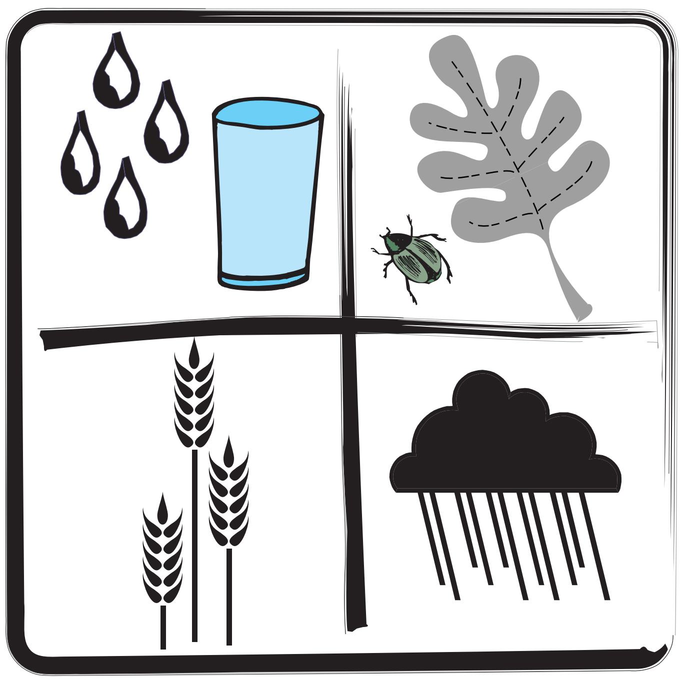
IBRCS White Paper

Rationale, Blueprint, and Expectations for the National Ecological Observatory Network



Infrastructure for Biology at Regional to Continental Scales (IBRCS) Working Group

American Institute of Biological Sciences

neon
National Ecological Observatory Network

American Institute of Biological Sciences

IBRCS
Infrastructure for Biology at Regional to Continental Scales
A community resource by AIBS

About the Infrastructure for Biology at Regional to Continental Scales Working Group

The American Institute of Biological Sciences (AIBS) established the ad-hoc Infrastructure for Biology at Regional to Continental Scales Working Group (IBRCS Working Group) in 2002 to:

- Involve a diverse array of biologists and other scientists--including and beyond the AIBS membership--in an exploration of the scientific activities, questions, and applications that can be better addressed with both enhanced infrastructure and data-networking capabilities that link field biology and other areas of biological and scientific activity across regional and continental scales

- Expose opportunities for interaction between infrastructure and data-networking projects in all branches of biology and complementary projects in other scientific fields

- Promote collaboration between the biological community and other scientific and technical communities

- Develop processes to build community consensus about the ways to use enhanced infrastructure and multidisciplinary collaboration to explore important research frontiers

- Serve as a comprehensive information source about relevant infrastructure and data-networking projects for the scientific community, the public policy community, the media, and the general public

- Provide means for both synthesizing information generated by the scientific community about the progress and needs of infrastructure and data-networking projects and conveying the information to NSF

Half of the seats on the IBRCS Working Group were filled through an election involving the leadership of the member societies and organizations of AIBS and half were filled through strategic appointments by AIBS, which served to balance the disciplinary expertise represented by the group. Members serve for two years with certain seats rotating annually. Additional information about the IBRCS working group is available at *http://ibrcs.aibs.org*.

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March 2003

About the American Institute of Biological Sciences

The American Institute of Biological Sciences is a non-profit 501(c)(3) scientific organization of more than 6,000 individuals and 85 professional societies. AIBS performs a variety of public and membership services, which include publishing the science magazine, *BioScience*, convening meetings, and conducing scientific peer review and advisory services for government agencies and other clients.

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Development of this document

To develop this white paper the IBRCS working group consulted with the scientific community in a variety of forms. The NEON concept was presented to the group at its first meeting by NSF staff. Additionally, the group studied reports from prior NEON planning workshops and other community-generated reports on frontier issues in environmental science. During the winter of 2002–2003, the working group convened three town meetings in cities across the United States at which the scientific community presented comments and suggestions on the NEON proposal to members of the working group. Because of the input received from all sources, this document represents the view of a broad segment of the scientific community.

