Archimedes 59 New Studies in the History and Philosophy of Science and Technology

Robert B. Waide
Sharon E. Kingsland *Editors*

The Challenges of Long Term Ecological Research: A Historical Analysis

Springer

Robert B. Waide • Sharon E. Kingsland
Editors

The Challenges of Long Term Ecological Research: A Historical Analysis

Springer

Editors
Robert B. Waide
Department of Biology
University of New Mexico
Albuquerque, NM, USA

Sharon E. Kingsland
Department of History of Science and Technology
Johns Hopkins University
Baltimore, MD, USA

ISSN 1385-0180 ISSN 2215-0064 (electronic)
Archimedes
ISBN 978-3-030-66932-4 ISBN 978-3-030-66933-1 (eBook)
https://doi.org/10.1007/978-3-030-66933-1

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Chapter 13
A Retrospective of Information Management in the Long Term Ecological Research Program

Susan G. Stafford

Abstract This chapter describes the evolution of information management protocols for Long Term Ecological Research, starting with work conducted at the Andrews Forest Long Term Ecological Research site in Oregon in the 1980s. This early work involved the design, testing, and implementation of a data and information management system that helped establish standards and protocols across the Long Term Ecological Research Network. Following this initial work, a growth period ensued. The chapter discusses the creation of Ecological Metadata Language, explores the impact of the internet on ecological data management and shows how other countries adopted the same model for their long-term research networks. The Network Information System that was developed had broad applications to other projects, such as EcoTrends, the Environmental Data Initiative, and DataONE. Innovations in information management represent major and far-reaching accomplishments of the Long Term Ecological Research Program, and have influenced the entire field of interdisciplinary ecological research. They have helped to change the culture of scientific collaboration by making it both feasible and fair for scientists to share their data, and have in general promoted greater data literacy within the long-term ecological network.

Keywords LTER program · Long-term ecological research · Ecological networks · Data management · Data literacy · Data sharing · Information management · Cyberinfrastructure · Ecological Metadata Language

---

S. G. Stafford (✉)
Department of Forest Resources, University of Minnesota, St Paul, MN, USA
e-mail: stafford@umn.edu

R. B. Waide, S. E. Kingsland (eds.), *The Challenges of Long Term Ecological Research: A Historical Analysis*, Archimedes 59,
https://doi.org/10.1007/978-3-030-66933-1_13

13.1 Introduction

The establishment of the first Long-Term Ecological Research (LTER) site in 1980 coincided with the beginning of my professional career as a tenure-track, Assistant Professor in the Department of Forest Science, College of Forestry, at Oregon State University (OSU), 40 years ago. At that time, investments of time and resources in data and information management were almost non-existent. As the first Information Manager for the Andrews Experimental Forest (AND) LTER, this fortuitous timing provided a blank canvas on which to design, test and implement a data and information management system that helped establish standards and protocols across the LTER Network. My job was to help faculty, researchers and graduate students design statistically sound experiments, to manage their experimental data, to assist with analyses, and to ensure that statistically sound results were reported. Today, data management is taken very seriously and plays a very significant role within the LTER Network and in all proposals submitted to the National Science Foundation (NSF).

This chapter is organized into three parts. The first describes what I refer to as the evolutionary period in the development of data management protocols. The second describes the growth period during which our initial work in this field took hold and grew across the entire field of interdisciplinary ecological research. In the third section I recount my personal journey over the past four decades and conclude with some thoughts on what the future may bring.

13.2 The Evolutionary Period – How We Established Data Management Protocols

13.2.1 History of the Andrews LTER

The Andrews Experimental Forest had been in the data generation business for a long time before the Andrews LTER (AND LTER) site was first established. The AND LTER benefitted from the strength of the relationship between the OSU College of Forestry and the US Forest Service. The Andrews Forest was a recognized Man and the Biosphere (MAB) site and a key player (along with some of the other early LTER sites) in the International Biological Program (IBP).

NSF, the LTER network, and the scientific community learned many valuable lessons from the IBP about the importance and value of collecting, documenting, and managing data from long-term studies (Aronova et al. 2010). For example, I remember walking past a vault of IBP data (punched cards in those days) that had not been properly documented and archived. Consequently, that data had limited value to others unfamiliar with the original projects. These types of shortcomings seriously reduced the benefit derived from the initial investment – both financially and scientifically. From the beginning of the LTER program in 1980, there was a new policy that 15% of a site's budget should be dedicated to data and information management (Porter and Callahan 1994).

Fallout from IBP created high expectations for LTER data availability and documentation (later to be called "metadata") completeness on the part of both NSF and the scientific community. Although individual Principal Investigators complied with the new 15% budgetary requirement, each site's data and information management protocols were not standardized and coordinated to facilitate sharing of the data among all the sites.

For the same reasons, early progress towards standardization of methods among the first cohort of sites was stymied when the second cohort of sites was chosen in 1982. The rapid growth of the LTER program from 0 to 17 sites in 8 years complicated efforts to create a networked approach to information management.

The early LTER Network had a serious game of catch-up managing an enormous amount of legacy data at each site. Such data had been acquired and archived using a wide range of approaches. Sites collected data differently depending on the kinds of ecosystems being studied, and they used different terms to describe these data. Even within a site, the same process might be labelled differently by investigators studying streams versus forests. Much of this data was collected before "metadata" was even a word, yet the inclusion of these legacy datasets was invaluable and irreplaceable for both current and future generations of students and researchers. Historical practices and legacy data had to be integrated into a system consistent with the new information management protocols (Karasti et al. 2010).

13.2.2 Forest Science Data Bank and the Quantitative Sciences Group

To manage more effectively new and existing LTER data at the AND LTER, we took several innovative steps. First, we created the Forest Science Data Bank (FSDB) (Stafford 1998; Stafford et al. 1984, 1988) and established the Quantitative Sciences Group (QSG). In addition, we developed protocols (Stafford et al. 1986) for managing and archiving data that soon became prototypes for other LTER sites.

My goal was to fully integrate sound data management practices into the research process. To do so, we needed to include protocols from the beginning of a research study in a proactive manner, rather than retroactively (Stafford et al. 1986, 1994). The guiding principle of the FSDB was that documentation about the data was just as important as the data itself. Working alongside the researchers, at the beginning of a study, allowed for the co-design of data management solutions in parallel with the scientific process. This practice helped create an early trust in data stewardship and reinforced the importance of sound data management practices from the onset of a project. My experience in developing an information management system for the AND LTER site was repeated by Information Managers (IMs) at each of the sites.

The members of the QSG were nearly equally split between OSU and U.S. Forest Service (USFS) employees. This closely mirrored the productive relationship between the OSU College of Forestry and the USFS at the AND LTER. The first LTER Network Office was housed in the OSU Department of Forest Science. Jerry Franklin, a USFS scientist, held a courtesy faculty appointment in our Department and chaired the first Network Office. The integration of OSU and USFS personnel gave me, as QSG director, greater leverage in maximizing the benefit from our pooled resources. This was not necessarily the case at other LTER sites.

In 1994, Mary Clutter, Assistant Director of NSF's Biological Sciences Directorate (BIO), invited me to serve as visiting Division Director of Biological Instrumentation and Resources (Stafford 1996). During that time, I invited John Porter, Information Manager from the Virginia Coast Reserve (VCR) LTER site, to serve as a rotator Program Officer for Database Activities, a role for which he was very well suited and in which he was highly effective.

In my opinion, this Division was the best kept secret in the BIO Directorate, housing programs that related to data and research infrastructure for programs in the other Divisions within BIO, and was eventually renamed the Division of Biological Research Infrastructure. This interdisciplinary leadership opportunity was invaluable to me in many ways (Stafford 2016), bringing more attention to LTER IM as well as providing a springboard for me to serve on various Advisory Committees going forward. These included chairing the BIO Advisory Committee (BIOAC) as well as the Advisory Committee for Environmental Research and Education (ACERE). The ACERE served all of NSF and reported directly to the Director of NSF (Arden Bement at the time.)

13.2.3 Forging an Identity for Information Managers

One of the early challenges among the various LTER sites was building a community and a culture of collaboration. Bill Michener, Data Manager of the former North Inlet (NIN) LTER, and I wrote the first proposal to secure funds for an annual meeting of LTER Data Managers. These meetings were highly successful in bringing cohesion and a common vision to the initially small and disparate group of Data Managers (who would later be known as Information Managers). Michener and I emerged as the *de facto* leaders of the Information Management Committee (IMC). With NSF support, we institutionalized the annual Information Managers meeting. These meetings have persisted to this day (LTER Network News, http://news.lterent.edu) and are used as a model to create cohesion and singleness of purpose within a diverse cadre of researchers who value collegiality and professionalism (Stafford 2016).

These meetings became community forums for discussion of issues that were not being broadly addressed elsewhere. DataBits, first a printed then an electronic newsletter (https://lternet.edu/?taxonomy=document-types&term=databits),

chronicles these discussions. By the end of 2017, there had been approximately 35 annual meetings of the IMC (Henshaw 2018).

Because LTER IMs have come from various backgrounds and have varying responsibilities, there is no standard description of the position. Individual sites have managed IM positions in many different ways; as faculty (as in my case), as research associates, as technical staff, as computer scientists, or as other positions. Some IMs have advanced degrees, including PhD's and doctorates that make it easier for IMs to have faculty positions. Predictable backgrounds include ecology, statistics, or computer science, but IMs have also been drawn from the field of archaeology (Peter McCartney, former IM at the Central Arizona-Phoenix LTER and now Program Officer at NSF) and civil engineering (IM Tim Whiteaker at the Beaufort Lagoon Ecosystem LTER) to name only a few. The IMs are an eclectic bunch!

Moreover, because the technical expertise required of IMs often dictates high salaries, it is difficult to fit IM positions into the standard academic human resources model. I recall a situation at the AND, when I was able for the *first* time to secure NSF funding for a person (a UNIX System administrator) rather than software or hardware. An interesting call from OSU Human Resources ensued because I had posted a salary on the position description far in excess of what an incoming Assistant Professor would make. I explained that I had to pay this person that salary because that was what she could easily make on the open market. Our success set a new precedent for hiring positions and helped pave the way for other sites to write similar grants with similar success.

