Science and Society: The Role of Long-Term Studies in Environmental Stewardship

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Long-term research should play a crucial role in addressing grand challenges in environmental stewardship. We examine the efforts of five Long Term Ecological Research Network sites to enhance policy, management, and conservation decisions for forest ecosystems. In these case studies, we explore the approaches used to inform policy on atmospheric deposition, public land management, land conservation, and urban forestry, including decisionmaker engagement and integration of local knowledge, application of models to analyze the potential consequences of policy and management decisions, and adaptive management to generate new knowledge and incorporate it into decisionmaking. Efforts to enhance the role of long-term research in informing major environmental challenges would benefit from the development of metrics to evaluate impact; stronger partnerships among research sites, professional societies, decisionmakers, and journalists; and greater investment in efforts to develop, test, and expand practice-based experiments at the interface of science and society.

Keywords: boundary spanning, environmental policy and management, Long Term Ecological Research Network, science communication

The growing urgency and complexity of challenges to global sustainability demands new approaches for engaging the intellectual capital of expert communities worldwide. To meet this demand, the scientific and social-science communities must expand their capacity to work at the interfaces between ecological science and environmental policy, natural-resource management, and conservation. The need for stronger, more-reliable linkages between science and society is well documented in both popular media and the academic literature (e.g., Lubchenco 1998).

The US National Science Foundation (NSF) recognized the importance of translating the benefits of research for society by establishing its "broader impacts" review criterion in 1997. In 2002, the NSF's 20-year review of the Long Term Ecological Research (LTER) Network recommended that the LTER Network program assume a more powerful and pervasive role in informing environmental solutions at local, national, and international levels. In 2005, the Ecological Society of America (ESA) established the foundation for its Earth Stewardship initiative (Chapin et al. 2011) when it recommended that ecologists must play a greatly expanded role in communicating their research and influencing policies and decisions that affect the environment. It is critical for the LTER Network and for other ecosystem research programs to move beyond broad calls for action and to build deliberate and effective long-term relationships between ecological science and environmental decisionmaking. In this article, we illustrate, as do the other authors in this special section (e.g., Thompson et al. 2012 [in this issue]), the growing role that LTER is playing to enhance science engagement with local, regional, and national policy and management issues. To develop such programs, the scientific community needs to build experience and learn from practical examples of effective synthesis and integration of LTER to meet the needs of society. In this article, we present and discuss five case studies of work at the interface of science, policy, and management from forested LTER Network sites across the United States. We distill a set of common strategies, lessons, and recommendations for improving and expanding interface efforts to improve the ability to meet the grand challenges in environmental science of our time.

Effective science interface efforts

Although the integration of science and society is often viewed as a relatively narrow issue of a need for more and better science communication, programs that build stronger interfaces between science and society require attention to the full range of boundary-spanning activities, such as public engagement, decision-relevant synthesis, distillation of results, and science translation and dissemination, through

BioScience 62: 354–366. ISSN 0006-3568, electronic ISSN 1525-3244. doi:10.1525/bio.2012.62.4.7

a variety of media to meet the needs of diverse audiences (Cash et al. 2003, Driscoll et al. 2011). *Boundary spanning* refers to “practices and processes that facilitate bringing science and society closer together in order to produce ‘useful’ information—that is, information that is salient, credible, and legitimate” (McNie et al. 2008, p. 9). Building credibility, salience, and legitimacy with stakeholders helps to solidify long-term relationships and increases the influence of scientific research in the decisionmaking process over time (Cash et al. 2003).

The role of the LTER Network

After 30 years of coordinated research and education, the LTER Network is well positioned to facilitate the integration of science and society by using its highly credible, long-term science to support engagement with decisionmakers to frame relevant questions for research and synthesis that can inform environmental policy and conservation. The LTER Network consists of 26 research sites throughout the United States and a few outside the United States, some of which have been operating for three decades or longer. The long-term ecosystem measurements and experiments that are a hallmark of the LTER Network address important environmental issues in coupled human–natural systems, including climate change, land use, pollution, and the loss of biodiversity (Knapp et al. 2012 [in this issue], Thompson et al. 2012 [in this issue]). Another distinguishing feature of the LTER Network is its core of researchers at each site, who are attentive to the well-being and future of their respective bioregions.

The LTER Network’s new Strategic Communication Plan (LTER Network 2010a) and Strategic and Implementation Plan (LTER Network 2010b) call for the network to reach out to decisionmakers at local, regional, national, and international levels. The communication plan specifically recommends engaging decisionmakers in the framing of cross-site synthesis and equipping these efforts with full-scale communication capacity, funding a supplement program for LTER Network sites to develop local and regional programs for public engagement and outreach, and partnering with existing LTER Network sites that have established science journalism programs to develop sustained outreach to the media.

The value of long-term monitoring and research

Environmental policy and management issues play out over decades or longer and benefit from the continuous advances in understanding that are derived from long-term research. Policy development is an iterative process that requires ongoing assessment, reevaluation, adaptive management, and consideration of future scenarios (Driscoll et al. 2010). For example, although the Clean Air Act was first passed by Congress in 1972, the development of amendments and rules to implement the act are ongoing and rely on quantitative information to evaluate the effectiveness of pollution-control measures and to guide program management (Lovett et al. 2007). Long-term measurements that link decreases in emissions with changes in soil and water quality and the health of aquatic and terrestrial ecosystems are vital to assessing the extent to which air pollution regulations meet the intent of the act (Driscoll et al. 2001).

Similarly, effective natural-resource management is adaptive and draws on lessons from past decisions and management experience distilled from the results of long-term measurements and experiments, regional surveys, and modeling (Spies et al. 2010). The practice of forestry in landscapes that support multiple uses must adapt to new knowledge regarding the nature and effects of climate change, forest management, land-use trends, intense storms, fire, and other disturbances. This understanding must include the impacts of these often interacting pulse and press stressors on management goals and ecosystem services, such as fiber production, biological diversity, carbon storage, trace-gas production and consumption, water quantity and quality, and recreation. Detailed, long-term measurements tied directly to management-relevant forest experiments have improved the scientific basis for forest management and policy. Important examples include the guiding principles for the conservation of old-growth forests (Franklin et al. 1981) and regional- and continental-scale carbon budgets important to climate-change mitigation (Lovett et al. 2007).

The five case studies presented here represent examples of outreach activities at selected forested LTER Network sites. We chose this suite of case studies because they have active programs for engaging decisionmakers, represent a range of policy and management issues, and use different approaches to achieve their outreach goals for a common ecosystem type. Reviewing efforts across forest sites provides the opportunity to consider how audiences, management and policy issues, and communication approaches vary across diverse regional research sites and programs. Specifically, the case studies incorporate the impacts of atmospheric deposition on forested ecosystems (Hubbard Brook), land-use change and forest conservation in a predominantly private-lands landscape (Harvard Forest), endangered species and public lands management (Andrews), urban forestry in developed landscapes (Baltimore), and forest stewardship in the context of changing fire and climate regimes (Bonanza Creek). These case studies represent only some of the many science–policy integration efforts that exist across the LTER Network (for other examples, see the *Translating Science for Society* brochure at *http://intranet2.lternet.edu/sites/intranet2.lternet.edu/files/documents/Network_Publications/Brochures/nsf0533.pdf*). In each of these cases, the ability to tap into core strengths of the LTER Network, such as long-term research that is relevant to policy and management issues, advanced information-management systems, and stores of long-term data, has proven essential to the synthesis and distillation of science for use in policy and management decisions related to coupled human–natural systems.

Case studies in linking LTER science with policy, conservation, and management

Below, we describe several case studies that link LTER science with policy, conservation, and management.

Air pollution effects on ecosystems: The Hubbard Brook Research Foundation Science Links Program. Air pollution can have marked effects on the structure and function of ecosystems through elevated atmospheric deposition of sulfur, oxidized and reduced nitrogen compounds and mercury, and high concentrations of tropospheric ozone. Recent efforts to channel this knowledge into decisionmaking through organized outreach and communication have increased the influence of long-term research on air-quality management in the United States (Driscoll et al. 2010). The LTER Network, through its long-term measurements and experiments (Driscoll et al. 2001), has been particularly effective in addressing policy issues concerning air pollution and atmospheric deposition effects on ecosystems.

