1 Changing the Nature of Scientists

Participating in the Long-Term Ecological Research Program

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INTRODUCTION

From the outside looking in, scientists are often characterized as old men in white laboratory coats, working in splendid isolation, usually within the confines of rather sterile-looking laboratories. Of course, this image was never quite accurate for ecologists, who abandoned white laboratory coats for more field-appropriate boots and khaki pants, but who nonetheless typically worked alone or with the benefit of a faithful field assistant (Figure 1.1a). The late 1900s was a time of rapid change in the way in which ecological research was conducted, in part because of opportunities for support from governmental agencies. Especially critical in effecting these changes was grant support that would allow scientists to comprehensively investigate the intricate and complex ecological interactions between organisms and their environment from a long-term and site-based perspective. Such efforts often involved large and diverse groups of scientists representing multiple disciplinary perspectives and investigative approaches (Figure 1.1b).

The US Long-Term Ecological Research (LTER) program, with support from the National Science Foundation (NSF), was one of the first governmental programs to catalyze long-term, site-based, multidisciplinary, and collaborative research. The scientific research arising from such support has been broad and deep, resulting in thousands of publications. The research insights have been integrated into a number of synthetic books, each dedicated to long-term research at a particular site in the LTER program (Knapp et al. 1998; Bowman and Seastedt 2001; Greenland, Goodin, and Smith 2003; Schachak et al. 2005; Magnuson, Kratz, and Henson 2005; Foster and Aber 2006; Chapin et al. 2006; Havstad, Huenneke, and Schlesinger 2006; Redman and Foster 2008; Lauenroth and Burke 2008; Brokaw et al. 2012). In contrast, the effects of the LTER program's many innovations on the participating scientists have not been explored in a comprehensive or systematic fashion. This book provides a window into how scientists have changed as a consequence of participation in the LTER program.

The LTER network of sites, begun in 1980, effectively implemented the first effort by the NSF to systematically fund long-term, site-based environmental research. The LTER program has successfully facilitated studies by environmental scientists from multiple disciplinary backgrounds (based on observations and experiments) who evaluate the structure and functioning of ecological systems at decadal or longer time frames.

Michael R. Willig and Lawrence R. Walker, *Changing the Nature of Scientists: Participating in the Long- Term Ecological Research Program.* In: *Long- Term Ecological Research Changing the Nature of Scientists.* Edited by Michael R. Willig and Lawrence R. Walker, Oxford University Press (2016).

DOI: 10.1093/oso/9780199380213.003.0006

FIGURE 1.1 Ecological research over the past half century has changed from a model involving one or a few scientists (Figure 1.1a) investigating disciplinary questions over local or short temporal horizons, to large collaborative groups (Figure 1.1b) investigating interdisciplinary questions over multiple spatial and temporal scales. (Artwork courtesy of Janine Caira.)

By supporting such approaches to environmental research projects, the LTER program has encouraged groups of scientists to work collaboratively to analyze multiple aspects of ecological problems (e.g., not only nutrient cycles but their interactions with plants, animals, and microbes, as well as their responses to disturbance and consequences to human well-being).

The LTER program, via the LTER network office, also pioneered web-based, centralized information management systems. It facilitated long-term monitoring studies and the storage, manipulation, and sharing of data and metadata among investigators within and among LTER sites, as well as with non-network scientists, educators, and natural resource managers. Although not explicitly formed as a synoptic network of sites for quantifying the same phenomena in the same manner at multiple locations, the LTER program, via activities of the LTER network office, has engaged scientists to compare and contrast system dynamics among sites with regard to salient environmental gradients. Moreover, the LTER network was among the first scientific organizations to promote a socioecological examination of how human and natural systems are coupled. The success of the LTER network is in part reflected in the extent to which other countries throughout the world have adopted a similar organizational structure and scientific agenda to broaden and deepen predictive understanding of socioecological systems. (The International LTER network is a multinational collection of LTER sites in various countries on most continents.) Finally, the LTER program has supported an innovative and effective outreach program that integrates research and education via its Schoolyard LTER program and a children's book series that is dedicated to site-based environmental themes. These many innovations have transformed the scientific nature of environmental research and education, and in doing so potentially have also changed how contemporary environmental scientists think and act as researchers, educators, and communicators to the public, all within a collaborative and multidisciplinary culture.

ORGANIZATION

The subsequent chapters in this book are organized into three parts. The first part comprises two chapters that provide an overview of the LTER program and network from the perspectives of those involved in science management at the LTER network office (Waide, Chapter 2) or at NSF (Gholz, Marinelli, and Taylor, Chapter 3). The second part includes 36 introspective essays in which participants in the LTER program examine how they have changed as a consequence of involvement in the program. The third part contains five chapters that comment on, integrate, analyze, or synthesize information contained in the second part. One chapter provides the perspective of an eminent ecologist (Schlesinger, Chapter 40); three chapters provide assessments from the perspective of behavioral scientists (Boyer and Brown, Chapter 41), a sociologist (Flint, Chapter 42), and an historian (Hamlin, Chapter 43); and the final chapter provides a synthesis by the coeditors (Walker and Willig, Chapter 44) that identifies emergent themes and suggests lessons that have been learned, especially as they presage directions for future environmental research and education.

SCOPE, FOCUS, AND LIMITATIONS

This book provides a broad assessment of the effects of a more than 35-year social, cultural, and scientific "experiment" (i.e., the LTER program) on the attitudes of its participants as well as on how they engage in research, teaching, service, mentoring, and outreach. It explores what happens when ecologists receive long-term funding in a network of site-based groups located across a diversity of biomes and habitat types. We wanted to know if and how such an innovative funding arrangement affected the scientists themselves: did perspectives, attitudes, or practices change as a consequence of participation in this “experiment?” We targeted participants in the LTER program who generally had at least 9 years of experience as principal investigators, co–principal investigators, or senior personnel, so that responses would be based on comprehensive participation in the program. We sought to involve one to three participants from each of a number of sites throughout the network, and to broadly represent sex and age groups, as well as disciplinary backgrounds. In some cases, authors began their association with the LTER program when they were graduate students or postdoctoral fellows. Some authors played a critical role in the formation of the program or its administration at NSF. Given our selection criteria, responses from potential participants, and publication timeline, not all LTER sites could be represented by chapters.