A perennial challenge for data managers has been their drive to get things done in the short-term rather than considering their own career trajectory. Within Universities, the role of data management typically was considered ancillary to existing job categories rather than as a wave of the future. The IM liaison roles that coordinated science, data and technology were difficult to convey in a market of specialists (Baker and Millerand 2007). Data managers have few colleagues (other than themselves) to teach them how to be project managers within existing power structures. They are, after all, in charge of data production, an endeavor distinct from but complementary to site-based knowledge production (Baker and Millerand 2010). It has been challenging for the LTER IM community to become more outward facing where their work would become more visible outside the Network.

13.2.4 Data Managers vs. Information Managers

In the early days, we were known as Data Managers. Over time, our title evolved to Information Managers. The term "information manager" first shows up in a 1992 report (https://lternet.edu/wp-content/uploads/2010/12/im_1992_report.pdf). This was a gradual transition and occurred for several reasons. First, the term "data manager" had menial connotations for many researchers who thought that managing data was simply a routine task, rather than the complex mix of tasks that we knew to be the case. Using the term "information manager" let us better define ourselves to the PIs rather than using an older, misleading label.

Second, this was near the advent of the use of Internet Information Servers (e.g. Gopher and shortly thereafter the World Wide Web). This meant that we were not dealing with data in the traditional sense of merely columns of numbers but rather text, images, bibliographies, and personnel databases, to mention only a few! Consequently, "information" was a far better fit than "data" for describing what we were dealing with. And lastly, the term "information manager" was showing up in other organizations.[1]

13.2.5 Building Collaboration

A collaborative approach emerged at the LTER IMC annual meetings that created a place of inclusiveness. Exposure to such diversity cultivated an understanding of and a sensitivity to a broad array of issues – issues that were not necessarily being addressed elsewhere. The genial attitudes of participants also fostered agreement on general standards and practices that were not as evident in cross-site scientific efforts. A sharing mentality developed for applications and data that eventually changed a very proprietary view of principal investigators' data to a more open and sharing perspective. This has now led to most of the LTER core data sets from all sites being available in federated systems such as DataONE (see below). It was through work within the LTER Information Management Committee that data managers began to learn that what might initially be perceived as an "individual trouble" may well be a "community issue" (Millerand et al. 2013).

It was always my intent to piggy-back the Annual IM meetings on larger scientific meetings (e.g., Ecological Society of America) to not only minimize cost, but equally important, to increase the visibility of IM efforts. Holding our meetings where large groups of ecologists were already assembling allowed us to open our discussions to a larger swath of the community. Guests were always invited and welcomed. The relevance of these meetings was evident in the number of requests for outside participation from the early 1990s into the 2000s (Henshaw 2018).

Co-locating these meetings in larger venues provided more opportunities for LTER IMs to present papers at larger conferences. To me, this was a way to provide a platform to encourage IMs to produce publications – the coin of the realm in academia – thus increasing their stock in the eyes of their PIs at their home sites. In the first 25 years, LTER IMs organized several successful symposia, resulting in several books and publications. Since the initial cohort of IMs were predominantly ecologists who also enjoyed working with data and computers, it made sense going to ESA and ESA-like meetings. Over time, as the IMs became more tech-savvy, conferences that were oriented towards computer science began to be more appro-

[1] J. Porter, personal communication, 22 September 2018.

priate. Regardless of the venue, the annual IM meetings created a level playing field among the great diversity of IMs. On more than one occasion, IMs have said that the single most important meeting they attended every year was the annual IM meeting.

The annual meetings helped the IM community to bridge the challenging divide between responsibility to the site versus responsibility to the Network. The generosity of spirit and openness that became a hallmark of the annual IM meetings facilitated efforts to work together toward common goals and solutions. More than any other group of LTER scientists, the IMs have consistently found ways to work together across site boundaries to forge viable partnerships and develop durable solutions to common network-wide challenges. The LTER IMs know how to play well together.

Technical advances in the LTER Network provide an example of how infrastructure for local site-based research can be configured as a distributed network in contrast to a centralized venue remote from where field data were generated (Karasti and Baker 2008). Parallel with advances in infrastructure, LTER forged a new kind of identity for scientists responsible for data stewardship. With an embedded data manager at each site, LTER grew its own workforce, one that took what was initially perceived by others as mundane work and unpacked it into a multi-faceted new kind of position shaped by an understanding of how to support both hypothesis–driven scientific inquiry and long-term data stewardship. In recognizing data's importance to science in the digital age, LTER data managers devoted their time, energy, and innovative thinking to data care (Baker and Karasti 2018).

The early data managers were faced with analyzing everyday data practices and carrying out the work of collective data management before the concepts of data repositories, data curation, and open data became part of the digital data scene (Karasti et al. 2006; Baker and Bowker 2007; Baker and Chandler 2008). The role of data management was emergent at a time when technologists and computer scientists thought in terms of standard technical solutions rather than designing processes adapted to the science and the times. For example, an LTER IM describing the data system at the Sevilleta LTER site complained:

> This solution has been called uninspiring, yet the fact remains it is a functional system that recognizes the way scientists work; it does not try to control the way they work. What scientists need from software and database engineers is fewer 'omnipotent' database packages and more tools to integrate existing software. (Brunt 1994)

I have described the great enthusiasm that IMs have for their responsibilities, but to be fair, that enthusiasm has not always been shared by all PIs. Some view the requirement for information management as a tax on their research dollars, and others consider the details of IM boring. At Coordinating Committee meetings, some PIs would roll their eyes and joke about going into a "data coma"[2] as the agenda turned to more technical topics. Part of the problem in this case was

[2] P. Groffman, personal communication, 14 June 2018.

communication, as IMs are accustomed to talking about their work in technical terms, and often have had a hard time translating their ideas into plain language.

Sometimes I questioned whether the true wealth of experience and technical knowledge represented by the LTER IM community was recognized and valued by the PIs and other LTER researchers. Today the LTER Network is at a point where the expectation for archiving data has become routine. However, individual IMs have had to devise their own approaches and ad hoc solutions for many sites because the industry and eco-informatics community investment in ready-to-use cyberinfrastructure for front-line environmental data management (sensor data management, Quality Assurance/Quality Control, metadata creation and management, etc.) has been sparse. IMs have created an on-line document library, all with the same general purpose of improving access to site information and facilitating easy navigation to information and data at the site, at other sites and across the LTER Network. Collectively, these resources provide a rich set of tutorial materials for incoming IMs to LTER as well as other information management professionals from other networks. In many ways, the IMs have served, and continue to serve, as a vanguard for new ideas and developments in an evolving technology.

13.2.6 The Challenge of Rapidly Changing Technology

It is easy to forget just how unsophisticated technology was in 1980, the year the LTER program was first funded. We didn't have many of the capabilities we take today for granted. It was "before WiFi, before the internet, before generic email, even before the first IBM PC. When LTER started, GenBank did not exist. When Amazon sold its first book and when Microsoft first shipped an operating system with built-in support for networking, LTER was already 15 years old. It was 20 years old when the DOT-COM bubble popped." (Robbins 2011).

Before LTER sites could function as a network though, they needed the technological capabilities to *be* a network. The establishment of a fully functioning network required equivalent infrastructure for communication, internet connectivity, and web access. Yet the technological capabilities across the Network were uneven, and NSF realized this. The North Inlet site and the Virginia Coast Reserve site were perhaps the most technologically advanced,[3] yet the overall strength of the Network was only as strong as its weakest link.

In 1988, NSF and the LTER Network defined the level of technology that needed to be available at all sites to allow robust interactions. This Minimum Standard Installation (MSI) included compatible Geographic Information Systems (GIS), local and wide area networks, and high capacity data storage systems. NSF awarded supplemental grants to sites to achieve the MSI across the Network. Moreover, NSF provided support to establish high throughput internet connections at field sites,

[3] R. Robbins, personal communication, 16 June 2018.

where connectivity was poor (Brunt et al. 1990). For the first time, NSF decided to provide collective support to sites for equivalent hardware and software platforms so that there would be comparable capability across the Network.

To achieve the MSI, NSF made available a pot of "new money." As a result, sites saw the mandate for data management as a *source* rather than as a drain of resources. This was a good example of using social engineering to accomplish things. By calling it "new" money and making it available as supplements to existing LTER sites, it transformed the role of data managers within the sites from cash sinks into a possible cash source. This required direct leadership from both within the Biological, Behavioral, and Social Sciences Directorate (the precursor to the Biological Sciences Directorate) from key individuals like David Kingsbury (Assistant Director), John Brooks (Division Director) and Tom Callahan (Program Officer) in concert with strong advocacy from LTER PIs, specifically Jerry Franklin and John Magnuson. Kingsbury was instrumental in creating the data-management supplement awards within LTER and those awards were crucial in shaping the improvement of LTER data management from 1987 onwards.[4]

This coordinated approach from both the NSF and key PIs helped guide the Network during its earliest years. NSF appeared to understand that they needed to exercise patience as LTER sites learned how to function successfully as a Network rather than as a collection of independent, strong-minded PIs. "Patience" was defined as allowing more time for the demonstration of results. As the nascent Network developed, interest was building in developing capability for obtaining spatially explicit data in the form of GIS. Early meetings between NSF and IMs determined that Arc Info would be the best software platform. A pattern was developing where NSF, in concert with IMs and domain scientists, collaborated to build the capabilities across the network in terms of computing, data storage, and analysis.

13.2.7 The Internet Impact

The development of the internet provided the opportunity for rapid communication via e-mail. In 1988, it became possible – with only a few keystrokes – to communicate with anyone and everyone within the LTER network if you knew their first initial and last name. Today the creation of an email alias system seems rather trivial, but the power of "sstafford@lternet.edu" or "im@lternet.edu" revolutionized how the LTER network functioned and helped facilitate a feeling of connectedness that heretofore had only existed for a few domain-specific groups.

The internet also provided the means for individuals and sites to share data, and the LTER Network embraced this opportunity by adopting a network-wide policy of making data accessible. This forward-looking approach anticipated the current requirement for data sharing by funding agencies and publishers and demonstrated

[4] R. Robbins, personal communication, 16 June 2018.

the leadership role that LTER assumed in providing open access to all publicly-funded data. It's been said "data sharing is not a natural state" (Robbins 2011), yet I submit that the LTER Network and early data sharing guidelines and policy have set the stage for the rest of biology. Guidelines for NSF's programs in BIO now require that there be a data management plan.