The effects of air pollution on forest and aquatic ecosystems have been a research focus since the inception of the Hubbard Brook Ecosystem Study and the Hubbard Brook LTER site. The value of long-term measurements of the chemistry of precipitation and streamwater at the Hubbard Brook Experimental Forest in documenting trends in acidic deposition and in assessing the effectiveness of the federal Clean Air Act represents an important example of the connections between long-term research and air-quality policy (figure 1). The Hubbard Brook Research Foundation (HBRF) launched Science Links in 1998 to build on this legacy and to develop new initiatives linking ecosystem science with public policy (*http://hubbardbrookfoundation.org/12-2*).

Science Links projects are state-of-the-science synthesis efforts of an environmental issue in the context of current policy discussions. The first three Science Links projects addressed air pollution impacts on ecosystems, including the effects of acid, nitrogen, and mercury deposition (Driscoll et al. 2001, 2011). Science Links projects involve teams of around 12 scientific experts, selected on the basis of their experience and disciplinary coverage, and a team of policy advisers. The science teams define the scope of the project, analyze relevant databases and conduct model calculations. The policy advisers are engaged in dialogue from the outset to frame policy-relevant questions, discuss the alternatives analyzed, and provide input on Science Links products.

A communication and outreach plan is integral to the success of Science Links projects. The written plan provides a roadmap to facilitate an exchange between scientists and policy stakeholders as well as direct outreach to journalists. The centerpiece of any Science Links project is the translation report aimed at congressional and government-agency staff involved in policy development. These reports are structured to facilitate communication of the major findings, with the conclusions presented first in clear, straightforward terms, followed by supporting information with layered details. A proactive media strategy has been critical

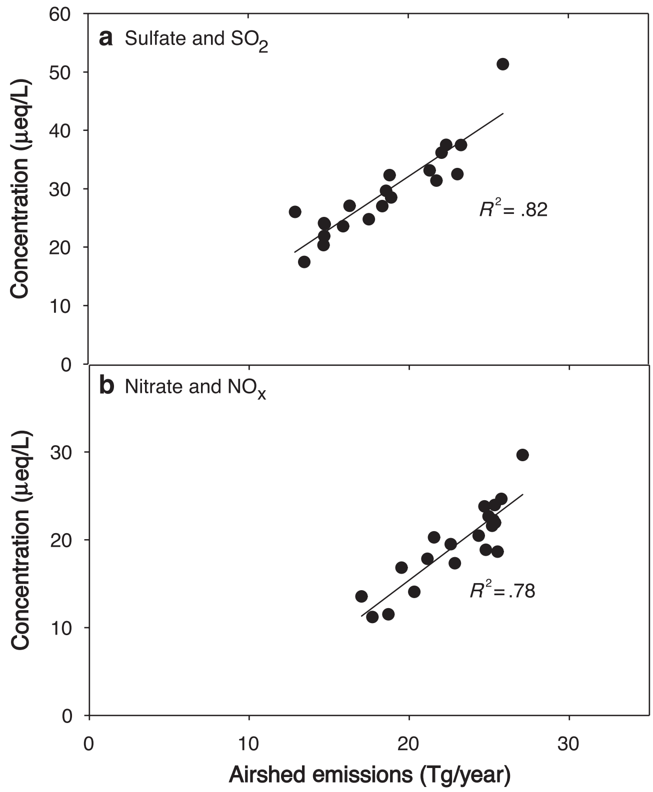

Figure 1. Relationships between annual volume-weighted concentrations of sulfate (a) and nitrate (b) in precipitation at the Hubbard Brook Experimental Forest and emissions of sulfur dioxide and nitrogen oxides, respectively, in the emission source area of the northeastern United States. The emission source area used is specified in Driscoll and colleagues (2001). Abbreviations: NO_x, nitrogen oxides; R^2, regression coefficient; SO_2, sulphur dioxide; Tg/year, teragrams per year; μeq/L, microequivalencies per liter.

to the impact of Science Links projects. Accurate and widespread media coverage has brought attention to Science Links results and verified the societal importance of the findings for policymakers. The initial public release of a Science Links report is followed by additional interviews, seminars, and briefings for up to a year. Science Links projects have also been coupled with the Hubbard Brook LTER site educational activities through the development of supplemental teacher guides.

There are several dimensions to quantifying the impact of Science Links projects (Driscoll et al. 2011). The scientific impact can be measured by the number of citations in the scientific literature; the six Science Links journal articles have been cited more than 1300 times in the peer-reviewed literature. The media impact can be measured by the extent and quality of media cover. Science Links initiatives have been covered in more than 475 media stories and have appeared in major news outlets, including an opinion–editorial piece in *The New York Times.* The impacts on policy are more difficult to quantify. Moreover, they are often beyond the control of the scientists, regardless of the process used to link science to policy. Timing is everything in this dance between science and management. Forms of evidence of policy uptake include reference to Science Links findings in proposed legislation (e.g., the Clean Power Act, the National Mercury Monitoring Act), legal briefs (e.g., the Northeast States New Source Review case against the US Environmental Protection Agency), and media accounts of major policy and court decisions (e.g., the Interstate Transfer Rule for nitrogen oxide emissions and the remand of the Clean Air Mercury Rule and its trading provisions). Beyond this evidence, policymakers and program managers routinely comment on the usefulness of Science Links in improving the scientific basis for decisionmaking because of its reliance on rigorous long-term research and effective translation.

Uniting conservation science and policy: Examples from the Harvard Forest LTER site. The Harvard Forest has oriented its long-term studies around forest management and conservation questions in New England since its inception in 1907. When it was established by Harvard University, its objectives were to serve as a model forest to demonstrate the practice of forestry, an experiment station for research in forestry, and a field laboratory for students (Fisher 1921). Today, Harvard Forest scientists remain dedicated to the founding tenet of drawing on insights gained through the historical and retrospective study of forests, natural disturbance, and land use (Fisher 1933, Foster 2000), and the Harvard Forest serves as a central gathering spot for meetings and workshops among forest managers, conservationists, policymakers, and scientists in the Northeast.

Long-term research at Harvard Forest has informed many important conservation efforts, as well as policy and management decisions in the region (figure 2; Foster et al. 2010). For instance, a review of land-ownership history and conservation patterns led to the creation of the North Quabbin Partnership and to an increase of conservation

Primary research 1997–2005

Research theme	*Key concepts*	*Conservation impacts*
Pattern of conserved lands in central Massachusetts (MA)[1,2]	Lack of coordination leads to haphazard conservation patterns. Effectiveness is enhanced by connectivity and large blocks.	Formation of the North Quabbin Regional Landscape Partnership and increased rate and effectiveness of land protection.
LTER forest disturbance experiments[3, 4, 5]	The ecological impact of hurricanes and insects is minimal compared to climate change, anthropogenic stress and logging.	Creation of statewide reserve system and change in salvage logging practices.
Structure and extent of old-growth forests[6]	The definition of "old-growth" varies across regions and little remains in MA.	Protection of old-growth forests from ski area development on Mount Wachusett, Massachusetts.
Illusion of preservation[7, 8]	Constraints on local timber harvesting increases detrimental logging elsewhere.	More balanced approach to harvesting and wildland protection in New England.
Retrospective analysis of primary forests[9]	Historical maps (legislatively mandated in 1830) support spatial analysis of primary forests.	Primary forest becomes critical GIS overlay in MA *BioMap* report of land protection priorities.

Synthesis 2005

Product	*Key concepts*	*Conservation impacts*
Wildlands and Woodlands (W&W) 2005[10]	• Old-growth forests and reserves are under-represented in Massachusetts. • "Hard" deforestation is increasing across the state. • Sustainable forest harvesting strengthens local economies while protecting natural infrastructure. • Conservation partnerships and outreach to private landowners are keys to advancing conservation.	• New England Conservation Finance Roundtable formed. • W&W vision for Wildlands informed the task force on management of MA state lands. • Wildlands and Woodlands Partnership established. • Woodlands Councils and Regional Conservation Partnerships promoted.