This book is an historical exposition from the perspectives of the participants of the broader impacts of LTER involvement on their professional and personal development. Although these essays represent data for integration and synthesis, they are not the product of a controlled experimental design. We did not randomize the selection of participants from among those with long-term associations with the LTER program. We have not asked the same kinds of questions to environmental scientists outside of the LTER program, or to those whose experiences within the LTER program were ephemeral. Moreover, we are not experts in crafting survey questionnaires, and there were no internal controls among the questions to detect consistency of opinion. Nonetheless, we did attempt to phrase questions so that they would be “outcome neutral,” and to encourage critical responses that include both positive and negative components.

The main body of the book comprises the responses of a broad selection of scientists, including several data managers or educators, to a series of probing questions (see Chapters 4 to 39). Initially, eight questions were presented for consideration by the authors in crafting their introspective essays.

1. How has your LTER experience changed you as a scientist? Consider if the LTER experience has made you more or less collaborative, multidisciplinary, theoretical, insightful, comparative, synthetic, or place-based.
2. How has your LTER experience changed you as a communicator of science? Has your teaching changed? How about your perspective or involvement in outreach activities, service, or administration?
3. How has your LTER experience changed your scientific tool kit? Have you expanded your skills (e.g., in molecular techniques, geographic information system [GIS], statistics) due to the LTER experience?
4. How has your LTER experience changed your appreciation of or contributions to applied science? Are you more or less involved in forestry, conservation, natural resource management, restoration, or similar activities due to your association with an LTER site?
5. How has your LTER experience changed your mentoring? Has the LTER changed (1) how you mentor students or junior faculty members or (2) your attitudes toward or involvement in mentoring of students, faculty members, or staff?
6. How has your LTER experience changed you as a person? Has the LTER experience altered how and where you travel, your friendship circles, and your approach to other cultures or ethnic groups?

7. How has your LTER experience changed your attitudes toward time and space and their role in ecological studies?
8. Are there any other notable changes in your life that you attribute to your association with an LTER program?

After receipt of the first draft and to facilitate evaluations of responses, we asked the authors to rearrange the content of their essay so that responses would address 10 themes: (1) approach to science, (2) attitudes toward time and space, (3) collaboration, (4) applied research, (5) communication, (6) mentoring, (7) skill set, (8) personal consequences, (9) challenges and recommendations, and (10) conclusion. In addition, we asked each essayist to address the costs and benefits of collaborating on multidisciplinary projects and of engaging in network-level activities in the collaboration section; to include activities that target teachers in the mentoring section; and to provide advice, admonitions, or recommendations for aspiring ecologists or students as they begin a career, especially as it relates to leveraging experiences in the LTER program to good effect.

PARTING COMMENTARY

Ecological scholars of the twenty-first century increasingly seek to understand complex environmental dynamics at large spatial and long temporal scales, often doing so in the context of multidisciplinary projects supported by "big data," cyber-infrastructure, and next-generation computing capabilities. The extent to which particular projects succeed in transforming scientific knowledge or understanding will be assessed in part based on scholarly publications and a historical record of paradigm shifts in the published literature. The influence of these scientific challenges and associated projects on the nature of scientists as researchers, educators, or communicators with the public is at the heart of NSF's broader impacts. Without concerted efforts to capture such changes in the nature of scientists during transformative periods, a ripe body of information is quickly lost, and assessments may be relegated to retrospective essays such as those in this volume. Clearly, these kinds of narratives provide rich fodder for historical and social science research, but at the same time, they are limited in the extent to which they can provide accurate portrayals of the transformation process itself. Our hope is that this book will provide a window into the kinds of transformations that have occurred as a result of NSF's experiment of changing the culture of scientific research via long-term collaborative funding. Equally important, we hope that this work will stimulate more formal scholarly investigation of the ways in which initiatives or programs such as the LTER program affect broader impacts and do so in a manner that is contemporaneous rather than solely retrospective.

SITE CONTEXT

In 2013 when much of this book was being written, the LTER program comprised 26 sites, mostly located in the continental United States, although there were two sites in Alaska, two sites in Antarctica, one site in French Polynesia, and one in Puerto Rico (Figure 1.2). The network encompasses a diversity of habitats including deserts, estuaries, lakes, oceans, coral reefs, prairies, forests, alpine and Arctic tundra, urban areas, and production agriculture. We provide a brief, alphabetically arranged overview of each of the 19 sites that are represented in one or more essays in this book. The commentary, mostly derived from Peters et al. (2013), gives a link to each site's official web page, identifies the scientific themes that characterize each research portfolio, and describes the ecology of each site.

