science Council*, with a membership that includes two representatives from each site and the chairs of each Standing Committee, establishes the scientific direction and vision of the LTER Network. The voting membership of the Science Council (the 26 lead principal investigators from each site) reserves ultimate authority for decisions affecting the network. Ten *Standing Committees* (Climate, Communications, Education, Graduate Students, Information Management, International, Network Information System, Networks Coordination, Publications, and Social and Economic Science) support and inform the governance process. A *Network Office*, (see Box 2) funded separately by the National Science Foundation, facilitates research, education, information management, and governance activities (Fig. 5).

The LTER Network Today

Twenty-six research sites and a central coordinating office constitute the LTER Network at present, and more than 1,500 scientists are involved in research at these sites. The annual budget of the LTER program approaches $30 million (Fig. 6). The Network includes a wide range of ecosystem types spanning broad ranges of environmental conditions and human domination of the landscape. The geographic distribution of sites ranges from Alaska to Antarctica and from the Caribbean to French Polynesia and includes agricultural lands, alpine tundra, barrier islands, coastal lagoons, cold and hot deserts, coral reefs, estuaries, forests, freshwater wetlands, grasslands, kelp forests, lakes, open ocean, savannas, streams, and urban landscapes. Collectively, the sites in the LTER Network provide opportunities to contrast marine, coastal, and continental regions, the full range of climatic gradients existing in North America, and aquatic and terrestrial habitats in a range of ecosystem types. All sites are sufficiently large to incorporate moderate to large landscape mosaics, and most sites include human-manipulated as well as natural ecosystems. Most sites embody considerable within-site variability in habitats and ecosystem processes and attempt to characterize this variability in the context of broad regional gradients covering hundreds of kilometers.

In accordance with the factors driving the development of long-term ecological research in the United States, the LTER Network has adopted a central, organizing intellectual aim: to understand long-term patterns and processes of ecological systems at multiple spatial scales. To achieve this aim, the LTER Network focuses on six interrelated goals [7]:

Understanding: Gaining ecological understanding of a diverse array of ecosystems at multiple spatial and temporal scales.

The mission of the LTER Network begins with research based at individual sites, each of which has a unique theme. This site-based focus has allowed for key scientific advances at each of the sites, while the common focus on long-term research in a diverse array of ecosystems and landscapes has facilitated broad comparisons and syntheses across sites. Together the network of sites covers a wide range of subjects at multiple temporal and spatial scales.

Synthesis: Using the network of sites to create general ecological knowledge through the synthesis of information gained from long-term research and development of theory.

The products of LTER research extend beyond the accumulation of knowledge about diverse, individual ecosystem types. At a higher level, synthesis of this site-based knowledge across the network provides the broader scientific understanding from which new theory is derived and general applications can be developed.

Information Dissemination: Creating well-designed, documented databases that are accessible to the broader scientific community.

Long-term research demands long-term data. The creation, curation, and dissemination of long-term databases are needed to assure that the data resources needed by researchers will continue to be available. These databases must include the additional information required to interpret data (i.e., metadata) as well as the data themselves. By adopting policies that promote the timely sharing of data (both inside and outside the LTER Network), the data can be used in a variety of ways not anticipated by the original collector such as regional, national, and global syntheses, thus providing a resource for the broader scientific community.

Legacies: Creating a legacy of well-designed and documented long-term observations, experiments, and archives of samples and specimens.

Many ecological phenomena change at decadal to century and longer time scales, and it is essential to maintain experiments and observations across periods appropriate to the questions addressed. The orderly transfer of experiments and interim results from one generation of scientists to the next requires a research design and setting that allows for multiple samplings (some unanticipated), long-term protection from competing uses, and meticulous documentation of experimental protocols. Also essential is a means to store protocols and observations in a manner that is secure and consistently accessible to the scientific community for use in syntheses and cross-site comparisons (both inside and outside the LTER Network).

Training: Developing a cadre of scientists who are equipped to conduct long-term, collaborative research to address complex ecological problems.

One of the major lessons from the first 30 years of LTER has been that success both within sites and within the network requires a nontraditional approach to ecological research. This approach is characterized by a commitment to long-term measurements that may yield only a few useful initial results but that are essential to understanding long-term change, by a willingness to work as part of large teams that may have priorities that are different than one's own, by a desire to interact closely with others in order to share ideas and data, and by the need to develop a broad interdisciplinary perspective. Disseminating this approach through the involvement of graduate and undergraduate students, postdoctoral and international scientists, and K-12 educators, students, and the general public can ensure the success of long-term ecology in the future.

Outreach: Providing knowledge to the broader ecological community, general public, resource managers, and policy makers to address complex environmental challenges.

Humanity faces increasingly numerous and serious environmental problems that range from local to global in extent, and that must be tackled by institutions at local to international scales. The LTER Network and emerging ILTER networks provide the most comprehensive and diverse system of sites for ecological observations on the globe, and research of the LTER Network has repeatedly demonstrated the ability of long-term ecological science to address these environmental challenges. Increasingly, LTER research is finding applications in the work of federal, state, and local agencies that manage environmental resources. The synoptic and detailed knowledge of individual LTER sites, and the opportunities for multidimensional comparisons among sites, also represents significant opportunities for other disciplines including social sciences, earth sciences, and basic biological sciences that must be pursued. Finally, knowledge from this breadth of views permits us to identify and anticipate new issues and challenges, test existing ideas about causation, and help provide the science that underpins the processes of open, participatory, and forward-looking decision making.

Achievements of the LTER Network

► "At each of the Network's 26 sites we know an extraordinary amount about organisms and processes important at the site, about the way the site's ecosystems respond to disturbance, and about long-term environmental change. A growing number of cross-site observations and experiments is also revealing much about the way that key processes, organisms, and ecological attributes are organized and behave across major environmental gradients. In total, research in the LTER portfolio is contributing substantially to both our basic knowledge of ecological interactions and our ability to forecast change and to test ecological theory." (p(i), [34])

LTER's long-term research and monitoring has led to important new discoveries and had a transformative effect on science and society. Hobbie [35] listed the benefits resulting from the existence of the network: value added to research sites in the network because of long-term stability; value added to ecological science because long-term sites provide ecology with sustained intellectual attention to fundamental ecological issues; LTER data bases, which are important resources for the broader scientific community; cross-site synthesis, enabling hundreds of scientists to ask similar questions in a wide variety of habitats and increasing the possibilities for creative breakthroughs from interdisciplinary collaboration; education and training of teachers and students as an integral part of research programs; cooperative research with government agencies (e.g., in national parks, wildlife refuges and reserves, and experimental forests); contributions to society through advice on public policy and environmental management; and the establishment of an international LTER Network that now numbers 40 countries, facilitating collaboration in addressing environmental challenges in different parts of the world.