Primary research 2006–2010

Research theme	*Key concepts*	*Conservation impacts*
Wildlands distribution[11]	Protected wildlands occupy <1% of the New England landscape.	MA Forest Vision process established permanent reserves on state-owned land.
Conservation finance[12]	Public funding through tax policy and ecosystem markets supports substantial conservation.	Massachusetts legislature appoints conservation finance legislative study commission.
Timber harvest as disturbance[13, 14]	Harvest patterns can be predicted by social factors; there is a negative relationship between harvesting and loss of forests to development.	Dataset used for statewide forest resource assessment, harvest regulations, and watershed planning.

Synthesis 2010

Product	*Key concepts*	*Conservation impacts*
Wildlands and Woodlands 2010[15]	• Forest cover is declining in all 6 New England states. • Land ownership patterns are shifting and parcelization is increasing. • The region's forests can support additional sustainable harvesting. • Mature forests show increasing rates of carbon sequestration.	• Key W&W message of accelerating the pace of forest conservation informs New England governors' report. • Conservation finance commission led to new legislation introduced in MA. • Central MA and New England forest aggregation projects launched.

REFERENCES
[1] Golodetz and Foster 1997; [2] Nudel 2003; [3] Foster et al. 1997; [4] Kizlinski et al. 2002; [5] Foster and Orwig 2006; [6] Orwig et al. 2001; [7] Berlik et al. 2002; [8] Mayer et al. 2005; [9] Hall et al. 2002; [10] Foster et al. 2005; [11] D'Amato et al. 2006; [12] Levitt and Lambert 2006; [13] Kittredge et al. 2003; [14] McDonald et al. 2008; [15] Foster et al. 2010

Figure 2. Harvard Forest research and conservation linkages: primary research and synthesis examples related to the Wildlands and Woodlands Initiative.

land in the region from 36.8% in 1993 to 45.1% in 2010 (Golodetz and Foster 1997). Research on the potential for local constraints on forestry to displace harvesting pressures to other, more sensitive parts of the world has broadened public acceptance of forestry in the region (Berlik et al. 2002). Surveys have documented how underrepresented old-growth forests are in southern New England, which has aided in the preservation of the few remaining sites (Orwig et al. 2001, D'Amato et al. 2006). Many of these linkages grew out of strong informal ties between scientists and stakeholders built by serving on local, state, and regional committees.

In 2005, the Harvard Forest launched its Wildlands and Woodlands (W&W) Initiative, which emphasizes decision-relevant synthesis, communication, and stakeholder partnerships. The knowledge gained from dozens of studies at the Harvard Forest was synthesized into a series of W&W publications that were aimed at nonscientists and that called for stemming the loss of forest cover now occurring in all six New England states as large areas (e.g., in Maine) experience significant shifts in landownership. The publications call for balancing the preservation of wildlands with large areas of actively managed woodlands and for promoting civic engagement through landowner-conceived woodland councils (Foster et al. 2005, 2010).

Since 2005, the W&W Initiative has produced two major reports, two update publications, and a Web site (*www.wildlandsandwoodlands.org*), with the purpose of raising awareness about the pace and consequences of land-cover change. Both W&W reports had extensive stakeholder input, and the second garnered comments from several hundred agency, nongovernmental-organization (NGO), landowner, and industry representatives. Harvard Forest has since teamed up with the nonprofit organization Highstead to form a partnership with more than 60 participating groups to sustain stakeholder engagement and to help implement the vision of the W&W Initiative. The reports were accompanied by press releases; webinars; stakeholder briefings; and, in May 2010, a public event with Harvard University's Kennedy School of Government.

Assessing the societal impact of Harvard Forest research over the past 100 years is beyond the scope of this case study. However, we compiled information on the impact of W&W communication to shed light on the value of this coordinated outreach effort. In the two months following its release, the 2010 report generated 137 media and newsletter stories and 62 visits per day to the new W&W Web site, including visitors from 35 countries from five continents. By contrast, Harvard Forest garnered 21 non-W&W news stories between 2008 and 2010. W&W authors participated in 21 briefings, presentations, and workshops in the nine months since publication, which expanded the project's influence and reach. These W&W synthesis and communication efforts have contributed to several notable policy and management advances, including the decision by the state of Massachusetts to establish permanent wildland reserves, the introduction of a conservation-finance bill in the Massachusetts General Assembly to accelerate the pace of conservation, and the launching of an innovative effort to aggregate multiple parcels into a single project with the goal of conserving approximately 10,000 acres of forest in western Massachusetts. The W&W efforts also fueled new research, including the establishment of new long-term study plots across sites with diverse histories, ownership, and management objectives; and a new cross-site LTER proposal on the Future Scenarios of Forest Change (see Thompson et al. 2012 [in this issue]).

Sustained research–management partnerships at the Andrews Forest LTER site. The H. J. Andrews Experimental Forest and LTER site in the Oregon Cascade Range contains many of the iconic and hotly debated elements of Pacific Northwest forests: old-growth trees; northern spotted owls; and cold, clear, fast streams. Societal conflicts over the future of the vast tracts of federal forestlands in the region have been profoundly affected by science findings from the Andrews Forest and, in turn, have strongly influenced the course of science in the region and more broadly.

The research history of the Andrews Forest, stretching back to its establishment in 1948, reflects a commitment to long-term ecological and watershed research by the US Forest Service and with NSF-funded programs under the International Biological Program in the 1970s, followed by LTER Network since 1980. These integrated science programs have produced high-quality studies and long-term records that underpin interpretations of ecosystem and environmental change and sustain an interdisciplinary cadre of scientists, all of whom are essential in investigating ecosystems that change abruptly and also gradually over time scales of decades and centuries. The context of extensive federal forestlands (e.g., US Forest Service, US Bureau of Land Management) provides an audience of land managers who are required to guide management using current science. And, if they fail to do so, litigants and the courts remind them.

A central feature of the Andrews Forest program is a research–management partnership that develops, tests, demonstrates, and critically evaluates alternative approaches to management so that when the policy window opens, new, scientifically and operationally credible approaches to management are ripe for broad adoption (*http://andrewsforest.oregonstate.edu/resmgt.cfm?topnav=35*). This partnership involves the research community centered on the Andrews Forest LTER site and land managers of the Willamette National Forest. The partnership has made substantial impacts on forest management and policy on topics such as the characteristics of and conservation strategies for old-growth forest ecosystems (Franklin et al. 1981, Spies and Duncan 2009); the ecological roles and management implications of dead wood on land and in streams (Gregory et al. 1991); the ecology and population dynamics of the northern spotted owl (Forsman et al. 1984); the effects of forest cutting and roads on streamflow, including floods (Jones 2000);

Primary research 1970–1993		
Research theme	*Key concepts*	*Conservation impacts*
Characteristics of old-growth forest[1]	Old-growth forests have complex structure, composition, and ecological functions.	Greater recognition of the value of old growth in National Forest planning.
Forest-stream interactions[2]	Forests regulate stream functions.	Riparian management guides for Willamette National Forest Land and Resource Management Plan (1990).
Northern spotted owl ecology[3]	Old growth is critical habitat for this and other species.	Foundation for design of several regional spotted owl conservation plans.
Wood in streams and on land[4]	Dead wood has many ecological functions.	Guides for retention of dead wood in National Forest planning.

Synthesis 1993–1994		
Product	*Key concepts*	*Conservation impacts*
Northwest Forest Plan (NWFP)[5, 6]	• Movement of organisms, disturbance processes, water, and other factors connect landscapes. • Forests strongly influence aquatic ecosystems. • Retained live trees and dead wood in harvest units sustain ecological functions.	• Interactive network of old-growth reserves. • NWFP Aquatic Conservation Strategy. • Harvest prescriptions on federal forest lands from northern California to Canada include retained live trees to enhance within-stand structural, compositional, and functional diversity.