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Preface

In November 2002, the IBRCS working group began work on this white paper on the National Ecological Observatory Network (NEON). The previous months had brought a series of highs and lows for supporters of the NEON initiative. On the upside, the fiscal year 2003 National Science Foundation (NSF) budget request included two NEON observatories as major research equipment expenditures, three NEON planning workshops had taken place, and the NSF had recently released an expanded description of the program. On the downside, the appropriations committees of both houses of Congress marked NEON out of their budget bills, and the chance of NEON being approved in the final NSF budget looked remote.

Still, the IBRCS Working Group took up its task with great enthusiasm and the hope, which recently came to fruition, that the first two NEON observatories would be requested in the subsequent federal budget. Our aim was to further advance the NEON initiative by explaining the scientific rationale behind the need for NEON, how NEON will operate to meet that need, and the results that NEON is expected to produce.

We were aided in the effort by the thoughtful comments of many individuals and by the excellent reports from six NEON workshops. In particular, we directly included many of the ideas from the fourth workshop on standard measurements and instrumentation and sixth workshop on information management. While this white paper fully explains the NEON concept and stands on its own, the reader should note that each of the topical workshop reports describe certain aspects of NEON in more detail.

While we have tried to highlight many of the opportunities that NEON presents, we have surely omitted some. We continue to seek comments and feedback about NEON and this, the first, IBRCS white paper, in particular. We hope that you will consider the NEON proposal presented here and continue to send your thoughts and ideas.

Kent F. Holsinger

Kent E. Holsinger, Chair
IBRCS Working Group

Contents

Executive Summary

This white paper was developed by the Infrastructure for Biology at Regional to Continental Scales (IBRCS) Working Group as part of an American Institute of Biological Science's IBRCS project. The aim was to further advance the National Ecological Observatory Network (NEON) initiative by explaining the scientific rationale behind the need for NEON, how NEON will operate to meet that need, and the results that NEON is expected to produce. The IBRCS Working Group was aided by input from other scientists and organizations. As a result, this white paper represents the views of a broad segment of the scientific community.

NEON Mission

In the past century we learned an enormous amount about individual species and about ecological processes at the scale of watersheds and landscapes, but there is much we do not understand. In this century we must further our understanding of ecological processes and learn how local processes can be scaled up to biomes or continents if we are to accurately predict changes in the composition, structure, and dynamics of the nation's ecosystems and understand how those changes are likely to affect us. To develop that understanding, a new type of scientific infrastructure is needed—an infrastructure that enables the simultaneous collection of compatible data on fundamental ecological and evolutionary processes over broad geographical and temporal scales. NEON is a National Science Foundation (NSF) research platform that will apply experimental, observational, analytical, communication, and information technologies to investigate the structure, dynamics, and evolution of ecosystems in the United States, to measure the pace of biological change resulting from natural and human influences at local to continental scales, and to forecast the consequences of that change. The mission of NEON is to establish and sustain the scientific infrastructure and develop the intellectual capital needed to address critical questions about changes in ecological systems and to evaluate the impacts of those changes.

Scientific Rationale

Studies of the processes that affect our nation's ecosystems have been limited mostly to small geographic areas because they were conducted by small teams at single sites. While such studies have generated critical insights into ecological and evolutionary processes, many of the most challenging questions in the ecological, evolutionary, and biodiversity sciences require us to understand processes that operate over larger spatial and temporal scales and at all scales of biological organization, from molecules to biomes. Recent advances in analytical instrumentation, computer networking, information management, experimental methods, and computational analysis have set the stage for national, coordinated observations of our biological, physical, and chemical world. NEON will provide the infrastructure that allows scientists to investigate the suite of challenging and significant scientific problems requiring coordinated observations over large spatial and temporal scales. In addition to enabling groundbreaking research in the ecological, evolutionary, and biodiversity sciences, NEON will foster research in engineering and technology, information technology, and statistics and mathematics. From the ecological perspective, NEON will help us to understand the present composition and functioning of contemporary ecosystems, to elucidate how contemporary ecosystems have been shaped by historical natural and anthropogenic processes, and to forecast how contemporary ecosystems may respond to changes in key drivers.