The LTER has been a leader in devising both technologies and policies to drive environmental data sharing (Porter 2010). The LTER Network supported long-term interdisciplinary projects and data sharing long before it became mandatory to do so, and LTER efforts pre-dated the data sharing mandate in the United States by 30 years.[5] This puts the remarkable vision of the LTER Information Management enterprise in greater perspective.

13.3 The Growth Years – Watching Our Work Take Hold

13.3.1 Challenges in Creating an Information System for Ecological Data

To assess the conceptual framework underlying long-term research at each site and to direct future research efforts, the LTER Network was charged with collecting, managing, and making accessible long-term ecological data collected over many sites using many different collecting techniques. These data needed to be described in detail, archived in perpetuity, and made discoverable by a broad scientific community. When the first LTER sites were selected, neither the approach nor the technology to achieve such goals existed. To address this challenge, the LTER IM community focused first on data collected at individual sites that needed to be shared and synthesized among investigators only at their individual sites. In many cases, site information systems were created from scratch, and as a result, a variety of information management solutions arose among the sites; see Brunt (1994) for an example. In the early stages of development of information systems, the IMs viewed this diversity as a strength because it allowed them to test and choose among different technical approaches to addressing common goals.

From 1990 to 2000 the emphasis began to shift from an IM strategy focusing on individual sites to a strategy that encompassed the entire LTER Network (Brunt 1999). Homogenizing technology, defining IM standards, and creating shared databases such as the Core Dataset Catalog (Michener et al. 1990) characterized IM efforts beginning in 1990. The development of the World Wide Web in 1991 and the first graphical web browser in 1993 (Porter and Brunt 2001) provided the tools to

[5] See memo of John P. Holdren, Director, Office of Science and Technology Policy, Executive Office of the President, to Heads of Executive Departments and Agencies, Feb. 22, 2013, on "Increasing Access to the Results of Federally Funded Scientific Research": https://www2.icsu-wds.org/files/ostp-public-access-memo-2013.pdf. Accessed 21 July 2020.

share data online. In 1994, the LTER Coordinating Committee agreed that all sites should post data sets online. The existence of online data facilitated comparison and synthesis across LTER sites and provided important input to the IMs. These collaborations encouraged the development of a more ambitious approach to building an LTER Network Information System (NIS) beginning in 1996.

13.3.2 The Decade of Synthesis (2000–2010)

The LTER Network announced a plan for a Decade of Synthesis from 2000–2010. This plan formalized the goal of sharing data and metadata broadly to facilitate "regional, national and global syntheses, thus providing a resource for the broader scientific community" (http://lternet.edu/wp-content/uploads/2010/12/lter_2010.pdf). This bold step envisioned collaboration and data sharing at an expanded scale, and this vision set the parameters for the developing NIS. Expanding the scope and goals of the NIS, coupled with rapid changes in technology and cyberinfrastructure capabilities, required close cooperation among IMs, domain scientists, and data engineers both at the LTER Network Office (LNO) and at collaborating institutions.

13.3.3 Data and Metadata Standards and the Long-Term Preservation of Data

Integration of data from different sources is one of the most common and frustrating challenges in ecology, and much thought and effort have gone into addressing this challenge. The decision to share data implied that scientists must also provide descriptions of their data and the methods used to collect them. Descriptions of data, or metadata, were more useful if they conformed to recognized standards, but at that time such metadata standards did not exist for ecological data. The next challenge for LTER IMs, therefore, was to develop standard approaches to formatting and describing data so that new users could interpret those data.

Issues with metadata content and data structure inconsistency and comparability potentially inhibit data discovery and re-usability. From the earliest days of LTER, the IMs have emphasized "standards" rather than "standardization." Some ask why we need such high standards for metadata. The answer is simple. If one knows how data were collected, one can later replicate a study and produce data to be compared to the earlier data. Strong metadata is a value-added component to the data. High standards for metadata help insure that data will be able to be used in perpetuity by future researchers totally unfamiliar with the original data collection effort and not associated with the original research project that generated the data in the first place. Reproducibility is particularly important for the LTER program because long-term studies are conducted by successive generations of scientists.

Metadata is one of those elements that requires the researcher and IM to “pay it forward”, i.e. the more time and effort that is invested up front, the greater the value and payoff in the future. This asymmetry of initial cost vs. future benefit, however, can be problematic. Michener et al. (1997) have noted “although increasing metadata structure reduces the burden on data re-users, it significantly increases the burden on the data originator.” The maximum benefits accrue to the future user. In this context, one could ask the question: “What does the present owe the future?” In my opinion, the failure to make this initial investment answers the question incorrectly.

13.3.4 Homogeneous Data

One simple approach is to standardize data formats and units to simplify comparison. Thus, instead of constantly transforming measurements from English to metric units, a better solution is to establish a standard so that all data are provided in the same units.

LTER IMs used this approach to create common databases of meteorological (named CLIMDB) and hydrological (named HYDRODB) data in which each site provided data and metadata in standard formats. A similar approach was effective in creating databases on site personnel (PERSDB) and site characteristics (SITEDB) as well as a basic catalog of data collected at each site, Data Table of Contents (DTOC) (Brunt 1999). IMs worked with domain scientists to develop these early databases, which used different technological approaches for comparison. These databases served as prototypes for the development of the LTER Network Information System (NIS) (Brunt 1999).

13.3.5 Heterogeneous Data

Other kinds of ecological data are more heterogeneous and less amenable to standardization. For example, measurement of primary productivity uses completely different methods in forests, grasslands, and lakes and the data are expressed in different formats. Because of the great diversity of formats, the focus therefore was on developing metadata standards that would facilitate the development of software tools to produce data in required formats (Servilla et al. 2016) to foster the exchange of data between sites.

The development of metadata exchange standards was a challenge that reached beyond the boundaries of the LTER Network. The Ecological Society of America convened a committee on the Future of Long-term Ecological Data (FLED) (Gross and Pake 1995) that addressed similar issues.

At the 1992 IM meeting, discussions of data and metadata standards resulted in articulating a vision for using machine-readable metadata to facilitate data manipulation and sharing. If data are described with detailed metadata that can be interpreted by computer programs, then software can be written that can analyze data stored in any format. To achieve this vision, metadata that were mostly written in plain text would need to be converted to something that a computer could interpret. This challenge required the development of a descriptive language that made sense to both humans and computers.

13.3.6 Ecological Metadata Language and Partnership for Biodiversity

The development of such a language was undertaken by the Partnership for Biodiversity Informatics (PBI; http://pbi.ecoinformatics.org/), a consortium of five institutions including the National Center for Ecological Analysis and Synthesis (NCEAS), the LTER Network Office, the San Diego Supercomputer Center, the Natural History Museum and Biodiversity Research Center at the University of Kansas, and the California Institute for Telecommunications and Information Technology. The goal of PBI was to enable scientists and other users to deploy vast amounts of ecological, biodiversity and environmental information in research, education and public service in order to help society achieve the means to safeguard our future and a sustainable planet. Ecological Metadata Language (EML), based on work initiated by FLED and described in Michener et al. (1997), was formalized through the Knowledge Network for Biocomplexity (KNB), a PBI project funded by NSF. LTER IMs and domain scientists played an important role in the development of version 1.0 of EML (Fegraus et al. 2005) by helping to define data needs of LTER research projects associated with KNB.

The PBI partners initiated two other projects aimed at improving the software and infrastructure available to support ecological and biodiversity science. SEEK (Science Environment for Ecological Knowledge) was a comprehensive knowledge management project for ecological and biodiversity science. RDIFS (Resource Discovery Initiative for Field Stations) initiated collaboration on software infrastructure for field stations and informatics training for field station personnel. LTER IMs and domain scientists continued to play a leading role in these projects by providing training, setting priorities, and testing developing cyberinfrastructure.

EML thus addressed a critical challenge in fulfilling the vision put forth by LTER IMs in 1992. EML was designed specifically for use with ecological data through a collaboration among ecologists, IMs, and software engineers. EML provides a common structure to describe ecological data so that subsequent generations of scientists can accurately interpret the data. Because EML is a machine-readable language, it allows researchers to develop software applications to search for, acquire, manipulate, integrate, and analyze data distributed through data archives connected via the internet.

Some researchers believe EML should establish a base-level of metadata standards while others advocate the benefits of having a higher level that captures the semantic elements to fully automate integration and analysis. A new version of EML may address some of these issues – but this would make EML metadata even more time consuming to prepare. Not surprisingly, LTER IMs tend to be more supportive of the idea that we need more metadata, not less, contending that high-quality, archival data will be used by researchers in the future.

EML has become the standard for documenting and describing in detail ecological data and their characteristics not only for the LTER Network, but also for many other national and international programs. Researchers are now able to find and use LTER data for their research using the Network Information System and accompanying EML metadata. By having more ready-access to data archives connected via the internet, researchers world-wide can now work together more effectively (see Wolkovich et al. 2012, Dornelas et al. 2014, Zhang et al. 2017, Collins et al. 2018, Hautier et al. 2018, Rodriguez et al. 2018, Sillett et al. 2018, and Song et al. 2018 for examples). In addition, Servilla et al. (2016) lists over 50 articles which cite LTER data as a basis for their research.

At the AND LTER site alone, an educated guess is that 20% of publications from that site come from work that they didn't participate in but which were made possible by having the data available on-line.[6] As ways are implemented to reward data creators and incentivize data publication (Kratz and Strasser 2015), the re-use of data should only increase. While some may contend that researchers find data from publications, not data banks, regardless of the route to the data, data can now be found with requisite metadata and can be used by researchers not associated with the original research.

13.3.7 Drupal Ecological Information Management System

A good example of the collaborative spirit of LTER was the development of DEIMS (Drupal Ecological Information Management System). DEIMS is a grass-roots, Drupal-based system that provides a unified framework for ecological information management for LTER sites, Biological Field Stations and other similar groups. Drupal is a free software package that allows an individual or community of users to easily publish, manage and organize a wide variety of content on the web. One needn't be a database expert to use DEIMS.

Marshall White at LNO recognized that the Drupal Content Management System represented an opportunity to build a form-based EML editor and thus to simplify the conversion of text metadata to EML and the ability to integrate content of different types of data (e.g., people and publications). In the words of one LTER IM, Kristin Vanderbilt, "It was slick." The success of the original DEIMS system (DEIMS 1) interested other IMs, and a group of IMs decided to pool their IM supplement grants to hire a team of Drupal developers to transfer DEIMS into Drupal

[6] J. Jones, personal communication, 7 October 2018.

