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The Challenges of Long Term Ecological Research: A Historical Analysis

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Chapter 8
How LTER Site Communities Can Address Major Environmental Challenges

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Abstract Long-term, place-based research programs in the National Science Foundation-supported Long Term Ecological Research (LTER) Network have had profound effects on public policies and practices in land use, conservation, and the environment. While less well known than their contributions to fundamental ecological science, LTER programs' commitment to serving broad public interests has been key to helping achieve their mission to advance basic science that supports society's need to address major environmental challenges. Several attributes of all LTER programs are critical to these accomplishments: highly credible science, strong site-level leadership, long-term environmental measurements of ecosystem attributes that are relevant to the public and to resource managers, and effective and accessible information that supports sound management practices. Less recognized attributes of three case study LTER sites (Andrews Forest, Harvard Forest, Hubbard Brook) which have contributed to major impacts include strong interdisciplinary research communities with cultures of openness, dispersed leadership within those communities, a commitment to carry science perspectives to society through multiple governance processes, strong public-private partnerships, and communications programs that facilitate the exchange of information and perspectives among sci-

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ence communities, policy-makers, land managers, and the public. Taken together, these attributes of sites drive on-the-ground outcomes. These case studies reveal a virtue of the long-term nature of LTER not anticipated when the program began: that the decades-long engagement of a place-based, science community can have a major impact on environmental policies and practices. These activities, and the cultivation of science communities that can accomplish them, go beyond the initial directives and review criteria for LTER site proposals and programs.

Keywords LTER program · Long-term ecological research · Acid rain · Ecosystem experiments · Environmental legislation · Environmental policy · Forest ecology · Forest management · Interdisciplinary research

8.1 Introduction

The US Long Term Ecological Research (LTER) Program has grown and evolved dramatically since its inception in 1980. In an era of short-term, single-investigator projects, the National Science Foundation (NSF) initiated a large-scale, pioneering experiment to understand key ecological processes and their interactions that unfold over decadal scales. The NSF launched this novel approach to environmental science by doubling the duration of single grants (from about 2 to 3 years to 5 to 6 years with potential for renewal), encouraging longer-term research planning with expectation of greater interdisciplinary scope and collaboration, promoting inter-site work, assuring continuity of leadership, and demanding a high level of attention to data management and sharing (see Jones and Nelson, Chap. 3, this volume). The LTER program has been fulfilling its initial objectives of establishing long-term experiments, collecting ongoing measurements, developing and applying models, interpreting long-term observations and results, and conducting synthesis across five core research themes (disturbance patterns, primary productivity, mineral cycling, organic matter cycling, and population studies). Over the past several decades, the network of LTER sites has grown in number, disciplinary scope, types of ecosystems studied, and support across NSF divisions (Jones and Nelson, Chap. 3, this volume). At the core of LTER are the individual site-based programs run by communities of scientists, students, support staff, and collaborators such as public and private land manager and land trust partners, foundations, and even artists. Cross-site meetings, research and synthesis, organized and coordinated through initiatives from groups of sites and through a Network Office, have facilitated network cohesion and identity. LTER has had sufficient success to stimulate government funders, science communities, and institutions in about 40 other countries to establish their own LTER-like programs and participate in a network referred to as International LTER (Vanderbilt and Gaiser 2017). These accomplishments have made LTER NSF's longest running program other than graduate research fellowships.

Over its 40-year history, the US LTER program has also exerted a profound impact on formal and informal education and on public outreach, as documented in the histories of individual programs (e.g., site synthesis volumes in the Oxford Press series) and in several multi-site syntheses (e.g., Colman 2010; Driscoll et al. 2012). In particular, LTER has had notable success in delivering science information to decision-makers and a broad public audience, consistent with the requirement for "broader impacts" in the NSF evaluation criteria. The sustained long-term nature of the LTER site research communities allows for greater impacts than programs funded by a kaleidoscope of short-term grants (Hughes et al. 2017). LTER communities provide (i) conceptual frameworks for exploring the coupled nature-human system in an increasingly human-dominated world, (ii) improved environmental literacy of the engaged public, (iii) information about plausible futures for ecosystems and the environment through modeling and scenario analysis, (iv) well-managed, readily-accessible, long-term environmental data for future use in addressing issues challenging society, and (v) insights into landscape vulnerability and resilience to global change (Robertson et al. 2012). These tasks require continuity and strong, lasting partnerships; the mission and sustained funding of the LTER program support those qualities at a site and network level.