In 2010, the LTER Network received the Distinguished Scientist award from the American Institute of Biological Sciences for its contributions to the biological sciences. LTER research is featured in two of NSF's "Sensational 60" transformative scientific discoveries or advances [36]. Results from LTER research are embodied in over 10,000 peer-reviewed publications [35], a book series from Oxford University Press, and summaries on network (www.lternet.edu) and site web sites. Since 1993, the LTER research model has been adopted by 40 other member countries of the International Long Term Ecological Research Network.

Research Progress in achieving the LTER Mission begins with the work of individual scientists, students, and educators at the 26 LTER sites. It is their work at the site level that forms the foundation of knowledge, data, observational and experimental legacies, and training that will ensure a lasting impact of the overall LTER program. Data and knowledge gained from intensive field experience are also key to development of syntheses of site-level information into models that allow prediction of long-term change and responses to human and other disturbances. Site-level synthesis activities often lead to new insights that feed back to affect the future course and evolution of site-level research.

Network infrastructure also promotes and facilitates cross-site and regional analyses, leading to larger-scale syntheses and to development and testing of ecological theory. In this work, the maintenance of a network database and protocols for data discovery and acquisition are particularly important. These efforts add to the basic body of scientific knowledge of long-term, large-scale ecological phenomena and, because students are deeply involved both at the site level and in intersite and network-level syntheses, they help to increase the numbers of people with appropriate expertise in both research and environmental problem solving.

Ultimately, both site and network-level activities feed back to the development of scientific capital, which includes well-trained scientists, a well-informed citizenry, and the basic data and understanding that underpin them. This accumulation of scientific capital also leads to new research and new applications of LTER research, including new forms of support for both research and education. Growth of scientific capital also includes interactions with new scientific disciplines, leading to expansion of the scope and applications of LTER research.

Research at LTER Sites The LTER Network comprises sites chosen competitively on the basis of research excellence, quality and duration of existing data sets, and strength of the commitment to long-term research and site security. The 26 sites that constitute the network at present represent a wide variety of research emphases and approaches. As part of their commitment to the LTER program, each site conducts a series of measurements and experiments directed toward the understanding of the five core areas as well as studies addressing ecological issues specific to the site. The most common scientific approaches include observation, experimentation, comparative analysis, retrospective study, and modeling, although emphases differ among sites. A sampling of key research results from LTER sites provides an idea of the potential impact of LTER research.

The Ecosystem Value Of Dead Wood – H. J. Andrews LTER scientists revealed the importance of dead trees to diversifying animal habitat and sustaining the flow of vital nutrients in forests and streams by tracking how fallen and standing deadwood changes as forests age. These studies profoundly influenced forest management by prioritizing the retention of dead wood in forests and streams.

Arctic Warming – Arctic LTER scientists discovered how Arctic warming is increasingly thawing frozen ground (permafrost), creating hot spots of erosion, nutrient release into rivers, and decomposition of ancient organic carbon. This information is essential for managers and policymakers grappling with how to mitigate and adapt to future climate change.

Fire and Climate – Through long-term studies of fire cycles and their links to climate, Bonanza Creek scientists have documented an increase in fire severity brought on by climate warming that will likely shift the Alaskan boreal forest from a spruce- to a broadleaf-dominated landscape.

New Climate Pattern – Long-term observations allowed California Current Ecosystem scientists to define a new climate pattern called the North Pacific Gyre Oscillation (NPGO), which links physical ocean changes, such as fluctuations in salinity and nutrients, with biodiversity and ecosystem processes in the eastern North Pacific. This climate pattern may affect marine ecosystems around the world.

Biodiversity Matters – Cedar Creek scientists discovered that the number of plant species in an ecosystem – its biodiversity – has a profound and surprisingly strong effect on ecosystem function. Long-term experiments have shown that ecosystems with greater plant species diversity are more productive and stable.

Integrative Research – Central Arizona-Phoenix scientists spearheaded efforts to integrate ecological and social research in urban ecosystems. Such interdisciplinary research has changed the way scientists and citizens perceive the natural environment in cities, transformed environmental education at all levels, and informed problem solving in cities.

Future Nitrogen Cycling – Drawing on two decades of research, Coweeta researchers discovered that warmer temperatures increase peak nitrate loading to forest streams during the growing season. These findings suggest that climate warming will triple the nitrogen export from forests, reducing water quality and long-term forest productivity.

Productivity Paradox – Florida Coastal Everglades scientists revealed how human-induced nutrient enrichment in the Everglade and Caribbean wetlands affect the "productivity paradox" in which an extraordinarily high level of algal growth supports far fewer aquatic animal consumers than expected. Understanding this dynamic is critical to the restoration of the Everglade ecosystems.

Sea-Level Rise – Georgia Coastal Ecosystem scientists predicted how rising sea levels will impact coastal marshes and reduce the benefits they provide society, such as clean water and fish habitat. Analyses have shown that new marshes created by rising waters do not fully offset the loss of existing marshes.

Legacies Shape Ecosystems – Using its century-long studies, Harvard Forest scientists have documented the persistent influence of human and natural history in shaping modern forest ecosystems. Ancient land use practices and prior forest conditions continue to influence a forest's potential to grow trees, respond to disturbance and stress, and support diverse plants and animals.

Shifting Songbirds – Hubbard Brook scientists have produced the longest continuous songbird record in North America and discovered that changing habitat, land use practices, and climate in eastern forests, tropical forests, and migratory routes drive the abundance of these beloved forest musicians.

Grassland Tipping Points – Jornada LTER scientists discovered that grasslands, shrublands, and other ecosystems have "tipping points," where dramatic and rapid changes can occur once certain thresholds are reached. A better understanding of these thresholds is paramount to management and protection of grasslands and other ecosystems.

Agriculture and Climate Change – Kellogg Biological Station researchers discovered and quantified how different crop management practices can interact to provide novel opportunities for greenhouse gas mitigation by agriculture. These discoveries inform agricultural greenhouse gas policies worldwide.

Sensitive to Change – Using long-term data on plant productivity and novel experiments to manipulate rainfall, Konza Prairie scientists demonstrated that grasslands are among the most sensitive ecosystems to changes in the water cycle. This research helps forecast the impact of climate change on the carbon balance of individual plants to whole ecosystems.

Tropical Carbon Cycling – Luquillo Experimental Forest scientists discovered that carbon cycling in tropical forests is highly sensitive to climate. Relatively small increases in temperature can decrease the ability of tropical forests to store carbon recently captured by photosynthesis, thus accelerating climate change.

