Decadal Review of the Long-Term Ecological Research Program

A Report of the 40 Year Review Committee

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Dear Colleagues:
The Advisory Committee for the Biological Sciences (BIO AC) has approved the Long-Term Ecological Research Program Report of the 40 Year Review Committee for public posting on the BIO AC web site. The BIO AC retains its prerogative to comment on the content of the report at a future date. The Advisory Committee would like to thank the Review Committee for its efforts in preparing this important report.

Dr. Michael Ibba, Chair
Advisory Committee for the Biological Sciences

I. PROLOGUE

Our charge from the National Science Foundation (NSF) was "to evaluate the significance of the long-term scientific findings and approach to research of the Long Term Ecological Research (LTER) Network over the last decade, and its readiness to support the research of future decades". The era of LTER science has been one of unprecedented advancements of ecosystem ecology, but also one of human transformations of the Earth system that were unimaginable four decades ago. During this era, the human population increased from 4.4 to 7.9 billion[1]. Anthropogenic CO_2 emissions increased from 21 to 33.5 gigatons per year[2]. Human use now directly affects over 70% of Earth's land surface[3] and now appropriates a volume of freshwater equal to half the river discharge to oceans[4]. We appropriated a quarter of net primary production from terrestrial ecosystems in 2000[5]. Nitrogen inputs for crop production increased fourfold from the 1960s to 2010[6], and the mass of plastic now exceeds the living biomass of all animals[7]. Every aspect of the Earth system is being altered by human activities, with implications for ecosystems, the biological communities they support, and life-supporting functions they provide. As the fifth decade of LTER science begins, we thought it appropriate to use human domination of planet Earth as a backdrop for evaluating the significance of the LTER program and the challenges and opportunities it faces as global changes accelerate.

LTER is poised to make great progress on synthetic, cross-ecosystem science that builds on decades of high-quality, site-specific research. A central conclusion of this report is that a foremost strength of LTER science is, and should remain, site-based research; however, we anticipate that some of the most important, transformative scientific discoveries in the coming decades will stem from use of LTER site data to address large-scale problems and questions. LTER is in the early stages of embracing the distributed network of sites to answer questions about ecological change and the mechanisms underlying that change across scales beyond local ecosystems. Hence, we see LTER at a transition point in its trajectory, with an opportunity to ask, and potentially answer, continental-, basin-, and global-scale questions based on comparative analyses across ecosystems. The challenge facing LTER in the next decade remains how to leverage the rich site-based knowledge for broader initiatives, while sustaining high quality, place-based research that remains the primary strength of the program.

II. EXECUTIVE SUMMARY

We have identified two major priorities that should be a focus of LTER activities in the coming decade.

1) After four decades of site-based observations, experiments and theory development, the LTER network has a unique opportunity to project and offer solutions to human-driven alterations of ecosystems and their life-supporting functions.
2) Following decades of work the LTER network has now established trusted and well-developed relationships with local communities – we see these relationships as having matured to the point where the network can now make demonstrable progress toward advancing Diversity, Equity, and Inclusion across the Ecological and Earth Sciences.

We view these two priorities with a strong sense of urgency and see the LTER network as one of the few ecological programs in the world positioned to make real progress in these areas over the coming decade. In this report, we offer 12 recommendations for strengthening the network over the next decade. We also offer numerous paths that we view as opportunities to make progress toward these recommendations. It is our hope that actions toward these recommendations will improve the network's capacity to address these two priorities in the coming decade.

Strengths

1. The LTER program plays an outsized role in driving the direction and establishment of new research frontiers in Ecology, and more generally in the Earth and Environmental sciences, including oceanography, hydrology, and climate science. Over the past decade, the program has demonstrated outstanding productivity, amassing >8,000 peer-reviewed publications and numerous graduate student theses from 2009 through 2018*, and offering substantial return on investment through leveraged funding. The effectiveness of LTER science is further demonstrated by its reach into local communities, schools, and use of program resources (data, people, physical infrastructure) providing opportunity for LTER to engage in conservation, environmental planning, and resource management.
2. The strength of the LTER network lies with high-quality, place-based, long-term observations and experiments conducted across a spatially distributed network of sites. This research will become increasingly valuable to our understanding of temporal and spatial ecological change across time and space scales ranging from hourly to decadal, local to regional. Such observations will become increasingly valuable to our understanding of temporal and spatial ecological change.
3. Over the past decade, LTER has made considerable progress in comparative, cross-site, synthesis science. This includes high-profile publications in top journals (e.g., Science, Nature, PNAS, Trends in Ecology and Evolution) and a large number of other top tier publications in a wide range of discipline-specific journals. Impressively, a considerable fraction of this science productivity has derived from funding leveraged against the core program support.
4. The model of longevity in funding (6 yr grants with opportunity for renewal in perpetuity) is unique to LTER, and this model allows the establishment of trusted research, education, and outreach partnerships. There are notable examples where

sites have utilized this long-term funding model to develop meaningful and highly effective educational and community outreach programs. Moreover, stability in funding allows for the development and pursuit of creative, higher risk science.

5. LTER has been able to define well-established educational and research programs (K-12, REU programs) that have been successful in engaging students from underrepresented minority groups in site science activities. LTER has a successful record of training graduate students and post-docs and these early career scientists benefit from networking opportunities afforded because of the network of sites. Moreover, the network model provides an advantage to retaining and tracking the professional and career trajectories of students trained within LTER.
6. The intellectual capital at LTER field sites and stations, deriving in many cases from people with deep historical ties to field sites, is profound, as is the accessibility of historical site-specific data essential for contextualizing contemporary science. Moreover, physical resources (equipment, sampling infrastructure, etc.) add significant value to sites.
7. Where successful, integration of social and ecological sciences by LTER sites has proven transformative. Human activities have touched on ecological processes in all of the ecosystems studied by LTER. In some cases, particularly for the urban LTER field sites, human activities are primary components of ecosystem function. How humans interact with and modify their environments will continue to be a focal point of ecological research in the coming decades. The LTER network is well poised to capitalize on the burgeoning area of research that studies the role of human actions and decisions, including ecosystem management, as central components of ecological processes. Continued focus on and expansion to LTER science that includes human-ecological interactions could prove a springboard for attracting a more diverse community of scientists, students, and educators into the disciplines of Ecology and Earth Sciences.
8. Data management has significantly improved with the establishment of the Environmental Data Initiative. This change, since the last decadal review, has positioned LTER to better provide data needed for synthesis work, and has helped strengthen the utility of LTER science for use among other observational networks. LTER site PIs and information managers have demonstrated commitment to providing FAIR (Findable, Accessible, Interoperable, and Reusable) data to the research community, a step that will enable the reuse of LTER data for future continental-, basin-, and global-scale research.

Challenges

1. Each decadal review of the LTER Program has provided guidance about what has been described as a “tension” between balancing site-based research and conducting network-level (cross-site, collaborative) science. LTER was conceived, funded and organized to use sustained observations and experiments to develop theories and principles of ecosystem dynamics. To date, it remains highly successful in place-based ecosystem science. But there is broad recognition that the combination of observational and experimental data deriving from multiple sites contains information essential for testing the generality of theories and principles across ecosystems. All previous decadal reviews have recommended further effort to

extract that information through cross-site and cross-ecosystem syntheses of LTER data. We see evidence that LTER has functioned more as a network over the past decade. That evidence includes a growing number of collaborations and data syntheses across sites and now across networks. This easing of the tension is a result of (1) LTER support for Synthesis Working Groups, and (2) initiatives taken by groups of researchers to support collaborative synthetic studies with external funding. We laud the network for these advances. However, we note that they have been made primarily at terrestrial sites with emphasis on the ecology of plant communities (there are exceptions). Rather than a fully integrated network, LTER appears to be siloed into groups of continental, coastal, and polar ocean sites, with continental and coastal sites seeming to be more actively engaged within their own groups in synthesis science, and polar ocean sites being less engaged. The opportunity to assess the generality of theories or concepts across continental, transitional and marine ecosystems has not been exploited. We identified a number of opportunities to sustain and build on momentum of the past decade to advance syntheses of LTER and other network data within and particularly across all ecosystem types.

2. As currently structured, LTER sites are united through a shared approach to studying ecological change. But each site is currently reviewed and evaluated based on their site-specific contributions to ecological science, rather than cross-site, network-level findings and scientific advances. As a result, the network aspects of LTER science are currently largely conducted on a post-hoc basis, where sites strive for excellence in their own place-based research and then look to identify commonality in trends or ecological patterns across sites or ecosystems as a means to comparative syntheses. We have tried to identify more proactive and deliberate approaches to moving LTER further toward syntheses. We hope these ideas might also enable greater flexibility in site resource allocation. Our ideas include potential revisions to the five core area model to develop cross-cutting thematic research foci and network-wide, purposeful discussions, identifying unifying research questions that might guide network-level science across all sites. Such intentional planning would structure data collection around a common set of questions, catalyzing future use of LTER data for cross-site and cross-ecosystem syntheses.
3. The role of social sciences in LTER remains unclear. There are notable examples where the integration of social science has been transformative and LTER has been instrumental in the development and advancement of the trans-discipline of socioecology. However, it is unclear if NSF views socioecology as within or outside of ecological science. LTER has now trained generations of scientists at this interface, yet there is a lack of clarity about the extent to which socioecology is supported by NSF core programs, or whether research on the role of humans in ecosystem processes is viewed by NSF as mainly supported by cross-Directorate collaborations such as Dynamics of Integrated Socio-Environmental Systems (DISES). Given this uncertainty, it is difficult for PIs to make decisions about what types of socioecological processes to study within the scope of LTER.
4. LTER efforts toward diversity, equity, and inclusion (DEI) are in early stages of development. A formal LTER DEI committee was initiated in 2019 and that committee has begun sharing ideas on DEI activities across sites. Given the severe

underrepresentation of students and faculty of color in both Ecology and Earth sciences across the United States, the LTER network is in a unique position to take a leadership role in changing this situation. This is one key part of the LTER community that will require coordinated, network-wide leadership, with clear guidance from NSF on expectations and goals. We recognize the challenges inherent to this model, not least including geographically dispersed sites and institutions, some not even in the US, with differences in the local underrepresented groups they serve. However, without clear leadership and a communicated vision coming from network leadership and NSF each site is left to manage this important issue on its own.

5. LTER science has progressed in an era of accelerating rates of global change as the human footprint widens and deepens. Each of the past four decades has been sequentially warmer than any previous decade; climate extremes are becoming more frequent and intense; human appropriation of water and land continues to reduce habitat and life-supporting functions for other species; a quarter of all species face extinction while the biomass of our livestock exceeds the biomass of all other mammals. While outstanding progress has been made in observational programs and advancing concepts, principles and theories of ecosystem science, the Nation's and world's ecosystems continue to degrade and species extinctions accelerate. This incongruity poses a singular grand challenge to anticipate how global change might evolve over the next few decades and to build a scientific foundation to guide action plans toward sustainability of ecosystems and their life supporting functions. We see LTER as well positioned to play essential roles in meeting this challenge.
6. LTER datasets are further along the road toward FAIR, especially with respect to being Findable and Accessible. EDI has helped in this regard through serving as a single repository for all LTER data, and by providing tools and personnel support that are bolstering the standardization and quality of the metadata associated LTER datasets. To achieve greater reuse of LTER data, particularly for the cross-ecosystem synthesis, there will need to be more effort devoted to discoverability and interoperability both within LTER and with similar networks. As datasets grow both in complexity and volume, LTER is wrestling with issues specific to indexing of data across disparate repositories and data storage (e.g., cloud- or data center-based), respectively.

Summary of Recommendations

1. As currently configured and funded, LTER functions largely as a collection of individual sites. We see opportunities for LTER to function to a greater extent as an ecological network, capitalizing on multi-decadal experiments and observations conducted at sites to answer cross-cutting questions at ecosystem, continental, and global scales. There has been notable progress over the past decade toward network functionality, much of which has resulted from initiative and resourcefulness within the LTER community. The fifth LTER decade will require continued leadership to promote and support syntheses of LTER and other network data at scales beyond the individual sites. Harnessing the collective strength of the site-based science that is the hallmark of LTER will require both NSF and LTER leaders to clearly

articulate and define a vision for the functioning of LTER as an ecological network. Given the limited budgets available for core, site-specific science, the desired expansion of network-level science that we envision will depend on continued successful leveraging of funding external to core LTER science budgets. Such opportunities may be available through NSF programs like Research Coordination Networks (RCNs) and Opportunities for Promoting Understanding through Synthesis (OPUS).

2. We see areas of the current LTER organizational structure that we think could be revised in ways that may yield additional flexibility in science, resource allocation, and data collection. For example, the growing anthropogenic footprint on Earth's ecosystems necessitates further consideration of human-ecological interactions at all LTER sites. Inclusion of human-ecological interactions as a core science theme provides new opportunities for engaging ecosystem management and conservation and for diversifying the LTER workforce. We offer suggestions on alternatives to the five-core area model that we think will provide greater flexibility in how sites allocate resources and could fuel greater scientific collaboration between sites. We view such changes as strengthening site-specific and cross-site syntheses efforts.
3. The on-going education and public outreach activities conducted and led by LTER sites are key pillars to network success. Longevity in funding provides LTER sites with a unique advantage in fostering and sustaining trusted, long-term relationships with local communities. LTER relies heavily on these relationships to engage underrepresented communities through site-based education and outreach programs. These site-based programs provide numerous examples of successful community engagement and we encourage continued focus on developing these programs. We see added benefit in providing additional opportunities for site Education and Outreach Coordinators to share information specific to their site programs, infusing new energy and enthusiasm across the network. LTER REU supplemental awards, while providing important research opportunities for undergraduate students, in some cases lack strong cohort support. Emphasis on the student experience for these REUs, specifically to forge strong cohort networks, will build support structures for REU participants, something particularly important given the role of REUs for engaging underrepresented communities into the LTER network. Finally, we see new opportunities for LTER public engagement if the network embraces human-ecological interactions as a central research theme, including possibilities of expanding network engagement *of* and partnership *with* underrepresented communities.
4. The reputation and scientific prestige associated with LTER places the network in a position to enable substantial progress toward Diversity, Equity, and Inclusion (DEI). The longevity of the funding model afforded by LTER provides unique opportunities for developing relationships, building networks, and creating opportunities to recruit, retain, and empower underrepresented individuals and communities. Now is the time for expanded efforts to increase representation by these communities at the graduate student, post-doc, staff, and PI levels. LTER has established programs for recruiting underrepresented participants at the K-12 and undergraduate student levels (e.g., Schoolyard and REUs). Nonetheless, there remain significant hurdles to advancing these students into graduate programs, post-

doctoral positions, and PI leadership positions within the network. We see a need for network-wide leadership on this topic, including conducting a top-to-bottom review of DEI activities and formulating an overarching DEI vision with clear, quantifiable metrics of success for the next decade. These efforts would also benefit from modification to the program solicitation to clearly define what success in DEI looks like and inclusion of a site-specific DEI plan. Finally, we see value in sites being evaluated (in both the mid-term and renewal reviews) on the basis of progress toward their DEI plans.

5. Over the past decade, the pathways and framework for management of LTER data have changed substantially, most notably through the creation of EDI and the responsibilities of EDI for archiving and disseminating LTER data. These changes have partly shifted data management responsibilities away from individual sites toward a central repository. However, within this new framework, we see benefit in clarifying responsibilities and roles specific to data management, data curation and harmonization for syntheses, and data publishing. Development of network-wide data management vision and mission statements will help clarify those roles and responsibilities. We see data management as central to furthering cross-site collaborations. We suggest that site information managers (IMs) be included as part of the LNO synthesis working groups. Data are a key strength of LTER - we identified several areas for improving LTER data discovery via EDI. We also see benefit to LTER synthesis efforts, notably including those stemming from the LNO working groups, in publishing the curated and harmonized data products that derive from these efforts. Finally, we see a need for solutions to the growing issue of archiving and disseminating large LTER datasets (e.g., those deriving from remote and autonomous sensing platforms, model output and products) which do not currently have a clear home in EDI or other third-party data repositories.
6. The first four decades of LTER science have been a remarkable era of advancing mechanistic understanding of ecosystem variability. However, that era has also been one of accelerating ecosystem degradation and species extinctions. LTER science in its fifth decade should exploit opportunities to leverage site-based experiments and observations to project future ecosystem changes, their consequences for humans and other species, and outcomes of different strategies to slow or reverse ecosystem disturbances from an expanding human footprint.

III. INTRODUCTION

After more than 40 years of sustained support from NSF the Long Term Ecological Research (LTER) program has become one of the most highly regarded and successful programs in Ecology. The value of LTER science, education, and outreach continues to increase and strengthen through time. Numerous metrics reflect the quality of the program and its value to the field of ecology: an accelerating number of high-quality peer-reviewed publications, increasingly leveraged external funding, and an excellent track record of training the next generation of ecologists. The program has risen to become a quintessential resource for ecological research and training. The 27 interdisciplinary LTER sites, encompassing terrestrial, aquatic and transitional ecosystems, provide critical data that span multiple decades and are essential to documenting planetary change and improving understanding of processes, organisms, and ecosystems most sensitive to the driving forces of variability. Importantly, LTER research has matured to the point of permitting development and testing of ecological theory. Moreover, the decadal-scale observations permit detection and attribution of ecosystem changes, including distinguishing natural variability from changes linked to anthropogenic activities. Hence, the LTER network is positioned to address some of the most pressing scientific and societal questions about the behavior of Earth's ecosystems and how humans interact with these systems.