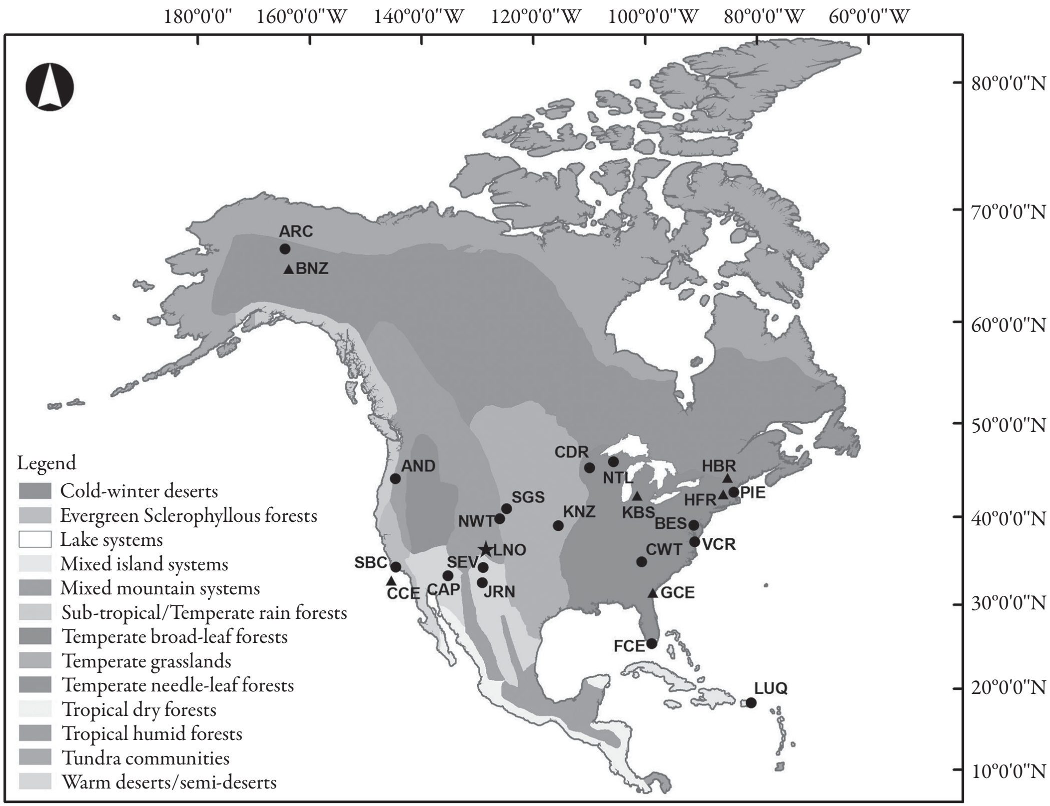

FIGURE 1.2 The Long-Term Ecological Research (LTER) network currently comprises 26 sites and a network office (LNO). Most of the sites (23) are disturbed across a diversity of biomes in North America (United States and Puerto Rico) and appear as circles (sites represented by essays) or triangles (sites not represented by essays) on the map. Two sites in Antarctica (McMurdo Dry Valleys site, MCM; Palmer Antarctica site, PAL) and one site in French Polynesia (Moorea Coral Reef site, MCM) are not represented in the graphic, although PAL and MCM are represented by essays in the book. Major biomes (Udvardy 1975) are represented by colors on the map; the LNO appears as a star. Three-letter acronyms identify particular LTER sites: AND, H. J. Andrews Experimental Forest site; ARC, Arctic site; BES, Baltimore Ecosystem Study site; BNZ, Bonanza Creek site; CEE, California Current Ecosystem site; CDR, Cedar Creek Ecosystem Science Reserve site; CP, Central Arizona–Phoenix site; CWT, Coweeta site; FCE, Florida Coastal Everglades site; GCE, Georgia Coastal Ecosystems site; HFR, Harvard Forest site; HBR, Hubbard Brook site; JRN, Jornada Basin site; KBS, Kellogg Biological Station site; KNZ, Konza Prairie site; LUQ, Luquillo site; MCM, McMurdo Dry Valleys site; MCR, Moorea Coral Reserve site; NWT, Niwot Ridge site; NTL, North Temperate Lakes site; PIE, Plum Island Ecosystem site; SBC, Santa Barbara Coastal site; SEV, Sevilleta site; SGS, Shortgrass Steppe site; and VCR, Virginia Coastal Reserve site. In 2016, funding for the LNO ended and the network communications office became operational at the National Center for Ecological Analysis and Synthesis in California (near SBC).

FIGURE 1.3 A tributary of McRae Creek within a stand of old-growth forest at the H .J. Andrews Experimental Forest Long-Term Ecological Research site. (Photo courtesy of Lina DeGregorio.)

H. J. Andrews Experimental Forest (AND)

This site (http://andrewsforest.oregonstate.edu/) was established as an Experimental Forest in 1948 and was part of the International Biological Program in the 1970s (Figure 1.3). In 1980, AND was funded as one of the original sites in the LTER program with a research focus on understanding how climate, natural disturbance, and land use, as controlled by forest governance, interact with biodiversity, hydrology, and carbon and nutrient dynamics. It is located in the western Cascade Range of Oregon in the 6,400-ha drainage basin of Lookout Creek, a tributary of the Blue and McKenzie Rivers. Elevation ranges from 410 to 1,630 m. The climate is wet in winter but warm and dry in summer. Precipitation occurs mainly as rain at lower elevations and as snow at upper elevations. The vegetation consists of coniferous forests that are intersected by streams. Forest age classes include 150- and 500-year-old stands developed after wildfire and younger stands established as Douglas fir (*Pseudotsuga menziesii*) plantations following clear-cutting in the 1950s through early 1980s.

Arctic (ARC)

The ARC site (http://ecosystems.mbl.edu/ARC/) was established in 1987 to understand and predict the effects of environmental change on the ecology of tundra, streams, and lakes (Figure 1.4). It is located at an elevation of 760 m in the northern foothills of the Brooks Range (Alaska), 254 km north of the Arctic Circle. Study sites occur within a 48-km^2 core watershed but are also dispersed across more than 1,000 km^2 of the tundra, including three other watersheds and a large burned area. The climate is typical of arctic regions, with a mean annual air temperature of about −7°C and low precipitation (200–400 mm; half falling as snow). The snow-free growing season extends from late May to mid-September, but freezing temperatures are possible at any time. The region is underlain by continuous permafrost that exerts a major influence on the distribution, structure, and function of ecosystems.