Primary research 1994–2010		
Research theme	*Key concepts*	*Conservation impacts*
Road hydrology and ecology[7]	Roads alter water runoff and increase exotic plant dispersal.	Guidelines to mitigate road impacts.
Fire regimes: implications for landscape management[8]	Landscape plans based on historic disturbance regimes provide a coarse filter approach to biodiversity conservation.	Prototype and concepts for use in other settings.
Meadow history and ecology[9]	Meadows are critical components of landscape diversity and habitat for species conservation.	Guides for meadow restoration in response to forest encroachment.

REFERENCES
[1]Franklin et al. 1981; [2]Gregory et al. 1991; [3]Forsman et al. 1984; [4]Harmon et al. 1986; [5]Forest Ecosystem Management Assessment Team (FEMAT) 1993; [6]USDA and USDI 1994; [7]Jones et al. 2000; [8]Cissel et al. 1999; [9]Halpern et al., *in press*.

Figure 3. Andrews Experimental Forest research and links with management and policy for forestlands and watersheds.

interactions of road and stream networks (Jones et al. 2000); and interactions of climate change with management and policy (Spies et al. 2010).

With roots in the early 1950s and the assignment of the first scientist to the Andrews Forest, the research–management partnership has become a continuous, place-based learning program with balanced, reciprocal communication between the management and research communities and their respective cultures. To facilitate communication, the research–management interface is staffed with a research liaison position at the Willamette National Forest, which facilitates outreach to land managers and the public. The technical findings of research and management experience are communicated through diverse media, such as journal articles, including ones jointly composed by scientists and land managers (Cissel et al. 1999); publications prepared for land managers and the general public (e.g., in the *Science Findings* and *Science Update* series of the US Forest Service; *www.fs.fed.us/pnw/publications/scifi.shtml, www.fs.fed.us/pnw/publications/sci-update.shtml*); workshops; and field tours. In some cases, social scientists have examined the effectiveness of communications on challenging topics, such as the use of historic disturbance regimes to guide future land management (Shindler and Mallon 2009). The net effect of this communication program is a continuing public discussion of the future of forest and watershed management and policy in the region.

The impacts of long-term research from the Andrews Forest and the research–management partnership are manifest in federal agencies' management of forest stands and landscapes throughout the Pacific Northwest and more broadly (figure 3). In particular, the Northwest Forest Plan, which drew heavily from research from the Andrews Forest, ushered in a new era of ecosystem-based management on 10 million hectares of federal lands in northern California and western Oregon and Washington (FEMAT 1993, USDA and USDI 1994). Andrews Forest–based science on old-growth forests, forest–stream interactions, aspects of biodiversity, and the roles of dead wood in forests and streams helped shape new federal land-management policies (FEMAT 1993). Several of the key publications have been cited in the scientific literature more than 1000 times each, which indicates the influence of the concepts in the environmental sciences. Since 1994, individual research themes have continued to influence management practices in the region (figure 3). Publications from the Andrews Forest–based work are widely cited in planning documents for timber sales and fuel-treatment projects on National Forests and US Bureau of Land Management districts across the Pacific Northwest. The impact of the research–management partnership has drawn social scientists to examine the dynamics, motivations, and public perception of these science–management–policy connections (Lach et al. 2003).

Tools for assessing services and values to improve urban natural-resources stewardship: Baltimore Ecosystem Study long-term data. Information on natural resources in urban areas is often lacking and limits the ability of planners and managers to properly steward or incorporate natural-resources services within urban ecosystems. Long-term research is currently being conducted in the Baltimore area to foster a better understand how urbanization affects natural system processes (e.g., Pickett and Cadenasso 2006). Baltimore, through its participation in the LTER Network, was one of the first cities to have its entire forest and tree structure assessed, along with the concomitant ecosystem services and values (e.g., pollution removal, carbon storage and sequestration, effects on building energy use; see, e.g., Nowak et al. 2008). It is also the first city (along with Syracuse, New York) to establish (in 1999) permanent vegetation-monitoring plots to assess long-term vegetation changes (Nowak et al. 2004). These data provide critical information for better understanding of urban vegetation systems, their environmental effects, and how these ecosystems are changing. These data have also helped in the development and testing of public-domain software tools designed to aid managers and the general public in assessing urban trees and their associated ecosystem services and values. Data collected in Baltimore and other cities in the mid to late 1990s led to the development of software to assess urban forest structure and functions: the UFORE (urban forest effects) model (Nowak and Crane 2000). Through time, a diverse collaboration developed among numerous partners to expand the development of this and other urban forest computer programs into a suite of free software tools known as i-Tree (*www.itreetools.org*), which was released in 2006.

The information provided by i-Tree software has been used to inform management and policies throughout the world in relation to urban forestry. The influence of i-Tree results from the use of the model and local data by consultants, managers, and local citizens to guide management and policies decisions related to issues such as emerald ash borer protection (Siyver 2009), building financial support for urban forestry programs (Society of Municipal Arborists 2008), linking local tree data with the US Conference of Mayors Climate Protection Agreement (Hyde 2009), public outreach campaigns (e.g., billboards) on the benefits of trees (Siyver 2009), developing urban forest strategic management plans (McNeil and Vava 2006), and helping secure financing for tree planting and management (e.g., Ibrahim 2009). Most of the data collected and analyzed through i-Tree are used to encourage municipal, county, and state leaders to establish or improve urban forestry programs, to recognize the role that trees play among urban natural resources, and to focus funds to improve stewardship. New tools were released in early 2010 (version 4.0) that include new approaches to help integrate science into local policy decisions related to streamflow, tree pests, local tree cover and effects, and related ecosystem services.

Information and results from i-Tree, its analyses, and impacts are generally communicated by the research partners and users to others through public presentations, reports and articles, webinars, the i-Tree Web site, and word of mouth. To assist in communicating project results, i-Tree automatically produces a standard report with graphics that users can export and customize for their own use (figure 4). Users can also report ideas, questions, or problems back to the i-Tree team, which are then used to update or develop future versions.

To date, more than 8200 unique users in 99 countries have downloaded the software. Use of i-Tree has grown at about 30% per year since its release in August 2006. i-Tree Web site traffic has increased about tenfold since the release of version 3.0 in June 2009 and continues to increase. Currently, about 20,000 unique users access the Web site every three months. Focused surveys of users have been conducted to help determine the types of impacts. Between 50 and 100 journal articles and reports have been published in which i-Tree was used, and the numbers have increased annually. New programs in development are focused on temporal and spatial modeling of forest effects, and the Baltimore long-term permanent field-plot data are critical to the development of these new tools. International urban forest data standards are also in development to aid in sharing and in the use of the programs among nations.

Climate-change impacts on wildfire: Bonanza Creek engagement with fire managers and indigenous communities. Alaska is warming twice as quickly as the global average, with little change in precipitation (Chapin et al. 2006a). The resulting drying of the boreal forest has increased the annual area burned, primarily through increased frequency of dry years and larger wildfires, which have important consequences for changes in forest cover and the closely coupled human and ecological communities (figures 5 and 6; Kofinas et al. 2010). Bonanza Creek scientists collaborate with fire managers and indigenous communities to share knowledge for predicting and adapting to changing fire regimes.

Working with fire managers, Bonanza Creek LTER ecologists have developed predictive models that provide a scientific foundation for fire-management decisions. Spatially explicit models of climate and wildfire suggest that, by 2050, a "typical" fire year in interior Alaska will be similar to the most extreme fire years in the historical record (*www.snap.uaf.edu*). These models were developed through extensive input from climatologists, ecologists, and fire managers (Duffy et al. 2005).