NEON Design

NEON will be a common science facility open to all qualified users. Each regional observatory in the network will itself be a network of facilities, such as biological field stations; LTER sites; national parks; college or university campuses; marine laboratories; federal, state, and local agency field stations; or nature preserves. To ensure that NEON encompasses a broad range of ecosystem types, a minimum of 17 observatories is needed, 16 in the United States and 1 in Antarctica. Each observatory will include both a core site that is extensively instrumented and a number of satellite observatories that are less extensively instrumented. Highly specialized research infrastructure, including field-based sensor arrays, flux towers, stable isotope analyzers, microarray analyzers, and automated DNA sequencers, will be part of the NEON infrastructure.

The process of creating NEON involves building observatories sequentially through a process involving competitive peer review of observatory proposals, which allows the final structure of NEON to capitalize on the most creative ideas from a broad spectrum of the environmental science community.

A NEON Coordinating Organization (NCO) is envisioned to handle the national-level organization and administration. The NCO should be an open membership-based organization, broader than the institutions that operate and manage the regional observatories. A representative governing body with appropriate officers will formulate procedures, and a professional staff will see to administrative matters and work with the regional observatories to implement procedures.

A standard suite of instruments will be deployed and standardized measurements taken at NEON observatories to provide compatible data sets and analytical capability. These comprehensive measurements of (1) climate and hydrology, (2) biodiversity dynamics, (3) biogeochemistry, (4) biosphere–atmosphere coupling, and (5) spatial analysis and remote sensing, combined with manipulative experiments, provide the foundation for addressing questions about biodiversity and ecosystem function, carbon dynamics, invasive species, coupling of human and natural systems, ecology of infectious diseases, and biogeochemical imbalances.

Information technology (IT) is a key infrastructural component of NEON. It must bind together the core and satellite sites of an observatory with those of other observatories across the nation and integrate these distributed sites into a single, functional research tool. An important IT challenge lies in seamlessly integrating massive volumes of data into useful products. Such integration requires the adoption or, when necessary, development of standard protocols for data specification, data storage and dissemination, metadata specification, and data accessibility. Strong and continuous collaborations among individual observatories, the NCO, and other relevant experts and organizations will generate the cyber-infrastructure that overcomes this challenge. An important goal for NEON is to provide timely and broad access to all data; thus, NEON data policies will promulgate a cultural change that values data sharing.

In addition to observational data, and syntheses from these data, NEON activities will result in acquisition of objects within the physical, chemical, and biological domains. Curation of objects for current and future use requires a variety of appropriate repositories. In turn, efficient use of the collected objects requires comprehensive tracking and inventory information.

NEON will promote scientific cooperation and partnerships as a way to leverage resources, expertise, and information among research universities; federal, state, and tribal agencies; and for-profit and nonprofit organizations. NEON proposals for individual observatories and the NCO must clearly indicate that significant partnerships have been developed and that others will be sought.

Scientific Results and Products

A well-executed NEON program will result in many difficult-to-anticipate advances in ecological science. One general advance from NEON will doubtless be the explosive development of regional ecology, involving integrated understanding of flows of material, energy, nutrients, biological entities, and information through regional landscapes and watersheds. In addition to such general theoretical advances, we can identify the specific types of data and other products that NEON will provide.

NEON will produce data on climate and hydrology, biodiversity and population assessment, biogeochemistry, and spatial analysis and remote sensing, in addition to the data generated by manipulative experiments. Other products include new instruments and technologies; ecological models; data processing, summarization, and communication technology; and specimens and samples.

Education and Public Outreach

To be effective over its life span, NEON must engage and involve students, scientific and nonscientific groups, and the general public at all levels. NEON's dynamic and user-ready knowledge base, comprising real-time and continuous network data, will be a considerable asset for the teaching community and other public and private organizations. NEON will serve as a model of true integration of research and education.