Chain Reaction – McMurdo Dry Valleys scientists documented how even small variations in climate can drive major changes in polar ecosystems: Seemingly slight changes in temperature can set off a cascade of magnified responses that affect stream flow, nutrient cycling, and biodiversity.

Diversity Matters – Coral reef ecosystems are highly sensitive to disturbances and climate change. Moorea Coral Reef research documented how genetic and species diversity among corals and their symbionts helps corals to rapidly adapt to changing environmental conditions such as warming seawater and ocean acidification.

Early Warning Signs – Niwot Ridge research indicates that alpine ecosystems provide important early warning signs of global climate change. Alpine plants and animals survive on the razor's edge of environmental tolerances, making them more sensitive to changes in climate than downstream ecosystems.

Tracking Ice Cover – By synthesizing long-term records of lake and river ice cover throughout the Northern Hemisphere, North Temperate Lake scientists discovered long-term climate-induced reductions in ice cover on freshwater ecosystems over the past 150 years.

Penguins and Climate Change – Palmer Station scientists have documented a 75% reduction in Adélie penguin populations since 1980 and determined the cause to be altered cloud cover, winds, snowfall, sea ice cover, and other climate changes.

Tipping Points – Plum Island Ecosystem scientists discovered regionally specific "tipping points" beyond which marshes can no longer keep up with rising sea levels, and that human alteration of watersheds can either enhance or compromise a marsh's ability to survive in the face of rising sea levels.

Underwater Forests – Giant kelp provides critical food and shelter for a wide diversity of economically important organisms. An interdisciplinary team of Santa Barbara Coastal scientists discovered that kelp plants disperse their reproductive spores over surprisingly great distances, furthering our understanding of how these important ecosystems establish and survive.

Climate and Disease – Long-term observations and experiments by Sevilleta LTER scientists revealed an important link between human hanta virus outbreaks and the population dynamics of small mammals in the southwestern United States as affected by changes in climate systems such as El Niño. The discipline of the ecology of infectious diseases that this research helped to establish is now a transformative area of ecological research.

Plague and Prairie Dogs – For over two decades, Short Grass Steppe scientists have observed black plague spreading through populations of the black-tailed prairie dog, an endangered species candidate. The effects of the resulting die-offs ripple through other populations including other rodents, flowering plants, pollinators, and large herbivores.

Dynamic Coastal Landscapes – By tracking long-term shifts in land cover on undeveloped coastal barrier ecosystems, Virginia Coast LTER scientists have learned how sea-level rise and storms interact to create a highly dynamic landscape. While the locations of lagoons, marshes, and other coastal ecosystems have changed over time, they have not experienced a net reduction in the area they cover.

Cross-Site Research and Synthesis In addition to transformative site–based research, LTER scientists conduct synthetic studies focused on general ecological principles underlying diverse ecosystems [22, 26, 35, 37–47]. Johnson et al. [21] demonstrated the evolution of the LTER program from a collection of research sites with common goals to a highly connected research network. A few examples illustrate the breadth of LTER cross-site research.

EcoTrends – The EcoTrends Project [47] is a collaborative effort among state and federal agencies and institutions in the United States to make long-term ecological data easy to access, analyze, and compare within and across sites (see http://www.ecotrends.info). The project is designed to promote and enable the use and synthesis of long-term data to examine critical trends (e.g., climate, land cover, and habitat availability) in the Earth's ecosystems. In addition to ecological data collected by participating sites, the EcoTrends database includes ancillary data from other sources. For example, LTER investigators obtained human population and economic data from 1790 to 2000, which was one of the four types of data being synthesized in the EcoTrends Project. The "Human Population and Economy" dataset contains over 200 separate variables suitable for describing changes in population and economic structure since the end of the eighteenth century. The dataset was collected for each of the more than 250 counties associated with the 21 continental North American LTER sites plus the Luquillo site in Puerto Rico. These datasets, tools, and information are available to anyone who would like to view trends in ecological variables for one or multiple sites or pursue additional statistical analyses of within-site and cross-site comparisons.

Climate Database (CLIMDB) and Hydrology Database (HYDRODB) – LTER sites have generally followed established LTER Climate Committee guidelines (see [29]) for collecting baseline meteorological data. Standardized measurements provided a basis for coordinating meteorological measurements at two or more sites and enabled intersite comparisons, but access to comparable datasets from multiple sites was often problematic because most sites, while making climate data accessible online, displayed them in different formats and aggregated them using different methods. Similarly, sites that conducted long-term hydrologic measurements needed to establish access to their long-term datasets for streamflow, precipitation, and ambient air temperature, in addition to the hydrologic data. LTER developed ClimDB and HydroDB in response to the science-based need for standardized measurements, format, and aggregation of these data. LTER sites, along with USGS, and USDA Forest Service sites, contribute climate (http://www.fsl.orst.edu/climhy/) and hydrological (http://www.fsl.orst.edu/hydrodb/) data, which are stored in centralized servers that provide open access to long-term meteorological and stream flow records from these research sites.

Long-Term Intersite Decomposition Experiment Team (LIDET) – Sixteen LTER sites participated in a 10-year, 28-site experiment to test the effect of substrate quality and macroclimate on long-term decomposition and nutrient dynamics – particularly the degree to which these two factors control the formation of stable organic matter and nitrogen after extensive decay. Reciprocal litter transplants of 27 species were conducted at sites in North and Central America. Decomposition rates were strongly affected by substrate quality, but climate also resulted in strong and consistent effects [25]. Large-scale patterns were better explained by variables including both moisture availability and temperature. In general, roots decomposed more slowly than leaves, but ratios of aboveground to belowground decomposition rates varied across ecosystem types. Predictions of decomposition rates were possible using uncomplicated models based on litter quality and climate, but ecosystem-specific factors also contributed to observed differences (see http://andrewsforest.oregonstate.edu/research/intersite/lidet.htm for more information).

Lotic Intersite Nitrogen Experiment (LINX) – The Lotic Intersite Nitrogen Experiment was a collaborative study of nitrogen cycling in streams involving simulation modeling, field tracer (^{15}N) additions, and intersite comparison. The central hypothesis was that the considerable variability among streams in uptake, retention, and cycling of nitrogen is controlled by key hydrodynamic, chemical, and metabolic characteristics that determine water retention, degree of nitrogen deficiency, and energy flow through food webs in stream ecosystems. LINX I ran from September 1996 through August 2001 and resulted in 26 publications, 7 theses and dissertations, and 69 presentations. The study demonstrated that the smallest streams had the highest uptake of inorganic nitrogen, and that small streams were potentially significant sources of atmospheric nitrogen via nitrification.