All LTER sites must accomplish substantive broader impacts to maintain their program funding, but several sites have had distinctive, major, direct impacts on environmental issues at regional and national scales. Three examples of major impact are reviewed here: Hubbard Brook's work on the effects of air pollution on terrestrial and freshwater ecosystems, Harvard Forest's conservation program for the New England landscape, and H. J. Andrews Experimental Forest's role in regional forest conservation planning. In each case, we acknowledge the existing site strengths and research programs that made these impacts possible and the pre-LTER roots of the site that established the basis for taking on the issues, but we also explore and highlight several critical but less known features. We pay particular attention to the confluence of attributes of these LTER sites that made the major impacts possible: attributes of the LTER program community itself; its science program; the major environmental issues it addressed; the "governance" systems in which the impacts played out; formation of partnerships that facilitate connections with society; and communications systems directed toward policy-makers and the public. In this context, the term *governance* refers to formal and informal processes through which public and/or private individuals and institutions can guide policies and actions concerning the environment. For example, governance includes public policy channels through which science can inform land-use planning and the management or regulation of environmental quality. This overview is undertaken in part to highlight some notable accomplishments by these particular sites and the whole LTER program. The larger purpose of this chapter is to identify the distinctive qualities of these individual research programs in the hope that this will aid other institutions, research communities, the LTER network, and NSF leadership in their administrative and management decisions moving forward.

8.2 Case Examples

The commonalities and differences among these cases are instructive. In order to highlight these and facilitate comparison, the case studies follow a parallel structure. Each begins with a brief review of the pre-LTER context of the site and program, the significance of each site's LTER programs in terms relevant to the major environmental issues addressed, and key features of the science emerging from the long-term research that influenced policy, planning, and execution of a path forward. This is followed by discussion of the governance context that was critical in connecting the site's scientists and their research findings with policy and management. Finally, we address special features of partnerships and communications programs that emerged in dealing with the big issues and have then persisted as channels for conversation between science communities and society on other topics.

We consider these cases with two important caveats: first, more complete description of the science involved and its connection with society are presented in greater detail elsewhere, and, second, in each case the issues are so vast that LTER science and research communities are only two of many factors in the process of dealing with big issues.

8.2.1 Hubbard Brook Ecosystem Study, LTER Program, and Experimental Forest

Perhaps the prime example of a long-term research site having a major impact on public policy is the story of the Hubbard Brook Ecosystem Study (HBES) and its role in the discovery and remediation of atmospheric deposition, or "acid rain" (Likens and Bormann 1977; Driscoll et al. 2001; Bocking 2016; Holmes and Likens 2016). This research is based on long-term studies conducted at the Hubbard Brook Experimental Forest in the White Mountains of New Hampshire. The Hubbard Brook is a 3519-ha experimental forest, established by the US Forest Service in 1955 as a center for forest hydrology research in New England. In keeping with the research methods of nearly a dozen other Forest Service sites, paired-watershed experiments were established for the study of forest hydrology (streamflow gauging at Hubbard Brook started in 1956). That watershed research approach prompted several professors at Dartmouth College, led by F. Herbert Bormann and Gene Likens, to realize that whole-ecosystem biogeochemistry research—the inputs, cycling, and outputs of chemical elements—could be piggy-backed on the small watershed hydrology study in what became known as the Hubbard Brook Ecosystem Study (HBES), commencing in 1963. The study advanced through a partnership of the academic scientists with Forest Service researchers led by Robert Pierce.

Although the term "acid rain" was first used in the mid-nineteenth-century in Britain, the first observations in North America were reported from Hubbard Brook, based on early measurements from the Hubbard Brook Ecosystem Study (Likens et al. 1972). (The simple yet evocative phrase "acid rain" conveys the notion that the rain that nourishes us can be fouled by acidity.) Thus, began a long and multifaceted engagement of the Hubbard Brook community of scientists with issues related to air pollution and biogeochemistry. The initial identification of acid rain at Hubbard Brook did not require long-term research, but the long-term studies, including those funded by LTER beginning in 1988, made it ultimately possible to track the cascade of effects of atmospheric pollutants through forest, soil, stream, and lake ecosystems and observe subsequent ecosystem recovery from declining pollution as policies regulating emissions were implemented. Hubbard Brook scientists have gone on to address other air pollutants, such as nitrogen, mercury, and carbon dioxide (Driscoll et al. 2001, 2003, 2007, 2012, 2015, 2016).

The Hubbard Brook Ecosystem Study and Hubbard Brook LTER had several important synergies; indeed, accomplishments of the HBES were used as support for NSF's decision to begin the LTER program in 1980. In his seminal paper introducing the LTER concept to the science community, for example, Callahan (1984, p. 363) cites Bormann and Likens' (1979) argument that long-term studies are essential for the study of "effects of atmospheric pollution, forest harvesting practices, and forest development cycles" on forest productivity. These early results emerged over the initial 20-year history of the HBES through a series of individual, short-term grants. At that initial stage of LTER development, and still four years before Hubbard Brook joined LTER, the benefits of the new LTER program were yet to materialize. As the HBES grew in thematic scope, facilitated substantially by LTER funding beginning in 1988, so too did the size and the disciplinary and institutional diversity of its community of researchers and educators. From its roots in hydrology and then biogeochemistry, the program grew to include studies of forest bird populations, tree community development and dynamics, organic matter budgets of streams, limnology, and many other topics. The LTER program has been an important means to both diversify and integrate the Hubbard Brook scientific enterprise, and integration has been particularly challenging with its researchers spread across many institutions and states and minimal senior academic science staff in residence at the site.