ARC represents a treeless tundra, with tussock tundra predominating but also including wet sedge tundra, drier heath tundra on ridge tops, and river-bottom willow shrub communities. The streams in the area constitute the headwaters of the Kuparuk River, and oligotrophic lakes of various ages are abundant.

FIGURE 1.4 Toolik Lake and the surrounding landscape at the Arctic Long-Term Ecological Research site. (Photo courtesy of James Laundre.)

FIGURE 1.5 West Franklin Street neighborhood and landscape at the Baltimore Ecosystem Study (BES) Long-Term Ecological Research site. (Photo courtesy of Steward Pickett, the BES LTER program.)

Baltimore Ecosystem Study (BES)

This site (http://www.beslter.org/) became part of the LTER program in 1997, with a mission to investigate metropolitan Baltimore as a socioecological system (Figure 1.5).

BES conducts research and educational activities in Baltimore City and surrounding counties. The project focuses on several watersheds to organize research from both spatial and functional perspectives. For example, the Gwynns Falls watershed encompasses 17,150 ha and drains into the Chesapeake Bay. The climate is humid temperate, with four distinct seasons, including cool winters (January average, 2.1°C) and hot, humid summers (July average, 27.1°C). Precipitation comes mostly as spring and summer rains; winter snowfall is sporadic, with total annual precipitation averaging 1,060 mm. The city is warmed by an urban heat island effect that lessens irregularly with distance from its center.

The watershed includes agricultural lands, recently suburbanized areas, established suburbs, and dense urban areas having residential, commercial, and open spaces. Vegetation of the watershed has changed from predominantly forest before European settlement to primarily herbaceous. There are no original stands of forest in the Baltimore area, although a reference second-growth forested watershed was established in a park in Baltimore County. Research on stream restoration centers on the Minebank Run catchment. A study of the ecological effects of residential neighborhood greening and restoration is being conducted in a 364-ha storm drain catchment in Baltimore City.

Cedar Creek Ecosystem Science Reserve (CDR)

The CDR site (http://www.cbs.umn.edu/cedarcreek) was established in 1949, and it became part of the LTER network in 1982 (Figure 1.6). Its mission is to improve understanding of the processes that govern the dynamics and functioning of ecosystems along the boundary between prairie and forests, using experimental manipulations of drought and additions of carbon dioxide and nitrogen. The site, located 50 km north of Minneapolis, Minnesota,

FIGURE 1.6 Aerial photograph of experimental manipulation plots and the surrounding landscape at the Cedar Creek Ecosystem Science Reserve Long-Term Ecological Research site. (Photo courtesy of David Tilman.)

encompasses an area of 22 km^2 at an elevation of 277 m. The climate is continental, with cold winters and hot summers. Precipitation (660 mm per year) is spread fairly evenly throughout the year. The mean July temperature is 22.2°C, and the mean January temperature is −10°C. Soils derive from a glacial outwash sandplain, and upland soils are nitrogen poor. Numerous nutrient addition experiments in old fields and native savanna document that nitrogen is the major limiting resource to plant growth. Much of the site comprises wetlands, including swamps, acid bogs, wet meadows, and marshes. Uplands include abandoned agricultural fields, savannas, and hardwood forests. Prescribed burns began in the oak savanna in 1964.

Central Arizona–Phoenix (CAP)

The CAP (http://caplter.asu.edu) site was established as part of the LTER network in 1997, with a mission to study human interactions with the environment in central Arizona and the Phoenix metropolitan area. Phoenix is now the fifth largest city in the United States (Figure 1.7).

The study area (6,400 km^2) is at the confluence of the Salt and Gila Rivers (331 m). With less than 180 mm of annual rainfall, which falls in winter and during summer monsoon storms, CAP is situated in an arid landscape with a high rate of evaporation, and the urbanized areas comprise a growing urban heat island with increasing nighttime temperatures. The site is located in a basin that once supported lowland Sonoran Desert vegetation and riparian ecosystems, as well as agriculture. Two plants, blue palo verde (*Parkinsonia florida*) and saguaro cactus (*Carnegiea gigantea*), visually dominate the desert portions of the landscape and distinguish the Sonoran Desert from other North American deserts. Plant associations in the urban portions of the CAP area contain many non-native species typical of the American lawn. The chief constraint on plant growth is water availability, which varies with substrate conditions in the desert but is almost entirely controlled by people in the urban area. Water quality and quantity, air quality, drought, and urban heat island effects are studied to examine the feedbacks between human decisions and environmental characteristics. In this context, land use change is a major driver of ecological patterns at multiple scales.

FIGURE 1.7 The Phoenix metropolitan area (background), situated within the Sonoran Desert (foreground), represents the landscape of the Central Arizona–Phoenix (CAP) Long-Term Ecological Research (LTER) site. (Photo courtesy of Eyal Shochat and the CAP LTER program.)

FIGURE 1.8 Image depicting a typical landuse (foreground) and the broader landscape (background) in the Caler Creek Watershed that are typical of the Coweeta Long-Term Ecological Research site. (Photo courtesy of Ted Gragson.)

Coweeta (CWT)

The CWT (http://coweeta.ecology.uga.edu/) site was established by the US Forest Service as the Coweeta Hydrologic Laboratory in 1934, with an initial emphasis on the effect of forestry management practices on the hydrological cycle in small, experimental watersheds of the Coweeta Basin (Figure 1.8).