7. DEIMS 2 is now being used at eight LTER sites. It has been adopted at a few field stations, as well, and has also been used by national networks in other countries. The aim was to develop an information management system that could be used to manage all the disparate kinds of information that a site generates.

Besides the technical aspects of this accomplishment, the behind-the-scenes collaboration that occurred cannot be overlooked or understated. Given that the aim of DEIMS was to develop an information management system that could be used to manage all the disparate kinds of information that a site generates, three sites and the LNO pooled their resources for a project that benefitted many others, representing an effort to harmonize data management across several sites. Although it is still something that needs work, it would not have been possible without the generosity of spirit and collaboration between IMs and the LTER Network Office.[7]

13.3.8 Managing Disparity Between Expectations and Resources: Development of the Network Information System (NIS)

Any LTER PI will tell you that the cost of maintaining a long-term ecological program in the face of increasing expectations is underestimated. The perennial tension between resources and expectations is particularly keen in the area of information management. Infrastructure is a funny thing – when it works, nobody notices and when it doesn't, everyone knows. The Report of the Twenty-Year Review of LTER (Harris and Krishtalka 2002) was quite emphatic about this tension when it stated:

> Increased NSF investment in the LTER informatics infrastructure is a particularly critical need. In addition to fostering synthesis science, *it will help reverse the perception that informatics is an "add-on" rather than a fundamental component of ecological research*. According to statistics from NSF's Division of Biological Infrastructure, research projects in biology allocate an average of 5% of resources to informatics when the actual need is between 35–40% of total project costs. LTER science, which is data intensive, exceeds this average, allocating approximately 10%–20% of total project costs to informatics depending on the site. Still, this short-changes informatics, which has diminishing returns in the long run, resulting in information that is less capable of integration, analysis, synthesis and prediction by LTER and other scientists. (Emphasis added)
>
> An appropriate level of investment in an informatics infrastructure for the entire LTER community will be cost-effective and achieve economies of scale for NSF and the LTER program. Part of the increased investment in informatics should target the management and maintenance of LTER data, an irreplaceable asset for current and future research and applications. LTER data are no different in this respect from federal census data, remote sensing and genomic data, taxonomic and culture collections and other national archives.

The report of the Twenty-Year Review highlighted the most significant problem standing in the way of creating a centralized LTER data system. The development

---

[7] Kristin Vanderbilt, personal communication, 28 March 2018.

of such a system would require significant inputs of time from an already overtaxed community of IMs as well as the participation of software engineers and programmers that did not exist in the LTER Network at that time. The task of defining the scope and capabilities of the Network Information System (NIS) had already been initiated by the IMC in collaboration with domain scientists, but progress was slow because of the complexity of the project and the absence of dedicated personnel. The philosophy behind the early development of the NIS was to use requirements for research synthesis to define NIS capabilities (Brunt 1999). This philosophy required IMs to participate in LTER cross-site and synthesis working groups and to gather requirements for the new NIS from participants. Then IMs needed to propose means of addressing these requirements and develop and test prototype solutions. Because of the technical complexity of these tasks, disproportionate responsibility fell on the most technically-capable IMs.

Two fundamental principles guided early development of the NIS prior to the Twenty-Year Review (Brunt 1999). The LTER NIS would focus on integrating site information systems, not replacing them. The NIS would be a dynamic system, evolving to incorporate technological advances and improvements in understanding of how scientists most efficiently use data. With these principles in mind, the IM community defined three goals for work on the NIS at the turn of the millennium: (1) the LNO would work to improve the utility of the existing components of the NIS (e.g., the data catalog); (2) an NIS working group composed of IMs and staff from the LNO would improve access and query capabilities for inter-site data and (3) diverse solutions to problems in design and implementation would be encouraged to take advantage of the variety of approaches developed at sites.

In preparation for the Twenty-Year Review, the LTER Network underwent an intensive self-analysis "to refresh and to update the overall aims and mission of the LTER Network". This analysis led to a document titled "LTER 2000–2010: A Decade of Synthesis" that laid out six goals for LTER:

- Understanding: Gaining ecological understanding of a diverse array of ecosystems at multiple spatial and temporal scales
- Synthesis: Using the network of sites to create general ecological knowledge through the synthesis of information gained from long-term research and development of theory
- Information: Creating well-designed, documented data bases that are accessible to the broader scientific community
- Legacies: Leaving a legacy of well-designed and documented long-term observations, experiments, and archives of samples and specimens
- Education: Using the uniqueness of the LTER programs and network to promote training, teaching, and learning about long-term ecological research and the earth's ecosystems
- Outreach: Providing knowledge to the broader ecological community, general public, resource managers, and policy makers to address complex environmental challenges.

These broad goals provided guidance for the further development of the NIS, but more specific strategic direction was needed. In 2002, the Executive Committee, responding to a recommendation from the IMC, created a NIS Advisory Group (later Committee; known as the Network Information System Advisory Committee (NISAC)) to draft a long-term strategic plan for the development of the NIS. Membership in this group was drawn from the Coordinating Committee, the IMs, and the LNO. Planning for the NIS was deliberate, with emphasis on prototyping and evaluation of different technologies. This strategy arose both from the recognition that it would produce a stronger NIS in the long-term, but also from the reality that IMs had only limited amounts of time given their other responsibilities. The planning effort was inclusive and long-term, and encouraged joint planning by information managers, domain scientists and LNO staff. All groups engaged in iterative cycles of software development and assessment across the network with teams of domain scientists, IMs, and graduate students. The process emphasized information exchange among groups to inform the next steps of development, thus building a "community of practice" (Karasti and Baker 2004).

The LNO provided reinforcements to the effort in 2003 by hiring a software engineer and a programmer, but the amount of work to be accomplished was still daunting. Researchers, IMs, and LNO staff formed a series of working groups focused on designing, funding, and implementing key components of the NIS. These working groups addressed issues of data standardization that arose from synthesis efforts, methods of data integration, interoperability with other national standards, guidelines for data and metadata longevity, and other topics. As issues were resolved, the LNO and IMs integrated solutions into the developing NIS infrastructure. In 2005, the LTER Coordinating Committee approved the LTER Network Information System Strategic Plan produced by NISAC (http://lternet.edu/wp-content/uploads/2010/12/ApprovedNISStrategicPlanVersion2.9.pdf). The 2007 LTER Network Cyberinfrastructure Strategic Plan projected the infrastructure needed to achieve the goals of the NIS Strategic Plan (http://lternet.edu/wp-content/uploads/2010/12/LTER_CI_Strategic_Plan_4.2.pdf). Finally, the 2011 LTER Strategic and Implementation Plan formalized the steps necessary to implement plans for the NIS (http://lternet.edu/wp-content/uploads/2010/12/LTER_SIP_Dec_05_2010.pdf).

By 2008, planning for the NIS was largely completed, but progress on implementation of the plans was still slow. Bob Waide, Executive Director of the LNO, made the decision to request additional resources to complete work on the NIS as part of the LNO's renewal proposal in 2009. NSF was amenable to the request, but eventually declined the proposal for additional funds because of budgetary constraints. The economic downturn and the subsequent stimulus package, however, provided another opportunity for funding. Ultimately, the LNO received an additional $2 million over 4 years to advance the NIS from funds made available under the American Recovery and Reinvestment Act of 2009 (ARRA).

This surge in funding allowed the LNO to recruit additional software engineers, to accelerate the work of information managers responsible for key components of the NIS, to simplify the process of encoding metadata in EML, to acquire key cyberinfrastructure, and to support working groups looking for solutions to outstanding technical problems. In January 2013, a functional version of the NIS that incorporated the major capabilities required by LTER scientists went live (Servilla et al. 2016).

Subsequently, a team of NIS developers including IMs and staff from the LNO continued to improve the software package underlying the NIS, dubbed the Provenance Aware Synthesis Tracking Architecture (PASTA). These improvements added requested features to the software, some of which were only identified once the NIS was in use. The basic functions of the NIS are to harvest data and metadata from each LTER site on a regular basis and to archive these data in a repository at the University of New Mexico. Data users can then browse or search for data from all LTER sites through a single data portal. Each package of data and associated metadata are assigned a unique Digital Object Identifier (DOI) so that they can be distinguished from every other data package in existence. Updates to a data/metadata package are assigned a new DOI, so different versions of the same data stream are identifiable. The PASTA software records the relationship between original and updated data packages (Provenance Aware). New data packages derived from the integration of one or more data packages during analysis are given a separate DOI, and the software keeps track of the data packages used in analysis (Synthesis Tracking). Thus, the metadata for each synthetic data package has all the information needed to replicate the analysis.

LTER developed a controlled vocabulary (http://vocab.lternet.edu/vocab/vocab/index.php) but the lack of uniformity of keywords across LTER sites made the ability to conduct more sophisticated keyword analyses problematic. In 2016, data were described by over 6000 unique keywords. As with all keywords, the hope is that a small number can be used to describe and organize a collection of items, in this case datasets. Unfortunately, this has not been the case. Of the roughly 6000 keywords, 2498 have been used *to describe only one data set* (Servilla et al. 2016). In hindsight, limiting the number of keywords to be used would have improved the usefulness of using a controlled vocabulary.

Other features of the software facilitate data management or use (Servilla et al. 2016). For example, each data package submitted is subject to a series of checks that determine whether the metadata accurately describes the structure of the data. Any mismatch is reported to the data provider. An open programming interface allows data users to write software to download data in desired formats.

Some LTER scientists were concerned that they would not get credit for re-use of their data, and this concern prevented some individuals from contributing data to the NIS. This concern was addressed by using DOIs to identify all data in the NIS, which provided a way of tracking data through citations in new publications. The widespread and continued contribution of data into the NIS from all active LTER sites has demonstrated that attribution concerns have largely abated within the LTER community (Servilla et al. 2016).

Data in the NIS is described by EML which makes the data amenable to manipulation and analysis by LTER IMs and other researchers who want to use the data. EML allows users to successfully combine disparate data sets and where appropriate, create integrated datasets for larger spatial and/or temporal scales. None of this progress would have been possible without the leadership from a very engaged, proactive and productive IM and LNO LTER community, their partners and domain scientists themselves.