This is the fourth occasion that the LTER program has undergone decadal review. At the inception of the program in 1980, funding for the original 5 sites totaled $1.2M annually. Ten years later the program had expanded to 18 sites with an annual operating budget of close to $11M. Twenty years after the program began, LTER had expanded to include 24 sites (notably including the addition of two urban sites) with a core annual operating budget of nearly $18M. At the time of this 40-year program review, the number of sites has stabilized (there are currently 27 active sites including two urban sites, plus the LTER Network Office, LNO) and core support from NSF exceeds $30M annually. This core budget does not include substantial additional support for field-site facilities and sampling infrastructure, for example funds in support of ship operations (from the NSF Ocean Sciences Division) and field station infrastructure (supported by the NSF Division of Biological Infrastructure).

The current 27 sites span a diverse, but not exhaustive, list of different ecosystems that include polar ecosystems, temperate forests, coastal wetlands, grasslands, lakes, deserts, and coastal oceans. The progressive programmatic expansion provides new opportunities, for example, asking regional to continental-scale science questions that can be answered using the time-resolved observations across the collection of LTER sites. However, such expansion also brings challenges, including management and leadership of the emergent network, and articulating common disciplinary foci that includes both natural and social sciences across this network of sites.

Since the inception of LTER, ecologists have made substantial progress on answering many of the questions initially motivating the formation of LTER. As part of this review, we considered whether such progress necessitates revisiting some of the core tenets and program structures to position the LTER network to be most effective at addressing science challenges for the coming decade.

LTER research is differentiated from other science supported by NSF in a few important ways: A) answers to LTER science questions require long-term studies, B) sites must be representative of major biomes or ecosystems, and C) all sites must collect data specific to five core areas:

1) Primary production
2) Population and food web dynamics
3) Organic matter cycling
4) Inorganic nutrient supply and cycling
5) The role of disturbance in ecosystem structure

Urban LTER sites have additional requirements to collect data specific to social, economic, or cultural processes, with an eye toward integration of human-environment interactions. The funding model for LTER is also unique: unlike other NSF awards, LTER sites are funded on a 6-year cycle with the opportunity for renewal of funding in perpetuity. Moreover, the renewal process for LTER proposals is effectively a closed competition, greatly increasing the probability of sustained support. All of these considerations make the LTER program unique, and motivate the necessity for review and assessment of program strengths, weaknesses, challenges, and opportunities.

Since the 30-year review there have been a number of important changes to LTER and the landscape of ecological research networks in which LTER operates. These include reconfiguration of the LNO (beginning in 2015) together with support for the Environmental Data Initiative (EDI) to oversee LTER data management and distribution. In addition, several large network observatories have become operational in the past decade, notably including the National Ecological Observatory Network (NEON) in 2011and the Oceans Observatories Initiative (OOI) in 2016. These NSF-supported, distributed observing networks monitor diverse terrestrial, freshwater, and marine ecosystems, providing time-resolved measurements across a wide range of spatial scales (local, regional, continental, and basin scales). With the implementation of these new initiatives, LTER has new opportunities to solidify its long-standing role as the leading ecological network. Doing so demands robust network-level communication and coordination (i.e., the LNO), distribution and management of data (i.e., EDI), and cutting-edge science.

Review of past decadal report recommendations

Programmatic expansion of LTER, both in number of sites and funding, has been motivated in large part by recognition of the value in the “whole is greater than the sum of the parts” model. That is, having LTER function as network, rather than a collection of individual sites, could permit addressing scientific questions at much broader spatial scales than would be possible based on place-based research alone. All of the previous decadal reviews emphasize the value of such a network approach to ecosystem science.

A recurrent theme from the past three decadal reviews of the LTER program is the potential scientific and societal value of using LTER science to address large-scale (in both time and space) questions about ecological change. All of the previous decadal reviews highlighted the unrealized value in synthetic, network-level LTER science. The first decadal review pointed to a number of areas where LTER could adjust to strengthen its emergence as a network for the coming decade. Specifically, this 10-year review emphasized that the goals for LTER research 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." This report went on to stress that after a decade of research, LTER was in a position to capitalize on cross-site synthesis science. Further, this review noted that although the 5 core research areas initially helped focus LTER science, those 5 areas could be viewed as guidelines for site-based research, and that each site should have flexibility to "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." A final finding from that initial decadal report focused on governance and leadership, with a suggestion that the historical "bottom-up" leadership model needed to evolve and mature with the program to allow for effective decision-making and strategic planning. It is clear that LTER was responsive to most of these suggestions; however, many of the same topics reemerge in subsequent decadal reviews (including this one).

A decade later, the 20-year LTER review recommended the network develop a decadal-scale strategic plan, crafted jointly by the LTER community and NSF, to better position the LTER for synthetic, systems-level ecological research in the coming decade. This second decadal review provided 26 specific recommendations aimed in large part at empowering LTER to develop a network-wide science approach. In response, in 2007, LTER developed a decadal-scale strategic plan that identified three social-ecological scientific areas where the LTER network was positioned for progress: 1) land and water use change, 2) climate change, variability, and extreme events; and 3) nutrient mobilization and species introductions.

The 30-year review, conducted in 2011, provided 8 specific recommendations aimed at encouraging the LTER program to take advantage of the decades of science, education, training, and outreach experience to propel the network into the next decade. In particular, this 30-year review called on the LTER network to: 1) clearly articulate its value to the scientific community and NSF, 2) leverage knowledge gained from decades of observations to develop cross-site experimental studies that would allow testing hypotheses at scales larger than any one ecosystem; 3) articulate and justify the value of social science in LTER; 4) embrace a leadership role in directing network-level ecological sciences, including positioning itself for leadership in large, emerging ecological monitoring programs such as NEON and OOI; 5) improve network-wide data management to facilitate cross-site comparative science; 6) leverage citizen-science initiatives across the network for increasing education, outreach, and research goals; 7) prioritize cross-site education programs; and 8) work to overcome limiting resources by either re-prioritizing LTER goals and/or proactively seeking new resources.

Approximately coincident with the 30-year review, in 2011 LTER released a new decadal-scale Strategic Implementation Plan (https://lternet.edu/wp-content/uploads/2010/12/LTER_SIP_Dec_05_2010.pdf). This plan identified the primary mission of the LTER network as: "use long-term observations and experiments to generate and test ecological theory at local to regional scales", and this document highlighted the evolution of LTER from "a loose federation of sites to an integrated research enterprise" with the capability to address "long-term continental-scale questions related to the biophysical and socioecological drivers underlying environmental change."

Partly in response to recommendations stemming from the last decadal review, the LTER network, and more generally the ecological landscape in which the LTER operates, has undergone several important changes. Beginning in 2015, NSF began supporting the

LTER Network Communications Office (NCO) as a core element of the LNO; the NCO's role is to facilitate network-wide communications, including maintaining the network website, writing and distributing a newsletter, overseeing network social media, and engaging in student training specific to science communications. The 2015 "Report of the Task Force to evaluate approaches for implementing the network level activities of the Long-Term Ecological Research Network" (the McKnight Task Force Report) sketches a new vision for the LNO, one where this office serves as a service entity, not a research and development entity, whose role is partly to lead LTER science branding for the network. In 2019, the LNO was relocated to UCSB to be managed as part of the National Center for Ecological Analysis and Synthesis (NCEAS), under the leadership of Dr. Frank Davis and Director Marty Downs. The LNO coordinates numerous site-based and network-wide activities, including managing cross-site synthesis proposals and organizing subsequent Synthesis Working Group (SWG) meetings; coordinating meetings of the LTER Executive Board, Science Council, and sub-working groups; and planning, funding, and executing the annual LTER All Scientists Meetings. Another important change to the LTER program since the last decadal review was the transition to EDI supporting data archiving and publication for LTER. This transition to EDI support of LTER data management was initiated partly in response to recommendations stemming from previous decadal reviews.

IV. THE FORTY YEAR REVIEW CHARGE AND PROCESS

In July 2020, NSF assembled eight scientists to serve on the fourth Decadal LTER Review Committee (Appendix A). The committee size and composition underwent changes over time, with 7 members eventually completing the review. The committee was charged (see Appendix B) with reviewing the significance of the long-term scientific findings, the network approach to research over the past decade, and how well prepared the network is to support the ecological research needs for the next decade. Specifically, the committee was charged with reporting to NSF an assessment of: 1) significance of the long-term ecological and environmental science produced by the LTER network over the last decade, and 2) strengths and weaknesses of the LTER network model of supporting long-term, site-based research through renewable funding.

The committee was given explicit guidance from NSF that any recommendations emerging from our review needed to be developed in the context of an NSF program with stable support, but with flexibility to make changes. Many of the recommendations presented in this report would clearly benefit from infusion of new funding into LTER; however, given the stable funding directive, we have tried to identify places where our recommendations could be accomplished through reallocation of existing program resources or continued leveraging of funding external to the core LTER support.

We divided our review activities into 4 primary working groups, each populated by 3-4 committee members. Working groups focused on the following topics:

- The LTER as a Network: Synthesis Activities, Cross-site and Beyond-site
- Assessing the Impact of LTER Science and Program Elements
- Education, Outreach, and Partnerships
- Data Management and Ecoinformatics

In addition, the entire review committee addressed the following review topics:

- Network Diversity, Equity, and Inclusion (DEI)
- Facing Forward: A Grand Science Challenge of the 21st Century

Working groups met regularly (approximately monthly) and the full review committee met semi-regularly for broader group discussion of key topics reviewed by the working groups. Each working group defined questions that established the scope of the review on each topic. Working groups gathered information based on meetings with LTER and NSF personnel, surveys, peer-reviewed papers, and reports. We had multiple meetings with LTER leadership teams (Executive Board, Science Council, LNO, LTER subcommittees), site principal investigators (PIs), current and past NSF program managers, site Education and Outreach (EO) leaders, the PIs of EDI, and site Information Managers (IMs).

This report represents a culmination of our review.

V. FINDINGS AND RECOMMENDATIONS OF THE FORTY-YEAR REVIEW

A. Synthesis Activities, Cross-site and Beyond-site

A1. Progress in the Advancement of Synthesis Science

LTER was launched to transform ecosystem science into a more rigorous and predictive science through development of new theories, concepts, and principles of ecosystem variability and to test their validity against site-based observations and experiments over time and across sites. The experimental design of the LTER was unprecedented and, in hindsight, brilliant. It mandated repeated measurements sustained indefinitely at sites representing a broad diversity of ecosystem types. The research was designed to measure and understand variability of biological communities, ecosystem processes, and drivers of that variability. This design provided empirical bases for understanding mechanisms of variability over time and space. The spatial dimension includes variability at three scales: (1) within a site, (2) across sites of the same ecosystem type, and (3) across ecosystem types. From its inception, LTER science has focused on variability over time at individual sites that were funded to synthesize place-based data. However, there has been clear recognition from the scientific community that measurements of variability across sites and across ecosystem types contain information essential for meeting LTER goals. Synthesis transforms data into information and knowledge, and syntheses of data collected across sites and ecosystems extract information that is required for developing robust theories, concepts, and principles.

The rich data sets, knowledge, and skill at synthesis science that have accumulated over four decades of LTER create an exceptional opportunity to advance ecosystem science across a dimension that has not been fully exploited. Guidance from NSF in its 1979 announcement for the LTER program defined its goal to “initiate the collection of *comparative* data at a network of sites representative of major biotic regions of North America”. The expectation of both site-based and cross-site data analyses was initially met with resistance because core funding to LTER sites provides support only for site-based syntheses. The disparity between NSF funding levels for site and larger-scale syntheses has been a conundrum for NSF and LTER leaders that has been discussed in each decadal review. The 10-year review recommended "replacing the five LTER core areas with goals that emphasize the breadth, integration and *cross-site, comparative* potential of the LTER program". The 20-year review recommended that the "LTER program should become ... a seamless, integrated continuum from site-specific to *cross-site to network- and systems-level ecological research*". The 30-yr review noted that: "there continues to be a tension between the goal of *network-level research and the goal of site-based research*."

John Magnuson and Robert Waide[8] recently recounted the history of NSF's varied responses to these recommendations. After the 10-year review, NSF took actions following the Division of Environmental Biology Director John Brooks' vision of LTER "to achieve a quantum jump in the science to create *a new comparative ecosystem science*". In this second decade the LTER Network was encouraged to plan for a significant expansion of comparative research and synthesis. It was deeply engaged in discussions about opportunities for comparative ecological research using LTER data, and NSF awarded 22 grants in 1994-95 to conduct new comparative research. However, by the end of the 20th century resources for cross-site comparisons were no longer readily accessible through the LTER program. Although Decade 2 was declared "A Decade of Synthesis", NSF eliminated cross-site research competitions after 2000 and this source of funding ended. Consequences were noted in the 30-year review: "resources are a key limiting factor for the future of the network. The network should: 1) make realistic prioritizations within the existing resource base to create more science per dollar, and 2) engage with NSF and others to proactively develop new resources." NSF's response was that "Priorities must be based on resources currently available" and "individual sites and the Network Office should examine other funding initiatives within NSF as opportunities to enhance the LTER research portfolio." NSF made cross-site research optional in its guidance to sites in 2014 and eliminated references to cross-site research in 2016. This history tells of a commitment by NSF to the *concept* of comparative and cross-site synthesis, but losses over time in the resources needed to realize that commitment. It also illustrates the power of NSF leadership to shape the balance between site- and cross-site synthesis. It was from this historical perspective that we evaluated the state of LTER synthesis science in its fourth decade, with focus on syntheses at scales beyond individual sites. We see multiple lines of evidence of a transformation in the balance between network- and site-focused syntheses in the past decade.

A2. Ecotrends

The Ecotrends Project (2004-2013) led by Dr. Debra Peters was a milestone effort to compare existing ecological data across space and time. Data were compiled from all 26 (at the time of the project) LTER sites as well as 24 other sites from the US Department of Agriculture: Agriculture Research Service, US Forest Service, and universities, and summarized as monthly and annual time series. These data were made freely available online through a single web portal. Numerous working groups convened to analyze data across systems. More than 15,000 datasets (each composed of a single data variable and a timestamp) were generated and a compilation of cross-site and cross-ecosystem syntheses–each a result of concentrated workshops between numerous site scientists including postdocs–was published in 2013: *Long-Term Trends in Ecological Systems: An Introduction to Cross-Site Comparisons and Relevance to Global Change Studies*[9]. Early graphs showing the value of this approach were published in the 2007 Integrated Science for Society LTER report. The data management system built by the LNO to store and publish the data was a predecessor of the Provenance Aware Synthesis Tracking Architecture (PASTA) system now used by EDI.

Some (not all) source and derived datasets from Ecotrends are available through DataONE (15,409 datasets retrieved using keyword "ecotrends") with complete metadata, and the derived datasets used in the book available on the outdated and unsecured

EcoTrends website (http://www.ecotrends.info). A search for EcoTrends data via the EDI portal based on the keyword "ecotrends" (or any of the project identifiers that were originally assigned to these datasets by the LNO) only brings up three results, all of which are individual site submissions for the project. Documentation of the project and the work taken to document and publish the source datasets do not appear to be available on the EDI website.

In their 2021 retrospective of LTER (*The Challenges of Long Term Ecological Research: A Historical Analysis*)[10], Robert Waide and Sharon Kingsland write that "The Ecotrends Project was an effort to provide access to comparable ecological data in a way that would promote synthesis of long-term data", but "Integrating Ecotrends with the developing Network Information System did not occur owing to lack of funds, and as a result data in Ecotrends have remained static." This end to a program that significantly advanced syntheses of LTER data, including cross-ecosystem syntheses, is another example of the decadal oscillation of NSF-LTER support for synthesis beyond the site scale. We wonder about the state of LTER synthesis today had this program continued.

A3. LNO and Synthesis Working Groups (SWGs)

LTER took a step to advance synthesis science in 2016 when it began funding grants administered by the LNO to support SWGs "to use existing data to probe novel theories, test generality, and search for gaps in our understanding". Ten SWGs have been selected for funding from 60 submissions, including five awards in 2020-2021. The SWGs address a range of ecological problems such as plant community responses to global change and disturbance, steam nutrient cycling, productivity-diversity relationships, drought effects on terrestrial plants, and riverine export of silica. The awards are small ($35-$50K per year over 2 years) and support travel to working group meetings but no salary. Most SWGs are designed to facilitate comparative/synthetic analyses by compiling and harmonizing data sets from multiple (the requirement is two or more) sites and/or developing tools to analyze them. Products so far include three published journal articles that present cross-site syntheses of: experiments at 52 sites to understand plant community responses to human disturbances; 62 plant community studies to show that asynchrony of population variability adds stability to ecosystem functions like primary production; and stream chemistry data from 2035 sites ranging from the tropics to the arctic. The first cross-ecosystem synthesis, of long-term experiments at 12 LTER sites, was published in 2021.