Education and public outreach committees created by the NCO will guide the NEON education and public outreach missions and formulate strategic plans. Professional staff in the NCO education and public outreach offices will implement these strategic plans and coordinate programs with regional observatories. The education committee will explore all areas of formal and informal education, specifically focusing on the K–12 and undergraduate levels, but also including continuing education and special programs targeting underrepresented groups.

The public outreach office will coordinate closely with the education office and enact relevant recommendations from the public outreach committee. Public participation at NEON observatories will be fostered, and special efforts will be made to reach sectors of society traditionally underrepresented in science and environmental programs. The public outreach office will actively promote NEON resources and opportunities to the public, interface with print and broadcast media, publish newsletters, and disseminate press releases about items of popular, scientific, or agency interest.

Benefits and Applications

This synergy of new tools and approaches will benefit scientists by advancing the frontiers of knowledge and research capacity in ecology and will produce new perspectives in ecosystem science. NEON will provide critical infrastructure to support NSF research programs, such as

Biocomplexity in the Environment. In addition, NEON will provide the platform for performing research in coupled human and natural systems research, coupled biological and physical systems, and people and technology, three priority areas designated by the NSF Advisory Committee for Environmental Research and Education. The NEON program can also fill a significant gap in infrastructure for researchers from smaller institutions who want to conduct large-scale ecosystem research.

The NEON infrastructure will encourage collaboration between the research community, environmental monitoring programs, and the natural resource management community. Data emerging from NEON research sites will help inform decisions regarding management of the nation's natural resources. For example, the location and design of the NEON sites will help establish regional reference points for biological and ecological indicators of ecosystem function, something that will help state and federal agencies in setting goals for environmental management and protection. NEON observatories will also support extensive research on molecular phylogenetics and phylogeography, tools that federal and state agencies are increasingly using to establish conservation priorities.

NEON will benefit society by improving our understanding of the implications of ecosystem change for human welfare. Healthy ecosystems provide many goods and services that are essential underpinnings of our nation's economy. Ecosystem services include drought and flood control, pollination of crops, purification of air and water, pest and weed control, carbon storage, and decomposition of wastes, while goods include food, fiber, and pharmaceuticals. Furthermore, data from NEON can be used to predict the ecosystem responses to major meteorological and geological events such as hurricanes and volcanic eruptions. In addition to forecasting the ecological and environmental effects of extreme natural events, the NEON program will allow us to assess ecosystem response to human-induced stresses such as acid rain and global warming. NEON is a powerful research tool for discovering and identifying new introductions of non-native species, whose cost to the economy can total $137 billion annually, and investigating their ecological impacts.

Conclusion

The forefront of ecological research is headed evermore toward a focus on questions and concepts that are relevant over large geographical regions, and this highlights the need for coordinated scientific infrastructure that is itself spread over large regions. Ongoing advances in our technical capability permit the development of networks of people and tools that can meet that need.

NEON has been designed by the scientific community to capitalize on such capabilities and to enable discoveries about our nation's ecosystems that until now have been impossible to address. By fostering collaboration, the development of new tools and technologies, and the study of regional- and continental-scale questions, NEON will produce new perspectives in ecosystem science and thus public benefits, both anticipated and unforeseeable.

1. NEON Mission

Forests, scrublands, grasslands, estuaries, marshes, rivers, lakes, and deserts form the natural context within which we live our lives. From the dense, temperate rain forests of the Olympic Peninsula in Washington to the arid sands of Lake Wales Ridge in Florida, from the rocky shores of Maine to the deserts of southern Arizona, the ecosystems of the United States contain an enormous diversity of species. They present both a stunning array of physical features and a gradient of human influence from the relatively untouched to the highly modified. Although the diversity of ecosystems is great, biological scientists have established many principles that apply to all of them. Here are some examples:

- The patterns of nutrient cycling and energy flow within an ecosystem depend on geology, climate, and the characteristics of the plants and animals found there.
- The ability of a species to adapt to environmental change depends on the rate at which change happens, the type and amount of genetic variability present within the species, and whether suitable habitat is available during and after the change.
- The degree of genetic, morphological, and ecological similarity between species depends on the degree of genealogical relatedness, the degree of similarity between the habitats the species occupy, and the degree of similarity in the species composition of their local communities.