At the community level, village tribal councils have invited Bonanza Creek ecologists to collaborate in developing new ecosystem-management strategies to respond to increasing wildfire risk. These strategies include the sustainable harvest of flammable black spruce stands near communities to heat public buildings, create new jobs, and generate secondary successional habitat that favors moose—an important food source (Chapin et al. 2008, Kofinas et al. 2010). Bonanza Creek social scientists and ecologists have also participated in federally mandated community wildfire protection planning by conducting interviews and focus groups among local residents and resource managers. These interviews

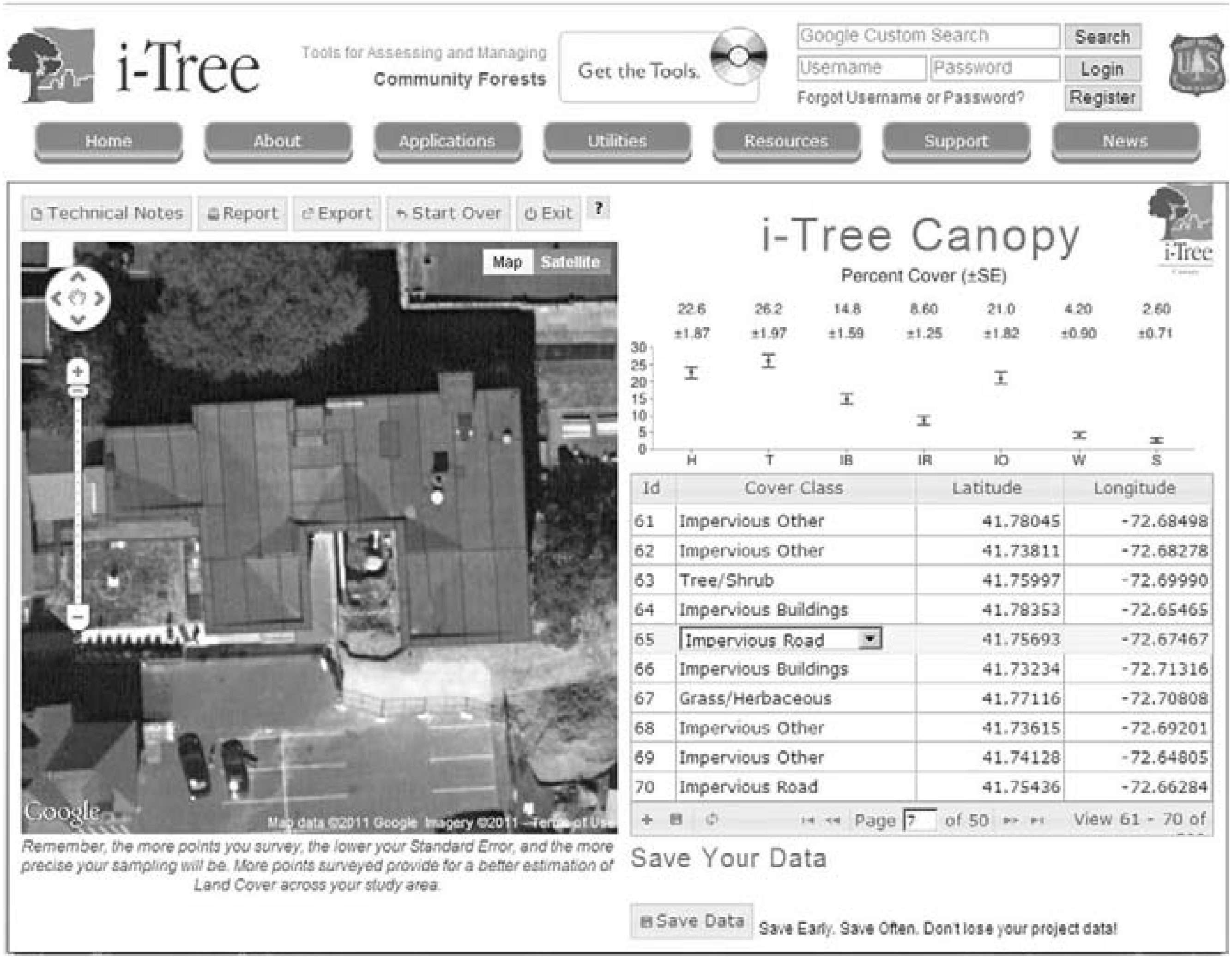

Figure 4. Example of the user interface for i-Tree. The page shows the i-Tree canopy survey page for urban forests.

demonstrated that local residents trusted managers to plan community-level wildfire protection but felt disenfranchised in regional wildfire planning for the surrounding lands, because their knowledge and concerns about future subsistence opportunities and places of cultural value were overlooked (Ray 2010).

Fire-modeling results are communicated to fire managers and the public through participation in annual wildfire strategic-planning workshops, agency meetings with the public, joint agency LTER planning of prescribed burns, and production of site-specific 2-kilometer-resolution climate projections and fire-risk projections on request (*www.snap.uaf.edu*).

Community workshops coorganized by tribal councils and Bonanza Creek ecologists allow an exchange of local, traditional, and scientific knowledge about wildfire ecology. This dialogue has enriched understanding by the LTER scientists of the ecological and societal consequences of climate change. The trust that develops through community partnerships enables Bonanza Creek researchers to learn from and contribute to societal responses to a rapidly changing socioecological environment.

The Bonanza Creek LTER site is forging new ground in identifying climate-change impacts that require immediate management and community action. The associated metrics of impact are therefore recent and qualitative. Judging from the ESA's Sustainability Science Award for Chapin and colleagues' (2006b) article, in which they described the socioecological framework for this research, the Bonanza Creek LTER site is contributing to fundamental science and to new approaches for integrating community knowledge and concerns in socioecological research (figure 6). Bonanza Creek collaborations contributed to Alaska fire managers' capacity to adapt federal guidelines on the basis of fire issues of the lower 48 US states to conditions and issues that are relevant to Alaska. Managers use the fire-risk model and routinely invite Bonanza Creek ecologists to participate in the training of wildfire managers, which indicates that they value the practical relevance of LTER. Bonanza Creek ecologists and Alaskan indigenous leaders have formed the Working Group