This basin is located in the Nantahala Mountain range of western North Carolina, and consists of a 1,626-ha bowl-shaped basin ranging in elevation from 670 to 1,592 m. The Coweeta LTER program, starting in 1980, initially focused on the basin but evolved from a site-based to a site- and region-based program by 1994 to better address the synergisms between substrate, society, and biology that underlie disturbance processes across the environmental gradients characteristic of southern Appalachia. Summer temperatures rarely exceed 30ºC and decrease from low to high elevation. Nonetheless, summer temperatures on the higher peaks are more similar to those in central New England, 1,400 km to the north, than they are to the lower Piedmont, only 100 km to the east. Precipitation is abundant, averaging above 1,800 mm per year and generally increasing 5% per 100 m of elevation along an east–west axis. Importantly, local mountain effects create wet zones and rain shadows that can differ by 100% in precipitation. The dominant vegetation is temperate deciduous forest, although an intermixing of northern and southern taxa results in one of the most biologically diverse regions of North America. The region represents an ideal natural laboratory for examining extensive and transient human disturbances (e.g., fire and logging) through localized and permanent disturbances (e.g., agriculture and urbanization), contributing to the growing understanding of how human practices influence forest and stream ecosystems at multiple scales.

Florida Coastal Everglades (FCE)

This site (http://fcelter.fiu.edu/) was established in 2000, with a mission to understand how population- and ecosystem-level dynamics of the coastal Everglades are controlled by water source, water residence time, and local biotic processes (Figure 1.9). Located in southern Florida, FCE occurs where a rapidly growing human population (> 6 million) lives in close proximity to—and in surprising dependence on—the Florida Everglades. FCE is entirely within the boundaries of Everglades National Park, the third largest wilderness area (6,110 km^2) in the continental United States and location of the largest mangrove ecosystem in the Western Hemisphere.

FIGURE 1.9 Aerial view of the coastal landscape that represents the Florida Coastal Everglades Long-Term Ecological Research site. (Photo courtesy of Stephen Davis.)

Although elevational variation in the Everglades is small, water flows from about 2 m at the northern boundary of the park to the estuaries. Average temperatures range from 12°C (winter lows) to 32°C (summer highs), with summer rains and total annual precipitation of 1,520 mm. The soils are deep, poorly drained peats. Wetlands include marshes, sloughs, and wet prairies, and uplands support tree islands, tropical hardwood hammocks, and pine forests. Because the coastal Everglades cover a large area that is, in effect, topographically flat, it is susceptible to dramatic changes in response to sea level rise. Hurricanes and storms are common, and add pulse disturbance to the slow press disturbances of rising sea level. The Everglades Restoration Project seeks to return the existing Everglades to a healthy and stable state so that it can continue to provide critical ecosystem services to human populations. FCE research focuses on population and ecosystem dynamics in the oligohaline regions of Taylor Slough and Shark River Slough, where freshwater and estuarine ecosystems meet to form ecotones.

Jornada Basin (JRN)

The JRN site (http://jornada-www.nmsu.edu/), located 37 km northeast of Las Cruces (New Mexico), became part of the LTER program in 1982, with a mission to understand the key factors and processes that control ecosystem dynamics and desertification in Chihuahuan Desert landscapes (Figure 1.10).

The study site includes the Jornada Experimental Range (78,000 ha), operated by the US Agricultural Research Service (ARS), and the Chihuahuan Desert Rangeland Research Center (22,000 ha), operated by New Mexico State University. Data have been collected since 1915, and vegetation records date to the mid-1800s. JRN (1,300–1,400 m) has mild winters (as low as 13°C) and hot summers (as high as 36°C). Annual precipitation averages 260 mm, with about 52% of rain occurring in summer. Extreme droughts are recurrent climatic phenomena with profound influence on the vegetation. The five major plant communities at JRN differ in degree of desertification and include upland and lowland, and a

FIGURE 1.10 Creosote shrubland is one of the five major plant communities of the Chihuahuan Desert that compose the Jornada Basin Long-Term Ecological Research site. (Photo courtesy of Debra Peters.)

series of desertified shrublands, including tarbush (*Flourensia cernua*) on lower piedmont slopes, creosotebush (*Larrea tridentata*) on upper piedmont slopes and bajadas, and honey mesquite (*Prosopis glandulosa*) on the sandy basin floor. Grazing by livestock was historically the predominant land use in the region, although urbanization has been increasing.

Konza Prairie (KNZ)

The KNZ site (http://www.konza.ksu.edu/) became part of the LTER program in 1980, with a goal of understanding how three key drivers (i.e., fire, grazing, climatic variability) affect ecological patterns and processes in tallgrass prairies (Figure 1.11). The Konza Prairie Biological Station (3,487 ha), at 330 m elevation in the Flint Hills of northeastern Kansas, is a C4-dominated grassland with a continental climate characterized by warm, wet summers and dry, cold winters. Steep slopes in the area are overlain by shallow limestone soils that are unsuitable for cultivation. These soils overlay as many as 10 distinct layers of alternating limestone and shale, contributing to the complex subsurface hydrology of the region. Because mean annual precipitation is sufficient to support woodland or savanna vegetation, periodic drought, fire, and grazing are important in maintaining the grassland. The vegetation is over 90% native tallgrass prairie dominated by perennial C4 grasses. Numerous subdominant grasses, forbs, and woody species contribute to high floristic diversity. Gallery forests grow along major stream courses. Long-term studies include a replicated watershed-level experiment, in place since 1977, which explicitly incorporates the major factors influencing mesic grasslands in a long-term experimental setting, as well as numerous plot-level experiments and stream weirs and groundwater sampling locations.

Luquillo (LUQ)

This site (http://luq.lternet.edu/) became part of the LTER program in 1988, with a mission to study the long-term effects of natural and human disturbances on tropical forests

FIGURE 1.11 Landscape image of the Konza Prairie Long-Term Ecological Research site, with a pair of bison in the foreground. (Photo courtesy of Edward Raynor.)