An important and perhaps under-appreciated contribution of some SWGs has been the effort given to find, compile, validate, harmonize, and publish data from multiple LTER sites, LTER linked projects (e.g., NutNet, DroughtNet, Dirt, and Community responses to resource experiments, CORRE), and other observational networks such as National Ecological Observatory Network (NEON), the International Long Term Ecological Research Network (ILTER), and Critical Zone Observatories (CZO). This facilitates synthesis at a scale not anticipated in 1980 – the scale of cross-network comparisons and syntheses. The LTER community has stepped up and taken major strides to publish user-ready data and tools for analyzing them. Notable examples include a global synthesis of soil data from 6 networks[11]; a 1943-2010 compilation of plant communities in US grasslands[12]; and R packages to compute indices of diversity and community stability[13] and community responses to experimental global change treatments (https://github.com/klapierre/community_difference_synthesis). The effort required to produce analysis-ready data and analysis tools is large, sometimes larger than the effort required to do the analyses themselves. Support from LTER SWGs provides a spark to initiate these essential steps, but the work itself has been mostly supported with funding secured by working group members from sources beyond LTER, NSF and the US. The SWG program adds value to LTER science by highlighting its importance in the context of other research being done globally. It also adds value by making user-ready data and tools available for syntheses by the global scientific community. It is our impression that members of the LTER network have embraced the goals of open data and open science. However, work remains because the multi-site datasets analyzed are not all published and many synthesis papers of LTER data are behind paywalls.

We were struck by the skewed distribution of SWGs weighted toward cross-site studies of diversity and functions of terrestrial plant communities and streams. None of the published cross-site syntheses considered other biotic communities (animals, microbes) or comparison across different ecosystem types. We were even more struck by the limited inclusion of data from polar and marine sites in the SWG syntheses. Only 1 of 60 proposals has come from a marine site, so the skewed distribution of effort across the 28 sites implies missed opportunities to take full advantage of the LTER design and the goal of SWGs to "probe novel theories, test generality, and search for gaps in our understanding."

A4. Syntheses outside SWGs

We also examined syntheses of LTER data that included studies outside the SWG program, using the LNO database of publications since 1985 (https://www.zotero.org/groups/2055673/lter_network/collections/JJY374KY/tags/Bering%20Sea/collection). We extracted from this large file (25,039 records) the journal articles tagged as "cross-site" – i.e., used data from more than one LTER site. This record includes 55 articles published in the second LTER decade (1990-1999), 183 articles in the third decade, and 325 articles in the fourth decade. We interpret this six-fold increase in multi-site analyses as evidence of growing collaboration within the LTER community. Further evidence includes a recent issue of *Ecosphere* that illustrates five common features of population and community variability[14–18]. Each article was a collaboration among dozens of authors, containing vignettes from data collected at multiple LTER sites.

The LNO published a different kind of analysis in 2020[19] showing that the number of authors and institutions per LTER article have also increased and the increase began to accelerate around 2000. These metrics show that the LTER community has steadily increased its functionality as a network, meeting a common challenge in previous decadal reviews. The bibliographic data also contain information about the use of data collected at individual LTER sites. We binned sites into four categories – continental (terrestrial and connected inland aquatic habitats), coastal wetland, marine, and polar. Data from the continental (prairie, grassland, forest, urban) and coastal wetland sites were all used in over 20 articles tagged as "cross-site" and published during the fourth decade, while data from the marine and polar sites were used in at least 10 articles. This disparity suggests that while LTER has become an increasingly collaborative network, the network has silos with different degrees of collaboration and cross-site syntheses. This difference between continental-coastal sites (18 of the 27 sites) and marine-polar sites (9 of the 27 total sites) reflects variability across ecosystem types in the extent to which LTER data have been synthesized across sites and ecosystems. This same pattern of highest engagement in terrestrial-plant syntheses was seen in the SWG program, a finding likely partly attributable to the disparity in the number of terrestrial-coastal vs marine-polar site, but also potentially reflecting scientific and funding-driven “siloing” among sites.

Bibliographic data compiled by the LNO do not provide complete information about trends in synthesis studies because articles tagged as “cross-site” are not all synthesis articles. In mid 2021, we performed a web search and found 28 journal articles published or submitted since 2010 that included 12 syntheses across ecosystem types (XE) and 16 across sites of the same ecosystem type (XS). The XS analyses included studies of: carbon storage in 946 seagrass meadows; climate and other regulators of streamflow in 35 headwater basins; sensitivity of different plant species to variability of annual precipitation at 10 LTER grassland sites; nutrient trends in 22 US streams within minimally disturbed forests; spatial patterns of streamwater chemistry in 32 tributaries; effects of climate change on carbon storage in a permafrost ecosystem; processes of ecosystem variability at 39 grassland sites; effects of forest harvest on water and climate regulation in 3 watersheds; a synthesis of under-ice ecology of 101 lakes; 3 coral reefs showing that larval transport conveys resilience to disturbance; projections of extensive loss of lake ice in the next generation from 513 lake sites; 72 grasslands to identify soil properties that regulate primary production; 2000 streams to show how nutrient enrichment alters their dissolved organic nitrogen:dissolved inorganic nitrogen ratios; and how atmospheric acid deposition alters carbon:nitrogen ratios in 74 streams.

The XE analyses included studies of: all LTER sites to develop a framework for understanding disturbance effects on ecosystems; 10 LTER sites showing different trends of atmospheric nitrate and sulfate deposition in the Eastern and Western US; 14 LTER sites to show how annual precipitation regulates primary production across a range of terrestrial ecosystems; 62 herbaceous plant communities showing that asynchrony and spatial variability of plant species adds stability to ecosystem functions; experiments at 52 sites to develop a global synthesis of plant community responses to multiple drivers of change; multiple LTER sites to learn how biodiversity patterns emerge across ecosystems and time. Our search only found five XE analyses that included data from terrestrial and aquatic sites: a study (supported by the Ecotrends program) to compare abrupt ecosystem changes across a grassland site, oceanic, coastal and polar marine sites; a regional carbon budget from measured carbon fluxes across connected forests, wetlands and lakes; a review to show how studies from 7 LTER sites spanning distinct biomes have shaped theoretical paradigms in disturbance ecology; meta-analyses of 100 experiments at 12 LTER sites to learn that detection of population changes requires experiments lasting a decade or longer; and several case studies from LTER sites showing how the COVID-19 ‘anthropause’ altered interactions between humans and ecosystems. Eight of these XE analyses were published in 2020 or 2021.

A5. Summary of Synthesis Activities and Progress

The third decadal review advised that: "with the right opportunities for synthesis, the site versus network tension could become an engine of creativity and more rapid scientific advancement. At present, though, an insufficient proportion of LTER scientists are as engaged in network level activities as would be optimal." We see evidence that this tension is easing, largely because of initiatives taken by Network members to leverage LTER funding to build cross-site and cross-network collaborations, some targeted toward syntheses products. The community understands the value of and is committed to larger-scale syntheses and sharing of data for syntheses by others. There is, however, wide disparity across sites in their successes at securing external funding to support large-scale syntheses. Some have recently published papers in high-impact journals because they are regional or global-scale syntheses, but other sites remain focused primarily on place-based or regional analyses.

While great progress has been made in the past decade, and the LTER community should be lauded for this progress, there remain many exciting opportunities to learn about the Earth system with support targeted toward global-scale syntheses of LTER and other observational/experimental data. Fundamental questions remain largely unanswered. Are there universal laws, theories, principles of ecosystem dynamics that apply across terrestrial, aquatic, and transitional ecosystems? If not, why not? What can be discovered from comparisons across all ecosystem types of nonlinear dynamics, regime shifts, nutrient enrichment, human and natural disturbance, climate extremes, multidecadal climate oscillations and climate change, relationships between biodiversity and ecosystem functions, integrative effects of top-down and bottom-up regulators, response/resilience to disturbance, and landscape connectivity? How can these discoveries be used to address the grand challenge of sustaining ecosystems and their biological diversity in the face of accelerating global change?

A6. Recommendations

We recommend that large-scale syntheses become a central theme of the fifth decade of LTER and we identify steps where we see opportunity to build on the momentum of the past decade.

1) **We recommend modifying the SWG program by extending grant duration to 3 years, recognizing the large effort required to compile and harmonize multiple data sets and develop new tools for their synthesis.** We suggest that the program solicitation should be revised to add emphasis for cross-site activities (see section B.3 of this report) and assessment of cross-site synthesis activities should be included as part of the site review process. We see strengthening the LNO SWGs as a key step toward advancing cross-site and cross-ecosystem synthesis. Large-scale syntheses of LTER data require collaborations across its network of sites. LTER support for SWGs administered by the LNO is now a proven model for advancing syntheses beyond the site scale. We see opportunities for expanding cross-site and cross-ecosystem synthesis through modification of the SWGs program goals, specifically to target: (1) syntheses of data collected across a broad range of ecosystems including terrestrial, aquatic and transitional ecosystems to address fundamental ecological questions such as those above, and (2) cross-site syntheses to address the uncertainty of ecosystem sustainability as global changes accelerate. We heard from Network members that "synthesis is hard because of the person hours and technical capacity that are typically required" and "working groups typically lack some of the technical capacity that's required to handle synthesis efficiently." We are encouraged by the recent establishment of two Data Scientist positions at LNO as evidence that LTER leaders value network-wide synthesis and are open to suggestions for further expansion. Co-locating such SWG fellows at one location, following the NCEAS model, could be an effective step for promoting

discovery in cross-SWG interactions. Funding for the desired expansion of synthesis activities will need to be identified, but we encourage looking to NSF-funded post-doctoral research fellowships (such as those offered through NSF's Division of Ocean Sciences and the Office of Polar Programs) as opportunities.

2) **We recommend experimenting with new approaches for catalyzing and funding syntheses of LTER data beyond the LNO organized SWGs.** LTER scientists should continue their success in leveraging funds from outside the core program, capitalizing on NSF programs like "Opportunities for Promoting Understanding through Synthesis (OPUS) or "Research Coordination Networks (RCNs)." We see the potential for considerable return on investment if "seed funding" were identified to develop workplans and proposals based on discussions initiated at All-Scientists and other Network meetings (we heard that "getting something done between workshops takes intellectual and financial commitment)". Additional support for synthesis could be pursued through collaborative proposals with other agencies, networks, and synthesis centers such as NOAA's Oceanic and Atmospheric Research and Integrated Ocean Observing System programs, NEON, the US Geological Survey Powell Synthesis Center, National Socio-Environmental Synthesis Center, and Inter-University Consortium for Political and Social Research. Adding language to the program solicitation that acknowledges the value of LTER partnering with such programs could further incentivize LTER scientists to pursue such opportunities. In addition, the LNO could play an important role in communicating and promoting access to new opportunities for synthesis science in other NSF programs such as the *Macrosystems Biology and NEON-Enabled Science (MSB-NES): Research on Biological Systems at Regional to Continental Scales.*

3) **We recommend LTER further advance synthesis activities by broadly communicating (e.g., through social media and other outlets) the availability of its synthesis-ready datasets and analytical tools as they are published.** From a global perspective, the most impactful advances of ecosystem ecology in the next decade will come from syntheses of data compiled from many observational programs. The value of LTER will grow with each re-use of the data it produces. The network should support publication of data articles as another mechanism of outreach and marketing to promote re-use of its LTER products. The global march toward fully open science will advance discoveries in all disciplines including ecosystem ecology, and we see extensive benefits from NSF policies to support and require publication of all derived data sets and to publish their analyses in open-access outlets.

B. Assessing the Impact of LTER Science and Program Elements

B.1. Preamble

A central element of our review was an assessment of the overall quality of science conducted by the LTER program over the past decade and evaluate the impact of that science on Ecology and Earth Sciences. For this component of the review we examined decadal progress toward leveraging funding from outside of the core program support and the network's record of disseminating knowledge in the form of scientific publications. We also considered the current state of socioecology in LTER research and the effectiveness of organizing site research around 5 core data collection areas. Finally, we reviewed the expectations of the required Conceptual Framework and examined the balance of observational, experimental, and synthesis science across the network. For this part of the review we considered numerous documents, including material presented in the 2019 LTER Self Study, LTER reports, and peer-reviewed papers and books. We met with the LTER Executive Board, the LTER Science Council, and held several meetings with PIs of specific sites.

B.2. Value-Added Aspects of LTER Science

LTER has played a disproportionate role in advancing the field of ecology, as demonstrated by an exemplary record of scientific accomplishments and advances that include publishing numerous high-quality papers; contributing to, editing, and publishing the LTER book series; and remarkable success in leveraging the core LTER funding to secure external research and education funding. The objective of this section of the report is to briefly summarize how these various achievements add value to the LTER network. Much of this information was summarized in the 2019 LTER self-study.

One of the most impressive metrics of LTER program success derives from the program's publication record. These include peer-reviewed journal articles, books or reports, and theses. There has been an exponential increase in the number of peer-reviewed articles published each year suggesting that leveraged funding has been key to fueling publications. Further, the number of cross-site journal articles per site per year has steadily increased, suggesting LTER is increasingly using cross-site, network resources to stimulate scientific impacts, achievements and advances. This conclusion is further supported by the significant number of citations of LTER-funded publications in primary research areas identified in the Web of Science that are not classified as "ecology" from 2008-2018 (50,238 out of 61,282 citations), a finding we attribute to the transdisciplinary scientific impact of LTER science.

Since the last decadal review, LTER scientists have contributed to, edited, and led the publication of several books, including new contributions to the edited volumes in the LTER Book series[20–24], in addition to chapters in books that describe the historical roots of LTER[10]; and sociology of LTER science and scientists[25]. Together with the Ecotrends book previously described, these contributions are valuable scientific resources and educational tools, providing excellent introductions to the functioning of the LTER network and site-specific findings.

Core site funding sustains site-based research and education programs (27 sites in total), together with funding to the LTER Network Office and Data Management Office. However, between 2008 and 2018, only 34% of the $912 million in total LTER-related research funding was "core" funding to the LTER program. The network has successfully used this core support to secure non-NSF resources, including grants from the Department of Energy, National Aeronautics and Space Administration, US Forest Service, the Environmental Protection Agency, state agencies, and private foundations. The success in leveraging significant funds outside of the LTER program is a key value-added component demonstrating how LTER helps to drive ecological research endeavors forward.

B.3. Assessing the Five Core Areas

For 40 years, core data collection at LTER sites has focused on five core areas: 1) primary production, 2) population dynamics and trophic structure, 3) organic matter accumulation or utilization, 4) inorganic inputs and movements of nutrients through the ecosystem, and 5) patterns and frequency of disturbances. The LTER program has identified the focus on these core areas as essential to providing the foundation for testing major ecological theories and to the integration of research within and among sites. The five core areas were selected in the earliest stages of developing the LTER program. In our judgement these limited focal areas may no longer reflect the diversity of core research conducted at all sites or the developments in ecological science over the past 40 years. In our conversations with LTER network and site representatives, the five core areas were described as foundational, but we see part of their utility deriving from the great flexibility in how each site allocates resources and prioritizes data collection specific to these five areas.

The structure of the "core areas" model is based on the idea that there is a small set of core ecological processes that is essential to quantify to improve understanding on the functioning of ecosystems. The LTER model currently assumes that the consistent measurement of these core areas across all LTER sites will catalyze the integration of research among sites. Rather than promoting consistency and integration among sites, we see that the five core area model may in fact limit flexibility in use of resources and the types of questions sites can explore. For example, the requirement to collect data specific to primary production may not be the best use of limited funding for urban sites. Similarly, the requirement to quantify organic matter accumulation and its utilization presents challenges in marine (and even some freshwater ecosystems), where mass balances demand robust physical context, including measurements to constrain lateral advection and transport of materials, and the expertise for this disciplinary focus often lies outside LTER. Moreover, in our conversations with LTER IMs, it became clear that data reporting requirements for the five core areas are not always clear and some sites struggle to categorize core datasets within these core areas. The core area of "disturbance" was the most difficult, and often used as a "catch-all" for datasets that didn't fit under the other four core areas. In addition, we heard that sites sometimes have their own core areas that they internally organize data under, and the five core areas are used more for external reporting.

We also see the requirement to collect data in all five core areas as a potential limit to a site's ability to conduct research on topics of greater relevance to their system. For example, LTER offers unique opportunities to investigate evolutionary mechanisms that underlie changes in biological communities. However, flexibility in site resource allocation to do this research may be constrained by the requirement to collect data in the five core areas.