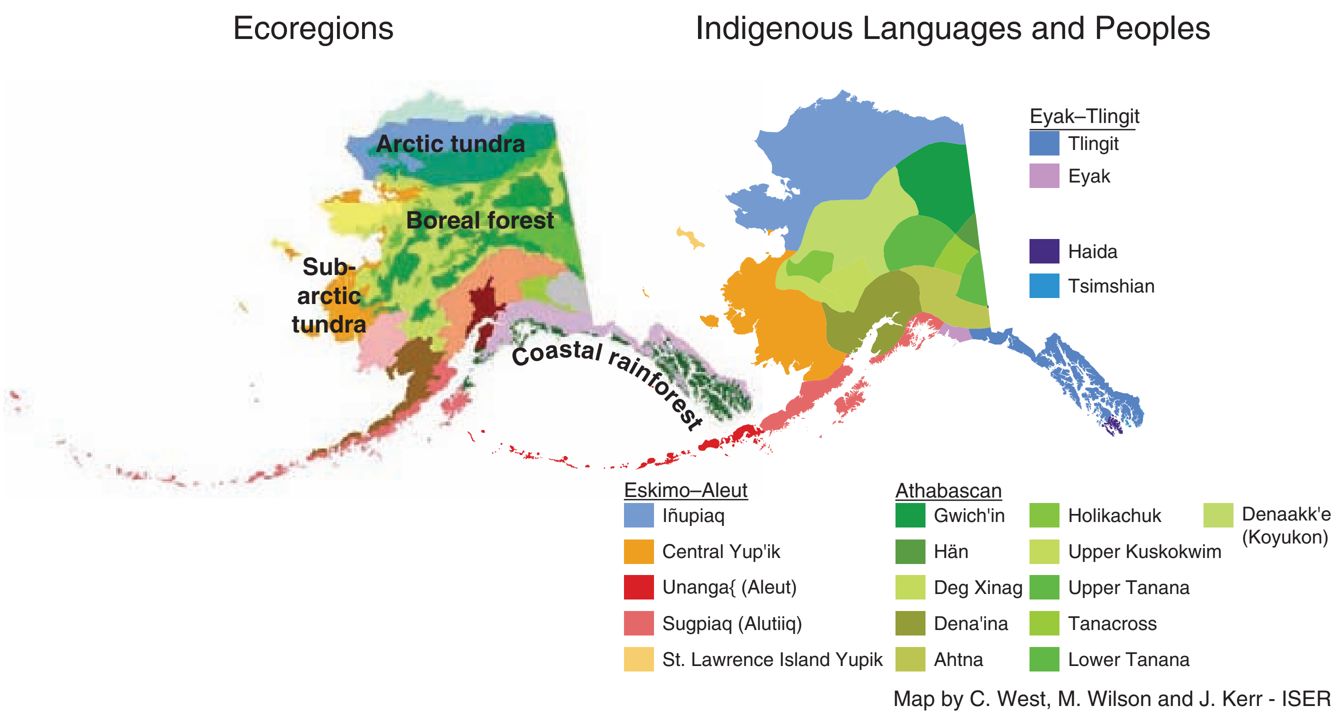

Figure 5. Cultural (linguistic) groups and ecoregions are closely coupled in the boreal forest region of Alaska (Chapin 2009). The Bonanza Creek Long Term Ecological Research Network site uses understanding of socioecological responses to climate change as a platform for exploring and implementing adaptation options that rural Athabascan communities would find consistent with their history and current commitment to sustainable subsistence lifestyles. Source: Reprinted from F. Stuart Chapin III, "Managing ecosystems sustainably: The key role of resilience." Pages 29–53 in Chapin FS III, Kofinas GP, Folke C, eds. Principles of Ecosystem Stewardship: Resilience-Based Natural Resource Management in a Changing World (2009), with permission from Springer.

on Rural Alaska Self-Reliance, a collaboration to implement community visions of adaptation to global change. This collaboration suggests that indigenous leaders value and trust their interactions with Bonanza Creek scientists.

Discussion of the case studies. Boundary-spanning efforts can facilitate the bridging of science and society by producing information that is salient, credible, and legitimate (Cash et al. 2003, McNie et al. 2008), which ultimately enriches scientific research through stakeholder engagement, the expansion of public awareness, and the improvement of the scientific basis for decisionmaking. The five LTER case studies presented here offer experiences and lessons to help answer the question of what characterizes successful collaborative outreach efforts. The case studies suggest that efforts to build a stronger interface between science and society are shaped in part by three overarching attributes that pertain to all ecosystems but vary in detail among ecosystems: (1) *Landscape and social context* refers to the pattern of land ownership (e.g., private versus public) and the role of the different types of knowledge (e.g., local versus expert) that influence the framing of environmental issues, the management objectives, and the science used in the decisionmaking process. (2) *Issue definition* involves determining the relevance of particular long-term research to policy and management issues at local, regional, or national scales (e.g., local fire- or fuel-management issues, regional air-quality concerns, federal forestland policy) and the extent to which individual actions or government actions are central to resolving the issues of concern. (3) *Communication pathways* entail understanding which communication approaches are most appropriate for specific decisionmakers, and the choice of pathway is determined in part by the context and issues addressed (e.g., direct briefings between scientists and policymakers; outreach to the media; working groups with managers; discussions with local communities, including tribes).

In addition to these three overarching attributes that distinguish individual efforts, a set of common elements of successful science communication efforts emerges from the case studies:

In all of the case studies, boundary-spanning efforts were built on credible, multidecade, interdisciplinary science, and peer-reviewed publications. These efforts combine retrospective analysis; long-term measurements and experiments; quantitative modeling; and, increasingly, scenarios planning. For example, the ability of the HBRF Science Links projects to assess the impacts of air-quality regulations and the extent

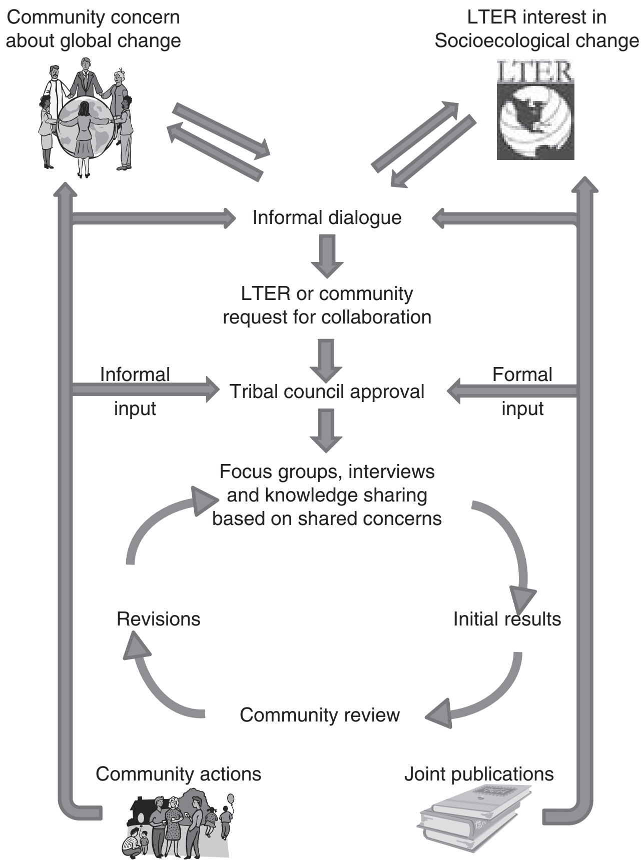

Figure 6. Processes of interaction between the Bonanza Creek Long Term Ecological Research (LTER) Network site's scientists and indigenous communities in sharing ecological knowledge. Informal discussions between scientists and community members lead to a formal request to the village tribal council to explore specific questions (e.g., climate-change effects on fire regime). One or more rounds of interaction involving interviews or focus groups, a review of the findings by the community, and a revision based on feedback. This leads to a formal report to the village council and joint publications by scientists and community members, as well as informal input to the village council, other community members, and LTER scientists.

to which ecosystems have recovered was entirely dependent on the existence of long-term precipitation, soil and stream chemistry, and relevant biological measurements. These data enabled scientists to analyze changes in atmospheric deposition and associated chemical and biological responses, to establish impact thresholds, and to apply dynamic models to evaluate the extent to which future emissions reductions would achieve policy objectives.

Among the most important activities is the collaboration of scientists and decisionmakers at the outset of and throughout a research effort. This interaction helps to define issues and questions salient to decisionmakers, to identify sources of knowledge beyond traditional scientific data sets, and to envision outputs that best meet user needs. This process also enriches scientific research. For example, the Bonanza Creek research framework was expanded through interactions with community groups to larger temporal and spatial scales and integration of cultural dimensions. This led to the recognition of critical thresholds of the resistance of the boreal socioecological system to climatic and socioeconomic changes.

Although scientists are accustomed to publishing focused research in peer-reviewed publications, these case studies point clearly to the need for policy- and management-relevant synthesis and distillation to support the effective use of science in the policy and management processes. This problem-oriented synthesis is necessary but not sufficient for promoting knowledge sharing and should be accompanied by work to translate the key findings into compelling terms relevant to stakeholders. For example, by pulling together disparate findings from across dozens of articles produced over a decade or more, the Harvard Forest W&W publications have drawn public and stakeholder attention to that body of work and catalyzed conservation initiatives far beyond what any single study could accomplish.

Successful outreach should not be an afterthought but a major and well-funded initiative with adequate staffing and supporting expertise ranging from traditional print publications to media, including Web-based, outreach. Innovative online tools that promote interaction and social networking and that are open source and easily accessible are increasingly important communication vehicles. For example, the i-Tree project built a program interface that is easy to use, open to all, supported, and free: The i-Tree partnership has built a platform to which others can contribute, and new peer-reviewed tools can be added and then supported through the existing i-Tree partnership and model structure.

Partnerships are critical to sustaining reciprocal flow of information among scientists, citizen leaders, managers, and policymakers; to applying scientific findings to policy and management through an adaptive process; and to fueling processes in which stakeholder experiences and knowledge inform research. For example, the research–management partnership developed by the Andrews LTER site and the US Forest Service provides a platform for sustained, place-based learning with substantial attention to communications with many audiences. Similarly, the Baltimore LTER i-Tree project also functions as a partnership that meets regularly and has open discussions, working toward meeting the needs of the urban community. In both cases, the involvement of a public entity (the US Forest Service) has been instrumental in coordinating and managing the activities of the partnerships.