FIGURE 1.12 Landscape image of the forests of the Luquillo Mountains, including suburbanizing areas in the lowlands, that represent the Luquillo Long-Term Ecological Research site. (Photo courtesy of Jerry Baurer and Oxford University Press.)

and streams in Puerto Rico (Figure 1.12). Research in this area dates back over 100 years, with LUQ being one of the most intensively studied tropical forests in the world.

The site is located in the Luquillo Mountains (300–1080 m; 11,330 ha), which harbors the largest area of primary forest and the most pristine rivers in Puerto Rico. The climate is subtropical maritime, and moderated by trade winds that maintain relatively constant air temperatures. Rainfall is in excess of 100 mm each month, although periods of lower rainfall occur between February and April and periods of higher rainfall occur in September. Severe hurricanes occur on average every 60 years. Drought (< 100 mm/month) recurs on decadal scales. Dominant soils are deep, highly weathered and leached clays with low pH and base saturation. The vegetation is evergreen broadleaf subtropical forest, with 240 tree species that vary in abundance along the elevational gradient to form distinctive forest types based on species composition and structure. Natural disturbances include hurricanes, landslides, tree falls, floods, and droughts. Human disturbances include changes in land use and land cover change, climate change, and species introductions. Forest cover on the island was reduced to about 5% in 1950, but with industrialization and abandonment of agriculture, has recovered to about 42%.

Moorea Coral Reef (MCR)

This site (http://mcr.lternet.edu/) joined the LTER program in 2004, with a mission to understand the long-term consequences of disturbance and changing climate regimes on coral reef ecosystems (Figure 1.13). MCR comprises a complex of coral reefs and lagoons that surround the 60-km perimeter of Moorea, a small volcanic island in French Polynesia, about 20 km west of Tahiti in the South Pacific. Average temperatures range from 21° to 31°C, with little seasonal variation. Most of the 1,760 mm of rainfall per year occurs between November and February.

Major coral reef types are easily accessible at MCR. Reefs are dominated by massive *(Porites* spp.*)*, branching *(Pocillopora* spp., *Acropora* spp.*)*, and encrusting *(Montipora*

FIGURE 1.13 Staghorn coral represent dominant components of the underwater landscape that is typical of the Moorea Coastal Reserve Long-Term Ecological Research site. (Photo courtesy of Melissa Holbrook.)

spp.) coral species that are periodically disturbed by cyclones (e.g., 1982, 1991, 2010), outbreaks of crown-of-thorns sea stars (*Acanthaster planci*) that consume coral (e.g., 1991, 2008), and coral bleaching events (e.g., 1991, 1994, 2002, 2003). Like coral reefs worldwide, those in Moorea are highly vulnerable to ocean warming and acidification. To date, the reefs of Moorea show high resilience to disturbances, making them an outstanding model system for exploring long-term dynamics and ecosystem processes.

Niwot Ridge (NWT)

The NWT site (http://culter.colorado.edu/NWT/) became part of the LTER program in 1980, with a mission to understand the effects of climate change on the ecological and hydrological processes in high-elevation areas in the Colorado Front Range of the Rocky Mountains (Figure 1.14). Research began at the site in the 1940s with the return of World War II veterans who had extensive experience in cold-region logistics. NWT is approximately 35 km west of Boulder, Colorado, and elevation ranges from 2,895 to 3,814 m. The research area (34 km^2) is bounded on the west by the Continental Divide and comprises extensive alpine tundra and a variety of glacial landforms. Snowfall accounts for more than 80% of precipitation. The interactions among wind, snow, and high topographic relief result in a mosaic of moisture availability. The vegetation includes subalpine forests and meadows, and patches of krummholz in the abrupt transition between forest and tundra. The major research area is the Saddle, with its western half being a snow accumulation area (up to 10 m in some years) and its eastern half remaining free of snow for most of the winter. Changes in abundance and species composition of the native flora and fauna of these mountain ecosystems are potential bellwethers of global change. A suite of short- and long-term experiments

FIGURE 1.14 Image of scientists collecting climatic data under harsh conditions typical of the Niwot Ridge Long-Term Ecological Research site. (Photo courtesy of John Marr and the National Science Foundation.)

provide insight into how alpine tundra and lakes respond to changes in climate and nutrient loading.

North Temperate Lakes (NTL)

The NTL site (http://lter.limnology.wisc.edu/) became part of the LTER program in 1981, with a mission to understand the ecology of lakes in relation to atmospheric, geochemical, landscape, and human processes (Figure 1.15). NTL comprises two geographically distinct regions: the Northern Highlands Lake District (NHLD) and the Yahara Lake District (YLD). These districts lie in formerly glaciated terrain of northern and southern Wisconsin, respectively. Research focuses on seven lakes ranging from small (< 1 ha) dystrophic lakes to large (> 1,500 ha) oligotrophic lakes in the north, and four eutrophic lakes in the south. The regional climate is continental, with cold, snowy winters (often reaching –40°C) and warm summers (typically reaching 33°C). Lakes are the focal landforms of both regions, providing unique habitats, ecosystem services, and foci for human activity.

The NHLD, one of the most lake-rich regions of the world, is largely forested and sparsely settled. Outdoor recreation centered on the 7,600 lakes of the region is a mainstay of the economy. The YLD is an agricultural, but urbanizing, landscape with scattered remnants of presettlement ecosystems. Ecological research began in the YLD in the 1880s and in the NHLD in the 1920s. Long-term, whole-lake experiments provide insights about lakes responses to changes in land cover and climate.

Palmer Antarctica (PAL)

The PAL site (http://pal.lternet.edu/) joined the LTER program in 1990 as the first marine pelagic site in the LTER network (Figure 1.16). It is situated at Palmer Station on the south coast of Anvers Island on the western Antarctic Peninsula.

FIGURE 1.15 Aerial photograph of the aquatic and terrestrial components of the landscape that represents the North Temperate Lakes Long-Term Ecological Research site. (Photo courtesy of Carl Bowser and Silver Pixel Images.)