In the past century we learned an enormous amount about individual species and about ecological processes at the scale of watersheds and landscapes, but there is much we do not understand. We understand little about how biosphere-atmosphere interactions are shaped by changes in water and land use or how those changes affect regional and continental responses to environmental change. We understand little about how global and regional change affects patterns of genetic, species, and habitat diversity and the ecological consequences that follow. We understand even less about how to recognize and ameliorate stress in natural and managed ecological systems, how to restore systems that are damaged, and how to manage those that are not damaged in ways that reflect our understanding of how ecological processes and human social systems interact (Lubchenco et al. 1991).

In this century we must further our understanding of ecological processes and learn how local processes can be scaled up to biomes or continents if we are to accurately predict changes in the composition, structure, and dynamics of the nation's ecosystems and to understand how those changes are likely to affect us. To develop that understanding, a new type of scientific infrastructure is needed—an infrastructure that enables the simultaneous collection of compatible data on fundamental ecological and evolutionary processes over broad geographical and temporal scales. Existing research programs are well suited to the analysis of short-term, place-based, and high-intensity effects, but many changes forecast for this century are long term, geographically widespread, and low intensity. Precisely because their impact will continue for a long time and will be felt across broad areas, however, such changes may have an enormous cumulative impact (Parmesan and Yohe 2003). Thus, an infrastructure that enables study of such spatially and temporally extensive processes is needed, and it is equally critical to understand the processes that regulate both natural and human-dominated ecosystems.

The National Ecological Observatory Network (NEON) is a National Science Foundation (NSF) research platform that will apply experimental, observational, analytical, communication, and information technologies to investigate the structure, dynamics, and evolution of ecosystems in the United States, to measure the pace of biological change resulting from natural and human influences at local to continental scales, and to forecast the consequences of that change.

> ***The mission of NEON is to establish and sustain the scientific infrastructure and develop the intellectual capital needed to address critical questions about changes in ecological systems and to evaluate the impacts of those changes (NSF 2002).***

NEON will provide a research platform for fundamental and applied research on major ecosystems throughout the United States; it will facilitate the integration of research across a wide range of biological, geophysical, and social sciences. Such research will make it possible to do the following:

- Develop a detailed understanding of how organismal physiology and species dynamics influence ecosystem processes, how regional- and continental-scale changes in climate and nutrient inputs are modulated within biotic communities, and how local and regional ecosystem processes affect continental-scale climate, nutrient, and energy dynamics.
- Provide conceptual, mathematical, and statistical tools to project how disturbance of communities and ecosystems affects their composition, structure, and functioning at local, regional, and continental scales.
- Lead to the development of new instruments, information technologies, and modes of data

sharing that allow measurement and analysis of processes beyond the reach of small groups of investigators.

- Enable the discovery of water- and land-use strategies that mitigate the impact of human activities on natural ecosystems while ensuring the sustainable use of our renewable natural resources.
- Enhance public understanding of the value and importance of biological diversity, the services that ecosystems provide to society, and the past and present influence of water- and land-use practices on contemporary landscapes.
- Train a new generation of researchers, teachers, and students of biology in conducting continent-wide research and teaching projects.

2. Scientific Rationale

Studies of the processes that affect our nation's ecosystems have been limited mostly to small geographic areas because they were conducted by small teams at single sites. While such studies have generated critical insights into ecological and evolutionary processes, many of the most challenging questions in the ecological, evolutionary, and biodiversity sciences require us to understand processes that operate over larger spatial and temporal scales (Hall et al. 1988) and at all scales of biological organization, from molecules to biomes (Michener et al. 2001). We must develop tools and infrastructure to measure and understand both acute and chronic, geographically widespread, long-term processes that have an enormous cumulative impact on organisms and ecosystems. In addition, we must develop the capacity to coordinate experiments across broad geographical and temporal scales to distinguish directional change from change associated with long-term cycles and to identify common causes for similar ecosystem phenomena. For example, reasons to develop such tools and infrastructure include these:

- Identifying reliable indicators of how land- and water-use histories affect the functioning of contemporary ecosystems requires extensive study of the current and past species composition of many sites as well as the evolutionary history and relationships of the variety of taxa found there.
- Understanding how physiology and population and community dynamics of microbes, plants, and animals influence differences in ecosystem productivity across biomes requires simultaneous, long-term measurements of the processes at work in a variety of different biomes.
- Accurately predicting how populations and communities of microbes, plants, and animals will respond to changes in the structure and functioning of ecosystems in which they occur requires detailed, long-term analyses of evolutionary and ecological dynamics in a broad range of ecosystems.
- Developing an integrated, continental-scale understanding of the influence of human activities on the functioning of ecosystems requires coherent spatial and temporal data and coordinated studies of ecosystem processes across the country.
- Predicting how subtle trends in climate and land use affect species invasions and distributions requires both environmental metrics and species diversity and composition data over large geographic scales and long time periods.

Recent advances in analytical instrumentation, computer networking, information management, experimental methods, and computational analysis have set the stage for national, coordinated observations of our biological, physical, and chemical world. Earth scientists, oceanographers, and civil engineers are using these new technologies to develop observatory networks that provide unprecedented opportunities to collect, analyze, and disseminate data for broad user bases and many purposes (e.g., EarthScope, Global Ocean Observing System, Network for Earthquake Engineering Simulation).

Through the Long-Term Ecological Research (LTER) and the Long-Term Research in Environmental Biology (LTREB) programs, NSF has supported long-term research at specific sites and on specific organisms for many years, but neither program provides the comprehensive infrastructure needed to investigate the short-term and long-term processes that affect many species and ecosystems at regional to continental scales. NEON will provide the infrastructure that allows scientists to investigate the suite of challenging and significant scientific problems requiring coordinated observations over large spatial and temporal scales.

In addition to enabling groundbreaking research in the ecological, evolutionary, and biodiversity sciences, NEON will foster research in the following:

- **Engineering and technology**, as scientists demand more sophisticated measurements of biological and environmental phenomena.
- **Information technology**, as scientists seek new ways to ensure that data collected through NEON are broadly and rapidly available in a form that can be easily understood.
- **Statistics and mathematics**, as scientists develop a quantitative understanding of the complex interactions among geology, soils, climate, flora, fauna, and land- and water-use history that explains the distribution and characteristics of the ecosystems we have now.

NEON will leverage our nation’s investment in ongoing research and assessment programs and collections, including LTER sites; museums; and federal, state, and tribal data-gathering and research programs. Results from NEON-supported research will aid land and water managers in placing the systems they manage and data they collect on those systems in regional and continental contexts and in understanding ecosystem change. NEON will foster formal and informal science education as scientists and educators find new ways to use the data that NEON provides in classrooms, laboratories, museums, botanical gardens, and zoological parks. Such education will provide children and adults with an unprecedented understanding of the structure, composition, and functioning of our nation’s ecosystems.

Accomplishing the NEON mission entails developing the research infrastructure to better understand the present composition and functioning of contemporary ecosystems, to elucidate how contemporary ecosystems have been shaped by historical natural and anthropogenic processes, and to forecast how contemporary ecosystems may respond to changes in key drivers. The remainder of this section provides several examples of how NEON will help us understand **present, past,** and **future** ecosystems.

2.1. Understanding the present

The ice-covered lakes, ephemeral streams, and exposed soil of the McMurdo Dry Valleys, Antarctica, could hardly be more different from Florida's Everglades. The average annual temperature in the McMurdo Dry Valleys is –20°C, with annual precipitation of only 6 cm, all as snow (MCM 1998). The Everglades are part of a vast system of wetlands in southern Florida, receiving an average of 130 cm of rainfall per year (FCE 1998). In spite of the obvious and enormous differences between them, the same fundamental processes affect the dynamics of both ecosystems. Patterns of sediment and nutrient transport interact with geology, hydrology, climate, and biotic processes to determine the distribution and availability of carbon, nitrogen, phosphorous, and other key nutrients in soils.