In addition to these lessons, the case studies presented here demonstrate the need for stronger metrics to measure the impact of science communications and outreach to decisionmakers. In general, metrics for evaluating public-engagement outreach efforts can be divided into three categories: output, uptake, and impact. The five case studies present outputs such as the number of publications and presentations given to nonscientific audiences. They also provide strong evidence of uptake such as media coverage, scientific citations, and Web site visitation. Quantifying the impact on policy, conservation, and stewardship decisions remains elusive.

Developing and applying meaningful metrics of impact is a common challenge. Under the auspices of the White House Office of Science and Technology Policy, the National Institutes of Health and the NSF are developing metrics of impacts for science, called STAR METRICS (Science and Technology for America's Reinvestment: Measuring the Effects of Research on Innovation, Competitiveness, and Science; Lane and Bertuzzi 2011). Several metrics have been proposed to measure the usefulness of scientific knowledge, many of which are applied in these case studies (e.g., download or hit rates, media coverage, citations in federal or state regulations). But in the area of broader impacts or *social outcomes*, such as those in health, safety, and the environment, recommendations are under development by an interagency working group. Impact metrics for science are an important gap in understanding that should be remedied by the STAR METRICS program and other science-policy research efforts.

Conclusions

If science is to aid in the advance toward a more resilient and sustainable society, we must experiment with more effective means of integrating ecological research and decisionmaking. As is evidenced by the five case studies presented here for forest ecosystems and by many other examples, the LTER Network has an important and unique role to play in addressing the grand challenges in environmental and sustainability science. The LTER Network and associated research, with its long-term interdisciplinary focus, its focus on place-based study, its geographic distribution, its sophisticated information-management systems, and its public-outreach capabilities, are well suited to boundary-spanning initiatives that address emerging environmental issues related to changes in biogeochemistry, biological diversity, climate change, ecohydrology, infectious disease, and land use. Policy-relevant synthesis and science communication should be a focus of the LTER Network, and these activities, in turn, would probably promote cross-site and network-wide coordination of matters important to both science and society. This work could be enhanced by partnerships with established scientific societies that are dedicated to similar work. For example, the ESA is advancing a partnership among academic societies, agencies, and NGOs "to foster Earth Stewardship by (a) clarifying the science needs for understanding and shaping trajectories of change at local-to-global scales; (b) communicating the basis for Earth Stewardship to a broad range of audiences, including natural and social scientists, students, the general public, policymakers, and other practitioners; and (c) formulating pragmatic strategies that foster a more sustainable trajectory of planetary change by enhancing ecosystem resilience and human well-being" (Chapin et al. 2011, p. 45).

Harnessing the power of long-term ecological studies to address the grand challenges in environmental science will require learning from and building on existing efforts to better integrate scientific research with societal concerns. The NSF can facilitate this process by expanding the bounds of informal education to include the engagement of decisionmakers and journalists in order to provide the requisite research and learning needed to develop, test, and expand these critical experiments at the interface of science and society.

Acknowledgments

The effort and contributions of KFL were generously supported by the Bullard Fellowship program of Harvard University's Harvard Forest and by a grant from Highstead. This is a contribution of the Long Term Ecological Research Network, which is supported by the US National Science Foundation and by the US Forest Service. We appreciate the efforts of David R. Foster in shepherding this series of articles.

References cited

Berlik MM, Kittredge DB, Foster DR. 2002. The illusion of preservation: A global environmental argument for the local production of natural resources. Journal of Biogeography 29: 1557–1568.

Cash DW, Clark WC, Alcock F, Dickson NM, Eckley N, Guston DH, Jäger J, Mitchell RB. 2003. Knowledge systems for sustainable development. Proceedings of the National Academy of Sciences 100: 8086–8091.

Chapin FS III. 2009. Managing ecosystems sustainably: The key role of resilience. Pages 29–53 in Chapin FS III, Kofinas GP, Folke C, eds. Principles of Ecosystem Stewardship: Resilience-Based Natural Resource Management in a Changing World. Springer.

Chapin FS III, Oswood MW, Van Cleve K, Viereck LA, Verbyla DL, eds. 2006a. Alaska's Changing Boreal Forest. Oxford University Press.

Chapin FS III, Lovecraft AL, Zavaleta ES, Nelson J, Robards MD, Kofinas GP, Trainor SF, Peterson GD, Huntington HP, Naylor RL. 2006b. Policy strategies to address sustainability of Alaskan boreal forests in response to a directionally changing climate. Proceedings of the National Academy of Sciences 103: 16637–16643.

Chapin FS III, et al. 2008. Increasing wildfire in Alaska's boreal forest: Pathways to potential solutions of a wicked problem. BioScience 58: 531–540.

Chapin FS III, Pickett STA, Power ME, Jackson RB, Carter DM, Duke C. 2011. Earth stewardship: A strategy for social-ecological transformation to reverse planetary degradation. Journal of Environmental Studies and Sciences 1: 44–53.

Cissel JH, Swanson FJ, Weisberg PJ. 1999. Landscape management using historical fire regimes: Blue River, Oregon. Ecological Applications 9: 1217–1231.

D'Amato AW, Orwig DA, Foster DR. 2006. New estimates of Massachusetts old-growth forests: Useful data for regional conservation and forest reserve planning. Northeastern Naturalist 13: 495–506.

Driscoll CT, Lawrence GB, Bulger AJ, Butler TJ, Cronan CS, Eagar C, Lambert KF, Likens GE, Stoddard JL, Weathers KC. 2001. Acidic deposition in the northeastern United States: Sources and inputs, ecosystem effects, and management strategies. BioScience 51: 180–198.

Driscoll CT, Cowling EB, Grennfelt P, Galloway JM, Dennis RL. 2010. Integrated assessment of ecosystem effects of atmospheric deposition: Lessons available to be learned. EM Magazine November 2010: 6–13.

Driscoll CT, Lambert KF, Weathers KC. 2011. Integrating science and policy: A case study of the Hubbard Brook Research Foundation Science Links program. BioScience 61: 791–801.

Duffy PA, Walsh JE, Graham JM, Mann DH, Rupp TS. 2005. Impacts of large-scale atmospheric–ocean variability on Alaskan fire season severity. Ecological Applications 15: 1317–1330.

[FEMAT] Forest Ecosystem Management Assessment Team. 1993. Forest Ecosystem Management: An Ecological, Economic, and Social Assessment. US Department of Agriculture Forest Service.

Fisher RT. 1921. The management of the Harvard Forest, 1909–1919. Harvard Forest Bulletin 1: 1–27. (18 January 2012; *http://harvardforest.fas.harvard.edu/publications/pdfs/HFpubs/b1.pdf*)

———. 1933. New England forests: Biological factors. Pages 213–223 in Wood W, ed. New England's Prospect. American Geographical Society. Special Publication no. 16.

Forsman ED, Meslow EC, Wight HM. 1984. Distribution and biology of the spotted owl in Oregon. Wildlife Monographs no. 87: 3–64.

Foster DR. 2000. From bobolinks to bears: Interjecting geographical history into ecological studies, environmental interpretation, and conservation planning. Journal of Biogeography 27: 27–30.

Foster DR, Orwig DA. 2006. Preemptive and salvage harvesting of New England forests: When doing nothing is a viable alternative. Conservation Biology 20: 959–970.

Foster DR, Aber JD, Melillo JM, Bowden RD, Bazazz FA. 1997. Forest response to disturbance and anthropogenic stress: Rethinking the 1938 hurricane and the impact of physical disturbance vs. chemical and climate stress on forest ecosystems. BioScience 47: 437–445.

Foster D[R], Kittredge D[B], Donahue B, Motzkin G, Orwig D[A], Ellison AM, Hall B, Colburn EA, D'Amato A. 2005. Wildlands and Woodlands: A Vision for the Forests of Massachusetts. Harvard University, Harvard Forest.

Foster DR, Aber JD, Cogbill CV. 2010. Wildlands and Woodlands: A Vision for the New England Landscape. Harvard University, Harvard Forest.