The core contribution of Hubbard Brook science in characterizing and understanding effects of air pollution was to reveal broad yet nuanced interpretations of complex effects throughout the ecosystem and over time. The supporting science included tracing the inputs, transport and fate of atmospheric contaminants through the forest canopy, soils, streams, and into lakes, as well as examining their cascading effects on plant, soil and microbial processes. Environmental monitoring was a foundational component of the work, which was complemented by process studies, the development and application of models (Gbondo-Tugbawa et al. 2001), innovative whole-watershed experiments (Peters et al. 2004), and other approaches. A critical dimension was to view ecosystem effects of air pollution in the context of other drivers of environmental change, such as climate variability and loss of species to species-specific pests and pathogens.

The national and regional discourse on air pollution and its effects provided the opportunity for Hubbard Brook science to impact federal policy. Well before the seminal 1970 amendments to the Clean Air Act, many elements of federal and state government involved in air and water pollution issues were informed by research from Hubbard Brook. Over the decades Hubbard Brook researchers and science have interacted with all three branches of the Federal government: the legislative process included amendments to the Clean Air Act, administrative rules were promulgated to reduce air pollution, and the judiciary enforced compliance (Driscoll et al. 2011). As intense political disputes about amending the Clean Air Act unfolded, the credibility of "high-quality, long-term data on precipitation and stream water chemistry helped ward off aggressive attacks from various science deniers and vested interests" (Holmes and Likens 2016, p. 216).

In 2012, Hubbard Brook joined with three other LTER sites (Harvard Forest, Plum Island Sound, Baltimore Ecosystem Study) and five other institutions to form the Science Policy Exchange (SPE) to promote the use and synthesis of long-term observations and ecosystem science in science translation and to inform initiatives on energy, land and water policy. The mission of the SPE is to promote the use of long-term observations and science in environmental policy decisions consistent with their mission "to harness the power of science to generate environmental solutions for people and nature." Another critical, if informal, aspect of the SPE has been contacts between scientists with members of the media and with individuals in state and federal agencies and non-governmental organizations (NGOs). Some of these relationships have been sustained over many years, and they remain vital in the ever-changing social and political environment.

Science communications from the HBES began with the prolific publication of articles in scientific journals and the synthesis of findings in landmark books on biogeochemistry and forest dynamics (Likens and Bormann 1977; Bormann and Likens 1979). But as the magnitude and increasing threat of air pollution in the form of acid precipitation became more apparent, an effort was made to synthesize and translate the science on effects at Hubbard Brook and regionally (Driscoll et al. 2001) and to use models to project ecosystem response and recovery in various emission reduction scenarios (Chen and Driscoll 2005). As public attention to the issue grew, venues for communication reached the highest levels of government, including a briefing of President Reagan and numerous Congressional hearings, contributing substantially to the 1990 Amendments to the Clean Air Act of 1970 (Holmes and Likens 2016, p. 216) and to other air quality management policies such as the Cross-State Air Pollution Rule, the Mercury and Air Toxics Standard, and the Affordable Clean Energy Rule. The initial effort and success in engaging in science communication prompted the HBES to institutionalize their outreach program through a series of reports collectively called *Science Links*, produced through the Hubbard Brook Research Foundation since 1998 (Driscoll et al. 2012). The Science Links reports are developed by interdisciplinary teams of scientists and policy advisers who frame policy-relevant questions and analyze alternatives in text and illustrations suitable for a readership of policy-makers and journalists. These seminal publications were accompanied by outreach to the public via op-ed pieces in major national print media, extensive media coverage, and presentations to civic and professional groups in order to more effectively affect policy shifts. Many lines of evidence attest to the success of this communications program, including numbers of citations in the scientific literature, quantity and quality of media coverage, and reference to Science Links reports in drafts of legislation (Driscoll et al. 2011).