Although the fundamental processes affecting all ecosystems are similar, the rates at which they happen, the identity of the organisms involved, the complexity of the food webs associated with the processes, and the sensitivity of those processes to disturbance may differ dramatically among them. At the most basic level we know that the characteristic properties of any ecosystem depend on its biological, chemical, and physical constituents and on the interactions among them (e.g., Cardinale et al. 2000, Gross et al. 2000). We know that differences in energy and nutrient inputs are related to the size and complexity of food webs and thus to the biotic diversity of resident communities (e.g., Mittelbach et al. 2001). And we know that changes in the distribution and abundance of individual species of plants, animals, and microbes reflect both individual species responses to changes in the physical environment and correlated responses to changes in other species (e.g., Swetnam and Betancourt 1998). The important next step for understanding processes at the regional level is to scale up these local-level processes (Box 1).

We also know that human activities have had enormous influences on many ecosystem processes. Urban and heavily managed agricultural areas are obvious examples of such influences. The biotic communities they support are usually less diverse, and the nutrient and energy dynamics are heavily influenced by human inputs of nutrients and energy, but human activities have also

Box 1. Scaling Up

A few studies demonstrate how site-intensive information on ecological processes can be scaled up to address regional questions. For example, site-intensive information on biogeochemical cycles has been combined with remote-sensing data and spatial analysis to estimate how carbon storage changes with climate variability (Burke et al. 1991). In this study, investigators used experimental manipulations to determine important variables and constraints affecting the carbon cycle. They then used these results to create a model that could be applied to spatially extensive biophysical data (for example, soils and precipitation). Scientists could then run simulations with various climate change scenarios to evaluate how carbon storage would change in grassland ecosystems.

Similar approaches have been used to estimate other regional patterns: grassland primary production and decomposition (Epstein et al. 2002), forest productivity and water yield (Ollinger et al. 1998), and energy fluxes between the atmosphere and biosphere (Hall et al. 1988). Although these existing studies demonstrate how a set of NEON observatories may be used to address regional- and continental-scale questions, the scope of each project was limited to a narrow set of ecological questions. The larger array of ecological and biological projects at NEON observatories will permit a more comprehensive understanding of biological, ecological, and biophysical interactions and scaling functions (see Figure 1).

changed ecosystem processes in ways that are less visible. They have altered the ways in which energy travels through ecosystems and the rate at which nutrients are transformed, even in relatively unmodified systems (Houghton 1994, Vitousek 1994, Vitousek et al. 1997). Establishing a link between human activities and ecosystem processes requires close analysis, and it cannot be made without understanding those activities in the context of ecosystem processes in places that are relatively unmodified and understanding them at regional or continental scales.

Understanding how the biological structure and composition of ecosystems interact with soils, climate, and geology to determine the ecosystem dynamics requires answers to questions like these:

- How are local ecosystem dynamics affected by regional- or continental-scale phenomena, and how can we combine data from the study of local processes to refine our understanding of regional- and continental-scale phenomena?
- How do the structure, composition, and dynamics of human-dominated ecosystems differ from those of ecosystems less modified by human activities?
- What causes species, communities, and ecosystems to differ in their resilience to change in either the physical or biotic environment?
- To what extent is community resilience to environmental change an additive result of the resilience of its species, and to what extent is it a result of synergistic interactions among components of the community?