The NIS addresses three of the primary goals of the LTER Network. It makes well-designed and documented databases accessible to scientists and the public. The NIS promotes synthesis by facilitating the process of data discovery across all sites and making data easier to reuse. Finally, the NIS provides a legacy of LTER research by describing the observations and experiments that form the core of the LTER Network. As envisioned at the beginning of the LTER program, the NIS integrates research across the Network and provides a resource that is greater than the sum of the individual site contributions. The significance of having a NIS is that now the community has a centralized LTER data system. The development of the NIS came at great expense, both in time and money, and represents another example of how the LTER Network has honored its debt to the future.

13.3.9 Information Management in the International LTER Network (ILTER)

Over 40 other countries have initiated long-term research networks based on the model of the U.S. LTER program. One of the strongest areas of collaboration among these international networks has been in information management. The ILTER grew from a satellite of the U.S. LTER to a self-sustaining and vibrant entity in its own right. The IM component of the ILTER was part of what helped cement it together. While the scientists in the ILTER were still figuring out how to collaborate at an international scale, the information managers were already doing so. For example, John Porter, IM VCR, introduced EML to information managers at the Taiwanese LTER Network (TERN) and the Taiwanese took the EML model all over Asia – China, Malaysia, Thailand, Vietnam, Mongolia. It is widely used in Asian LTER sites today.

The U.S. LTER contributed significantly to the development of the ILTER information management systems, including the dissemination of the DEIMS information management framework mentioned above. David Blankman, formerly of the LNO, is now an Israeli citizen and heavily involved with LTER Europe. David knew about DEIMS from attending U.S. LTER All Scientists Meetings, and he convinced LTER Europe to use it to develop a website where the whole ILTER can enter site information and describe datasets. This was a major undertaking for ILTER, and it was built on the shoulders of the U.S. LTER collaboration to create DEIMS. Although the U.S. is no longer the IM leader in the ILTER, the LTER IM efforts and success enabled the evolution of the ILTER information management strategy.

In 2006 the ILTER adopted a new governance model that called for standing committees, and the ILTER IM Committee was formed. As a committee activity, IM experts from around the ILTER were brought together in China in 2008 to consider all the IM systems within the ILTER and to choose a path forward for the entire ILTER. EML was chosen because of its maturity and because there were tools to support it. To their collective credit and foresight, the LTER IMs also recognized that there were challenges in making data discoverable in a multilingual network, and co-authored a paper on this topic (Vanderbilt et al. 2015). This was followed by a second workshop (Vanderbilt et al. 2017) during which they considered how to make the ILTER information management system accept input languages other than English and return relevant data. Participants from around the ILTER attended this workshop and co-authored a paper (Vanderbilt and Gaiser 2017). These were among the earliest collaborations that were branded as ILTER.[8] This collaboration is another profound example of how the U.S. LTER IM community embraced the larger international IM challenges. Working collaboratively with their international colleagues, they facilitated and enabled durable IM solutions for future generations.

13.3.10 Broader Applications of the NIS Concept

The intent was always to design the NIS in such a way that it could continue to evolve in tandem with the growth and evolution of the LTER program. One of the successes of the NIS has been the way that it has led to new applications of the concepts that define it.

EcoTrends EcoTrends is an excellent example of a productive collaboration among the PIs, researchers, IMs, and the LNO with other ecoinformatics partners that helped inform and guide a significant landmark accomplishment of the LTER IM enterprise, namely the NIS. The EcoTrends project started in 2004 as a simple idea between two scientists (Debra Peters and Ariel Lugo) asking the question: how do we make long-term data easily accessible to a large group of people who may not be familiar with the raw data? A committee of scientists and technical experts from several agencies and sites was formed to ensure that different kinds of data (e.g., population, community, ecosystems) from a variety of ecosystems (e.g., lakes, grasslands, marine, polar, alpine) would be well-represented, documented, and made accessible through a common web page. This committee provided the guidance and determination to pull together over 1200 datasets from 50 sites into the EcoTrends project (www.ecotrends.info).

Although the approach to data management was much different in EcoTrends than it is in NIS, the experience provided invaluable insights that guided the development of the NIS. The EcoTrends project manipulated LTER data sets *by hand* to standardize their formats for comparison. Because this work was labor intensive, fewer data sets could be presented than in the NIS, and data were never updated

[8] K. Vanderbilt, personal communication, 28 March 2018.

after the initial analysis. The challenges faced by the EcoTrends project in sorting though and cleaning up a multitude of datasets, however, contributed significant insight into the issues involved in standardizing data that informed and guided the development of the NIS. In addition, software developers in the LNO helped design and develop the cyberinfrastructure for the EcoTrends Project. Many of the approaches they used in this work were incorporated into the NIS.

The Environmental Data Initiative The Environmental Data Initiative (EDI) is derived from the LTER NIS, but EDI serves the broader ecological community as well as the LTER Network. EDI is funded by the National Science Foundation to provide support, training, and resources to help archive and publish high-quality environmental data and metadata, particularly data from projects funded by the NSF's Division of Environmental Biology (DEB). Programs served include, but are not limited to, Long Term Research in Environmental Biology (LTREB), Organizaton for Biological Field Stations (OBFS), Macrosystems Biology (MSB), and Long Term Ecological Research (LTER). The EDI data repository uses an improved version of the PASTA software to serve these communities (as discussed in Sect. 13.3.8).

To fully understand the emergence of the EDI, it is helpful to relate a bit of history. In 2009, NSF made the decision to hold an open competition for the LNO in 2015. The call for this competition split the communications and data management components of the LNO into two entities to be funded separately. Concurrent with the LNO competition, a few key IMs had been invited by NSF to create a plan for a more comprehensive data center that would include funds for collaborative software development, cross-site technology transfer and a mechanism for cross-site work by informatics specialists (i.e., centers of expertise within the network). That work on a Network Information Management Office (NIMO) formed the centerpiece of a proposal headed by University of Wisconsin (UW), specifically the North Temperate Lakes (NTL) LTER site. Scientists and data engineers from the LNO submitted a parallel proposal to maintain the operations of the NIS and to continue development of the PASTA software framework (dubbed PASTA+). The LNO proposal, submitted from the University of New Mexico (UNM), aimed at serving the whole ecological community, including LTER. Both the NIMO and PASTA+ teams originated from the LTER NIS community and had some overlap of personnel. NSF decided to link the two proposals into a single entity, the EDI. In the process, some goals were re-assigned between University of Washington and University of New Mexico, and support for LTER cross-site collaboration work on shared IM solutions was eliminated.

Thus, EDI is a re-branding of the LTER NIS aimed at a broader audience. The EDI includes the full archive of LTER data packages and uses PASTA+. This new configuration resulted in pulling the EDI away from direct LTER influence – the EDI would now serve *all* environmental biology with LTER as only one of many client projects. The PASTA+ portion of the EDI was awarded to University of New Mexico (the old LTER Network Office) and the NIMO portion went to North Temperate Lakes at University of Wisconsin. In some ways this made sense, as there is nothing about PASTA+ functions or good IM practice that is exclusive to LTER, and there are great needs for improved IM in Environmental Biology.[9] NSF saw value in the separation of EDI and LTER to get the value of EML, PASTA+, and what LTER had learned to the wider community.

The creation of the EDI as an entity separate from LTER resulted in several potential issues. Support for cross-site, collaborative work on shared IM solutions for LTER, originally part of the NIMO proposal, was not funded in either EDI award (NTL or LNO). Thus, there is no support for information technology or IM development across sites in the LTER Network other than what can be squeezed and justified from site budgets. Moreover, neither the EDI nor the new National Communications Office (NCO) at the University of California-Santa Barbara has allocated funds to support meetings of the IMC. These two issues threaten to affect the strong collaborative spirit that has developed in the LTER Network that led to the development of the NIS and ultimately the EDI. In addition, support for *scientific* synthesis in LTER comes from the NCO while support for *data* synthesis resides with EDI. LTER IMs have always bridged the gap between information management and synthesis, but with their diminished role, this function seems less likely to be successful. Despite its strong, competent leadership and a highly capable but small team, given its budget, it will be a tall order for the EDI to meet the full range of NSF expectations and researcher needs.

DataONE Data Observation Network for Earth (DataONE) (Michener et al. 2012) is a digital metadata catalog that provides links to data with shared characteristics across the whole ecological community (Waide et al. 2017). DataONE provides access to data from multiple member repositories, including the EDI. DataONE serves as a high-level aggregator of metadata, allowing domain and data scientists to discover and access ecological data from over 40 repositories (Waide et al. 2017). EDI is one of the three principal coordinating nodes of DataONE, and as such provides additional search and display tools beyond those available at EDI to cooperating scientists.

The LTER Network played an important role in the development of DataONE along with our PBI partners. Bill Michener, principal investigator of DataONE, was a member of the LNO when he developed the initial proposal to create DataONE. The ideas behind DataONE are drawn in part from the KNB and SEEK projects, both of which had strong participation from LTER IMs and the LNO. Thus, the existence of DataONE as the most important source of ecological data in the country is a direct offshoot of work from the original PBI collaboration.

[9] J. Porter, personal communication, 29 March 2018.

13.4 A Retrospective and Where We Go From Here

Information management in the LTER Network evolved from: (a) an initial approach in which data were archived and accessed directly from each site, to (b) a more centralized approach in which data contributed by all sites could also be accessed through a single LTER portal, to (c) the present configuration, where data from the LTER Network are also discoverable, along with data from 39 other entities, through DataONE (Michener et al. 2012).

NSF Program Officer, Tom Callahan noted in 1984: "Neither NSF nor the LTER investigators intend to make LTER data the exclusive province of scientists associated with the LTER projects. In fact, the intent is exactly the opposite, and it is hoped that the scientific community at large will come to regard the data sets as valuable resources" (Callahan 1984). After nearly 40 years, it's fair to say that this box has been checked: mission accomplished!

13.4.1 Accomplishments

The early emphasis NSF placed on sound IM practices resonated across the Network from the very beginning. Ecologists gained a new appreciation for long-term data and in effect improved their data literacy. Willig and Walker (2016) chronicled the careers of over three dozen LTER-affiliated individuals. In their individual essays, most mention an aspect of IM as being a valuable component of their skill set and an important take-home lesson from their LTER experience.