8.2.2 Harvard Forest and its LTER Program

Harvard University established the Harvard Forest in north-central Massachusetts in 1907 as a center for forest and forestry research, education, and demonstration (Foster and Aber 2004). A central theme for the research, education, and outreach programs at the Harvard Forest was the trajectory and consequences of the four-century history of human land use involving European settlement, deforestation, and agricultural development (ca. 1650–1850) that dramatically reduced the nearly-complete regional forest cover, followed by the progressive expansion of forest cover in the wake of farmland abandonment, industrialization, and urbanization. Incredibly detailed dioramas in the Fisher Museum at the Harvard Forest depict this history of landscape dynamics and the resiliency of the forests in the face of sustained environmental degradation. These dioramas, as well as stonewalls, the former farmland fence lines that run through the region's forests, remind all who visit or work at the Forest that the modern landscape is strongly conditioned by its past and that ongoing recovery from that history will strongly control every ecosystem's future. During the pre-LTER period, much of the research by Harvard Forest staff centered on silviculture, forestry and forest ecology, and related studies of soil properties and processes and wildlife, on the Forest's 1200 hectares and more broadly across southern and central New England.

Upon entering the LTER network in 1988, Harvard Forest greatly expanded its research portfolio of major processes shaping forest ecosystems by establishing large, long-term, ecosystem experiments concerning hurricane damage to forests, climate change and soil warming, and nitrogen deposition from air pollution (Foster et al. 2014). The establishment of one of the first forest-based eddy flux towers initiated what has become the world's longest running record of exchanges between the atmosphere and a forest ecosystem. Research on environmental history and prehistory intensified, using archival, paleoecological, archaeological (of both indigenous and European peoples), and even literary sources (Foster 1999). Despite the differences in cultures between experimentalist and historical researchers, synergies emerged early in the twenty-first century when it became clear that land-use history provided an indispensable foundation for the interpretation of the modern landscape and results emerging from experimental ecosystem studies. The legacies from the history of land use and natural disturbances shaped the landscape with enduring consequences for ecosystem structure and function (Foster and Aber 2004).

The understanding of long-term landscape change also helped to galvanize a vision for the future of the region's forests. Among the many components of the Harvard Forest portfolio of research and outreach activities, the Wildlands and Woodlands regional conservation strategy stands out as exerting a growing influence on regional policy and management. This program, grounded in LTER science and environmental history, was a response to residential and urban sprawl into rural forest and farm lands that by the late twentieth century had reversed the century-long expansion of forest cover across all New England states (Foster et al. 2014). This conservation strategy was first applied to Massachusetts, with the goal of permanently protecting 50% of the state in forest cover (Foster et al. 2014).

The Wildlands and Woodlands vision comprises two major components: "wildlands", large forest reserves covering about 10% of the conserved forest area, which sustain landscape-scale ecological process in the absence of active management, and expansive "woodlands" across the remaining 90%, in which sustainable forest management is encouraged for a diversity of private and public objectives. Harvard Forest scientists built their case on the dynamic and resilient properties of New England's forests and the "illusion of preservation," the argument that strongly protectionist policies in populated regions with intensive resource use and resilient ecosystems, like New England, can displace the environmental impacts of resource production to more pristine and vulnerable ecosystems elsewhere in the country or globe (Berlik et al. 2002; Foster et al. 2014).

The Wildlands and Woodlands vision gained traction following its initial application to Massachusetts in 2005 (Foster et al. 2005) and was widely endorsed at a state level. With growing support by conservation groups, active involvement of leading scientists across the region (including many LTER collaborators and the two principal investigators of the Hubbard Brook LTER), and major collaboration from the Highstead Foundation and New England Forestry Foundation, the Wildlands and Woodlands program was expanded to the forests within the six New England states (Foster et al. 2010), and then expanded further to include the entire landscape, including farmlands and associated communities (Foster et al. 2017).

Wildlands and Woodlands is founded in the recognition that, although New England is one of the nation's most densely populated (> 15 million people) and economically thriving regions, it is also the country's most heavily forested area (81% forest cover; 7% farmland, 10% developed area). It therefore has the potential to support much more strategically focused development and land conservation activity in ways that will conserve the bulk of its forest and farmland to support both nature and society. The vision's regional goal for 2060 is to conserve approximately 80% of the region: 70% of it as intact forest (63% woodlands and 7% wildlands), 7% as agricultural land, and the rest as other semi-wild lands (wetland, water, etc.). Since 2010, protected forest has increased from 22 to 26%, but forest conversion by development continues to proceed at a rate of 9700 ha a year and wildland reserves remain less than 1% of the landscape (Foster et al. 2017). The regional vision has spawned an integrated network of regional conservation partnerships, expanded capacity focused on conservation finance, and recognized the role of well-managed forests and farmlands in providing conservation infrastructure that supports human health and well-being. These advances also represent a more strategic linkage between academic research and policy and management needs.