LINX II was a 5-year project that began in September 2001 and ended in 2006. Data from tracer experiments across 72 streams and eight regions representing several biomes showed that biotic uptake and denitrification were less efficient at removing stream nitrate in streams with high nitrate concentrations. As a result, high nitrate streams export a disproportionate amount of nitrate to receiving waters. In addition, these patterns suggest that small streams become less important as nitrate sinks as nitrate concentration increases [48].

In addition to the specific cross-site and intersite research mentioned above, LTER sites also participate in numerous long-term interdisciplinary and multi-site syntheses with both LTER and non-LTER organizations. These include studies of above- and belowground productivity, carbon dioxide (CO_2) and climate change, biodiversity, disease control, microbial ecology, remote sensing, and geographical information systems, the adsorption of trifluoroacetate (TFA) in soils, among others.

National and International Networking – As a global leader in long-term and broad-scale ecological research, the LTER Network establishes linkages with existing and developing long-term ecological research programs in the United States and abroad. These relationships range from exchanges at the individual scientist and site research program levels, to participation in national and international meetings, to global-scale research planning and collaboration.

Nationally, LTER develops innovative partnerships with leading ecological research organizations and synthesis centers; facilitates the advancement of current ecological science and innovative research technologies; develops strong multidisciplinary science and public education programs; and pursues a multi-agency approach to develop databases of long-term research in key biomes and along major gradients.

Internationally, LTER assists in the establishment of networks for long-term ecological research worldwide; creates opportunities for collaboration between US and International LTER sites and networks; develops and operates a communication and data-sharing system among an international network of sites; facilitates the establishment of a global network of environmental research sites; and participates in other international scientific efforts.

Education Education and outreach efforts are integral aspects of the LTER program. As a network of sites with a preponderance of academic scientists, graduate and undergraduate education is central to the goals of the network. Students at both graduate and undergraduate levels are routinely engaged in collecting LTER data, performing experiments, and analyzing results. This participation forms an important part of their educational experience, and hence education and research are highly integrated in most LTER programs.

The network has many examples of former undergraduate students that have become research scientists in the LTER program.

In addition, LTER provides a unique opportunity to address the educational needs of teachers and students from grades K-12. As a long-term program, LTER has the potential to provide continuous opportunities for students to participate and learn throughout their entire academic life.

The LTER Network has adopted a strategic vision for education and outreach with three components. The first component addresses the structure needed to enable LTER research to have a public impact. This structure includes leadership within the network, a distributed organization that provides resources for sites to implement education programs at the local level, and cyberinfrastructure that enables broad collaboration among local education projects and between researchers and educators. The second element of the LTER vision for education establishes the goal of conducting programs in research and development that address environmental science literacy by respecting and including the diverse perspectives that exist within the LTER Network. The final aspect of the LTER vision addresses inclusion of key constituent groups, including K-12 teachers and administrators, undergraduate and graduate students and professors, and end citizens active in LTER communities.

K-12 Schoolyard LTER Program In 1998, LTER formally expanded its education efforts to include K-12 students and teachers, mainly through the Schoolyard LTER (SLTER – http://schoolyard.lternet.edu/) program, which is funded through supplements by NSF's Division of Environmental Biology (DEB). The SLTER approach emphasizes the connection to local communities, for which an LTER site can serve as a "schoolyard" for understanding ecology and environmental science. The sites design their own programs in relation to the ecological research conducted at the site and the particular needs and resources of the local school district and community ([49], http://schoolyard.lternet.edu/LTEREduHandbook.pdf). SLTER funds support a wide range of education activities, including field trips and lab work for students, teacher professional development workshops, teaching supplies, community outreach, and program and research coordination. The schoolyard approach is particularly consistent with the development of empathy for their local environment ("Environmental Empathy") as discussed by Sobel [50] as a basis for teaching elementary age students. All the 26 LTER sites participate in the SLTER program.

As the SLTER program matured, LTER scientists devised the idea for a Children's Book Series to supplement SLTER activities – thus using children's science literature to overcome "ecophobia" while fostering environmental empathy [51]. The series currently includes three titles: "My Water Comes From The Mountains" by Tiffany Fourment (Note: the title has since been modified to reference specific mountains, e.g., "My Water Comes From The Rocky Mountains" and "My Water Comes From The San Juan Mountains"), "The Lost Seal" by Diane McKnight; and "Sea Secrets" by Mary M. Cerullo and Beth E. Simmons. Each book is richly illustrated with scenes derived from the story, with many artworks and sidebar comments by elementary school children.

Graduate and Undergraduate Education The LTER science community includes academic and government scientists and educators, graduate and undergraduate students, and professional staff. The research conducted at the sites is diverse, encompassing all aspects of ecology and ecosystem science, as well as investigations in atmospheric science, hydrology, and geomorphology. As centers of excellence in ecological research, LTER sites hosted by universities, government agencies, and nonprofit research institutions also provide important training grounds for the next generation of scientists and leaders. LTER offers opportunities for graduate and undergraduate training and education. Many undergraduate and graduate students are supported directly from LTER awards each year and others use LTER facilities and equipment in support of their research programs. In addition, the LTER Network, through its association with other networks worldwide, provides opportunities for the international interchange of students and faculty.

In addition to typical university-based training, many LTER sites are involved in NSF-funded Integrative Graduate Education and Research Traineeship

(IGERT) programs, and serve as hosts for Undergraduate Mentoring in Environmental Biology (UMEB) and Research Experience for Undergraduates (REU) site activities. The programs integrate field and laboratory techniques with education, providing the students with deeper understanding of the scientific process in ecology.

Most LTER sites or their home institutions participate in the REU and UMEB programs, which offer opportunities for students at both LTER and non-LTER institutions to work with LTER scientists. Participating sites fund REU students through separate grants and supplements or out of project funds. REU students receive stipends and course credit and work closely with scientist mentors on ongoing site research programs or specially designed projects. The UMEB program provides stipends to minority students during the summer and academic year to undertake independent research projects in environmental biology under the direction of departmental faculty. Students in the program come from a wide variety of disciplines including chemistry, geophysics, and biology. Some sites provide similar opportunities through private foundations and other sources.