The accomplishments of the IM Enterprise embody the success of the LTER Network. Our significant achievements, of which Tom Callahan would be proud, include the following:

- Created a functioning computer network (hardware and software) between and among all LTER sites
- Forged an identity for and an awareness of Information Management as an integral part of scientific research
- Promoted "data literacy" within the LTER network
- Established a collaborative and inclusive working environment among LTER IMs for other domain scientists to emulate
- Developed EML to describe datasets so that they can be personnel-independent and used into perpetuity by researchers unfamiliar with the original research
- Created the NIS as a robust community-driven information system
- Changed the culture of scientific collaboration by developing PASTA which addressed the attribution issue of researchers not wanting to share their data for fear that they wouldn't get credit when others re-used their data
- Incorporated the use of DOIs in PASTA, to provide a way of tracking data through citation in new publications that didn't infringe upon individual accomplishments

- Created the platform upon which the EDI and DataONE emerged thus expanding the principles of information management across disciplines and fields of science
- Facilitated the establishment and growth of the ILTER IM program thus expanding the LTER geographically.

The adoption and implementation of EML by the entire LTER and ILTER community deserves special mention. The IM community worked collectively to make that happen, and for IMs from the U.S. LTER, that represents a remarkable ability to work together. Most of the impetus for this project came from the IMs themselves.[10] The collective effort involved in structuring legacy text metadata to meet the technological demands of this complex metadata standard was an enormous accomplishment.[11] The LTER IM enterprise facilitated research far and beyond the LTER Network. Researchers and students are now able to find and use LTER data for their research that simply wouldn't have been possible without the NIS and the accompanying EML metadata.

13.4.2 Issues Moving Forward

We have shown how LTER IM is replete with examples of how sound information management practices, while taking time and expense early, accrue benefit for future generations of researchers and ecologists. Yet, despite these significant accomplishments issues persist. Cheruvelil and Soranno (2018) describe the future of science as being more data intensive and characterized by more open and more team-based approaches.

To support synthesis science today and into the future, researchers are going to need more high-level integrated datasets. Because support for synthesis and data management were decoupled in the creation of the EDI and the NCO, however, a greater coordinated effort is now required to capture these new data sets. Historically, LTER IMs have always bridged the gap between information management and synthesis but since the support for cross-site, collaborative work on shared IM solutions was dropped in the descoping of the EDI, IMs have fewer opportunities to contribute to this process. As a result, the LTER IM enterprise is at a tipping point. This issue needs to be addressed and will require NSF support for LTER scientists to continue to produce these value-added data sets as part of the synthesis working groups sponsored by the NCO.

If the strengths of the past accomplishments are an indication of the promise of the future, I'm very optimistic that a strategy can be found. Modelling a behavior of collaboration, IMs working productively with data scientists, domain scientists, cyberinfrastructure specialists, and data engineers from the LNO to solve problems

[10] K. Vanderbilt, personal communication, 11 April 2018.

[11] W. Sheldon, personal communication, 28 March 2018.

and work toward common goals has served ecology and ecologists well and will continue to do so going forward.

13.5 Conclusion

I have been associated with the LTER Information Managers for nearly four decades. I stayed actively involved even when I left Oregon State University to become Department Head of Forest Sciences at Colorado State University (CSU) in 1998. At that time, CSU was the home of the former Short Grass Steppe (SGS) LTER site. The SGS was administratively housed in my Department. It was only after I became Dean of the College of Natural Resources at the University of Minnesota in 2002 that I stepped away from my role of chairing the LTER Information Management Committee and IM Executive Committee (IMEXEC).

I was very fortunate to begin my association with the LTER at the AND. This experience taught me many invaluable skills and helped me develop a managerial style that served us well within the IM community. The culture at the AND site tended to attract other like-minded researchers with an *a priori* tendency to trust others already in the group (Grier 2007). Over time, I came to realize and value the true collaborative culture at the AND site.

As was the case at several LTER sites, long-term research at the AND was conceptually positioned at the interface of basic and applied science. Communicating research results across a wide spectrum of stakeholders – from state, federal, international and non-governmental organizations – was commonplace. Watching the AND leadership cultivate, nurture and build enduring partnerships provided invaluable lessons for effective communication with diverse and numerous constituencies. I learned first-hand how to work towards successful conflict resolution by tackling issues directly to find common ground, an approach we honed within our Annual IM meetings. Direct participation in a collaborative and openly inclusive atmosphere has served as an excellent working model for the LTER IMC, domain scientists, data engineers and cyber specialists working together successfully and productively for the last four decades. The rapid growth and maturation of the infrastructure available to manage ecological data engendered a parallel evolution in the culture of data sharing and collaborative science. The LTER Network has been at the forefront of this cultural shift, and the LTER IM community led the way. I am forever grateful to have had the opportunity to be a part of this organization and to have worked with so many of my esteemed colleagues.

Acknowledgements I want to thank Bob Waide, John Porter, Wade Sheldon, Kristen Vanderbilt, Corinna Gries, Karen Baker, Don Henshaw, Bob Robbins, Dave Schimel, and Bill Michener for providing their respective insights and candid thoughts on the successes and challenges facing the LTER IM enterprise.

References

Aronova, E., K.S. Baker, and N. Oreskes. 2010. Big science and big data in biology: From the international geophysical year through the international biological program to the Long Term Ecological Research (LTER) network, 1957–present. *Historical Studies in the Natural Sciences* 40 (2): 183–224.

Baker, K.S., and G.C. Bowker. 2007. Information ecology: Open system environment for data, memories, and knowing. *Journal of Intelligent Information Systems* 29 (1): 127–144.

Baker, K.S., and C. Chandler. 2008. Enabling long-term oceanographic research: Changing data practices, information management strategies and informatics. *Deep Sea Research II* 55: 2132–2142.

Baker, K.S., and H. Karasti. 2018. Data care and its politics: Designing for local collective data management as a neglected thing. In *PDC '18: Proceedings of the 15th participatory design conference, August 20–24, Hasselt and Genk, Belgium*, vol. 1. https://doi.org/10.1145/3210586.3210587.

Baker, K.S., and F. Millerand. 2007. Articulation work supporting information infrastructure design: Coordination, categorization, and assessment in practice. In *Proceedings of the 40th Hawaii international conference on Systems Sciences*.

———. 2010. Infrastructuring ecology: Challenges in achieving data sharing. In *Collaboration in the new life sciences*, ed. J.N. Parker, N. Vermeulen, and B. Penders, 111–138. Farnham: Ashgate.

Brunt, J.W. 1994. Research data management in ecology: A practical approach for long-term projects. In *Seventh international working conference on Scientific and Statistical Database Management*, 272–275. Charlottesville: IEEE. https://doi.org/10.1109/SSDM.1994.336941.

———. 1999. The LTER network information system: A framework for ecological information management. In *North American science symposium: Toward a unified framework for inventorying and monitoring forest ecosystem resources, 2–6 Nov 1998, Guadalajara, Mexico*, ed. C. Aguirre-Bravo and C.R. Franco, 435–440. Fort Collins: US Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Brunt, J.W., J. Porter, and R. Nottrott. 1990. *Internet connectivity in LTER: Assessment and recommendations*. Seattle: LTER Network Office, University of Washington, College of Forest Resources.

Callahan, J. 1984. Long-term ecological research. *Bioscience* 34: 363–367.

Cheruvelil, K.S., and P.A. Soranno. 2018. Data-intensive ecological research is catalyzed by open science and team science. *Bioscience* 68 (10): 813–822.

Collins, S.L., M.L. Avolio, C. Gries, L. Hallett, S.E. Koerner, K.J. LaPierre, A.L. Rypel, E.R. Sokol, S.B. Fey, D.F.B. Flynn, S.K. Jones, L.L. Ladwig, J. Ripplinger, and M.B. Jones. 2018. Temporal heterogeneity increases with spatial heterogeneity in ecological communities. *Ecology* 99 (4): 858–865.

Dornelas, M., N.J. Gotelli, B. McGill, H. Shimadzu, F. Moyes, C. Sievers, and A.E. Magurran. 2014. Assemblage time series reveal biodiversity change but not systematic loss. *Science* 344: 296–299.

Fegraus, E., S. Andelman, M.B. Jones, and M.P. Schildauer. 2005. Maximizing the value of ecological data with structured metadata: An introduction to the Ecological Metadata Language (EML) and principles for metadata creation. *Bulletin of the Ecological Society of America* 86: 158–168.

Grier, M.G. 2007. *Necessary work: Discovering old forests, new outlooks, and community on the H.J. Andrews Experimental Forest, 1948–2000*, General Technical Report PNW-GTR-687. Portland: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Gross, K.L., and C.E. Pake. 1995. *Final report of the Ecological Society of America Committee on the Future of Long Term Ecological Data (FLED). Volume II: Directories to sources of long-term ecological data*. Washington, DC: Ecological Society of America.

Harris, F., and L. Krishtalka. 2002. *Long Term Ecological Research Program twenty-year review: A report to the National Science Foundation*. http://lternet.edu/wp-content/uploads/2014/01/20_yr_review.pdf. Accessed 22 May 2020.

Hautier, Y., F. Isbell, E.T. Borer, E.W. Seabloom, W.S. Harpole, E.M. Lind, A.S. MacDougall, C.J. Stevens, P.B. Adler, J. Alberti, J.D. Bakker, L.A. Brudvig, Y.M. Buckley, M. Cadotte, M.C. Caldeira, E.J. Chaneton, C. Chu, P. Daleo, C.R. Dickman, J.M. Dwyer, A. Eskelinen, P.A. Fay, J. Firn, N. Hagenah, H. Hillebrand, O. Iribarne, K.P. Kirkman, J.M.H. Knops, K. la Pierre, R.L. McCulley, J.W. Morgan, M. Pärtel, J. Pascual, J.N. Price, S.M. Prober, A.C. Risch, M. Sankaran, M. Schuetz, R.J. Standish, R. Virtanen, G.M. Wardle, L. Yahdjian, and A. Hector. 2018. Local loss and spatial homogenization of plant diversity reduce ecosystem multifunctionality. *Nature Ecology & Evolution* 2 (1): 50–56.

Henshaw, D. 2018. *A history of LTER Information Management Committee meetings: Venues and participation. LTER Databits: Information Management Newsletter of the Long Term Ecological Research Network*. Spring 2018 Issue. https://lternet.edu/wp-content/uploads/2018/03/2018DatabitsSpringIssue-web.pdf. Accessed 20 May 2020.