Wildlands and Woodlands, and its strong private and public partnerships and linkage of basic research to conservation applications, has become an increasingly important element of the *broader impacts* in the Harvard Forest LTER program over the past three funding cycles. LTER science has helped leverage significant funding from other NSF grants and programs (e.g., Research Coordination Network and Coupled Natural and Human Systems) and private foundations, thus providing the scientific input needed for extensive stakeholder engagement and outreach to policy and decision makers. Harvard Forest Director and LTER Principal Investigator David Foster has been the central catalyst and leader of both efforts, but the breadth of topics and lists of co-authors make clear that a large, diverse, collaborative group of colleagues—forest and landscape ecologists, policy specialists, environmental historians, biogeochemists—from many institutions has figured prominently throughout. In the formative steps of Wildlands and Woodlands, this Harvard Forest community identified a critical regional issue, laid the conceptual framework for addressing it, mapped a conservation strategy for the region, and began to pursue a solution, including working with state government and land trusts. A distinctive contribution of the LTER program has been co-designing future scenarios of land change with hundreds of diverse stakeholders from throughout New England, and then evaluating their consequences for people and nature using ecosystem models developed using LTER science. By using a participatory process for scenario creation, the scientists improve the relevance and maximize the uptake of the results (Thompson et al. 2012, 2014, 2016; McBride et al. 2017, 2019).

The governance of regional conservation strategies set in a predominantly private lands context, such as Wildlands and Woodlands, involves navigating a challenging blend of governmental (mainly municipal and state level) and private entities (e.g., land trusts and other conservation enterprises) (Foster et al. 2014). The New England setting puts a premium on development of institutional partnerships and social networking to carry findings from long-term ecological research into the public sector. A critical step has been partnering with the Highstead Foundation, which supports Regional Conservation Partnerships comprised of 42 groups of partnerships and land trusts covering 60% of the New England region (Labich et al. 2013; Foster et al. 2017). Broadly, Wildlands and Woodlands seeks to advance the success of partner organizations as they advance conservation either through the direct purchase of land or, increasingly, by securing conservation easements on private land parcels, often in collaboration with state and federal agencies, private foundations, and individual philanthropic support. Harvard Forest's partnership activities extend beyond Highstead Foundation to include teaming up with Hubbard Brook and other institutions such as the New England Forest Foundation and as a founding partner of the New England Science Policy Exchange to promote the use of long-term observations and science in land policy decisions (Templer et al. 2015; Lambert et al. 2018).

Through much of the twentieth century, the Harvard Forest community had a rather traditional communications program that included scientific publications and various forms of reports in many cases aimed at local audiences of the general public, small woodlot owners, and foresters. And, of course, the Fisher Museum collection of dioramas and other displays concerning forest and land history gave visitors distinctive learning opportunities. With the development of research topics of broad significance and interest during its LTER era, Harvard Forest's communication efforts diversified greatly to include editorials and various forms of reporting in major regional and national outlets, the special communications of the Wildlands and Woodlands reports, and arts/humanities programs, including installation art exhibits in the forest and on campus (Leigh et al., Chap. 11, this volume). A collection of beautifully illustrated and engagingly written books has found a wide readership. More recently, the Schoolyard LTER program has incorporated a module on forest and landscape dynamics to integrate some of the historical, ecological, and conservation perspectives of Wildlands and Woodlands into the classroom for some 6000 students across Massachusetts and adjoining states.

8.2.3 H.J. Andrews Experimental Forest LTER Program

The H.J. Andrews Experimental Forest is well known for its science-rooted role in the major forest policy shift in the 1990s to stop logging of old-growth forests on the extensive Federal lands of the Pacific Northwest (Johnson and Swanson 2009; Spies and Duncan 2009; Colman 2010; Robbins 2020). Ironically, this Forest Service experimental forest (originally named Blue River Experimental Forest) had been established in 1948 for use in applied studies to support conversion of the native forest, notably old growth, to intensively-managed tree plantations. With the inception of the NSF funding of the International Biological Program (IBP) at Andrews Forest in 1969, academic ecosystem scientists joined Forest Service researchers in intensive, basic, multi-disciplinary investigations of forests, streams, and whole watersheds. Forest Service scientist Jerry Franklin and Oregon State University professor Dick Waring teamed up to lead the group during the IBP era, and Franklin continued to lead into the LTER period beginning in 1980. Blending applied forestry and watershed research with basic ecosystem science, since 1970 the program has been managed jointly by the US Forest Service's Pacific Northwest Research Station, Willamette National Forest, and Oregon State University working in tight partnership at the research-management interface. Franklin's leadership in the site's participation in IBP and then LTER, and his role in the inception of LTER as a whole, including a stint as a program officer at NSF in the early 1970s and later as coordinator of the LTER Network while he was a professor at University of Washington, all proved vital in advancing long-term ecological research globally.