LTER Education in the Future The LTER Network has adopted the goal of advancing the theory and practice of ecological and environmental education at all levels and in all areas of LTER expertise. The LTER sites and network are uniquely poised to promote education at the program, institution, state, and national levels. This work builds on, and is linked closely to, LTER scientific expertise in its five core research areas and its long-term, comparative approach. LTER education addresses some of the most important but vexing objectives for ecological and environmental education; that is, it uses outdoor, inquiry-based teaching and learning to build ecological literacy; it creates effective strategies for interdisciplinary and collaborative learning about ecology and it teaches about local ecosystems while fostering an understanding of distant ones as well. Strategic objectives for future LTER education programs [2] include:

1. Expanded resources for education and outreach at both site and network levels by developing new funding sources and improving coordination with existing education and outreach programs
2. Increased participation by LTER sites in education and outreach through collaboration, coordination, training, and exchange of best practices among sites
3. Preparation and dissemination of new instructional materials designed and developed through strategic partnerships with constituent organizations, with particular attention to the needs of traditionally underrepresented groups
4. Development of metrics to evaluate and guide education and outreach activities at site and network levels
5. Increased use of appropriate cyber technologies to improve indication among partners and to disseminate educational and outreach materials more effectively
6. Regular adaptive assessment by external evaluators to monitor progress of LTER education and outreach programs and to design new approaches when necessary

Data and Information Long-term research and synthesis demands the long-term stewardship and ready accessibility of data. The creation, curation, and dissemination of long-term databases are needed to assure that the data resources needed by researchers will continue to be available. In addition, by adopting policies that promote the timely sharing of data (both inside and outside the LTER Network), scientists can use the data in a variety of ways not anticipated by the original collector, including for regional, national, and global syntheses, thus providing a rich resource for the broader scientific community [2].

LTER has led the ecological community in developing protocols and practices for documenting, curating, and sharing data. The strategic goals for LTER information management are (1) to provide sources of high-quality, well-documented, and error-checked data at each site that support local science, stimulate synthesis and the creation of new knowledge, and facilitate transformative network-wide research at broad scales; (2) to improve existing data practices and information management systems at sites to make them uniformly easy to use, sustainable, and consistent with LTER protocols; (3) to develop a central network-level data discovery and integration platform comprising databases and servers connected through web services for single-portal data publication, discovery, and access; (4) to improve information flow between LTER and other networks; and (5) to evaluate recent developments in computer science, information technology and design, cybersecurity, community standards, and communication and collaboration technology for potential application in LTER Network and site information management.

The recent proliferation of long-term collaborative research programs has created a parallel need for scientific information systems that allow data, information, and knowledge to flow across disciplinary and cultural boundaries [52]. Scientific information systems expand the potential for scientific inquiry and are leading to a paradigm shift in biology [53] most evident to date in the genomic community [54]. Other disciplines, including ecology, are primed for similar dramatic changes driven in part by new tools and approaches to managing data. The success of long-term studies is measured both on the generation of new knowledge and the creation of data and information that will facilitate subsequent studies.

Future Directions

LTER is moving increasingly toward research that integrates ecological and social sciences (Fig. 7), having realized that fundamental questions related to the services that society receives from ecosystems, how these services are perceived, how perceptions affect behavior, and how behavioral changes affect ecosystem form and function are central to understanding the sustainability of ecosystems on which society depends. By blending ecological and social science theories, methods, and interpretations, LTER is better able to understand and forecast environmental changes at a time when no ecosystem on Earth is free from human influence. The *Decadal Plan for LTER* [34] laid out a plan for integrated, network-level research to address crucial long term social-ecological questions in three thematic areas: (1) land and water use change – the dynamics of urban, exurban, and working systems; (2) climate change, variability, and extreme events; and (3) nutrient mobilization and species introductions. These questions are interdisciplinary in nature, and were developed after extensive discussions and consultations among teams of biophysical and social scientists, educators, and information managers. The questions are also multi-scale, and require observations and experiments at multiple sites to test hypotheses at scales ranging from regional to continental.

In fact, LTER is uniquely positioned to address these questions for a variety of reasons related to their long-term nature, the geographic distribution of network sites, the core strength of the network's biophysical science, its considerable and growing strength in the area of coupled human-natural systems, and its commitment to K-12 education and leadership in environmental cyberinfrastructure. Nevertheless, LTER recognized that it will require new long-term social-ecological observations, experiments, and modeling to address these questions effectively; advanced environmental cyberinfrastructure to collect, store, retrieve, visualize, and integrate the resulting complex data streams; partnerships with other environmental observatory networks to achieve this integration and facilitate synthesis; and education initiatives to train the next generation of environmental scientists to address transdisciplinary issues, and to enhance environmental literacy among the public.

Specific details of how the Decadal Plan's goals are to be achieved are constantly being worked out by Network science, education, and cyberinfrastructure teams, who identify individual questions, design observations, experiments, and modeling activities to address them, and the corresponding education and cyberinfrastructure needs for the resulting transdisciplinary research initiative. Science teams are presently developing four projects to advance the goals of the LTER Decadal Plan. The first of these projects is an effort to develop future scenarios to understand the vulnerability and resilience of regional landscapes to climate and land use change. Vulnerability to future climate change is also the theme of a second working group that will examine the affects of sea-level rise, increased storm surge, ocean acidification, and increases in water temperature, loss of sea ice, and changes in fresh water inflows on coastal LTER sites. Another working group is developing an experimental approach to evaluate the sensitivities of inland social-ecological systems to climate change to be conducted on a continental scale. Finally, a fourth group will examine how changes in the global cryosphere will affect ecosystem services such as planetary cooling, sea-level regulation, carbon storage, soil insulation, and water storage. Together, these four developing projects reflect the future direction of the LTER program.