PAL encompasses a large region extending several hundred kilometers offshore, with several circumpolar pelagic habitats, including the continental shelf within the marginal ice zone covered seasonally by sea ice and the open ocean beyond the continental shelf break, as well as a nearshore zone influenced by glacial meltwater. Within the nearshore zone are small islands that have become deglaciated in the last few centuries. Seabirds, including penguins, petrels, and skuas, inhabit these islands along with mosses and

FIGURE 1.16 Sea ice and glacier-covered mountains in Marguerite Bay (Andelaide Island) represent typical land- and sea-scapes of the Palmer Antarctica Long-Term Ecological Research site. (Photo courtesy of Hugh Ducklow.)

two species of vascular plants. The nearshore waters abound in large marine mammals including seals, orcas, humpback whales, and minke whales. Palmer Station is occupied by humans year-round, but most scientific activity is concentrated in the austral spring and summer. Research focuses on understanding the dynamics of the Antarctic marine ecosystem as it is affected by interannual variations in sea ice, documenting and predicting ecosystem responses to rapid climate change.

Plum Island Ecosystem (PIE)

This site (http://ecosystems.mbl.edu/PIE/) joined the LTER program in 1998, with a mission to (1) develop a predictive understanding of long-term responses of watershed and estuarine ecosystems to changes in climate, land use, and sea level and to (2) apply this knowledge to the management and development of policy that aims to protect the natural resources of the coastal zone (Figure 1.17).

The coupled watersheds and estuary of Plum Island Sound are located near the Boston metropolitan region (Massachusetts). The Ipswich River (400 km^2), Parker River (160 km^2), and Rowley River (40 km^2) basins are areas of low-relief and expansive wetlands. Temperatures are highly seasonal, ranging from lows of 5°C in January to highs of 18°C in July. Temperatures are highly seasonal. Water temperature ranges from a low of 2°C in February to a high of 19°C in July, whereas air temperature ranges from an average winter minimum of −7°C to an average summer maximum of about 28°C. Rainfall (total, 900 mm) is evenly distributed throughout the year. The estuary includes salt marsh habitats, fresh marshes, intertidal flats, and open-water tidal creeks and bays. Marine species diversity is low, with half the number of fish species found in areas south of Cape Cod. The Plum Island Sound estuary supports productive commercial and recreational fisheries for soft-shell clam

FIGURE 1.17 Tidal creek and salt marsh habitats are typical of the landscape at the Plum Island Ecosystem Long-Term Ecological Research site. (Photo courtesy of David Johnson.)

and striped bass. Land-use composition in the watershed during 2001 was approximately 46% forest, 34% urban or suburban, 10% agriculture, and 10% wetland or water.

Santa Barbara Coastal (SBC)

The SBC site (http://sbc.lternet.edu/) became part of the LTER program in 2000 with a mission to understand the linkages among ecosystems at the land–ocean margin, particularly as demonstrated by giant kelp forests (Figure 1.18). The principal study site is the semiarid Santa Barbara coastal region, which includes steep watersheds, small estuaries, sandy beaches, the neritic and pelagic waters of the Santa Barbara Channel (5,850 km^2), and the habitats encompassed within it. SBC is characterized by a Mediterranean climate, with mild, moist winters and moderately warm, generally rainless, summers. Winter rainstorms provide the majority of freshwater input to rivers, streams, and the nearshore marine environment. One of the more notable habitats is shallow rocky reefs dominated by giant kelp (*Macrocystis pyrifera*) forests, which are among the most productive ecosystems in the world. The amount of nutrients and organic matter delivered to these forests from the surrounding ocean and adjacent land varies in response to short- and long-term changes in climate, ocean conditions, and human use. Variation in the supply of nutrients and organic matter interacts with physical disturbance and biological interactions to influence the abundance and species composition of the forest inhabitants and the ecological services that they provide.

Sevilleta (SEV)

The SEV site (http://sev.lternet.edu/), founded in 1988, studies the effects of variability, extremes, and directional change in climate in arid land ecosystems (Figure 1.19).

FIGURE 1.18 Giant kelp forest and fish compose typical seascapes of the Santa Barbara Coastal Long-Term Ecological Research site. (Photo courtesy of Ron McPeak and University of Santa Barbara Digital Collections [item 16822].)

Research is focused at the Sevilleta National Wildlife Refuge, an ungrazed refuge of about 300 km^2 located 80 km south of Albuquerque (New Mexico), where the transitions among shortgrass steppe, Chihuahuan Desert grassland and shrubland, juniper savanna, and pinon–juniper woodland facilitate the study of controls on community and ecosystem structure and function.

Precipitation is a dominant driver of ecosystem processes, with mean annual precipitation of about 250 mm, 60% of which occurs during the North American Monsoon (July–September). Multiyear droughts recur every 50 to 70 years. High light and low relative humidity favor soil drying, and biotic activity occurs in bursts following precipitation

FIGURE 1.19 The Blue Grama Meteorological Station (foreground) on the Sevilleta Long-Term Ecological Research site, looking east toward the Lost Pinos Mountain Front. (Photo courtesy of Doug Moore, the Sevilleta Photo Archives, and the National Science Foundation.)

events. Studies of pulse dynamics have addressed the effects on soils, nutrient cycling, vegetation structure, and species interactions among habitats and across biome transition zones, and have emphasized long-term manipulative experiments.