The trajectory of Federal forestry issues in the Pacific Northwest both influenced and was influenced by the Andrews Forest program from the start of the Timber Era at the end of World War II through its transition to the present era emphasizing biodiversity on Federal land forests of the Northwest. In accord with the founding charge to help guide development of the Federal forestry program, logging and road construction in the experimental forest proceeded during the 1950s and 1960s. Applied studies by US Forest Service scientists addressed effects of forest operations on plants, animals, soil, and watershed processes, especially streamflow and water quality. This set the stage for IBP ecosystem research of the 1970s to inadvertently reveal salient features of old-growth forests and for a solitary Oregon State University M.S. student, Eric Forsman, to begin his career-long investigations of the preference of northern spotted owl (*Strix occidentalis caruina*) for that habitat and the progressive decline of their numbers. The IBP directive was to study the native forest ecosystem; it happened to be old growth in the Andrews Forest, because of the mid-1940s decision to locate the research property where there was extensive old growth in order to study its liquidation. A published synthesis of 1980-vintage knowledge of old growth (Franklin et al. 1981) and the emerging understanding of the spotted owl prompted environmentalists to work over the 1980s to achieve an injunction in 1990 to stop logging in the 10 million ha of Federal lands in the range of the spotted owl from San Francisco to the Canadian border. The injunction was not lifted until a team of scientists, including many from the Andrews Forest program, crafted the foundation for the Northwest Forest Plan (NWFP) (Duncan and Thompson 2006; Robbins 2020).

As with Hubbard Brook and Harvard Forest, participation in LTER proved critical in sustaining and expanding a diverse, interdisciplinary community of academic and federal science personnel at the Andrews Forest. Existing long-term studies of vegetation dynamics and watershed processes could be extended with LTER support and new topics added. Entirely new experiments were undertaken, such as Mark Harmon's monumental 200-year log decomposition experiment, which became a stage for public discussion of future management of dead wood on land and in streams in terms of habitat, carbon dynamics and sequestration, soil fertility, fuels for wildfire, and other topics. Regional networks of forest plots, remote sensing studies, and landscape modeling have been used to assess past and alternative future forest change in response to land use, wildfire, and forest growth (Thompson et al. 2012).

The governance context of change in Federal forest policy in which Andrews Forest scientists participated involved all three branches of government and a variety of formal and informal venues over time (Swanson 2004; Johnson and Swanson 2009). For example, findings from IBP and LTER science of forest-stream interaction research found their way into management policy and practice at the scale of local collaborations between researchers and Ranger District staff concerning timber sales, at the scale of the 700,000-ha Willamette National Forest as it developed its management plan of 1990, and across the entire Pacific Northwest though the Northwest Forest Plan. The original basic-science work on old-growth forests and streams influenced the arc from a Federal policy of old-growth liquidation through to its protection in the Northwest Forest Plan in the mid-1990s with many governance instruments along the way. The intensity of conflict over old growth drew global attention, stimulating conservation efforts and calling for consultations in places (Tasmania, Taiwan, Scandinavia) where very different governance contexts prevailed.

A long-standing partnership between scientists and land managers and a sustained culture of close cooperation between academic and agency scientists have been central to the capacity of the Andrews Forest program to participate in these processes (Swanson et al. 2010). These relationships are institutionalized in part in a funded Research Liaison position and in regular monthly meetings. The intensity of public issues waxes and wanes, and the topics shift with time, but the partnership has persisted for decades.

The communications portfolio of Andrews Forest scientists and science along this trajectory represents its diversity of roles in public decision-making concerning forests and watersheds. Scientists offered suggestions about ways to mitigate impacts of forestry operations, beginning with the first researchers stationed at the Andrews Forest (e.g., Timberman 1957). In the 1970s, basic science revealed the incredible richness and complexity of native forests, especially old growth, at a time when it was derisively referred to as a “biological desert,” “decadent,” and “over-mature” (Johnson and Swanson 2009). During the 1980s, as the “Old-growth War” unfolded, and more recently, scientists and their findings were featured in the *New York Times*, coffee table books with evocative writing and photography, books for a general readership, and many other venues for public outreach, including the arts and humanities (e.g., Kelly and Braasch 1988; Luoma 2006; Brodie et al. 2016). Applied studies of impacts of forestry operations on watersheds and ecosystems, and the resulting publications, were used extensively in challenges to continued logging.