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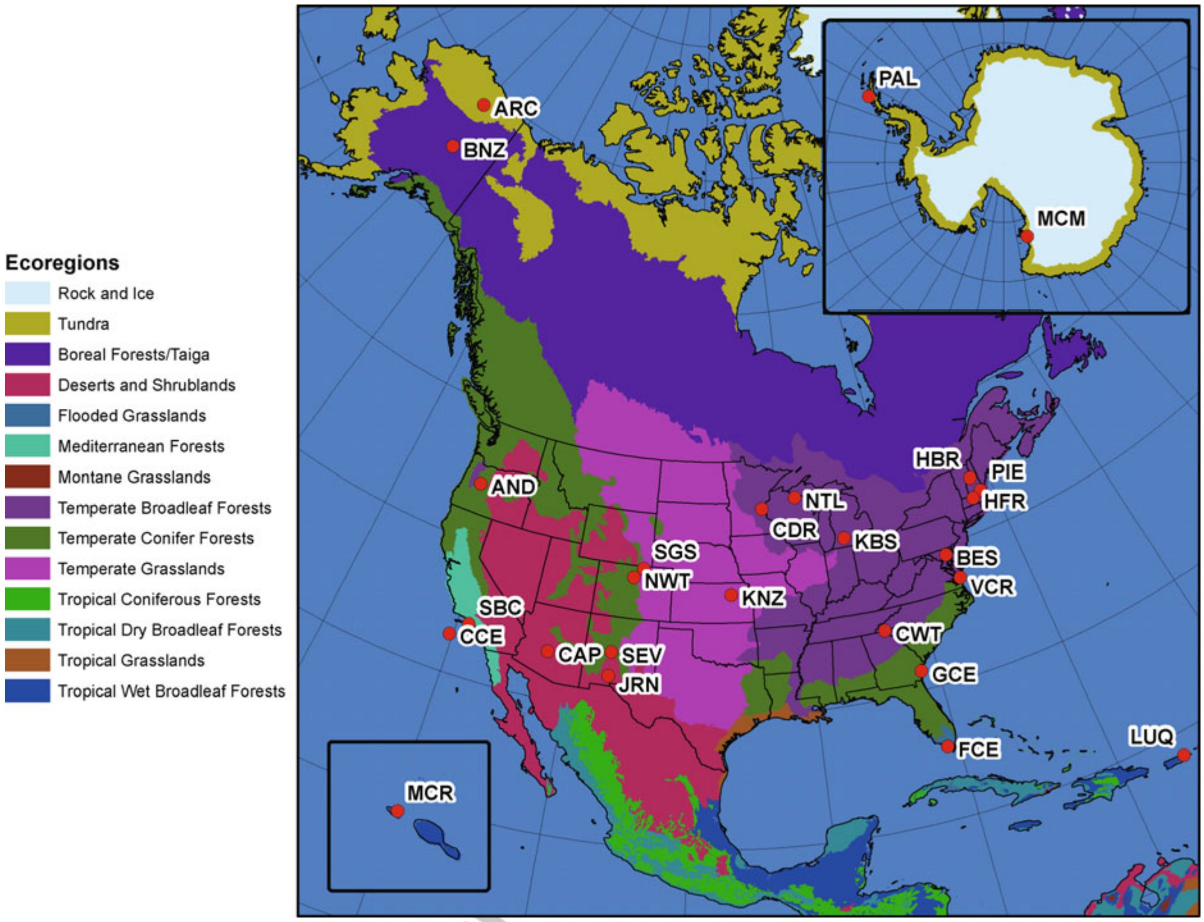
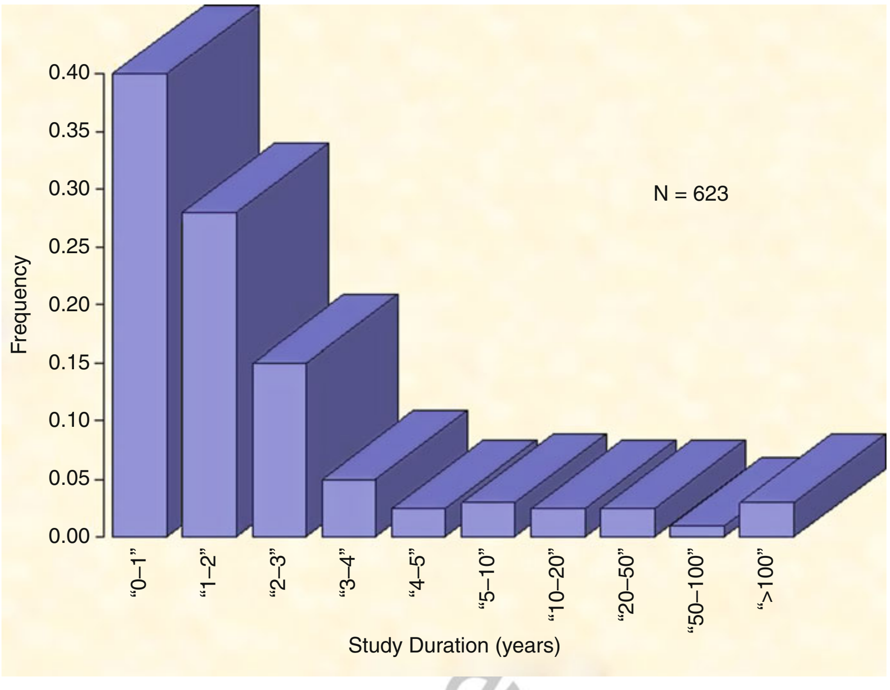
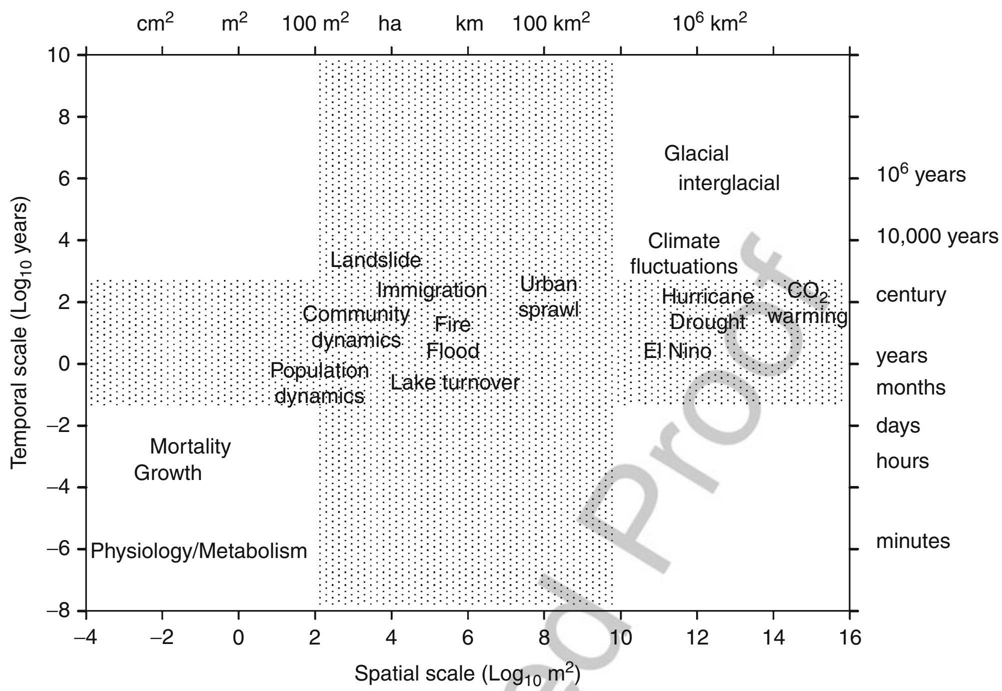