To begin to consider how the five core areas could be revised, we first acknowledge that the real strength of the LTER program lies in the *site-based* long-term research conducted at *individual* sites. The most significant scientific contributions of the LTER program in the past 40 years have come from the analysis of long-term studies at individual sites. The recent LTER-centric special issue published in Ecosphere, "*Forecasting Earth's Ecosystems with Long-Term Ecological Research*", highlights this point. The papers[14–18] in this issue use a site-specific, case-study approach to cross-cutting science themes common across the network. Such an approach is an important initial step toward building the conceptual foundation on which future quantitative, cross-system comparative analyses can be developed. However, an alternative strategy to such post-hoc synthesis would be to proactively identify cross-cutting themes or questions that would inform and guide the data collection. This would potentially serve to move LTER closer to a coordinated network addressing cross-cutting science questions.

Given that site-based research remains a defining strength of the LTER program, any revisions to the five core areas must consider whether requiring all sites to measure the same core areas is the best approach to produce the most compelling research at each site. The LTER network has already implicitly acknowledged the limitations of the five core area model: sites are not required to put equal effort into measuring each of the five core areas, there are no efforts to standardize measurements across the network, and sites are not required to demonstrate that their approach to measuring these properties and processes yield data that are easily comparable across sites. Nevertheless, all sites must still explain how they will address each of the five core areas in their proposals, in some cases potentially allocating limited resources toward collecting these data.

We see benefit in revising the LTER program solicitation in a way that allows sites greater flexibility to propose research on topics most applicable to their sites. Such revisions to the solicitation could be crafted in such a way to encourage cross-cutting research. This will allow for intentional planning and expansion of cross-site and cross-ecosystem synthesis, and strengthen site-specific research by allowing sites to put limited resources toward the most compelling research areas for their site, while also simultaneously promoting cross-site interactions.

One possible model is to identify a broad set of thematic areas that sites could choose from to frame specific research efforts. Sites would need to justify how the chosen themes are integrated into the conceptual framework for the proposed research. The recent LTER self-study identified eight thematic areas that have broad importance across the LTER network that could provide an excellent starting point for establishing a set of thematic areas:

- Nutrient supply effects on ecosystems
- Consumer controls on communities and ecosystems
- The role of historical legacies in today’s ecosystems
- Biodiversity and ecosystem functioning
- Physical, chemical, and biological connectivity
- Coupled social-ecological systems[1]
- Resistance, resilience & state change
- Evolution in ecological experiments

These thematic areas could provide the basis for an expanded menu of options that could be selected from at the proposal stage to make up the core data collection areas of individual sites.[1]

Another possible approach to revising the five core areas would be to develop a “grand challenges” approach to framing LTER science. This approach could be applied in addition to or instead of the expanded menu approach described above. Such a model

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[1] The review committee agrees that “coupled social-ecological systems” should not be included here and instead the study of “human-ecological interactions” should be an overarching research objective across all LTERs.

would include identifying cross-cutting questions, rather than data collection areas, that maintain high-quality, site-specific research, while also forming the framework for cross-site collaboration. We imagined that these questions could be developed and revisited every 10 years or so, with some questions likely continuing for multiple cycles. Existing efforts toward long-term core data collection would continue where relevant for addressing questions at individual sites, but cross-site efforts would be guided by these grand challenge questions.

Importantly, any shift from the five core areas approach should not require that sites abandon efforts toward measuring any core area that is integral to understanding ecosystem functioning at their site, or that maintain collection of valuable long-term data. Rather, our hope is that adopting a different model, perhaps the menu of broad thematic areas or cross-cutting questions, will remove constraints on sites that require them to use limited resources to collect data of limited value to their primary research objectives while allowing for the continued collection of data that are key to the understanding of long-term patterns and processes at individual sites.

B.4. Assessing the Role of Social Science and Socioecological Science in LTER

Collaborative teams of social scientists and ecologists in the LTER network have been important and highly impactful in understanding the dynamic role of humans in ecosystems. Humans strongly influence, and are influenced by, numerous ecological processes. Historically, human and biophysical sub-systems were studied separately in most NSF-supported disciplines including ecology, in part due to disciplinary silos at NSF and many other institutions. However, in the last decade several LTER sites have made significant contributions to understanding the dynamic interactions between human and non-human ecological processes. Indeed, LTER teams have now trained multiple generations of scientists at the interface between the social and natural sciences, particularly (though not exclusively) at the urban sites.

Nevertheless, the extent to which NSF considers human and social interactions to be explicitly part of ecological science is not currently clear. The disciplinary boundaries of what constitutes ecology, socioecology, and the socioenvironmental sciences are changing, and there is a need for greater clarity in the coming decade about how NSF defines these fields in relation to the LTER network. There remains enormous scientific uncertainty in the two-way interactions between human dynamics and other biological, evolutionary, and geophysical components of ecosystems, across a range of spatiotemporal scales. Improving our understanding of these interactions is currently a significant priority for ecologists, as well as decision-makers and stakeholders. LTER is uniquely poised to make important contributions in this area, as it is much more engaged in studying human-ecosystem dynamics than other major NSF investments such as the National Ecological Observatory Network (NEON) and the Ocean Observatories Initiative (OOI). However, the positioning of socioecological and socioenvironmental research at NSF is not currently clear outside the Dynamics of Integrated Socio-Environmental Systems (DISES) program. More than simply an assemblage of collaborative teams of social and natural scientists, socioecology is now a transdiscipline with its own research questions that may fall outside the traditional scope of the NSF BIO, GEO, and SBE directorates. We strongly encourage NSF to find mechanisms of encouraging and supporting socioecology research within LTER going forward.

With that said, research questions and methods central to the social sciences may or may not be appropriate at each LTER site. What we consider more pertinent is the extent to which an explicit, mechanistic understanding of human actions and/or dynamics is necessary to understand ecological dynamics in terrestrial and coastal ecosystems. Ecosystems across the LTER network are being dramatically impacted by a range of human actions. Conversely, human communities and economies at a variety of scales are dependent on ecosystem processes. There is merit in considering these dynamics at all LTER sites, because they may interact with multiple core areas and research themes. As the human footprint grows, human and other ecological processes become more interrelated.

Humans impact, interact with, and are an integral part of all ecosystems globally. At many sites, human activities and decision-making play a large role in determining the ecology and ecosystem change; in other regions, particularly the more remote LTER sites, human impacts may be less direct, but still important. We see benefit in revising the LTER program solicitation to explicitly require that sites describe how their research will address human-ecological relationships. For example, investigations of human *impacts* on ecosystems may address the ecological effects of climate change, nutrient pollution, or seawater acidification; human *interactions* may include understanding the effects of different approaches to management, such as with habitat restoration or fisheries; *integrated* socio-ecological systems would address how human-environment relationships influence ecological processes and human well-being. We highlight the potential for such human-ecological research as central to meeting the Grand Challenge (see section F of this report).

Asking all sites to include research specific to human-ecological interactions might eliminate some of the special requirements at the urban sites, with sites considering the role of human actions in ways that are appropriate to their location. This will often entail collaborations with various sub-disciplines in the social sciences or socioecology. There are examples within LTER (e.g., Kellogg Biological Station, Harvard Forest, Konza Prairie) where collaborations with engineers, artists, land and coastal managers, agronomists, or other academic and non-academic disciplines have advanced understanding of dynamic interactions of human actions with the LTER research themes. We argue that collaborations between LTER researchers and local land, water, or coastal ecosystem managers have already been shown to advance LTER science. Furthering such interactions, across all LTER sites will position LTER to take advantage of new opportunities and stimulate interest in conducting stakeholder-engaged research related to climate change, restoration, resilience, and other urgent socioenvironmental issues.

It would be incumbent on each site to propose and justify tractable methods and compelling research questions relevant to human-ecological interactions. We describe a Grand Challenge (section F of this report) facing the planet in the next decade, with LTER uniquely poised to quantify past ecosystem changes, consequences of future ecosystem changes; and assess how such changes will impact humans, the ecosystems they create, and those they impact. Most LTER sites already consider various human actions, though it is not required. In some ecosystems there are also important human actions that may not necessarily be characterized as disturbances. We see opportunities to explicitly include research on human-ecological interactions under an expanded menu of potential core themes (see section B.3 of this report), where human actions could be defined to include *intentional or unintentional human activities that interact with other ecosystem components* *and processes*. A more explicit consideration of human-ecological interactions at all LTER sites also has the potential to make LTER science more relevant to a broader range of stakeholders and has the potential to increase participation of groups historically underrepresented in ecological science. We discuss this further in the Education and Outreach section.

B.5. Value and Expectations of the Conceptual Framework

LTER proposals are required to formulate a conceptual framework that provides justification for the science. As outlined in the most recent LTER solicitation (NSF 19593):

"LTER research should be developed around a conceptual framework that motivates questions requiring experiments and observations over long time frames. The conceptual framework should explicitly justify the long-term question(s) posited by the research and it should identify how data in LTER core areas and any experimental work contribute to an understanding of the question(s) while testing major ecological theories or concepts. The framework should provide the justification for all studies outlined in the proposal; ideally, it should be informed by analyses of existing long term data."

Hence, the motivation for the conceptual framework is to justify long-term experiments and observations and identify how data in the five core areas can be leveraged to answer specific questions that are grounded in ecological theory. The program solicitation points to the conceptual framework as the unifying foundation justifying all of the proposed research, and hints that this framework should be flexible enough to evolve as new findings emerge and are analyzed in the context of long-term data.

The rationale and value of framing LTER research in a conceptual foundation that is strongly rooted in ecological theory seems self-evident. However, in discussions with NSF program officers, it became clear that panelists and renewal and mid-term site reviewers can use a site's Conceptual Framework to pinpoint program weaknesses, and in some of the more extreme instances, this has led to site probations or retirements. Thus, we felt it was important to examine whether LTER PIs felt the Conceptual Framework requirement was beneficial to organizing research questions and whether the value of and expectations for the Conceptual Framework were being clearly articulated in the program solicitation.

The decadal review committee was interested in how LTER sites deal with the need for continuity in data collection over long time scales, while also being responsive to evolving changes in the theoretical and conceptual scientific underpinnings that motivate site-based research. Doing so requires flexibility in the formulation and implementation of the Conceptual Framework, specifically, a framework that defines the foundational scientific questions and motivates long-term data collection, while also being responsive to changes in theory, methods, and progress in understanding of site-specific ecosystem behavior. In our review of Conceptual Frameworks presented in renewal proposals it became clear that many sites rely on box and arrow cartoons to depict directional flows and interactions between exogenous and internal ecosystem drivers and functional responses to those drivers. The observation that so many sites use this approach to convey the Conceptual Framework suggests such cartoon models have been used to convincingly justify questions and the need for long-term research. However, the oversimplification of complex ecosystem feedbacks may make such depictions easy targets for criticism during proposal review.

The committee met with representative PIs from 5 LTER sites (Moorea, Florida Coastal, Sevilleta, McMurdo-Dry Valleys, and Andrews Forest). Site PIs were asked to provide feedback on the value of the Conceptual Framework requirement, their views on whether the requirement is given too much emphasis during proposal and site reviews, and whether or how the conceptual framework might be improved. In addition, PIs were asked whether their site-specific Conceptual Framework served as a beneficial vehicle for organizing research questions and motivating site science. Based on these discussions, and our own review of site-specific Conceptual Frameworks, we have several observations and considerations:

1. When appropriately defined and communicated, the Conceptual Framework serves a valuable role in organizing and grounding site research in ecological theory. Sites which most effectively communicate their conceptual framework do so throughout the proposal narrative, rather than relegating the description of this framework to a cartoon with a few paragraphs of descriptive text. In some cases, sites have also described the temporal evolution of their site's Conceptual Framework, demonstrating how ideas and questions shift in response to acquisition and analyses of new data and application of new ecological theory. Examples include capturing how episodic or persistent forcings (e.g., socioeconomic pressures, sea-level rise, drought, invasive species, etc.) have altered the behavior of the ecosystem and how the site-focused research shifts to consider such changes. Increasingly, sites will need to devise frameworks that consider human activities and decisions as key drivers of ecosystem change. *One thing is clear: The program solicitation should be revised to better clarify that the Conceptual Framework be viewed as a unifying theme that compels and justifies site-focused, time-resolved observations and experiments.* LTER PIs should also consider modifying the way such frameworks are depicted in proposals, for example, moving away from cartoon-like figures, and rather articulating that the framework is inclusive of all the research elements described in the proposal. Some of the most effective Conceptual Frameworks (in the opinion of the review committee) are those able to depict predicted ecological responses to external or internal drivers. For example, the Conceptual Framework guiding the Sevilleta LTER site outlines specific, predicted trends and variation in functional responses like organism fitness and species abundances to time-variable dynamics like climate variability, or species-specific traits. Such frameworks create space for hypothesis testing and predictions.
2. Although the Conceptual Framework is the appropriate vehicle for conveying extant knowledge on ecosystem interactions and drivers, the framework does not provide a mechanism of highlighting knowledge gaps or emphasizing the important role for discovery at LTER sites. Unlike "standard" core program grants, LTER sites are compelled to motivate the need for continued and sustained observations and experiments; often some of the best means of communicating these needs are by demonstrating the role of discovery and key unknowns - at most sites, the Conceptual Framework has not been exercised for this purpose.
3. Recently implemented changes to the flow of information from NSF to LTER PIs (and vice versa) are positive steps toward improving communication between NSF and the LTER community. Moreover, improved communication should allow for iterative

feedback between NSF and LTER scientists regarding the most effective means of presenting these frameworks and should help clarify the value and expectations on each site for presenting their Conceptual Frameworks. Recent positive steps toward improved communication between NSF and LTER include: A) virtual Townhalls hosted by NSF, currently occurring every 6 months, allowing regular opportunity for the LTER community to engage NSF program officers; B) monthly meetings between representatives of all the major Divisions of NSF involved with LTER (DEB, OCE, OPP) and the LNO provide avenues for exchange of information and sharing of ideas and concerns; and C) monthly meetings between the chair of the LTER Executive Board and the chair of the NSF LTER working group. Together, we view these steps as improving communication channels and are likely to go a long way toward resolving misunderstandings specific to the value and expectations of Conceptual Frameworks.

B.6. Integration of Observational, Experimental, and Synthetic Science in LTER

Since the last decadal review, the landscape of network ecology has changed considerably. These changes include development and implementation of infrastructure specifically designed as observational, ecosystem networks. Since the last decadal review programs like NEON, OOI, and the Global Lake Ecological Observatory Network (GLEON) are now fully operational. Moreover, the ILTER network has continued to mature, providing sites that allow testing of ideas across global ecosystems. The formation and operation of these observational networks shines light on the key strengths of LTER: conducting hypothesis-driven science that requires long-term observations to address, rooted in a strong sense of placed-based understanding. Owing in part to the maturing of these larger observing networks, future investment in LTER should strengthen the existing sites, rather than look toward network expansion via formation of new sites.

NEON funding formally began in 2011 (although there were many years of planning in place prior to this start) and since that time, NEON has grown into a fully operational (as of 2019) freshwater and terrestrial network. Both LTER and NEON are, by design, widely distributed across a range of ecosystems. NEON is designed to provide local-scale observations across terrestrial and freshwater ecoclimatic domains in the US. However, from the existing 27 LTER sites (not including the LNO), only a third (9 sites in total) are co-located with NEON nodes (note some LTER sites are co-located with more than one NEON node): HFR = HARV, HOPB; NTL=LIRO (at/near Trout Lake); KNZ = KONZ, KING, KONA; NWT=NIWO, COMO; JRN=JORN; AND=WREF, MART; ARC=TOOL, TOOK, OKSR; BLE=BARR, BNZ=CARI. Since the last decadal review, the OOI has also become fully operational; only 1 of the 5 operational OOI was co-located near an LTER site (North East Shelf- NES), but that OOI array is scheduled to be relocated to the mid-Atlantic by 2024, resulting in none of the marine LTER sites co-located near the OOI network. The decision to relocate this OOI site has detrimental impacts on existing leveraged connections with the NES LTER. *The review committee views the decision not to co-locate these observational networks more closely with the LTER sites as a lost opportunity to leverage and advance these scientific resources.*

Where possible, potential linking of LTER science to the monitoring activities of NEON (and OOI) could lead to powerful new mechanistic insights into ecosystem change. As monitoring networks, NEON and OOI are specifically designed to allow upscaling of local site-specific observations to address continental- or basin-scale questions on biogeochemistry, climate, and ecology. Hence, the synergistic potential in co-leveraging LTER with NEON and OOI science positions LTER as the potential hypothesis-testing, experimental arm to balance NEON's and OOI's observational and measurement capacities.

The potential synergies between LTER and NEON and OOI are numerous, but notably include opportunities to vastly increase sampling resolution of ecosystem properties which may have historically been identified through LTER observations as key drivers of ecosystem variability, but quantifying the importance of these drivers was limited by undersampling in space and time. We see numerous opportunities for synergies between LTER-NEON. The LTER network has much to offer NEON, not least including invaluable insights into observational time-series science, network-level integration of site-focused science, management approaches to long-term data records, and tools for increased engagement of the scientific community and public in ecological sciences. One of the single greatest assets of the LTER network is the experience-based knowledge obtained from the 40 years of conducting networked science at the continental scale. Such experiences will be invaluable to NEON's success and empower LTER science into the future.