Scientists presented interpretations of the past, present, and possible future states of the environment to leaders in the legislative and executive branches of government, including President Clinton in his Forest Summit in April, 1993. Central features of the IBP and LTER eras of ecosystem science--forest-stream interactions, roles of dead wood in terrestrial and aquatic ecosystems, forest succession following disturbance by fire and logging, watershed processes, biodiversity of the major components of the ecosystem, landscape dynamics in response to fire and flood—all found a place in the regional conservation strategy, the Northwest Forest Plan (e.g., Harmon et al. 1986; Gregory et al. 1991). Andrews Forest scientists had many forums to communicate: Congressional hearings, NAS-NRC committee reports, National Forest planning processes, as well as the one-of-a-kind NWFP processes. Science discoveries have been delivered to a wide readership, including Congressional staffers, through the Pacific Northwest Research Station’s *Science Findings* and *Science Update* print and digital communications. Some LTER experiments, such as Mark Harmon’s 200-year log decomposition experiment, have come to symbolize the commitments of scientists and land manager colleagues to long-term learning and adoption of new information. Messages about the science and these commitments to learning have been conveyed during the hundreds of field tours that serve as forums for discussion of the future of the forest.

8.3 Discussion

These case studies reveal features of all LTER site programs that create the potential for research and activities at LTER sites to have important impacts on major, societally-relevant environmental issues. Several up-front, intrinsic properties stipulated in requests for proposals of all LTER sites facilitate their capacity to contribute (Jones and Nelson, Chap. 3, this volume). First, the five core areas of LTER research direct sites to address key components of the environment, which are commonly central to big environmental challenges. Second, this research charge from NSF requires LTER site communities to have specialists in a wide range of disciplines to address environmental topics of interest and concern to the public. Third, NSF requires these science communities to operate a conceptually integrated research program which is reviewed by NSF-designated panels every three years to affirm this integration (i.e., at times of grant renewal and mid-term review). Consequently, over the past 40 years, these required features of LTER programs have produced strong science communities that are actively engaged in societally-relevant environmental issues to varying degrees.

Another feature common to many of the early sites to enter the LTER network is a deep, highly relevant pre-LTER history, which was important in the site's selection to join the LTER network. For example, the framework of long-term monitoring of precipitation and surface water hydrology and chemistry, along with the penchant of the Forest Service for establishing experimental watershed studies long before LTER was established prepared research communities in the culture and practices that are critical to successful long-term ecosystem research, including data management. Therefore, it is not surprising that several Forest Service sites--H.J. Andrews, Bonanza Creek, Coweeta, Hubbard Brook Experimental Forest, and Luquillo Experimental Forest—are or were part of the LTER network. In some cases, participation in the International Biological Program during the late 1960s and 1970s prepared site communities to successfully compete in calls to join the LTER network by giving them a decade head start in long-term, interdisciplinary ecosystem research.

As LTER sites have matured, they have acquired key characteristics that positioned them to make the big step to addressing major environmental issues. A strong background of highly credible science and records from many types of environmental monitoring that are relevant to emerging issues lends credibility and brings value-neutral information resources to public deliberations. For a site to effectively contribute on important issues over the long term, strong site leadership at the top has to be complemented by strong distributed leadership among the disciplines and institutions within the communities. Members of site communities must be able to articulate a strong sense of the history of past environmental conditions and prospective future conditions across their home bioregions. Key leaders in the site communities must be willing to participate in governance processes, even though they sacrifice time and resources that would otherwise go to traditional science activities that are rewarded in their home institutions (Lach et al. 2003). As big issues emerge and evolve, it is important for a site community to be ready, receptive, and adaptable to take on new, emergent science questions, such as assessing outcomes of alternative futures or the actual responses of an ecosystem to efforts to deal with the issue. Adaptive science is an integral part of adaptive management processes that are commonly an implicit part of addressing big environmental issues.

Emergence and persistence of an issue and the relevance of that issue to an LTER program occurred in similar ways across the three cases. In each case, a lingering regional problem festered, site science was highly relevant, and a science community with strong leadership stepped forward with willingness to participate in the often-messy governance processes. As a first step, site scientists clearly and with authority called out the issues: Hubbard Brook science showed that elevated air pollution was affecting forests and waters; Harvard Forest research revealed that urban and rural sprawl had reversed a 150-year trend of forest expansion and recovery throughout the New England landscape, and Andrews Forest science characterized the complexity and diversity of old-growth forests. Once a site community engaged with an emerging issue, the scope of relevant science expanded as did the scope and demands of the governance processes, such as providing science input to policy-makers.

These cases provide a small but diverse sample of possible governance contexts in which LTER sites exist. The Hubbard Brook case of air pollution played out in the national legislative, judicial and executive arenas, resulting in modification of a highly influential federal law (the Clean Air Act) directly affecting the entire country. The Andrews Forest case of contributing to the development of an ecosystem conservation strategy was regional in its biological and policy scope; but it rose to the national political stage with a federal judge's injunction stopping logging on National Forest and Bureau of Land Management lands throughout the vast Pacific Northwest region, and then the executive branch stepped in to develop the Northwest Forest Plan when Congress would not enact a solution. This case stimulated interest and actions to protect old native forests in other parts of the world. Harvard Forest's Wildlands and Woodlands regional forest conservation strategy takes place in a dominantly private landownership context, so "governance" must be more a bottom-up than a Federal top-down approach and must be carried out through individual landowner decisions, land trusts, and local or state-level governance mechanisms of policy and practice.