Long-Term Ecological Research Network (LTER). Figure 1

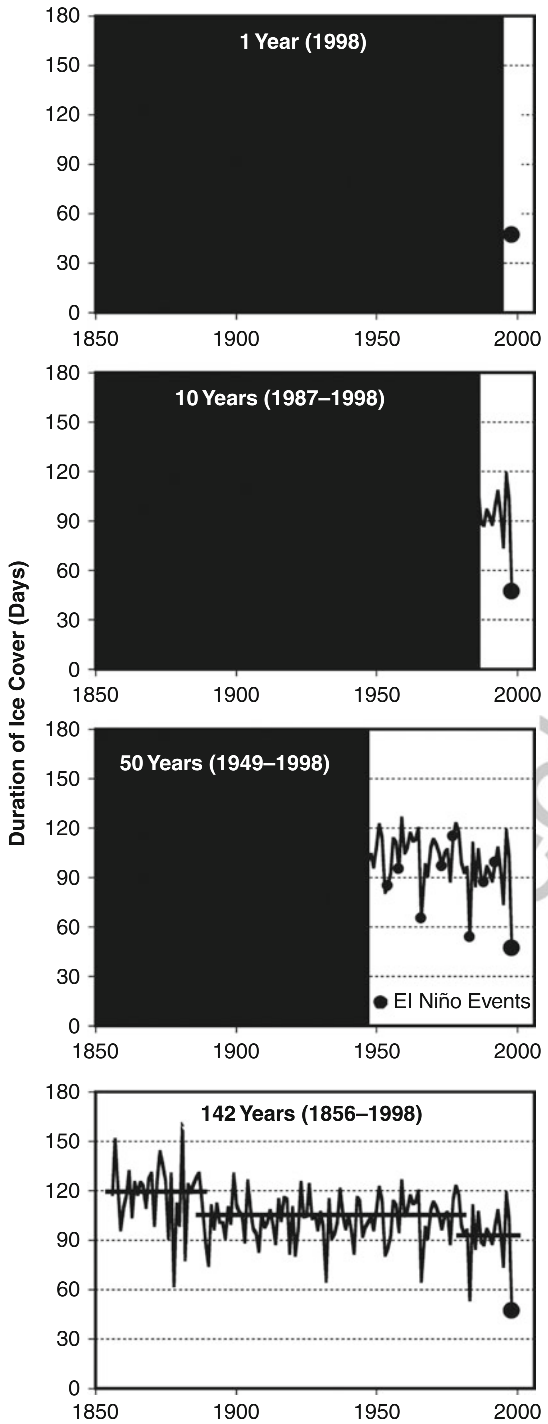
Locations of current LTER sites within global ecoregions. Site names, acronyms, and home institutions are as follows: Andrews Experimental Forest LTER (AND) – Oregon State University; Arctic LTER (ARC) – The Ecosystems Center, Marine Biological Laboratory; Baltimore Ecosystem Study (BES) – Cary Institute of Ecosystem Studies; Bonanza Creek LTER (BNZ) – University of Alaska – Fairbanks; California Current Ecosystem (CCE) – Scripps Institution of Oceanography; Cedar Creek Natural History Area LTER (CDR) – University of Minnesota; Central Arizona – Phoenix (CAP) – Arizona State University; Coweeta LTER (CWT) – University of Georgia; Florida Coastal Everglades (FCE) – Florida International University; Georgia Coastal Ecosystems (GCE) – University of Georgia; Harvard Forest (HFR) – Harvard University; Hubbard Brook Experimental Forest LTER (HBR) – Cornell University; Jornada Basin (JRN) – New Mexico State University; Kellogg Biological Station (KBS) – Michigan State University; Konza Prairie LTER (KNZ) – Kansas State University; Luquillo Experimental Forest LTER (LUQ) – University of Puerto Rico; McMurdo Dry Valleys (MCM) – Ohio State University; Moorea Coral Reef (MCR) – University of California-Santa Barbara; Niwot Ridge LTER (NWT) – University of Colorado; North Temperate Lakes (NTL) – University of Wisconsin-Madison; Palmer Station (PAL) – The Ecosystems Center, Marine Biological Laboratory; Plum Island Ecosystems (PIE) – The Ecosystems Center, Marine Biological Laboratory; Santa Barbara Coastal (SBC) – University of California-Santa Barbara; Sevilleta LTER (SEV) – University of New Mexico; Shortgrass Steppe (SGS) – Colorado State University; Virginia Coast Reserve (VCR) – University of Virginia (Courtesy of Jamie Hollingsworth; data from The Nature Conservancy [1])



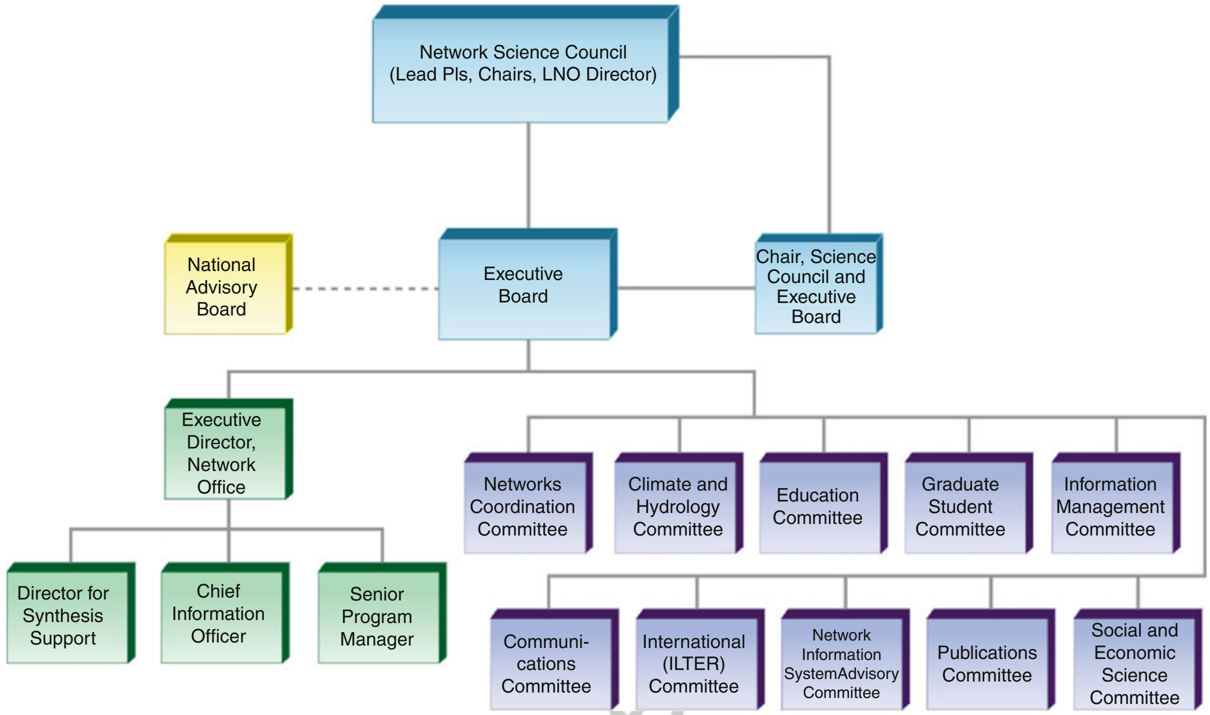
Long-Term Ecological Research Network (LTER). Figure 2
Frequency distribution of a random sample of observational and experimental studies published in the journal Ecology between 1977 and 1987 (From Gosz et al. [7]. Data from Tilman [8])