B.7. Recommendations

High-quality, site-focused research continues to be the hallmark of LTER science. We present ideas for modifying the current LTER structure to offer sites additional flexibility in research activities, resource allocation, and data collection.

4) **We recommend modifying the five core areas framework toward a model that retains the high quality, site-specific research that is the hallmark of LTER science, while also proactively strengthening network-level, cross-site collaborative science**. The five core areas do not include some research areas that we feel are important to include as "core" to the LTER (e.g., human-ecological interactions, evolution, sustainability). We propose alternate models that might be considered in a revision of the five core areas framework. We stress that adopting any new model should leverage the existing strengths of the LTER network, while also offering opportunities for the emergence of question-driven networks across sites. Doing so may allow reallocation of site resources to address themes or questions most appropriate to each ecosystem and promote cross-cutting science to fuel within-network collaboration. Adoption of this recommendation may allow sites to reallocate some of the resources currently invested in measuring all five existing core areas toward other priorities.
5) **We recommend modifying the LTER program solicitation to ask all sites to explicitly address human-ecological interactions.** The growing anthropogenic footprint on Earth's ecosystems necessitates further consideration of human-ecological interactions at all LTER sites and all sites, even those remote from urban areas, are impacted by human interactions. An underlying goal of incorporating social science into LTER has been to better understand human-ecosystem interactions, rather than explicitly advancing social science as a discipline. While the collaborations between social and natural scientists are a common and valued way of studying human-ecosystem interactions, they are not the only way.

Addressing human-ecological interactions could include, but would not be limited to, socioecological processes. We see the current need to integrate social and ecological sciences into the LTER network as continuing to create tension (or at least uncertainty in what is required) among LTER scientists and NSF. We also see inclusion of LTER research on human-ecological interactions brings opportunities to potentially strengthen network diversity through greater participation of underrepresented groups and solidify the perceived value of LTER science to the public.

C. Education, Outreach, and Partnerships

C.1. Preamble

Education and Outreach (EO) is a key component of LTER. EO activities occur at both the network level and at individual sites. EO activities are the major path for engagement of local communities, including K-12 and college students, teachers, community groups, and land managers into LTER. Although EO represents a relatively small portion of the budget for the network and at individual sites, the EO site programs are well developed and highly leveraged. As a result, the EO component of the LTER program is one of the most effective examples of connecting ecological science to a broader audience.

The 40-year review committee assessed the EO activities through a review of the information provided by individual sites in published reports and online, by examining EO programs such as the Schoolyard LTER book series and Data Nuggets program, and in discussions with the Network EO Committee Chairs, representatives from LTER sites involved in REU programs, and several site EO coordinators. Based on our review, we see LTER EO programs as an outstanding component of the network.

At the network level, activities are focused on data literacy (through programs such as "Data Nuggets"; http://datanuggets.org/lter/) designed to make scientific data approachable and useful in classroom settings. The long-term data sets from across the LTER sites provide a rich resource for developing standardized curricula for learning the scientific method in schools, from inception of questions and hypotheses to developing methods for studies to statistical evaluation and conclusions. Scientists from various LTER sites work with the local K-12 teachers to develop curricula that fulfill learning skill requirements at different age levels. Such educational opportunities offer hands-on activities most engaging to students. Similarly, these educational activities feedback to the core LTER science goals, for example by enhancing communication skills to take scientific findings to a level of understanding accessible to the general public. The LTER sites provide an important source of time series data for site-specific and cross-site data analyses useful within educational STEM programs.

EO programs at individual LTER sites are "highly entrepreneurial". Sites substantially leverage modest LTER funding to co-develop local partnerships with K-12 schools, teachers, museums, community groups, resource management professionals, and outdoor organizations. The long-term nature of these partnerships allows for unique and long-lasting relationships that strengthen the substance and impact of EO activities. The success of these programs is largely due to the excellent work and passion of site EO coordinators. Coordinators develop and foster partnerships, develop curricula, host events, recruit and mentor staff and students, and provide assessment of their programs.

The REU programming at LTER sites is also a significant component of EO activities that links science and research. There are two models of support for REU students at LTER sites. A small number of sites have REU site awards (grants independent of LTER core funding) that support a cohort of students and give them extensive training and mentoring. In addition, LTER sites receive supplemental support for two REU students. As we describe below, we found that the experiences of the undergraduate students differed substantially between these two models. We offer ideas (section C.4) on how to better strengthen the student experiences across LTER REUs, including emphasis on cohort building and sharing of best practices in training and mentoring REU students.

C.2. Site-level activities

We agree with the assessment of the self-study that “the education programs at individual LTER sites are tailored to the science, communities, ecosystems, and partnerships where they are located and sites have to prioritize opportunities with the greatest promise of impact for their communities.” We see this as a strength of the existing EO program structures at LTER sites and a model that encourages authentic, lasting, and impactful relationships with educators, students, and community members.

In section B.4 of this report we describe future opportunities at LTER sites with an increased focus on research relevant to ecosystem management and human-ecological interactions. Future emphasis on this area will likely demand greater emphasis on outreach to land managers, restoration practitioners, and the general public. Outreach to these groups will be essential to building lasting partnerships that support high quality research on human-ecological interactions.

The 30-year report recommended greater emphasis on citizen science. A number of sites have strong citizen science programs, with some that have partnered at local scales and others, via remote activities, that are broadly accessible to the general public. Over the last decade many sites have expanded their citizen science programs. For example, the Palmer (PAL) site has supported outreach to the general public using science data products, making an already strong educational program even more accessible to a larger audience. The Beaufort Lagoon Ecosystems (BLE) site has formed a panel of traditional knowledge holders in Kaktovik, Alaska to advise LTER scientists on emerging ideas and research plans, acting as a conduit for knowledge exchange between BLE and the local community. Other coastal LTER sites, such as Plum Island (PIE), the Virginia Coast Research (VCR), the Santa Barbara Coastal (SBC), and the Florida Coastal Everglades (FCE) sites all have developed strong citizen science programs that bring community members into the research process. Many of these sites have recently capitalized on virtual forums to broaden their audience. We view citizen science programs as one of the many ways that sites can engage with the public; however, given the pressures on sites to develop EO activities that reach a wide diversity of audiences in different ways, we recommend that sites see investment in citizen science programs as an opportunity, but not a required aspect of public education and engagement.

C.3. Cross-site collaborations

The 30-year review also recommended that cross-site education programs should receive higher priority for funding and effort. Cross-site education programs have historically been challenging due to variability of results across sites. However, support for these activities would provide enhanced educational and collaborative opportunities to support the increased cross-site collaborations that we have identified as opportunities for the next decade. We do not believe these cross-site collaborations should be prioritized at the expense of site-specific EO activities. Where possible, support for cross-site collaborations should be external to the core funding for LTER sites, given the small portion of the overall site budgets allocated to EO activities.

One area where we do see that an increased effort in cross-site collaboration is essential is in identifying and promoting networking opportunities for EO site coordinators. In our meeting with EO coordinators, it was clear that they have developed a strong sense of community and this should be fostered and strengthened. Coordinators gather informally (generally over videoconferencing) to share ideas and best practices among sites. The site EO coordinators put substantial effort into seeking external funding, maintaining local partnerships, and managing the programming at their sites. However, at most sites these coordinators largely work independently or with a small support staff. Providing in-person networking opportunities for the site EO coordinators (beyond the regular All Scientist Meetings) would allow them to foster a stronger sense of community, improve collaboration among sites, and enhance the sharing of best practices for EO activities.

C.4. REU students in LTER

The overarching goal of the REU program is to provide a research experience for undergraduates to work closely with faculty and other researchers on independent projects. In many ways LTER sites are ideal locations to host REUs. The large community of researchers and diversity of projects at LTER sites allows students to be exposed to a broad range of experiences in ecological research. The network aspect of LTER also provides unique opportunities to foster a sense of community among REU participants. However, we found that the experience of REU participants at LTER sites (those funded on supplemental awards) is very different to REU students that are involved in established REU site awards. We see significant opportunities to leverage the structure of the LTER program to improve the experiences for all students.

In our discussions with site-based award PIs and EO coordinators, it was clear that sites with external REU awards tend to provide a more developed and intentional experience for student participants, helping to matriculate this group into graduate school and beyond. There have been attempts by the LTER network to share information on best practices among sites, but the REU site model provides opportunities that simply cannot be replicated in an experience for only two students. We see a need for sites to develop more robust mentor-training and opportunities for network-building among REU students. For example, virtual-based REU cohort-building activities and career-development modules that were created by many site-based REUs during the COVID-19 pandemic could be adopted to provide an improved cohort training experience. Similarly, cross-site synthesis projects for REU students could foster cohort building while simultaneously moving synthesis science forward.

We see value in assuring that LTER REU mentors receive training similar to mentor training required through the REU program. The LNO is likely in the best position to coordinate REU mentor training and participant cohort development across sites. We also think sites should consider sending a representative that works directly with REU students to attend the Biology REU site PI meeting every other year. These PI meetings offer a significant amount of mentor and PI training that would greatly benefit the REU participant experience at individual LTER sites. Finally, we see value in LTER sites using some of the assessment tools that have been developed at formal REU sites.

The LTER program recognizes REUs as “one of the most promising avenues for engaging members of groups that have been underrepresented in science”. The K-12 programming at LTER sites represents an excellent source of potential future REU participants. Further, these students may be more likely to envision themselves going into science careers if they have excellent mentors and interactions with identifiable role models. Moreover, retention of these students within the network requires significant preparatory training in the nature of science careers, the ethics of science, and developing graduate student role models. Efforts to increase the diversity of LTER scientists at all career stages (discussed in section E below) will also enhance the recruitment and mentoring of REU participants. Revising the LTER program solicitation to add emphasis on the value of sites using the REU awards as a tool to advance underrepresented groups into STEM careers would be beneficial. The Biology REU site award program solicitation and reporting guidelines could serve as models for this purpose.

C.5. Recommendations

6) **We recommend strengthening the experience of LTER REU students to focus on the student experience, including strengthening cohort and networking opportunities for REU students across sites and mentor training.** The objectives of the LTER REUs should be made clear in the program solicitation, particularly in reference to the importance of LTER leveraging this opportunity to engage underrepresented groups into the network. When possible, demographic, educational, assessment and career outcome data for REU participants should be collected and required as part of the site annual reports. REU students should be required to participate in training and cohort development and the value of doing so should be articulated in the program solicitation. LTER should consider how it can strengthen cross-site mentor training. We encourage sites to allocate funds (e.g., ~$1000/PI meeting) every other year so that a representative working with REU participants can attend the Biology REU site PI meeting. We also encourage sites to experiment with approaches aimed at cohort development and network-building among the REU participants.

7) **We recommend sites develop opportunities for networking among EO coordinators.** Developing partnerships among EO coordinators will facilitate sharing of best practices for both cross-site and site-specific EO activities, and promote sharing of ideas among sites on most effective programs for EO funding. Site EO coordinators are asked to develop activities and programs to engage a wide range of groups (e.g., K-12 students and teachers, undergraduate students, citizen scientists, land managers) at their individual sites and through cross-site collaboration, all with a very limited budget. LTER sites have done an impressive job of leveraging funds for their EO programs, but these funds often require EO activities to be directed toward a specific group or initiative. An increased emphasis on human-ecological interactions will create needs and opportunities for further public engagement. Outreach activities with land managers and restoration

practitioners will place additional demands on EO activities. Over the past 40 years, LTER EO programs have demonstrated that there are many effective and impactful approaches to education and outreach. While sites will undoubtedly continue to maintain programs that reach a diversity of groups, we see strength in allowing sites to be strategic about where EO funds are allocated. For example, efforts toward cross-site synthesis or citizen science should be developed for sites and projects where those activities represent the best approach, but in other cases focusing on site-based programming or targeting a particular demographic could be the most effective approach.

D. LTER Diversity, Equity, and Inclusivity

D.1. Preamble

Diversity, equity, and inclusion (DEI) are essential elements of a vibrant scientific community. The quality of our science and its relevance to society depend upon the development of a community that is broadly representative of diverse people and perspectives. Investing time and effort toward DEI has the potential to transform lives of current and future scientists. Even more than other STEM fields, the disciplines Ecology, Evolution, and Earth Sciences have struggled in broadening participation by underrepresented minority (URM) communities. Although substantial progress has been made over the past three decades, particularly toward achieving gender parity in the training of scientists, much work remains, particularly with respect to engagement and retention of Black, Indigenous, People of Color (BIPOC) in science. For example, the National Science Board estimates that the number of African Americans in the STEM workforce must more than double by 2030 to be representative of the U.S. population[26].

We use the term underrepresented to include people whose proportional representation in STEM remains lower than their representation in the US population, inclusive of gender, racial, ethnic, disability, veterans, and sexual and gender minority groups. Inequality in representation is particularly striking among BIPOC, with this issue becoming progressively worse at more advanced STEM education and career states (e.g., graduate student, post-docs, faculty). In 2017, BIPOC earned 22% of all postsecondary degrees in STEM fields; however, the number of doctorate recipients (of which ~75% were in STEM fields) earned by BIPOC was just 16%, with Black and African Americans earning 7%, Hispanic and Latinx earning 8%, and American Indian and Alaska Natives earning <1% of these degrees. In comparison, these communities account for 12.4% (Black and African American), 18.7% (Hispanic and Latinx), and 1.1% (American Indian and Alaska Native) of the US population, respectively[27].

Underrepresentation of BIPOC is even more pronounced for the fields of Ecology, Evolutionary Biology, and Environmental Sciences. In 2019, Black and African Americans earned <2% of all Ph.D.s awarded in Ecology and Evolutionary Biology, compared to 6% for all of Biology, and for American Indians and Alaska Natives the numbers are much worse (<0.2%). Asian Americans, a demographic not underrepresented in STEM in general, also remain underrepresented in Ecology. In 2018, Asian Americans were 5.6% of the U.S. population but earned only 3.0% of Ph.D.s in Ecology.

Retention of BIPOC communities in STEM career paths continues to present challenges; BIPOC currently hold ~12% of all faculty positions at academic institutions. Not surprisingly, these inequalities grow even more alarming when gender is considered.

For example, 2019, Black, Indigenous, Women of Color (BIWOC) received 13.3% of all STEM bachelor's degrees, 12.4% of master's degrees, 6.8% of doctorate degrees, and held <4% of the STEM faculty positions[28].

Despite promising trends over the past two decades, women also remain underrepresented in STEM fields, particularly in more advanced career positions that often lead to scientific leadership. While the proportion of women receiving undergraduate degrees was 57.3% in 2018, only 38.6% of those degrees were in STEM disciplines, with women comprising 44.3% of STEM master's degree recipients, 41% of STEM doctorate degrees, and 36% of postdoctoral fellows. Women currently hold 34.5% of the faculty positions in STEM disciplines.

The loss of underrepresented minorities (URMs) with advancement through career stages in science is often referred to as a "leaky pipeline". However, it is probably more accurate to see this situation through the lens of historical, discriminatory, systemic biases that have been constructed on the basis of race, ethnicity, gender, disability, age, socioeconomic status, sexuality, etc., all of which layer to create unique hurdles that inhibit the advancement of URMs. Hence, the intersectionality of an individual's identity ultimately defines the individualized path through the STEM workforce. Increasing the participation of underrepresented communities in science will require proactive and intentional efforts. These efforts should include: identifying avenues to promote engagement and subsequent retention of underrepresented students in science; development and placement of structural supports designed to increase and accelerate retention of marginalized communities as they navigate STEM educational and workforce ladders; increasing training and education of the extant scientific community so that biases, injustices, harassment, and discrimination can be identified and eliminated; and reexamining the criteria on which we evaluate academic success, including incentivizing work specific to DEI (e.g., mentoring). These are just some of the numerous potential steps toward promoting a more diversified, inclusive scientific community.

As a hallmark program in Ecology and Earth Science, the LTER network is in a position, and has the responsibility, to make real and substantive commitments to DEI that will undoubtedly benefit the broader ecological community. Efforts devoted to diversifying the LTER network promise to infuse new perspectives and ideas and ultimately produce better science.

The decadal review committee assessed the current status of DEI across the LTER network, relying on discussions with the LTER Executive Board, the network DEI committee, disseminating and reviewing a network-wide PI DEI survey, and reviewing numerous documents (including peer-reviewed papers, National Academy reports, and directives prepared by federal agencies) that highlight issues and point to concrete solutions to DEI issues. The LTER network DEI committee has only recently (2020) been formalized, and at the time of our meeting they had not yet articulated a network-wide vision for DEI or established network-wide policies specific to DEI. The current network-level strategy is aimed at facilitating the propagation of ideas, showcasing models of success at specific sites, and working to promote wider adoption and implementation of successful models across sites.

D.2. Summary of decadal review findings

Although there are promising trends in shifting demographics within the network (in particular with respect to gender equity), we view diversification of the LTER workforce as a top priority for the next decade. The LTER network would benefit from a top-to-bottom review of on-going DEI activities at each site. Doing so will provide valuable information on site-specific DEI successes and failures. Most LTER DEI activities are initiated and implemented by sites, with network-wide DEI activities in very early stages of development. Much of the current LTER effort (and successes) focus on engaging underrepresented communities at the K-12 and undergraduate levels. These activities build a foundation of diverse students; the network now needs plans to support and advance this community of students through more advanced career stages in the network (graduate students, post-docs, staff, PIs). This work will demand more proactive, top-down leadership at the network-level.