The full suite of LTER sites operate in a wide array of governance settings, raising interesting issues about the potential for LTER science impacts on major issues. Urban sites, for example, are in densely populated human landscapes with complicated governance contexts. Some of the polar sites, on the other hand, are in areas nearly devoid of human residents, yet their subject matter has profound significance to global change and governance. Despite this great difference in proximity to population centers, the potential for big impacts may be more a matter of the alignment of research themes, societal-relevant issues, and systems of governance that can connect the science with society.

A critical feature of engagement in governance processes is that it is a two-way street of communication; generally, scientists are learning throughout the process, and do not serve simply as providers of data and information (Lach et al. 2003). Conversations with land managers, state and federal agency personnel, and NGOs not only inform decisions and actions in land and resource management but also provide perspective for new site science to address important management questions.

These case studies reveal a value of the long-term nature of LTER not anticipated when the program began—decades-long engagement of a place-based science community with environmental issues can have major impact. Each of these efforts played out over several decades and continues today, despite the illusion of finality in the form of a culminating or landmark accomplishment, such as a piece of federal legislation or regulation or the publication of a regional conservation plan. Persistence of engagement has been very important, and LTER provided a necessary base of continuity. The extended tenure of LTER-based communities facilitates development of social networks with the public and policy-makers through a wide variety of formal and informal channels. The long intergenerational tenure common among scientists and other members of research communities at LTER sites facilitates long-term institutional memory, in contrast to the characteristic short-term memory of the political realm.

Partnerships with non-science entities are extremely important in connecting the science communities with society. For example, in the case of regional conservation strategies, partnerships with land management agencies (e.g., federal and state) and non-governmental land stewardship organizations (e.g., land trusts) can channel science information and perspectives to land management decision-making, and understanding of research needs back to the science community. Partner relationships forged during periods of social conflict persisted in some cases, because the science communities experienced their effectiveness and wished to channel other science findings into policy and practice. This is evident, for example, in the New England Science Policy Exchange involving Harvard Forest and Hubbard Brook. In the Andrews Forest case, the research-management partnership of the science community with the Willamette National Forest was staffed by a Research Liaison position charged with flow of information between the two communities and the two cultures and to society at large.

In all three case studies, the LTER site communities undertook new forms of communications essential to serving society more directly than traditional science communications. In terms of print media, all three sites issue attractive, color booklets aimed at public and policy-maker readers. The Hubbard Brook group, for example, launched *Science Links*, developed collaboratively by scientists and advisers to policy-makers. Harvard Forest has been reporting to a general readership on the Wildlands and Woodlands project at five-year intervals, and Andrews Forest has shared information via the *Science Findings* and *Science Updates* communiques of the Forest Service. A variety of other outreach engagements have been deployed, including field tours, workshops, opinion pieces in traditional and social news media, and sustained, one-on-one, informal relations with key contacts in policy, news media, and land management arenas.

In summary, important impacts occur when there is a confluence of science community capacity and an environmental issue for which that community and its LTER science has been relevant. These confluences have occurred in part because LTER scientists strive to communicate their science to broader communities of policy-makers, land managers, educators, students, and the general public. These self-selected participants have a commitment to the wellbeing of their home bioregion.

LTER site research and the careers of participants have now spanned a professional lifetime, so the accumulated wealth of knowledge and social networking are mature on topics of broad social relevance – air, water, climate, vegetation, animals, and use of natural resources. The well-known examples of major impacts outlined above show that big accomplishments are possible, but they require patience, flexibility, and willingness to sacrifice work on science objectives in order to participate in governance processes (Lach et al. 2003). Hopefully, these successes will encourage others to take on the challenge.

8.4 Looking Forward

Speculation about the future development of LTER-site communities in this regard is quite challenging, given their continuing evolution, the dynamism of big environmental problems, funding limitations for such efforts at the interface of science and society, and, above all, the funding future for long-term, place-based ecological science. Maintenance of adventuresome communities is not a review criterion in an NSF proposal; it is outside the scope of this NSF program. However, it is important for all involved—the communities themselves, administrators in their home institutions, NSF program officers, and reviewers of proposals and mid-term site reviews—to recognize the importance of community culture as LTER moves forward with generational change in leadership and participation within the LTER ranks. Engagement with the arts and humanities, an emerging feature of many LTER programs, may influence site community culture and the ability to reach a wider public (Swanson 2015; Leigh et al., Chap. 11, this volume). Clearly, this topic of LTER community connection with society deserves careful scholarship; the case study research sites discussed here have extensive archives that contain relevant resources.

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