Karasti, H., and K.S. Baker. 2004. Infrastructuring for the long-term: Ecological information management. In *Proceedings of the 37th Hawaii international conference on system sciences*. Washington, DC: IEEE Computer Society. https://doi.org/10.1109/HICSS.2004.10014.

———. 2008. Digital data practices and the long-term ecological research program growing global. *International Journal of Digital Curation* 3 (2): 42–58.

Karasti, H., K.S. Baker, and E. Halkola. 2006. Enriching the notion of data curation in e-science: Data managing and information infrastructuring in the Long Term Ecological Research (LTER) Network. *Computer Supported Cooperative Work* 15 (4): 321–358.

Karasti, H., K.S. Baker, and F. Millerand. 2010. Infrastructure time: Long term matters in collaborative development. *Computer Supported Cooperative Work* 19: 377–415.

Kratz, J., and C. Strasser. 2015. Making data count. *Scientific Data* 2: 150039. https://doi.org/10.1038/sdata.2015.39.

Michener, W.K., A.B. Miller, and R. Nottrott, eds. 1990. *Long-Term Ecological Research Network core data set catalog*. Columbia: Belle W. Baruch Institute for Marine Biology and Coastal Research, University of South Carolina.

Michener, W.K., J.W. Brunt, J.J. Helly, R.B. Kirchner, and S.G. Stafford. 1997. Nongeospatial metadata for the ecological sciences. *Ecological Applications* 7: 330–342.

Michener, W.K., S. Allard, A.E. Budden, R. Cook, K. Douglass, and M. Frame. 2012. Participatory design of DataONE—Enabling cyberinfrastructure for the biological and environmental sciences. *Ecological Informatics* 11. https://doi.org/10.1016/j.ecoinf.2011.08.007.

Millerand, F., D. Ribes, K. Baker, and G.C. Bowker. 2013. Making an issue out of a standard: Storytelling practices in a scientific community. *Science, Technology &Human Values* 38 (1): 7–43.

Porter, J.H. 2010. A brief history of data sharing in the U.S. Long Term Ecological Research Network. *Bulletin of the Ecological Society of America* 91: 14–20.

Porter, J.H., and J.W. Brunt. 2001. Making data useful: The history and future of LTER metadata. *LTER Network News* 14 (2): 12–13. http://lternet.edu/wp-content/uploads/2010/12/fall01.pdf. Accessed 22 May 2020.

Porter, J.H., and J.T. Callahan. 1994. Circumventing a dilemma: Historical approaches to data sharing in ecological research. In *Ecological information management*, ed. W.K. Michener, S. Stafford, and J.W. Brunt, 193–203. Bristol: Taylor and Francis.

Robbins, R.J. 2011. *Data management for LTER: 1980–2010*. http://lternet.edu/wp-content/uploads/2012/01/report-RJR-fin-revised.pdf. Accessed 22 May 2020.

Rodriguez, N.B., K.J. McGuire, and J. Klaus. 2018. Time-varying storage-water age relationships in a catchment with a Mediterranean climate. *Water Resources Research* 54 (6): 3988–4008.

Servilla, M., J. Brunt, D. Costa, J. McGann, and R. Waide. 2016. The contribution and reuse of LTER data in the Provenance Aware Synthesis Tracking Architecture (PASTA) data repository. *Ecological Informatics* 36: 247–258.

Sillett, S.C., R. Van Pelt, J.A. Freund, J. Campbell-Spickler, A.L. Carroll, and R.D. Kramer. 2018. Development and dominance of Douglas-fir in North American rainforests. *Forest Ecology and Management* 429: 93–114.

Song, C., W.K. Dodds, J. Ruegg, A. Argerich, C.L. Baker, W.B. Bowden, M.M. Douglas, K.J. Farrell, M.B. Flinn, E.A. Garcia, A.M. Helton, T.K. Harms, S. Jia, J.B. Jones, L.E. Koenig, J.S. Kominoski, W.H. McDowell, D. McMaster, S.P. Parker, A.D. Rosemond, C.M. Ruffing, K.R. Sheehan, M.T. Trentman, M.R. Whiles, W.M. Wollheim, and F. Ballantyne. 2018. Continental-scale decrease in net primary productivity in streams due to climate warming. *Nature Geoscience* 11 (6): 415–420.

Stafford, S.G. 1996. Finding leadership opportunities in an era of dual-career families. *Bioscience* 46: 52–54.

———. 1998. Issues and concepts of data management: The H.J. Andrews Forest Sciences Data Bank as a case study. In *Data and information management in the ecological sciences: A resource guide*, ed. W.K. Michener, J.H. Porter, and S.G. Stafford, 1–5. Albuquerque: Long-Term Ecological Research Network Office.

———. 2016. Data, data everywhere. In *Long-term ecological research: Changing the nature of scientists*, ed. M.R. Willig and L.R. Walker, 63–71. New York: Oxford University Press.

Stafford, S.G., P.B. Alaback, G.J. Koerper, and M.W. Klopsch. 1984. Creation of a forest science data bank. *Journal of Forestry* 82: 432–433.

Stafford, S.G., P.B. Alaback, K.L. Waddell, and R.L. Slagle. 1986. Data management procedures in ecological research. In *Research data management in the ecological sciences*, ed. W.K. Michener, 93–113. Columbia: University of South Carolina Press.

Stafford, S.G., G. Spycher, and M.W. Klopsch. 1988. The evolution of the Forest Science Data Bank. *Journal of Forestry* 86: 50–51.

Stafford, S.G., J.W. Brunt, and W.K. Michener. 1994. Integration of scientific information management and environmental research. In *Environmental information management and analysis: Ecosystem to the global scales*, ed. W.K. Michener, J.W. Brunt, and S.G. Stafford, 3–19. London: Taylor and Francis.

Vanderbilt, K., and E. Gaiser. 2017. The International Long Term Research Network: A platform for collaboration. *Ecosphere* 8 (2): e01697. https://doi.org/10.1002/ecs2.1697.

Vanderbilt, K.L., C.-C. Lin, S.-S. Lu, A.R. Kassim, H. He, X. Guo, I. San Gil, D. Blankman, and J.H. Porter. 2015. Fostering ecological data sharing: Collaborations in the International Long Term Ecological Research Network. *Ecosphere* 6 (10): 1–18.

Vanderbilt, K., J.H. Porter, S.-S. Lu, N. Bertrand, D. Blankman, X. Guo, H. He, D. Henshaw, K. Jeong, E.-S. Kim, C.-C. Lin, M. O'Brien, T. Osawa, E.O. Tuama, W. Su, and H. Yang. 2017. A prototype system for multilingual data discovery of International Long-Term Ecological Research (ILTER) Network data. *Ecological Informatics* 40: 93–101.

Waide, R.B., J.W. Brunt, and M.S. Servilla. 2017. Demystifying the landscape of ecological data repositories in the United States. *Bioscience* 67: 1044–1051.

Willig, M.R., and L.R. Walker, eds. 2016. *Long-term ecological research: Changing the nature of scientists*. New York: Oxford University Press.

Wolkovich, E.M., B.J. Cook, J.M. Allen, T.M. Crimmins, J.L. Betancourt, S.E. Travers, S. Pau, J. Regetz, T.J. Davies, N.J.B. Kraft, T.R. Ault, K. Bolmgren, S.J. Mazer, G.J. McCabe, B.J. McGill, C. Parmesan, N. Salamin, M.D. Schwartz, and E.E. Cleland. 2012. Warming experiments underpredict plant phenological responses to climate change. *Nature* 485: 494–497.

Zhang, M., N. Liu, R. Harper, Q. Li, K. Liu, X. Wei, D. Ning, Y. Hou, and S. Liu. 2017. A global review on hydrological responses to forest change across multiple spatial scales: Importance of scale, climate, forest type and hydrological regime. *Journal of Hydrology* 546: 44–59.

In the mid-1990s, while James Gosz was DEB Division Director, NSF received an unexpected budget windfall from which DEB held a competition within the LTER Network to expand site based research regionally and to increase disciplinary breadth. The North Temperate Lakes (NTL) and Coweeta (CWT) LTER sites were selected following peer review to receive budget increases from ~$560,000 per year (the Network standard at the time) to $1,000,000 per year. The ultimate plan was to repeat this competition periodically so that more sites could expand their research programs. In truth, the budget windfall was intended for other federal agencies (NASA, USDA, Department of Energy), not NSF. This funding bonanza occurred because NSF had room in its budget request for additional global change research funds through its annual request to Congress. These funds were directed to NSF by the Office of Management and Budget with the intention of NSF participating in a cross-site competition for global change research. As a consequence, rather than continuing to expand LTER site science, most of these funds were used for NSF's contribution to the Terrestrial Ecology and Global Change interagency competition, known as TECO. That effectively ended the plan to use these funds to expand the scale and scope of sites in the LTER Network.

As the LTER Network grew, there was a clear need for a governance structure to promote cross-site interactions. The Coordinating Committee (CC) meeting initially served in that capacity. Starting in the mid-1990s research symposia at the CC meetings were used to explore interconnections among LTER sites. For example, one highly successful CC workshop hosted by Dave Tilman (Cedar Creek LTER) resulted in an LTER working group led by Bob Waide and Mike Willig and supported by the National Center for Ecological Analysis and Synthesis (NCEAS). That working group resulted in several impactful cross-site publications (e.g., Waide et al. 1999; Dodson et al. 2000; Gough et al. 2000; Gross et al. 2000; Mittelbach et al. 2001). This was one of the first of numerous cross-site efforts, many of which were funded by resources provided through NCEAS and, more often, the LTER Network Office.

In fact, the LTER strategic planning at the time of the Twenty-Year Review identified the third decade of LTER science as one of cross-site research and synthesis that would lead to a better understanding of complex environmental problems and result in knowledge that serves science and society. Despite the increase in synthesis and cross-site research that had occurred by that time, most such activities were *ad hoc*, somewhat idiosyncratic, and relatively uncoordinated, thus preventing the LTER Network from achieving its full potential. This deficiency called for a coordinated, organized approach to Network-level science, collaboration and synthesis driven from the bottom-up by the LTER research community. Network level science to address Ecological Grand Challenges, a list of urgent research priorities identified by the National Research Council (National Research Council 2001), was incorporated into the LTER Network's vision, mission, and scientific priorities. In addition, Network-level science required improvements in governance and organizational structure, infrastructure needs, advanced informatics and integration with education and policy initiatives all built around a strong science-driven research agenda.

planning process (STF-AC) along with input from the broader LTER Network via the Executive Committee, Coordinating Committee and All Scientists Meetings. The goal was to start broad and then to narrow both the focus and the scientific team tasked with organizing the planning process. Shortly after the process got started, Jim Gosz retired from University of New Mexico, leaving me to take over as PI of the planning award.