We recommend that the LTER network craft a DEI action plan that describes the vision, code of conduct, policies, and metrics for success on DEI. We recognize the challenges in developing a one-size-fits-all network DEI action plan. However, we see the network as a currently underutilized resource to make progress on DEI goals. This action plan should include the establishment of network-wide training on issues of workplace conduct, harassment, and bullying. Developing a network-wide action plan should occur through discussions with NSF leadership. The commonality of NSF funding across all sites provides a potential lever to assure adoption of DEI policies and practices across the network. We recommend that NSF add a requirement to the LTER program solicitation that all sites develop a DEI plan that clearly articulates site-specific goals, metrics, and assessment tools, and explicitly consider progress on DEI goals in site evaluations for renewal.

Longevity in funding is a unique strength of LTER to make progress on DEI. This funding longevity has allowed for maturation and sustained development of relationships with local communities. In particular, many sites have cultivated trusted relationships and partnerships with local community schools and outreach organizations and these are being effectively used to reach out to underserved, low-income communities. The LTER Schoolyard programs appear highly effective tools for engaging both students and teachers from underserved communities. Sites are active in leveraging external NSF funding to promote engagement of K-12 teachers from underrepresented communities (e.g., RET, Noyce Scholar programs). At the undergraduate level, sites are successfully leveraging REU programs to recruit students from underrepresented communities. Such efforts are having an impact with respect to increasing gender, racial, and ethnic representation.

These efforts are working to increase representation among K-12 and undergraduate students, yet striking inequity in representation remains apparent at more advanced career states (graduate students, post-docs, faculty). In particular, underrepresentation of BIPOC among LTER faculty and science leadership positions is notable. We see positive signs that this is changing: several sites have recently benefitted from their host universities recruiting and hiring women and non-white faculty and sites are actively engaging these new faculty in LTER activities. Similarly, we see action at the network-level to balance gender representation, as evidenced through representation on LTER network committees. The on-going generational turnover of PIs and scientists at many LTER sites presents unique opportunities to refocus on improving the leadership contributions by underrepresented communities.

D.3. Student and teacher DEI activities and engagement

Some of the clearest LTER successes in DEI have emerged through development of education and outreach programs that target local communities. Most sites host school field trips and provide in-person and online educational materials to local schools. Many sites have developed programs where culturally-considerate, science education materials are developed *with* and distributed *to* local communities, including many that are predominantly non-white and economically-disadvantaged. For example, when developing new K-12 curriculum the Jornada Basin site screens these materials to assure that they meet DEI-specific criteria, including: incorporating stories of diverse people and careers in STEM; connections to Spanish, Native, and other languages and cultures when possible; Spanish versions of worksheets and other materials are available for any student who wants to use them; and lesson materials can be easily used by students with color blindness or other visual needs. Another example is the LTER Schoolyard book series which has published and distributed children's books (in some cases translated into multiple languages) highlighting LTER science to local-area schools. Sites located outside the United States (e.g., Luquillo, Moorea), have done an excellent job engaging local K-12 programs. The Moorea Coral Reef LTER partners with the Tahitian educational NGO Te Pu 'Atiti'a to translate their sites science into Tahitian and French, allowing integration of their site's science into local schools.

Sites have invested considerable effort in teacher training, often specifically focused on teachers serving predominantly BIPOC communities. To support this work, sites have successfully leveraged NSF support from programs like RET to engage non-white teachers. For example, in 2021, the Florida Coastal Everglades LTER supported BIPOC teachers through their RET program; two of these teachers also received support through the NSF Robert Royce Teacher Scholarship program. The Harvard Forest site leveraged an RET grant for partial support of a diversity consultant to help develop a strategy for attracting and retaining new teachers (urban teachers, teachers of color, teachers in schools with a high percentage of students receiving free or reduced lunch) in their Schoolyard Ecology program.

Sites are also successfully leveraging their REU programs to recruit underrepresented students. The Northern Gulf of Alaska site has an Alaska Native REU program. In other cases, sites have partnered with national organizations and societies to engage underrepresented students in LTER activities. For example, both the Central Arizona-Phoenix and Florida Coastal Everglades sites are actively partnering with the Ecological Society of America (ESA) including leveraging the ESA SEEDS Partnerships for Undergraduate Research (SPUR) Fellowship program to fund internships for undergraduate students interested in teaching. We encourage LTER to continue to seek opportunities to recruit both undergraduate and graduate students from Historically Black Colleges and Universities (HBCUs), Hispanic-Serving Institutions (HSIs), and tribal colleges. Similarly, sites should look to recruit students through organizations like Hispanic Association of Colleges and Universities and the National Association for Equal Opportunity in Higher Education. Several sites are benefitting from institutional fellowships specifically earmarked for recruiting and supporting underrepresented graduate students. Other successful approaches for retaining students rely on leveraging site-based institutional networks. For example, the Moorea Coral Reef site has promoted the movement of students between institutions at progressive stages in their career training. Two Moorea site Ph.D. participants (both female, one African American) started with the site as undergraduates and moved within the site network to different institutions for their Master’s, Ph.D. and post-doc training.

D.4. LTER DEI leadership

Although there are promising signs of an increasingly diversified STEM workforce, the fact remains that faculty positions in Ecology and Earth Sciences across the US remain dominated by white males, and this continues to present challenges for diversifying LTER site leadership. At the network level, this issue is being confronted where possible, at least with respect to gender disparities, as evidenced through gender equity in the composition of the LTER Executive Board. However, in a sign of continued representation disparities among LTER PIs, the composition of the current LTER Science Council remains disproportionately male dominated (17 of the 27 members are male). Moreover, representation by BIPOC in LTER network leadership positions remains extremely low. Changing the representation of LTER leadership will require top-to-bottom efforts to recruit, mentor, and retain URMs. Numerous studies highlight the lack of role models as a key hurdle toward retaining URMs. Where possible, the LTER Network Office should specifically feature the accomplishments and science being conducted by URM scientists and a means to strengthen the position of role models for URM students and early career scientists. The Network Office could also facilitate opportunities for virtual or in-person gatherings of URM graduate students, post-docs, and faculty to foster community and develop support systems within and across career stages of LTER scientists.

Sites are actively addressing issues of underrepresentation among their leadership teams. For example, the Central Arizona Phoenix LTER has recently involved 9 Black, 3 Indigenous, and 1 Latinx scientists in their site. Other sites are taking advantage of recent institutional faculty hires to diversify their site science team. The Florida Coastal Everglades site has recently involved 3 tenure-track faculty that were hired by Florida International University via an initiative through the Office to Advance Women, Equity & Diversity (AWED). The California Current Ecosystem site invited 5 new faculty hires at Scripps Institution of Oceanography, all of whom are women and 3 of whom are from underrepresented communities, to join their site and contribute to renewal proposal planning. The Harvard Forest site is actively recruiting a new BIPOC to serve as co-PI, and the Virginia Coastal Reserve site is using site-based 'affiliate researchers' to try and diversify representation among science personnel.

We encourage all sites to take advantage of NSF opportunities available to diversify their science leadership teams. For example, the “Facilitating Research at Primarily Undergraduate Institutions” program could be more effectively used to recruit diverse faculty into LTER site research. Similarly, partnering with faculty at HBCU to take advantage of the “Historically Black Colleges and Universities” solicitations would provide funding mechanisms for supporting both students (undergraduate and graduate) and faculty in LTER research. LTER PIs should seek opportunities to advance DEI through NSF programs like NSF INCLUDES (Inclusion across the Nation of Communities of Learners of Underrepresented Discoverers in Engineering and Science), NSF ADVANCE (Organizational Change for Gender Equity in STEM Academic Professions), and identify opportunities to leverage connections to professional ecological societies (e.g., ESA) to take advantage of the NSF BIO-LEAPS (Leading Culture Change Through Professional Societies of Biology) program.

One of the central recommendations stemming from this decadal review is that all sites explicitly include studies on human-ecological interactions. This recommendation, and the attendant shift in research that would accompany this recommendation if implemented, has the potential to impact DEI. By expanding the definition of LTER science to include questions of human-ecological interactions we see an opportunity to broaden the pool of potential graduate students, post-docs, and PIs interested in interdisciplinary science. Expansion of LTER research into more applied research, including topics that address ecosystem sustainability, socioecology, and community-engaged scholarship, would allow the network to build a more inclusive tent of researchers with a wider range of interests and expertise.

D.5. Site-specific and network activities

There are an alarming number of examples where workplace harassment, bullying, and misconduct have proliferated at field stations and field sites. These are issues that strike close to home within the LTER network. The same isolated and remote characteristics that make field sites and field stations excellent places for conducting ecological research can also promote lack of supervision, amplification of power inequities, and lead to poor accountability and unclear reporting structures for dealing with inappropriate behaviors. Many sites currently require personnel to complete Title IX training and many sites (and the LTER network) have formed DEI (or JDEI) committees. These steps represent important progress on this issue, and the time is right for the network to take a greater leadership role. The recent establishment of an LTER network-wide DEI committee demonstrates rising awareness and a commitment to these issues. We recommend this committee, with guidance from NSF, work toward establishing a network-wide vision for DEI. This vision should articulate policies and practices applicable across the network and identify clear metrics for success in network DEI. Moreover, we encourage the network to consider training sessions for all LTER personnel on issues specific to DEI. There are a number of programs that could be engaged for such training, including sessions specifically focused on fieldwork (e.g., "Building a Better Field Work Future" (https://fieldworkfuture.ucsc.edu). While most field-stations and institutions that manage field-sites have begun to offer Title IX training classes, we encourage a network-wide push toward uniformity in the material provided through such training. Doing so will help instill a sense of recognition and importance within the network of these issues. We recognize the complicated nature of establishing such a network-wide vision and even more complicated process of trying to establish uniformity in reporting and enforcement across the geographically-distributed institutions, often with multiple institutions engaged in research at each site. This is further complicated by some sites being located outside of the US. However, a commonality across all sites lies with the funding source, namely NSF. Thus, we see a key role for NSF in providing guidance to enable network progress on DEI activities and training.

Network-wide leadership on DEI has the potential to increase awareness of these issues, setting the tone across the network that LTER is a safe, welcoming habitat for everyone to work and thrive. However, much of the responsibility for setting DEI policies, including promotion and retention of URMs, and reporting and enforcement of violations in DEI policies, continues to lie with individual institutions, in particular those which oversee LTER site activities. Hence, much of the burden for change lies at the local level, among the universities, institutions, and government labs whose employees conduct research at LTER sites. All LTER sites should write and disseminate a DEI code of conduct that includes actionable initiatives to increase participation at all levels and describe mechanisms for assuring accountability and pathways for reporting. Similarly, where applicable, sites should write and widely distribute land acknowledgement statements, instilling recognition and respect for the history and continuing human occupation at their sites.

D.6. Paths toward the next decade of DEI activities

Although the decadal review charge asked the committee to evaluate the future of the LTER network under a stable funding model, the committee sees additional NSF investment in site-specific and network-level DEI activities as key to their progress. Additional investment in this area has the potential to have a major impact on diversifying scientists in Ecology and Earth Sciences over the next decade. LTER has been proactive in recruiting underrepresented communities at the K-12 level, which is the key first step toward advancing the representation of these groups into sciences. However, advancing these communities into undergraduate, graduate, and post-doc, and PI positions within the network remains challenged. We view opportunities aimed at supporting advancement of underrepresented communities into science leadership positions (specifically at the graduate, post-graduate, and PI level) within LTER as having the potential to rapidly accelerate the advancement of these communities in Ecology and Earth Sciences. This could occur through LTER recruiting and supporting early-career scientists through new or existing graduate and post-doc fellowships that specifically target URMs. In addition, we encourage support for programs to facilitate cross-site interactions by providing sustained funding for promising students as they transition through progressive career stages in the network. For example, URM undergraduate interns or REU participants who meet performance criteria for graduate programs could be funded to pursue graduate work at another LTER site. Upon receiving their Ph.D., these same students could be offered post-doc scholarships to continue their research at different LTER sites. The American Geophysical Union Bridge program (https://www.agu.org/bridge-program) provides an example of such a program that might be modified for use within the LTER network.

LTER scientists should seek opportunities to broaden collaborations with faculty working at institutions serving primarily underrepresented communities, including HBCUs, tribal colleges, and HSIs. The LTER has several notable examples of highly successful engagement through these efforts (e.g., at the Florida Coastal Everglades LTER); we encourage broadening these efforts across the network. There are NSF programs currently in place to support such efforts.

Site REU activities are another clear path toward diversifying the scientific workforce in LTER. REU students have already self-identified as having interests in ecology and environmental science, so efforts to bring them into the network could have a big impact. Mentorship is another key element to promoting inclusion and retention of URM graduate students, postdocs, and junior faculty in the network. Such mentoring work often falls disproportionately on a few PIs, especially the small number of URM PIs in

LTER. Hence, robust mentoring plans should be developed for the network, and mentors should receive training and compensation for their efforts.

We see a need for top-down, network-wide leadership in DEI. The recent establishment of the LTER network DEI committee is a positive step in this direction – this committee should be empowered to take steps across the network. The network should develop required, regular (e.g., annual) network-wide DEI training for all students, staff, and scientists. Such training will allow participants at all levels of LTER activities to recognize and eliminate bias and harassment on the basis of gender, race, ethnicity, and sexuality. The LTER network should set clear goals and metrics for success in DEI, and progress toward success should be assessed regularly (e.g., annually) by sources outside the network.

We suggest that a network-wide, top-to-bottom review of DEI practices, policies and their enforcement would be a valuable exercise. Such a review should assess which structures are proving effective in supporting URMs and those that seem to fail. A central aim of this process should be to widen and build upon successful efforts supporting underrepresented communities and identify obstacles to entrainment and retention of URMs within the network. Some of the key questions to be asked as part of this review include:

- What structural changes to policies and practices are needed to increase and support DEI?
- How will efforts on DEI be recognized and rewarded?
- How will people be trained in DEI?
- What systems of support can be put in place for URMs across the LTER community?

Broadening participation within the LTER community will require purposeful and intentional steps at the network level. Such steps could include things like training workshops for PIs on mentoring of diverse students, allocation of graduate student and post-doc funds specific to underrepresented minorities, and the creation of research opportunity awards specific to increasing participation of BIPOC PIs and those from minority serving institutions.

D.7. Recommendations

8) **We recommend that LTER conduct a top-to-bottom network review of efforts toward DEI.** We see need for drafting a network-wide vision statement and an action plan. These plans will need to consider on-going DEI activities at individual sites. We encourage sites to write and distribute land acknowledgement statements. We also see a need for network-wide DEI training, including training for faculty on mentoring of diverse students. LTER should continue to seek opportunities to engage students and faculty from universities and institutions that serve URMs, including HBCUs, HSIs, and tribal colleges.

9) **We recommend adding a DEI plan requirement to the LTER program solicitation, and assessment of progress toward DEI goals as components of mid-term reviews and renewal proposals.** The LTER sites would benefit from more explicit guidance regarding expectations for DEI training, recruitment, and retention of URMs in the network. Where possible, we see substantial benefit in

additional funding directed toward scholarships/fellowships for LTER graduate students and post-docs from underrepresented groups, and identifying funds to compensate those PIs who engage in mentoring of URMs in the network.

E. Data Management and Ecoinformatics

E.1. Preamble

The management of data, from the point of collection to publication, is essential for transparency of research and for future accessibility for reuse. Making data FAIR (Findable, Accessible, Interoperable, and Reusable[29]) is now the minimal goal for data providers and repositories globally, yet is difficult to fully realize. Management and sharing of data are fundamental to doing good science, and for the LTER network, which has accumulated decades of data, good data management practices are essential to the program's sustained success and its utility to future generations. Practices in environmental and ecological data management are shifting, in part motivated by the increasingly collaborative and team-led science and the rapid expansion of "big data". These trends have placed renewed emphasis on proper data management, data sharing, and open data. However, movement in data management toward these areas places new challenges on data repositories, in particular to assure data are truly interoperable and reusable. As a long-term program with decades of experimental and observational data, excellence in data management within LTER is essential. Good data management will be integral to allowing LTER to take a leading role in forward-looking, ecosystem-scale synthesis over the next decade.

To inform its discussions, the Data Management Subcommittee met with 1) several PIs from both newer and older LTER sites that represented a wide range of ecosystems, 2) the Information Management Executive Committee that was functional in 2019, 3) representatives from EDI, and 4) representatives from the Biological and Chemical Oceanography Data Management Office (BCO-DMO), the latter two being data repositories funded by NSF. Finally, Peter McCartney, former NSF Program Officer for the LNO, provided valuable historical information about data management over the past two decades.