Franklin JF, Cromack K Jr, Denison W, McKee A, Maser C, Sedell J, Swanson F, Juday G. 1981. Ecological characteristics of old-growth Douglas-fir forests. US Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. General Technical Report no. PNW-GTR-118.

Golodetz AD, Foster DR. 1997. History and importance of land use and protection in the North Quabbin Region of Massachusetts (USA). Conservation Biology 11: 227–235.

Gregory SV, Swanson FJ, Mckee WA, Cummins KW. 1991. An ecosystem perspective of riparian zones. BioScience 41: 540–551.

Hall B, Motzkin G, Foster DR, Syfert M, Burk J. 2002. Three hundred years of forest and land-use change in Massachusetts, USA. Journal of Biogeography 29: 1319–1335.

Halpern CB, Haugo RD, Antos JA, Kaas SS, Kilanowski AL. 2012. Grassland restoration with and without fire: Evidence from a tree-removal experiment. Ecological Applications. Forthcoming. doi:10.1890/11-1061.1

Harmon ME, et al. 1986. Ecology of coarse woody debris in temperate ecosystems. Pages 133–302 in MacFadyen A, Ford ED, eds. Advances in Ecological Research, vol. 15. Academic Press.

Hyde G. 2009. President's message. City Trees: Journal of the Society of Municipal Arborists 45 (6): 5.

Ibrahim M. 2009. US benefit analysis snared over $220m for trees. Horticulture Week 01 October 2009. (18 January 2012; *www.hortweek.com/news/942310*).

Jones JA. 2000. Hydrologic processes and peak discharge response to forest removal, regrowth, and roads in 10 small experimental basins, western Cascades, Oregon. Water Resources Research 36: 2621–2642.

Jones JA, Swanson FJ, Wemple BC, Snyder KU. 2000. Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks. Conservation Biology 14: 76–85.

Kittredge DB, Finley AO, Foster DR. 2003. Timber harvesting as ongoing disturbance in a landscape of diverse ownership. Forest Ecology and Management 180: 425–442.

Kizlinski ML, Orwig DA, Cobb RC, Foster DR. 2002. Direct and indirect ecosystem consequences of an invasive pest on forests dominated by eastern hemlock. Journal of Biogeography 29: 1489–1503.

Knapp AK, et al. 2012. Past, present, and future roles of long-term experiments in the LTER network. BioScience 62: 377–389.

Kofinas GP, Chapin FS [III], BurnSilver S, Schmidt JI, Fresco NL, Kielland K, Martin S, Springsteen A, Rupp TS. 2010. Resilience of Athabascan subsistence systems to interior Alaska's changing climate. Canadian Journal of Forest Research 40: 1347–1359.

Lach D, List P, Steel B, Shindler B. 2003. Advocacy and credibility of ecological scientists in resource decisionmaking: A regional study. BioScience 53: 170–178.

Lane J, Bertuzzi S. 2011. Measuring the results of science investments. Science 331: 678–680.

Levitt JN, Lambert KF. 2006. Report on the Woodlands and Wildlands Conservation Finance Roundtable. Harvard University, Harvard Forest.

Lovett GM, Burns DA, Driscoll CT, Jenkins JC, Mitchell MJ, Rustad L, Shanley JB, Likens GE, Haeuber R. 2007. Who needs environmental monitoring? Frontiers in Ecology and the Environment 5: 253–260.

[LTER Network] Long Term Ecological Research Network. 2010a. LTER Strategic Communication Plan: Bridging to Broader Audiences. LTER Network. (8 February 2012; *http://intranet2.lternet.edu/sites/intranet2.lternet.edu/files/documents/LTER%20History/Planning%20Documents/Final%20LTER%20Strategic%20Communication%20Plan%20-%20Nov%2011%202010.pdf*)

———. 2010b. Strategic and Implementation Plan. LTER Network. (18 January 2012; *http://intranet2.lternet.edu/documents/lter-strategic-and-implementation-plan*)

Lubchenco J. 1998. Entering the century of the environment: A new social contract for science. Science 279: 491–497.

Mayer AL, Kauppi PE, Angelstam PK, Zhang Y, Tikka PM. 2005. Importing timber, exporting ecological impact. Science 308: 359–360.

McDonald RI, Motzkin G, Foster DR. 2008. The effect of logging on vegetation composition in western Massachusetts. Forest Ecology and Management 255: 4021–4031.

McNeil J, Vava C. 2006. Oakville's urban forest: Our solution to our pollution. Town of Oakville, Parks and Open Space Department, Forestry Section. (8 February 2012; *www.itreetools.org/resources/reports/Oakville%27s%20Urban%20Forest.pdf*)

McNie EC, van Noordwijk M, Clark WC, Dickson NM, Sakuntaladewi N, Suyanto JL, Joshi L, Leimona B, Hairiah K, Khususiyah N. 2008. Boundary Organizations, Objects and Agents: Linking Knowledge with Action in Agroforestry Watersheds. Center for International Development at Harvard University and World Agroforestry Centre. Working Paper no. 80.

Nowak DJ, Crane DE. 2000. The Urban Forest Effects (UFORE) Model: Quantifying urban forest structure and functions. Pages 714–720 in Hansen M, Burk T, eds. Integrated Tools for Natural Resources Inventories in the 21st Century. US Department of Agriculture, Forest Service, North Central Research Station. General Technical Report no. NC-212.

Nowak DJ, Kurodo M, Crane DE. 2004. Urban tree mortality rates and tree population projections in Baltimore, Maryland, USA. Urban Forestry and Urban Greening 2: 139–147.

Nowak DJ, Crane DE, Stevens JC, Hoehn RE, Walton JT, Bond J. 2008. A ground-based method of assessing urban forest structure and ecosystem services. Arboriculture and Urban Forestry 34: 347–358.

Nudel M. 2003. Better conservation through partnerships. Exchange: Journal of the Land Trust Alliance 22: 17–21.

Orwig DA, Cogbill CV, Foster DR, O'Keefe JF. 2001. Variations in old-growth structure and definitions: Forest dynamics on Wachusett Mountain, Massachusetts. Ecological Applications 11: 437–452.

Pickett STA, Cadenasso ML. 2006. Advancing urban ecological studies: Frameworks, concepts, and results from the Baltimore Ecosystem Study. Austral Ecology 31: 114–125.

Ray L. 2010. Can Community-Based Natural Resource Management Improve Wildfire Policy Planning in Interior Alaska? Addressing Value Differences, Ineffective Participatory Processes, and Conflicts over Traditional Ecological Knowledge. Doctoral Dissertation. Department of Geography. Clark University, Worcester, Massachusetts.

Shindler B, Mallon AL. 2009. Public Acceptance of Disturbance-Based Forest Management: A Study of the Blue River Landscape Strategy in the Central Cascades Adaptive Management Area. US Department of Agriculture, Forest Service, Pacific Northwest Research Station. Research Paper no. PNW-RP-581.

Siyver D. 2009. Milwaukee UFORE: Taking it to the streets. City Trees: Journal of the Society of Municipal Arborists 45 (5): 10–12.

Society of Municipal Arborists. 2008. More than cows and cowboys: Urban forestry in Casper, Wyoming. City Trees: Journal of the Society of Municipal Arborists Sept/Oct: 44(5): 6–10.

Spies TA, Duncan SL, eds. 2009. Old Growth in a New World: A Pacific Northwest Icon Reexamined. Island Press.

Spies TA, Giesen TW, Swanson FJ, Franklin JF, Lach D, Johnson KN. 2010. Climate change adaptation strategies for federal forests of the Pacific Northwest, USA: Ecological, policy, and socio-economic perspectives. Landscape Ecology 25: 1185–1199.

Thompson JR, Wiek A, Swanson FJ, Carpenter SR, Fresco N, Hollingsworth T, Spies TA, Foster DR. 2012. Scenario studies as a synthetic and integrative research activity for long-term ecological research. BioScience 62: 367–376.

[USDA and USDI] US Department of Agriculture, US Department of the Interior. 1994. Record of Decision for Amendments to Forest Service and Bureau of Land Management Planning Documents within the Range of the Northern Spotted Owl. USDA Forest Service.

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