The first step in the process began with the Meeting of 100, which was to be broadly inclusive, involving a number of social scientists (anthropologists, sociologists, economists, geographers) as well as biophysical scientists from within and outside the LTER Network. At one point during the initial Meeting of 100, I said to one of the resource economists at the workshop that we needed more sociologists at the next meeting, to which he replied, “oh, we don’t need any more of those.” I invited more sociologists anyway. The purpose of the Meeting of 100 was to focus the research themes, which ultimately resulted in four Network Science Working Groups (NSWGs). The themes for the four NSWGs were organized somewhat hierarchically (Fig. 14.2): at the broadest scale was climate variability and climate change. Embedded in that was coupled natural-human systems, which encompassed altered biogeochemical cycles and altered biotic structure. These themes were considered to represent the existing strengths of the LTER Network and provided a sound foundation for initiating network-level science. What followed was a series

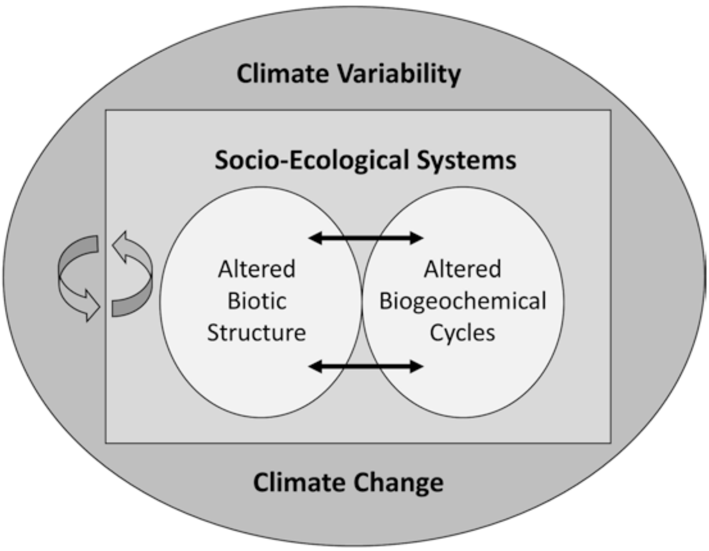

Fig. 14.2 A hierarchical schematic of the key strengths of the LTER Network research., which were the focus of four Network Science Working Groups. Altered biological structure and altered biogeochemical cycles were nested within social-ecological systems, all of which are affected by climate change. These research domains and their interactions are built around Environmental Grand Research Challenges (NRC 2001) and formed the basis of the expanded LTER Network research agenda

broader scientific community. As a consequence, we put together a funding initiative directed at NSF, Integrated Science for Society and the Environment (ISSE; Collins et al. 2007), to justify a substantial increase in research funds that would be distributed across at least three research Directorates and multiple programs (Fig. 14.4). Therefore, when we approached NSF with our new plan for network-level science, we would also provide a scientifically based justification for a funding initiative that would broadly benefit and further integrate the biophysical and social sciences.

14.4 Outcomes of the Planning Process

It is safe to say that not all LTER scientists were enthusiastic about the goals of the planning process. The members of the Science Task Force did their best to communicate plans and progress to NSF and the LTER Network along the way. One All Scientists Meeting (2006) was dedicated to the planning process, many site scientists were involved in working groups throughout the process, and we regularly reported on progress at annual Science Council meetings and to the LTER Executive Board. Nevertheless, a few PIs felt that an unwanted research agenda was being forced on them. Others argued that human impacts were not that important at their sites, so they were concerned they would be punished for not being more engaged in social-ecological research. Still others just wanted more money for what they were already doing, which was simply not going to happen. And yet most sites and PIs fully embraced the planning process and the organizing framework, incorporating the loop diagram into their renewal proposals, with various degrees of success.

The planning process ran from 2004 to 2007. A lot can happen within a funding agency over a 3 year time span. In fact, during this period, Dr. Mary Clutter, Assistant Director (AD) for Biological Sciences, retired. Dr. Clutter was a strong supporter of the LTER Network and considered LTER to be one of the flagship programs in the Directorate. Dr. Clutter had been the AD since 1988. She was replaced by a series of rotators, all of whom had different interests and priorities. The BIO Directorate at NSF has a history of insularity from the research community. Although BIO occasionally reached out to the community (i.e., regarding the need for the national center to promote ecological synthesis), unlike other Directorates, BIO rarely sought advice about potential research-oriented funding initiatives from the community of active research scientists. But with new leadership, we hoped that the culture within BIO might have changed, and that the new management would be receptive to the social-ecological integration inherent in ISSE.

We were wrong. There was considerable skepticism expressed about ISSE and the plans for an expanded research agenda for the LTER Network. Although we regularly briefed NSF management on our progress and goals throughout the planning process, they were, in fact, completely unprepared for our initiative. Instead, Directorate-level management claimed that they were expecting a “strategic plan”

Millennium Ecosystem Assessment. *Proceedings of the National Academy of Sciences* 106: 1305–1312.
Chapin, F.S.I.I.I., E.S. Zavaleta, V.T. Eviner, R.L. Naylor, P.M. Vitousek, H.L. Reynolds, D.U. Hooper, S. Lavorel, O.E. Sala, S.E. Hobbie, M.C. Mack, and S. Diaz. 2000. Consequences of changing biodiversity. *Nature* 405: 234–242.
Childers, D.L., E. Gaiser, and L.A. Ogden. 2019. *The coastal Everglades*. Oxford: Oxford University Press.
Clark, C.M., S.M. Simkin, E.B. Allen, W.D. Bowman, J. Belnap, M.L. Brooks, S.L. Collins, L.H. Geiser, F.S. Gilliam, S.E. Jovan, L.H. Pardo, B.K. Schulz, C.J. Stevens, K.N. Suding, H.L. Throop, and D.M. Waller. 2019. Potential vulnerability of 348 herbaceous species to atmospheric deposition of nitrogen and sulfur in the U.S. *Nature Plants* 5: 697–705.
Collins, S.L., S.M. Swinton, C.W. Anderson, B.J. Benson, J. Brunt, T. Gragson, N.B. Grimm, M. Grove, D. Henshaw, A.K. Knapp, G. Kofinas, J.J. Magnuson, W. McDowell, J. Melack, J.C. Moore, L. Ogden, J.H. Porter, O.J. Reichman, G.P. Robertson, M.D. Smith, J. Vande Castle, and A.C Whitmer. 2007. Integrated science for society and the environment: A strategic research initiative. Publication #23 of the U.S. LTER Network. Albuquerque, New Mexico: LTER Network Office. http://www.lternet.edu/planning/. Accessed 20 Apr 2020.
Collins, S.L., S.R. Carpenter, S.M. Swinton, D.E. Orenstein, D.L. Childers, T.L. Gragson, N.B. Grimm, J.M. Grove, S.L. Harlan, J.P. Kaye, A.K. Knapp, G.P. Kofinas, J.J. Magnuson, W.H. McDowell, J.M. Melack, L.A. Ogden, G.R. Robertson, M.D. Smith, and A.C. Whitmer. 2011. An integrated conceptual framework for long-term social-ecological research. *Frontiers in Ecology and the Environment* 9: 351–357.
Dodson, S.I., S.E. Arnott, and K.L. Cottingham. 2000. The relationship in lake communities between primary production and species richness. *Ecology* 81: 2662–2679.
Edwards, E.J., C.P. Osborne, C.A.E. Strömberg, S.A. Smith, and C4 grasses consortium. 2010. The origins of C4 grasslands: Integrating evolutionary and ecosystem science. *Science* 328: 587–591.
Fahey, T.J., and A.K. Knapp. 2007. *Principles and standards for measuring primary production*. Oxford: Oxford University Press.
Fountain, A.G., J.L. Campbell, E.A.G. Schuur, S.E. Stammerjohn, M.W. Williams, and H.W. Ducklow. 2012. The disappearing cryosphere: Impacts and ecosystem responses to rapid cryosphere loss. *Bioscience* 62: 405–415.
Galloway, J.N., A.R. Townsend, J.W. Erisman, M. Bekunda, Z. Cai, J.R. Freney, L.A. Martinelli, S.P. Seitzinger, and M.A. Sutton. 2008. Transformation of the nitrogen cycle: Recent trends, questions, and potential solutions. *Science* 320: 889–892.
Gholz, H.L., D. Wedin, S. Smitherman, M.E. Harmon, and W.J. Parton. 2000. Long-term dynamics of pine and hardwood litter in contrasting environments: Toward a global model of decomposition. *Global Change Biology* 6: 751–765.
Golley, F.B. 1993. *A history of the ecosystem concept in ecology*. New Haven: Yale University Press.
Gough, L., C.W. Osenberg, K.L. Gross, and S.L. Collins. 2000. Fertilization effects on species density and primary productivity in herbaceous plant communities. *Oikos* 89: 428–439.
Greenland, D., D.G. Goodin, and R.C. Smith. 2003. *Climate variability and ecosystem response at long-term ecological research sites*. Oxford: Oxford University Press.
Grimm, N.B., S.T.A. Pickett, R.L. Hale, and M.L. Cadenasso. 2017. Does the ecological concept of disturbance have utility in urban social-ecological-technological systems? *Ecosystem Health and Sustainability* 3. https://doi.org/10.1002/ehs2.1255. Accessed 20 Apr 2020.
Gross, K.L., M.R. Willig, L. Gough, R. Inouye, and S.B. Cox. 2000. Patterns of species density and productivity at different spatial scales in herbaceous plant communities. *Oikos* 89: 417–427.
Haberl, H., V. Winiwarter, K. Andersson, R. Ayers, C. Boone, A. Castillo, G. Cunfer, M. Fischer-Kowalski, W.R. Freudenburg, E. Furman, R. Kaufmann, F. Krausmann, E. Langthaler, H. Lotze-Campen, M. Mirtl, C.L. Redman, A. Reenberg, A. Wardell, B. Warr, and H. Zechmeister. 2006. From LTER to LTSER: Conceptualizing the socio-economic dimension of long-term socio-