Throughout this report, we discuss the importance of including more cross-site and cross-ecosystem synthesis in LTER activities; there are two major avenues to doing so. One is through aligning research at the onset across sites to standardize collection and processing. Another, often less expensive and more inclusive path (particularly for scientists without large funding sources), is to find, download, harmonize, and reuse publicly available datasets. This latter avenue is one way LTER has conducted syntheses (although not exclusively) and where thorough, well-thought-out data management practices are essential. We have found that with EDI serving as a stable repository on which the site IMs can build, the network is now better poised to support both site- and network-wide science. With some moderate updates, the LTER repository can become even more useful to LTER PIs, external researchers, and partnering networks.

E.2. Continuous Improvement in Data Management

In 2016, the newly-formed EDI was charged to assist LTER with submission of datasets for publication to its repository, and to manage these datasets for the long-term. Formerly, such tasks were the responsibility of the LNO. As EDI grew from the LTER

Information Management community and infrastructure, this was a natural progression and fit. Continued development of the Ecological Metadata Language (EML) by LTER and EDI demonstrates commitment by both programs to improved data management. EML, a globally adopted standard for documenting ecological and environmental datasets, is now the primary metadata language for several other major NSF-funded repositories and data providers (e.g., DataONE, Arctic Data Center, NEON), and has played a central role in supporting FAIR principles among the landscape of ecological data.

Today, EDI is clearly perceived by both PIs and IMs as a major improvement for LTER data management in the few years since it was implemented. Some comments from PIs and IMs include:

- *"EDI is an amazing resource! Both to (1) enable reproducible research and data preservation… and (2) to enable some degree of quality checking…"*
- *"EDI has been invaluable for our data management program. In addition to providing a repository with well defined standards of metadata, EDI's systems include quality control systems to ensure complete and congruent between data and metadata. Their staff has delivered excellent support, both in assisting us with dataset submissions and in harvesting information."*

The strength of EDI in part comes from the history of EDI's development; both staff and infrastructure come from LTER and have rich ties to the program. The other part comes from a strong commitment of both EDI and LTER IMs to continue working closely together to improve data management systems that meet the needs of both LTER and EDI goals. This strong commitment is essential to the sustainability of LTER data management moving forward. However, sustainability of EDI as both a stand-alone organization and as the primary repository for LTER is concerning in that its funding comes from a different NSF division from LTER and is subject to rotating grant cycles - here, on a 5-year cycle. The scope is currently limited to maintenance, through the sustaining track supported by the Division of Biological Infrastructure. As EDI increasingly supports other organizations and researchers outside of LTER, NSF will need to carefully examine continuity in the governance structure linking LTER and EDI to assure the scope of both programs remains closely aligned.

We noted successes within the PI and IM communities in the use of EDI beyond serving as a primary repository of site data. In particular, PIs have leveraged EDI tools (e.g., software, code scripts, APIs) to submit data to EDI and facilitate data analyses, while IMs have built site-specific data catalogs that point back to the original data sources at EDI. Both communities are increasingly finding efficiencies in using EDI tools rather than developing custom solutions.

Sites are wrestling with how best to make large and complex datasets and data products increasingly being generated by LTER sites FAIR (e.g., model output, remote and autonomous sensors, nucleic acid sequence data). As currently configured, EDI is not equipped to make these large datasets highly accessible due to the cost of server-based storage and must instead store them on hard drives. Yet such data are increasingly being generated by LTER sites. In some cases, such data are archived or published via a local university repository and made available via the site websites. This may be the most cost-effective means of archiving and sharing these data; however, this solution runs the risk of loss in discovery and access unless metadata are submitted to EDI or another major third-party repository. Moreover, in the event the site is not renewed, using site websites for data archival risks complete loss of these datasets. In other cases (e.g., nucleic acid sequence data), data may be archived via public repositories (e.g., NCBI), but "cross-referencing" of these data that archived across different repositories demands increased effort to compile these data across platforms. This is not a problem unique to LTER and it is not incumbent on them to uniquely solve this problem; however, given the longevity of the program and their long history in data management, LTER should be an active participant in finding solutions to make these data easily accessible and cross-referenceable.

We heard concerns about the spread of data across multiple third-party repositories. For example, the Office of Polar Programs requires that Antarctic sites deposit their data in the Antarctic Data Center, while Arctic sites deposit their data in the Arctic Data Center. Further complicating this issue, some researchers deposit their data directly into repositories such as the Dryad Digital Repository or Zenodo without notifying their IMs or EDI. And as noted above, some datasets go directly to local university or domain-specific repositories. Because there is no central index of DOIs associated with all LTER data, it is impossible to track or query all LTER datasets. Some organizations cross-reference datasets; for example, BCO-DMO now has LTER sites submit datasets to EDI, and then BCO-DMO indexes relevant LTER datasets by EDI DOIs such that data can be found via both catalogs without redundancy. DataONE has several but not all of the above-mentioned organizations as member nodes and is the closest thing the network has to a central index, but to get a comprehensive review of all LTER data, it still falls upon researchers to do thorough internet and online catalog searches. Larger initiatives like Google Dataset Search provide potential avenues for more thorough indexing, but require JSON-LD metadata provided for each dataset using the less-than-mature Schema.org schema. An exciting outcome of the scaling that mature repositories such as EDI and BCO-DMO provide is the automated generation of much machine-readable metadata, such that Google can automatically harvest, index and make LTER data discoverable. For example, a search of "LTER" yielded many datasets, an example of one being "Data from: SBC LTER: Long-term experiment: Kelp Removal: Transect depth data" (https://datasetsearch.research.google.com/search?query=LTER&docid=L2cvMTFqbnp5em4weQ%3D%3D), which is indexed via its DOI at EDI, DataONE, and DataCite. Initiatives such as these, which are only possible through 1) the leveraging of knowledge of multiple communities via working groups and conferences and 2) the willingness and resources to incorporate new technologies into the publication pipeline, are a testament to the high level of partnership and commitment between LTER and EDI. Resources should continue to be made available for such collaborations and technological upgrades.

E.3. LTER Data Management Mission and Goals

LTER has been pioneering ecological and environmental data management techniques and best practices for decades, and one reason that LTER has stood out globally for its development of conceptual frameworks, standardized data and metadata standards, and cyberinfrastructure is that data or information management has been treated not only as a task, but as an area of research for many in the LTER IM community.

Given the importance of data management for the network, we noted the lack of a network-wide vision and mission statement for data management, particularly in the context of our discussions around the importance of supporting cross-site synthesis projects. We explored the similarities and differences in missions and goals of EDI and

LTER PIs and IMs in data management. EDI, as a repository serving not only LTER, but more broadly the ecological community (e.g., NSF Macrosystems grantees, Organization of Biological Field Stations, etc.), considers its primary mission to LTER as providing a trustworthy data repository, supporting data providers to easily submit data, and helping to improve the quality of the data and metadata that are submitted. LTER PIs, IMs, and EDI representatives identified similar broad goals: for example, to make LTER-funded data FAIR and to ensure the longevity of the data. There were expected divergences based on the placement of the responders within the data life cycle. PIs cited the importance of preserving the legacy of site research, providing clear and thorough metadata, supporting long-term ease of use of high-quality data, and tracing the connections between researchers and their projects. IMs cited the importance of supporting team and site science goals, and preserving data in archival form. All of these goals are worthy and important but we noted divergence from individual to individual and from site to site, and site-specific generation of data management goals rather than unified network-level goals.

We think that management of LTER data could be improved across the network, and therefore the impact of LTER's data management practices on other networks in the US and beyond, if the network PIs and IMs were to collectively develop a public-facing vision, mission statement, and site- and network-scoped set of decadal goals for data and information management. These could be communicated internally and externally as well as used as a foundation for training practices as discussed in section E.5.

E.4. Data Management and Data Science for Cross-Site and Cross-Ecosystem Synthesis

This decadal review, like all previous decadal reviews, has recommendations for continued and expanded roles for synthesis using LTER data. In our review of network synthesis activities, we emphasize the progress that has been made over the past decade with respect to site-based syntheses. We also identify additional opportunities for developing cross-site and cross-ecosystem collaborations. We view expansion of network synthesis as low-hanging fruit for the next decade, with potentially powerful impacts on Ecology and Earth Science.

In the 2011 LTER SIP, the network identified data as a challenge to cross-site integration. Specifically, this plan states: "cross-site integration is inhibited by the diversity of data types, formats, sampling strategies, and collection methods, and the locally specific and context dependent nature of site data." As part of our conversations with the LTER IMs we heard encouraging statements that the move to EDI helped alleviate some of these data-specific historical roadblocks to cross-site interactions. In particular, EDI's role in organization and publication of robust metadata and standardization of data formats has facilitated data exchange across sites.

We heard from LTER IMs that scientists are increasingly going directly to EDI for LTER data, rather than working through the site IMs to access historical site datasets. This is gradually changing the roles that IMs play in site data management. Site IMs' responsibilities now include organizing and running data bootcamps, producing and disseminating code used for data extraction and analyses, and mentorship of graduate students and postdocs in best practices for data management. These are critical and important services for LTER. Where possible, we encourage continued sharing and centralization of such activities at the network-level.

Moving syntheses efforts to the forefront in the next decade will demand close interactions between LTER scientists, IMs, and EDI. Based on our conversations with PIs, EDI, and IMs, we found it unclear which of these groups views it as their responsibility to facilitate the curation and harmonization of LTER data across sites in support of network-level syntheses. Even for site-level synthesis we sensed that while IMs were charged with responsibility for making core site datasets available to EDI, responsibilities specific to synthesizing site data products were unclear. This issue is compounded for cross-site syntheses where there needs to be clear delineation of roles specific to data compilation, curation, and publication across multiple sites. Within LNO SWGs, PIs currently invest substantial resources toward harmonizing (and in some cases publishing) datasets for subsequent synthetic analyses. Much of that effort is currently overseen by post-docs and network scientists, who often do not receive direct support via the core LTER program funds. We encourage the LNO SWGs to proactively involve site IMs in the development of synthesis proposals when a deep history of site data is needed. This step will facilitate data management for subsequent cross-site synthesis. We also view the recent hiring of a data scientist and two post-docs based at the LNO as a significant positive step toward future synthesis activities.

New data dissemination practices and tools have the ability to improve the visibility and reuse of harmonized and synthesized LTER data. One important change is specific to publication of datasets. The streamlined path of data publication that EDI and other robust, trusted repositories offer is one example of such change. Another is that several journals now offer the option to publish papers describing the utility of synthesized datasets (including assignment of a digital object identifier, DOI). We strongly encourage the LNO SWGs and individual sites to take advantage of these resources to publish the datasets deriving from these synthesis efforts. Doing so will allow subsequent data users direct access to the finalized datasets and provide opportunities for follow-up future analyses. Many sites currently serve “hallmark” datasets on their site websites - these should be available via EDI or another high-quality third-party repository as appropriate (with links made clear via site websites), facilitating their use for retrieving time-varying patterns and trends at each site. Doing so will also provide a citable DOI to recognize the effort invested in generating these data and making them available. Publishing of the long-term, harmonized datasets for use in synthesis will add new value to these data. We were surprised to find that the curated and harmonized datasets that went into the recent site syntheses conducted for contributions to the *Ecosphere* special issue were not published as datasets and assigned DOIs, challenging future reuse of these data.

We discovered opportunities for improvement in discoverability and usability of LTER data. As part of our review, members of the decadal review committee explored the usability of LTER data for examining time-varying trends in core LTER datasets. We sought to evaluate how easily we could examine temporal changes in these data at one site and across sites. For example, we queried LTER data in the EDI data portal using keywords like “primary production” or “nitrate concentration” in hopes of answering simple questions like: “are there long-term trends in primary production across different LTER sites and if so, how do the trends compare?” or “are there seasonal differences in concentrations of nitrate within a given LTER site or across different LTER sites?”. We considered our queries to represent those that might be attempted by scientists working outside of the LTER network, with familiarity of specific types of data available via LTER and some rudimentary knowledge of LTER sites. Our cursory searches encountered several issues that made answering these basic questions difficult. In particular, we found that the site-specific LTER datasets (those retrieved when searching using these general keywords) are often a mixture of data obtained from experimental manipulations and routine "monitoring" based observations (including a mix of sensor-based measurements and more traditional lab-based determinations), making extraction of time-varying changes difficult. Moreover, we found that site datasets were often binned into discrete time periods or arranged based on specific field sampling campaigns (for example arranged by research cruises), making the process of extracting data for subsequent time-series analyses a laborious task. We also did not find software tools available to help data users visualize datasets prior to download. Finally, we noted inconsistencies in reporting of data units across different sites despite the data having been derived using similar methodologies (e.g., units for nitrate concentrations, all obtained based on colorimetric laboratory analyses, included mg L^{-1}, ppb, μmol L^{-1}). In summary, we found that the process of obtaining data via EDI was not well configured for examining long-term data trends or synthesizing data across sites and ecosystem types. Part of the solution to this will lie with data generators considering how the data will be explored and reused by others in the future (for example, comparing long-term trends or seasonal patterns), and formatting, documenting, and submitting datasets in ways that facilitate their future use. Part of the solution to this issue will also lie with EDI working more closely with LTER scientists and IMs to continue to develop a data system that is optimally configured toward analyses of LTER datasets (discussed further in Section E.5). Admittedly, our efforts here were far from exhaustive and we did not contact EDI or site PIs for assistance with our queries, nor did we query DataONE (partly because we did not see anywhere that this *should* be the primary point of exploration). However, this experience convinced us that the initial steps in *discovering*, let alone harmonizing, data for subsequent synthesis efforts, particularly across sites, demands considerable time investment. Reducing this effort will require concerted, proactive planning, across the network, in advance of data submission (and arguably even prior to data collection).

We also encourage the network to identify key, LTER-specific datasets that could be developed into visuals useful for broadly advertising the utility of LTER science, the utility of long-term data collection, and the necessity for site-specific, time-resolving observations and experiments. Identifying a few key LTER datasets that could be used to highlight ecosystem to continental-scale changes and thus become synonymous with LTER science, something akin to LTER-specific 'Keeling curves', would go a long way toward public outreach and promotion of the network as a barometer of planetary change.

E.5. Technology Development, Data Management Gaps, and the Role of Scientists

The pace of technology development has proceeded quickly over the past several decades, including instrumentation, networking, software, and data storage. Robbins, in his position paper written in conjunction with the 30-year LTER review, predicted that data and metadata collection costs could be lowered over time using automated, programmable sensors, thus leading him to recommend "LTER data-management operations should be optimized to take advantage of falling technology costs, especially in the area of automated data and metadata collection, while simultaneously maximizing the efficiency of LTER data-management staff." To a large extent this recommendation appears to have been realized, with more automated and programmable sensors deployed in remote areas and automated data ingest and processing workflows at the sites. Several proactive LTER IMs and EDI staff participated in the founding and continuation of the Earth Science Information Partners (ESIP) Environmental Sensing Cluster (https://wiki.esipfed.org/EnviroSensing_Cluster) to develop and promote best practices for sensor data management and environmental data networks - from field design and deployment to data processing.

However, improved technology has also meant that more sensors can be deployed; more data may be extracted from collections (e.g., metagenomics data from environmental samples); more data points per unit time, often year-round (e.g., flux data at 40 Hz) may be ingested and processed; drones can carry increasingly sophisticated imaging and sampling sensors farther and longer into the field; etc. This has led to increased data management needs, and the increased volume of these data is straining the current storage and management capacities of both LTER and EDI. In addition, the availability of near-real- to short-time data from the field has substantially improved respective ecological forecast models as well as macrosystems modeling and the education about modeling. Such models are computationally intensive and yield products that are storage intensive. For very large datasets, the only option EDI can currently offer is "cold storage" on redundant hard drives, provided by the researchers; thus, the data are preserved, but not easily accessible following FAIR principles. Cloud storage options may provide a path forward for such large datasets that do not currently have obvious third-party repositories.

Another marked gap is the handling of environmental and biological samples and specimens taken from the field as part of LTER-supported research. This may include biological and environmental specimens (in whole or part), which may be of significant use not just as vouchers or chemical archives, but as genomic reservoirs (e.g., metagenomics from frozen soils). NSF has shown significant and thoughtful support for improving sample data discovery and quality, through the Advancing Digitization of Biodiversity Collections (ADBC) program and more recently through a call to the community to imagine collections in the 2020s, one output of which was the concept of the "Extended Specimen Network". Yet in our discussions, one IM mentioned that their site has no funding for physical sample management and they are not currently satisfied with the archives that are currently available to them, though they do ship their samples to their local university. There is currently no consolidated physical repository for LTER samples or online repositories cataloging sample collections. As a result, this information is virtually invisible to the research community. LTER in discussion with NSF should consider how to better encourage the archival of materials in a way that sampling records and sample availability are shared freely across the network.

An area of rapid improvement and collaboration is software. LTER IMs noted a marked improvement in the availability of both off-the-shelf software and community-developed software that help them complete their work with less need for custom, site-based software development as was more prevalent in past decades. Some sites are still bound to older software, and we recommend that even if these custom software packages fulfill very specific desires of the site, that these sites look for ways to modernize and plug into the same software that other sites are using, to improve interoperability and scalability.