Shortgrass Steppe (SGS)

This site (http://www.sgslter.colostate.edu/) was established on a foundation of research data and infrastructure produced by the US Department of Agriculture (USDA) in 1939 and the International Biological Program (1968–1974), and was a member of the LTER network from 1982–2014. Research at the SGS site sought to understand how climate, natural disturbance, physiography, and human activities in the shortgrass steppe drive structure and processes within the ecosystem (Figure 1.20). Monitoring campaigns, manipulative experiments, and models were used to study population and community dynamics of plants and animals, conceptualize and measure nutrient cycling, and identify important drivers in the system. Core field studies were conducted on the USDA–ARS Central Plains Experimental Range in Nunn, Colorado and expanded to sites within the Pawnee National Grassland of the US Forest Service and Great Plains region.

SGS (1538 ml) encompasses 63 km^2 of low hills, broad valleys, and ephemeral streams. The climate is semiarid with a mean annual temperature of 8°C and 340 mm of precipitation per year. Approximately 70% of the precipitation falls during the growing season (April–September), with high variability in amount and location. The site is dominated by short grasses (64%), succulents (21%), and dwarf shrubs (8%). Blue grama *(Bouteloua gracilis)* predominates and contributes 60% to 80% of plant cover and net primary productivity. The disturbance regime includes a long history of grazing by large herbivores, periodic drought, and infrequent fires. Over time, intense selection by grazing and drought has created an ecosystem with low-standing vegetation and biological activity and organic matter concentrated below-ground. Currently, grazing by domestic livestock is the primary

FIGURE 1.20 Panoramic view of the landscape from the top of Owl's Peak in the Central Plains Experimental Range (the Front Range of the Rocky Mountains appears in the background) that represents typical habitat in the Shortgrass Steppe Long-Term Ecological Research site. (Photo courtesy of John Moore.)

use of native grassland, which occupies about 60% of the shortgrass steppe, but row-crop agriculture, energy development, and urbanization continue to increase as land uses.

Virginia Coast Reserve (VCR)

The VCR (http://www.vcrlter.virginia.edu/) became a part of the LTER program in 1987 with a mission to understand how long-term changes in climate (storms, temperature), sea level, and land use affect the dynamics and biotic structure of coastal barrier systems and the services they provide to humans. VCR extends over 110 km on the eastern shore of Virginia from the Maryland border to the mouth of the Chesapeake Bay, and is characteristic of coastal barrier ecosystems along much of the Atlantic and Gulf Coasts (Figure 1.21).

The coastal barrier landscape is heterogeneous and extremely dynamic, with barrier islands, shallow lagoons with extensive tidal flats, tidal marshes, and mainland watersheds. Transitions between ecosystems can be abrupt with threshold responses to external drivers. Some ecosystems show inherent bistability, which means that they have two alternative stable states. The islands of VCR are among the most dynamic in the United States; lateral accretion and erosion rates are as high as 40 m per year—the highest along the mid-Atlantic seaboard. The shallow seaward slope of the landscape (< 0.1%) makes it a particularly sensitive location for studying responses of intertidal marshes to sea-level rise, which, at 4 mm per year, is the highest along the Atlantic Coast. The maritime temperate climate has temperatures ranging from 1° to 31°C, and receives circa 1100 mm of precipitation that is distributed fairly evenly across the year. Long-term storm records indicate that storminess has increased since the late 1880s, with about 15 extratropical storms per year hitting the VCR. At the turn of the twentieth century, the barrier island and lagoon system supported one of the most prosperous farming and fishing communities in the country. Towns on the islands were abandoned after the Great Storm of 1933, and the scallop fishery collapsed with the loss of seagrass around the same time.

FIGURE 1.21 Aerial photograph of the coastal barrier landscape that represents the ecosystems of the Virginia Coast Long-Term Ecological Research site. (Photo courtesy of John Porter.)

Restoration during the last decade has resulted in more than 1800 ha of healthy seagrass meadows, which once again support scallops.

NETWORK DYNAMICS

The LTER network was relatively stable prior to 2014. At that time, it had been 23 years since a site was lost from the network, 10 years since a site had been added to the network, and 17 years since the Network Office had moved from one hosting institution to another. As a consequence of recent events, the site composition of the LTER network has become quite dynamic, as has the structure by which it is organized to facilitate cross-site comparison, integration, and synthesis. A number of events illustrate this dynamism. At the end of 2014, the Shortgrass Steppe LTER site was no longer funded by NSF. Similarly, the Sevilleta LTER site learned in 2015 that it would not be renewed for funding by NSF. In response to the reduced size of the network and opportunities for expansion in marine systems, NSF recently (2016) issued a call for proposals to establish three new sites, two with a focus on ocean or coastal ocean ecosystems, and one with a focus on arid or semi-arid ecosystems. In addition, NSF did not renew the LTER Network Office at the University of New Mexico (funding expired in 2015). Rather, NSF issued a new solicitation for an LTER National Communications Office, charged with (1) coordinating research, education, and outreach activities across the network; (2) facilitating network governance; (3) fostering communication among LTER sites and with the broader scientific community; (4) promoting the dissemination of information and resources among LTER sites and to additional stakeholder communities; (5) organizing meetings and workshops; and (6) advancing the LTER program both nationally and internationally. The National Center for Ecological Analysis and Synthesis at the University of California Santa Barbara, was selected in 2015 by NSF to lead the network in these endeavors.

ACKNOWLEDGMENTS

We sincerely thank J. N. Caira and B. T. Klingbeil for producing Figures 1.1 and 1.2, respectively. We are also grateful to S. J. Presley, A. R. Sjodin, and B. T. Klingbeil for helpful comments on earlier versions of the manuscript. The principal investigators (see websites listed in site descriptions) of the various LTER sites that are included in this book provided commentary that improved site descriptions and assisted in securing representative photos of the sites. Finally, we gratefully acknowledge support from the NSF LTER program (grants DEB-0620910 and DEB-1239764). In addition, M. R. Willig was supported by NSF grant DEB-1354040 to the University of Connecticut, and L. R. Walker was supported by a sabbatical from the University of Nevada Las Vegas.

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