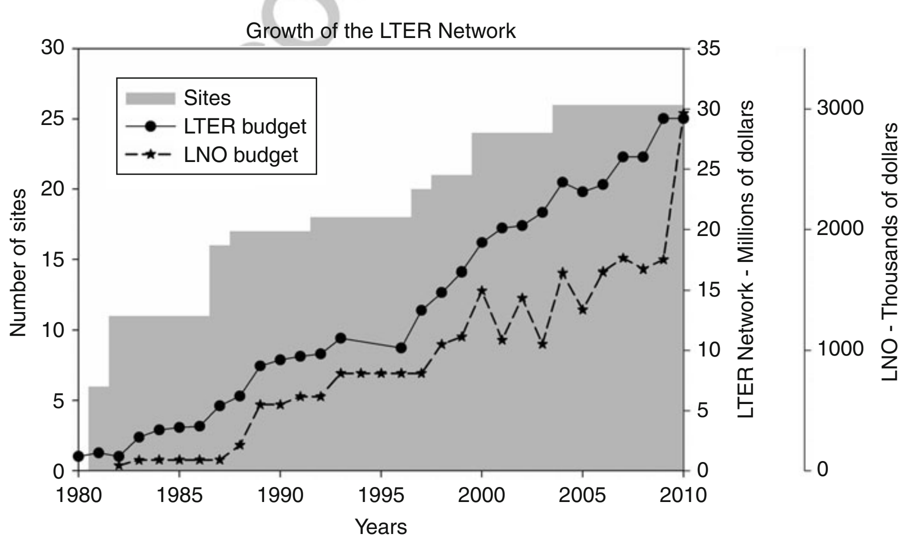
Long-Term Ecological Research Network (LTER). Figure 3
Temporal and spatial domains of the LTER program focus on biological phenomena and physical events that operate on year to century time scales and plot to regional spatial scales (Redrawn from Magnuson et al. [13], with permission)



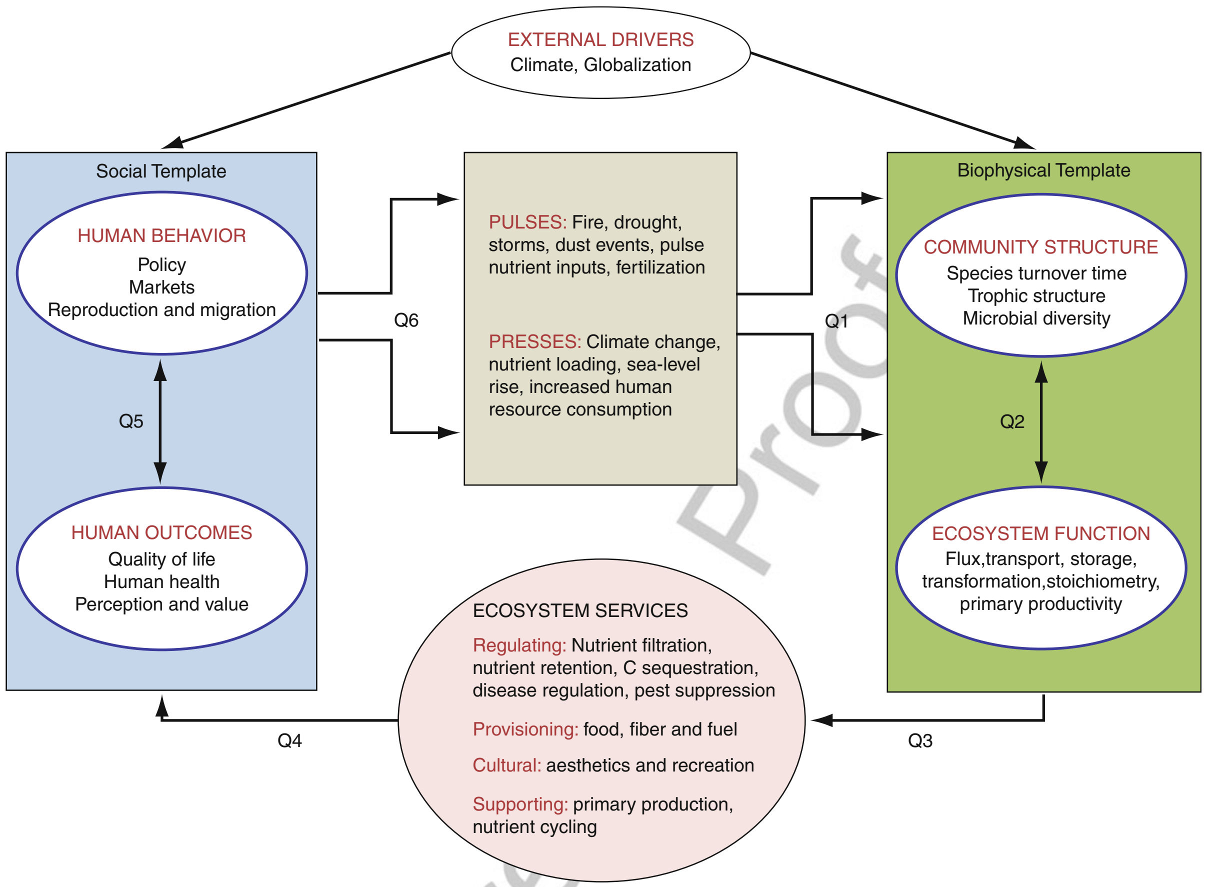
Long-Term Ecological Research Network (LTER). Figure 4
Observations of ice cover records of Lake Mendota demonstrate the importance of broad temporal scale in rendering the present visible (From Magnuson et al. [14])



Long-Term Ecological Research Network (LTER). Figure 5
Organizational chart for the LTER Network (Courtesy of Phil Robertson)



Long-Term Ecological Research Network (LTER). Figure 6
Growth of the LTER Network



Long-Term Ecological Research Network (LTER). Figure 7
Integrated science for society and the environment, a framework for future LTER research (From Collins et al. [55])