E.6. Data Management Training

Good data management starts at the conception of new projects. The data management lifecycle requires attention to documentation of study design, parameters (including data quality flags and remarks), and processing steps. IMs should be involved throughout the lifecycle and can assist with many aspects such as cleaning data formats, recommending modifications to documentation fields for clarity, and providing tools to simplify the documentation process. But final published data products will be of greater use to the public if LTER researchers receive training in data management. It was noted in our conversations that although there are new tools to help researchers manage and publish data and metadata (e.g., ezEML), many scientists would benefit from training in understanding what it takes to build "good" metadata. One site IM mentioned that they organize annual training sessions and that this is a good time to work on data documentation and structuring data with students and PIs. Moreover, data management training could develop broader understanding of the expectations for each site under the network agreements; identification of specific repositories that are of highest value for their sites and research themes (e.g., EDI, linkages via BCO-DMO and NCBI); and educate LTER scientists on services that their IMs and EDI staff can provide.

Training also applies to the IM community, particularly incoming staff. Our discussion with the former IM Exec highlighted that the more recent IMs do not need to develop as much custom software as longer-term IMs have had to, and that the newer training resources and workshops have been helpful.

As mentioned above, we see a need for writing of network-wide missions and goals; such materials should be included as part of training materials generated for data management.

E.7. Recommendations

10) **We recommend that as a unified body, the stakeholders of LTER data management (LTER site PIs, IMs, LTER researchers, and EDI) clarify the mission, vision, and roles of stakeholders in data management for the network.** Doing so will improve upon already strong practices at the site level and strengthen practices that will promote and catalyze network-level science. This clarification should permeate through all levels of the network, including through training materials for students, PIs, and new IMs, LNO synthesis workshop inclusivity of data scientists (including site IMs as need arises) and data management best practices (e.g., publication of all working group code and datasets in formats that are accessible for reuse), and network-wide guidelines for dataset development, documentation, publication, and citation.

11) **We recommend that LTER and EDI continue to work on making synthesized and synthesizable data more FAIR**. This includes:
    a. identifying and minimizing aspects of data discovery and harmonization that currently inhibit within-site and cross-site collaborations;
    b. working with LTER researchers and the wider ecological research community to identify adjustments to existing software and development of new software that would help users better discover, acquire, visualize, explore, extract, harmonize, and otherwise work with LTER datasets in synthesis or modeling;

c. identifying methods of making datasets that are published or otherwise archived in less utilized repositories (e.g., university holdings, genomic databases, natural history collections) more FAIR and discoverable as LTER data to the external community;
d. better advertising of LTER data to the global ecological research community through the promotion of published datasets from LNO synthesis working groups and any other synthesis activities across the network.

F. Facing Forward: A Grand Challenge for the 21st Century

Every aspect of the Earth system is now being altered by human activities, with implications for ecosystems, the biological communities they support, and life-supporting functions they provide. The last four decades have each been sequentially warmer than any previous decade. Intensification of hurricanes, heat waves, wildfires, precipitation and flooding events are now definitively attributed to planetary warming[30]. The heat content of the world's oceans is increasing, seawater pH is decreasing[2], ocean circulation patterns are changing[31], and microplastics are ubiquitous in zooplankton[32]. More than half of coral reef area has been lost since the 1950s[33], and coastal forests are now being lost to sea-level rise, salinization, and tropical storms[34]. The warming of lakes has led to altered mixing regimes, expansion of hypoxia and harmful cyanobacterial blooms[35]. The cryosphere is shrinking and ice masses in Greenland and the Antarctic both reached record lows in 2020[2]. The rate of global tree cover loss has more than doubled since 2001[2], and the annual area burned in the US has tripled since 1980[2]. A quarter of all species now face extinction[5] while the biomass of humans plus our livestock now exceeds the biomass of all other mammals[36]. The certainty of continued warming and all other manifestations of an expanding human footprint has generated an urgency in the scientific community about the sustainability of planet Earth as habitat to support humans and all other species[2,5,37].

While there has been outstanding progress in observational and experimental research to advance concepts, principles and theories of ecosystem science, ecosystems continue to degrade and species extinctions accelerate. This incongruity poses a grand science challenge to anticipate future ecosystem changes, assess their consequences for us and other species, and anticipate outcomes of different strategies to slow or reverse the ecosystem consequences of human activities. The LTER model is proven, and we see an opportunity for it to play a crucial role in meeting this challenge.

We have a broad vision for meeting the challenge. It is forward looking, using the deep knowledge and data accumulated over the past four decades to forecast ecosystem responses to an expanding human footprint. It includes a strong modeling component to identify those ecosystem types, functions, biological communities, and human populations at greatest risk from accelerating global changes, and it includes strategies for slowing or reversing the loss of natural ecosystems and their life-supporting functions. This vision is tightly aligned with NSF goals described in the LTER solicitation of: (A) "achieving a mechanistic understanding of biological responses to past and present environmental change", and (B) "using this understanding to predict ecological responses at population, community, and ecosystem levels, and - if appropriate - evolutionary responses and social responses to ongoing or future environmental change." The LTER program has been extraordinarily successful at meeting goal A, but less progress has been made in meeting goal B. We view the uncertain consequences of future ecosystem changes as strong motivation for advancing NSF's goal B.

Our vision is also tightly aligned with recommendations made earlier in this report. It includes explicit recognition of the role of human activities as drivers of change, feedbacks between human activities and natural processes, and the consequences of lost ecosystem functions for human welfare and global biodiversity. Those peoples most at risk from global change are the same as those under-represented in the Earth system sciences. Addressing the grand challenge will create opportunities to diversify the LTER workforce and attract and train the next generation of Earth system scientists – the generation facing the greatest threats from global change. Sound forecasts are built from sound conceptual models derived from and validated with data syntheses across sites and ecosystems. Those syntheses require analysis-ready data sets compiled from LTER and other networks.

One of the many strengths of the LTER program is its bottom-up approach to scientific research. Members of the LTER community have demonstrated impressive initiative and resourcefulness to leverage network support through partnerships with government agencies, stakeholders, other networks and across sites. This community is clearly motivated to meet the challenge of ecosystem sustainability, and progress is being made. Long-term experiments at some sites are designed to anticipate plant community responses to global warming, elevated CO_2, and nutrient enrichment. The GCE and CCE LTER sites have used model simulations to *forecast* the effects of accelerated sea level rise on tidal marsh ecosystem services and future responses to biotic processes in the California Current. The LTER Self Study explains that: MCR researchers "are positioned to *forecast* the effects of intensifying global change and the expanding human footprint on oceanic coral reef ecosystems"; NTL site researchers envision expansion of their work to "describe, understand, and *forecast* shifting baselines and ecological transitions in lakes and their landscapes"; NWT site goals are to "elucidate the mechanisms driving ecological sensitivity and … use this information to enhance *forecasting*, management, and conservation in mountain areas". We encourage the LTER community to accelerate the exploration and creation of opportunities to advance these directions of forward-looking and solution-driven research.

Success will require NSF leaders to embrace, promote, facilitate, and incentivize LTER research to assess sustainability of ecosystems and their life-supporting functions in a rapidly changing world. We see many possible avenues for moving forward. For example, LTER proposals and Mid-Term site reviews could include plans for meeting and progress made to advance NSF's goal of predicting ecosystem responses to environmental change. NSF leaders could communicate to the LTER community that they embrace forward-looking research (goal B) that builds from the first four decades of LTER science, includes human-ecological interactions, examines the evolutionary basis for change, and assesses future states of ecosystems across scenarios of global change. They could actively promote use of new NSF funding opportunities, such as the *Biodiversity on a Changing Planet* program that supports "interdisciplinary proposals addressing grand challenges in biodiversity science within the context of unprecedented environmental change". They could explore opportunities for collaboration with programs in other Directorates, such as the *Chemical, Bioengineering, Environmental and Transport Systems Division*. Collaboration with that Division has a potential for bringing valuable and needed resources and expertise to LTER, such as expertise in hydrology, hydrodynamics, water and air quality, coupled physical-biogeochemical-biological models, uncertainty analyses, data science, green infrastructure, and artificial intelligence.

To be clear, we are not recommending the restructuring of a highly successful field-based program or diminishment of the self-determination of LTER scientists. Rather, we see an urgent need to use that component of LTER science to address the uncertainty of how accelerating global changes will continue to transform ecosystems and the services they provide to us and other species. Meeting this need is consistent with the LTER 2011 SIP prescribing: "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. Within this vision, our primary mission is to use long-term observations and experiments to generate and test ecological theory at local to regional scales." Our vision for a more forward looking LTER that emphasizes human-ecological interactions, grows diversity and inclusivity, trains the next generation of LTER researchers, and advances cross-system syntheses is also tightly aligned with guidance from the National Academies of Sciences, Engineering and Medicine in their 2021 report *Next Generation Earth Systems Science at the National Science Foundation*[38]: "The time is ripe for an Earth Systems Science that recognizes the urgency to inform decisions about human stewardship of the planet; builds on the scientific advances of the previous decades; incorporates all relevant disciplines, approaches, and perspectives into convergent approaches; utilizes the vast expansion in data and advances in computation, takes advantage of new analysis methods, and addresses the mandate for diversity and inclusion of a wide range of perspectives in the endeavor."

F.1. *Recommendation*

12) **The LTER Program has an opportunity to address the challenge of global change by expecting and supporting research to meet NSF's stated goals of both understanding past ecosystem changes and anticipating future ecosystem changes and their consequences.** We lay out a broad vision throughout this report to provide a framework for implementing this high-priority recommendation.

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VII. Appendices

Appendix A

Members of the LTER 40 Year Review Committee:

Matthew Church, Chair
Flathead Lake Biological Station, University of Montana

James Cloern
United States Geological Survey (emeritus)

Jacqueline Grebmeier
Chesapeake Bay Laboratory, University of Maryland Center for Environmental Science

Daniel Hernández
Carleton College

Christine Laney
Battelle Memorial Institute

Gretchen North
Occidental College

Michelle Evans-White
University of Arkansas

In addition, the following individuals provided service to the committee:

Diane Pataki
University of Utah

Bryan Foster
University of Kansas

Appendix B

Charge for the Fourth Decadal Review of the NSF Long-Term Ecological Research Network

This is the fourth decadal review of the NSF Long-Term Ecological Research Network. Long-term research is essential to understanding many of the ecological processes that shape our environment. The NSF began funding the Long-Term Ecological Research program (LTER) in 1980 to support site-based ecological research over broad temporal and spatial scales. Today the NSF LTER network is comprised of 28 distinct research sites, a network office, and a data management initiative. The disciplinary breadth of LTER research includes population and community ecology, ecosystem science, evolutionary biology, urban ecology, oceanography, and, in some cases, social and economic sciences. The LTER investment across NSF exceeds $30 million annually with most contributions coming from the Directorates of Biological Sciences and Geosciences. In addition to science funding, some sites in remote locations require and receive substantial support for ships and logistics.

LTER research is characterized by the study of ecological phenomena motivated by a strong conceptual framework and in that respect is similar to other ecological programs at NSF. However, three main components differentiate the science conducted through the LTER program. First, the questions addressed required long-term studies to answer. Second, LTER sites are chosen to represent major biomes or ecosystem types. Third, all sites are conceptually united by the requirement that data be collected in five core areas: 1) primary production, 2) population dynamics and food web interactions, 3) organic matter accumulation and decomposition, 4) inorganic inputs and movements of nutrients through soils, groundwater, and surface waters, and 5) disturbances. In addition to data all LTER sites collect in the five core areas, Urban LTER sites must collect data in at least one social, economic, or cultural process, and those data should be integrated with other core data to examine effects of human-environment interactions on urban ecosystem dynamics.

The LTER network incorporate a range of broader impacts both at individual sites and at the network level. The longevity of LTER sites makes them well-suited to develop and maintain relationships with stakeholders, educators, and the public. LTER sites receive support for a “Schoolyard” program and two Research Experience for Undergraduates students each year. The “Schoolyard” program is intended to enable sites to create and sustain activities that engage K-12 students and teachers.

Prior to 2015, the network office was responsible for (1) supporting network-level activities, which included governance and synthesis, and (2) data management, which included repository and methods development. Based on concerns raised in the thirty-year review and infrastructure needs at the network level, these two functions were divided. Network-level activities currently managed by the LTER Network Communications Office (NCO) involve communication and coordination among all LTER sites and the establishment and support of synthesis activities. NSF has worked with the LTER sites and the NCO to streamline data management. This effort culminated in the development and support of the Environmental Data Initiative (EDI), which provides informatics expertise and serves as a repository for LTER data and data from ecological community at large. EDI works closely with the LTER Information Management committee to coordinate data management best practices and stewardship.

LTER Program Summary and Solicitation:
LTER Network: https://lternet.edu/

Charge: The charge to the Fourth Decadal LTER Review Committee is to evaluate the significance of the long-term scientific findings and approach to research of the LTER Network over the last decade, and its readiness to support the research of future decades. The evaluation will culminate in a report to NSF assessing the 1) significance of the long-term ecological and environmental science produced by the LTER network over the last decade, and 2) strengths and weaknesses of the LTER network model of supporting long-term, site-based research through renewable funding. Any recommendations that emerge from the review should be developed in the context of an NSF program with stable support, but with the flexibility to make changes. The report will be delivered to the Directorates of Biological Sciences and Geosciences, including the Office of Polar Programs and Division of Ocean Sciences, for review and response.

Report Guidance:
The structure and length of the report will be determined by the Committee. The LTER Network will provide the Committee self-study reports for each site and a response to the thirty-review report. The Committee may also choose to visit individual sites, the NCO, EDI headquarters, meet with LTER PIs, and meet with NSF Staff and Program Officers overseeing the Program. In addition, NSF has developed the following overarching questions to guide, *not limit*, the decadal review.

Research
1. How well has the LTER network advanced important long-term research objectives and demonstrated a clear need for continuing the current model of long-term site-based research?
2. Could comparable results have been obtained through shorter-term awards to individual investigators through core Programs?
3. The current model for the LTER network requires data collections in at least five “core” areas, intended to characterize the defining structural and functional components of regions or biomes and to facilitate synthetic research. What are the strengths and weaknesses of this model?

Synthesis
4. How effective have synthesis activities (cross-site and beyond-site) been in expanding use of long-term data collected at the individual sites and expanding the research capacity of the network?

Expanding Resources

5. How effectively has the network addressed the resource challenges discussed in the thirty-year review recommendations?

Education

6. How effective has the LTER network been with fostering education and outreach activities that engage diverse communities in science?
7. Does training fostered by the LTER network broaden participation?
8. Are sites equipping the next generation of researchers to innovatively address complex ecological challenges?

Outreach and Partnerships

9. To what extent has the long-term data provided by LTER sites been instrumental in informing policy making and resource management?
10. How effectively have partnerships with federal agencies (other than NSF), non-profit organizations, state agencies, or other co-located research efforts provide mutually beneficial leveraging of resources at the LTER sites and expanded the overall research capacity of the LTER network?
11. How have the LTER sites interacted with NSF-funded observatories such as NEON, OOI, NCAR, and CZO in addressing their science objectives? What are the strengths and weaknesses of these interactions?

Data Management and Ecoinformatics

12. How do data generated by LTER research meet the recommendations of the FAIR principles (Findable, Accessible, Interoperable, and Reusable - https://www.nature.com/articles/sdata201618)?
13. How effective is the network in releasing data through independent repositories such as Environmental Data Initiative, Biological and Chemical Oceanography-Data Management Office and broader data portals such as DataONE?
14. How does the network keep up with or contribute to advances in data management, cyberinfrastructure, computational methods, and data standardization?

Planning for the next decade

15. How does ongoing work at LTER sites address past and emerging topics relevant to cross-NSF initiatives or areas of national interest, such as sea level rise, ocean acidification, and climate change?
16. How well prepared is the LTER network to advance ecological science and meet future disciplinary and interdisciplinary research challenges in ecology, ecosystems science, and other fields of environmental biology?
17. What are some of the network’s most compelling opportunities and pressing challenges?

Appendix C

Table of common acronyms used throughout this report

Title	Acronym
National Science Foundation	NSF
Long Term Ecological Research	LTER
LTER Network Office	LNO
LTER Network Communications Office	LNCO
Environmental Data Initiative	EDI
Biological and Chemical Oceanography Data Management Office	BCO-DMO
National Ecological Observatory Network	NEON
Oceans Observatories Initiative	OOI
LTER Network Communications Office	NCO
National Center for Ecological Analysis and Synthesis	NCEAS
Strategic Implementation Plan	SIP
Diversity, Equity, and Inclusion	DEI
Principal Investigator	PI
Education and Outreach	EO
Information Manager	IM
Synthesis Working Groups	SWGs
Syntheses across ecosystem types	XE
Syntheses within the same ecosystem type	XS

* The original report contained a typographical error stating that the network had produced ">800 peer reviewed publications." This was an underestimate by an order of magnitude; the error has been corrected in this updated version of the report. The correction was approved by Dr. Michael Ibba, Chair of the Advisory Committee for the Biological Sciences, on behalf of the whole committee.