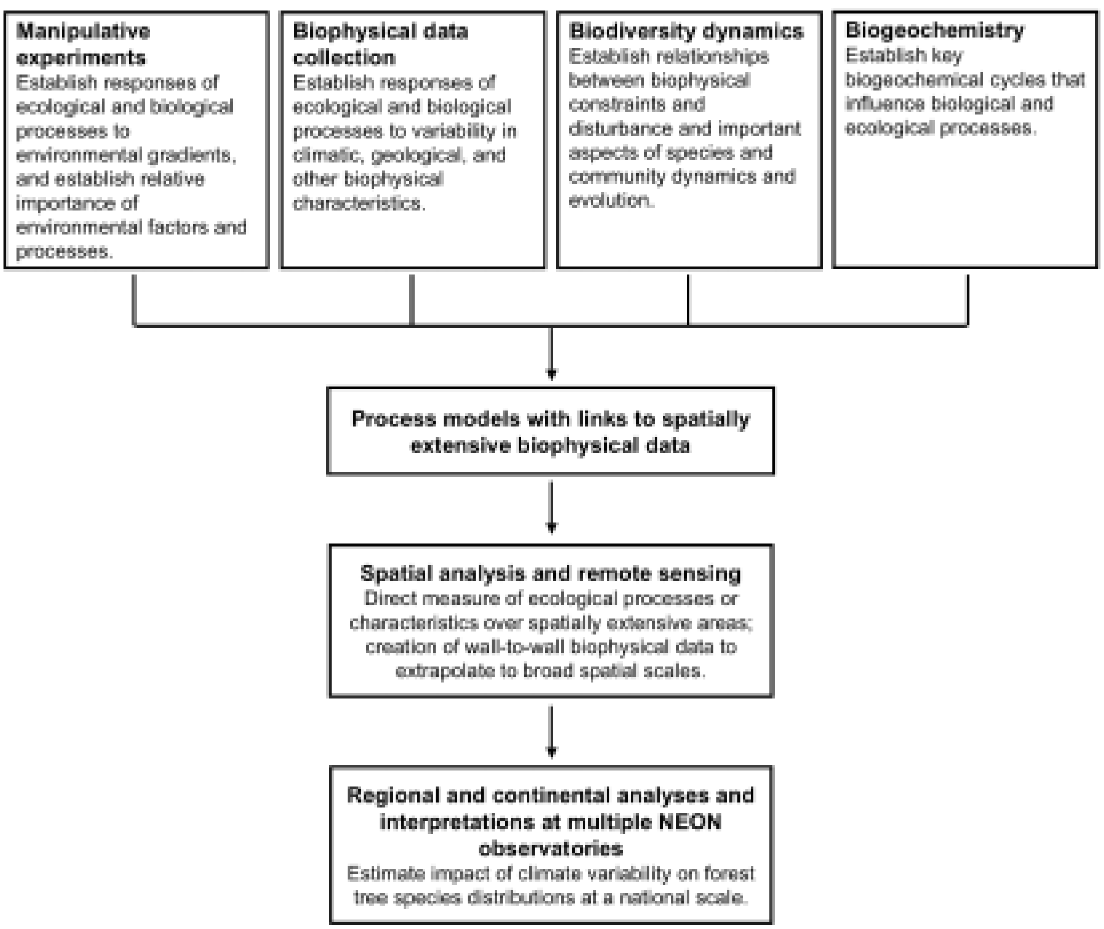

Fig. 1. An example of potential scaling of NEON observatories to answer regional and continental questions.

- How do the species and community composition of an ecosystem interact with soils, geology, and climate to govern ecosystem dynamics?
- In what way do the scale and intensity of disturbance affect the structure, composition, and dynamics of ecosystems at regional to continental scales?

Answers to these questions will help us to recognize when differences between natural and managed systems are an indicator of stress, to develop methods of relieving stress when it is present, and to manage natural systems in ways that minimize the stress to which they are subject. By providing a geographically diverse set of observatories at which the interaction of biological and geophysical components are well understood, NEON will provide the infrastructure necessary to answer these questions.

2.2. Understanding the past

The composition and structure of forest communities in places as distinct as the southern Yucatán Peninsula and southern New England are greatly affected by past land-use practices. In the Yucatán, small-scale variation in topography often reflects ancient houses, stone walls, and terraces; soil structure is related to Mayan deforestation of the area over a millennium ago. In New England, contemporary forests are more homogeneous than those of precolonial times because they also have been subject to agriculture, logging, and reforestation (Box 2; Foster et al. 2003). On an evolutionary time scale, the structure and composition of these communities and the resulting dynamics of ecosystem processes reflect not only contemporary interactions among resident microbial, plant, and animal species, but also a complex mosaic of dispersal, speciation, adaptation, and coevolution.

At the broadest level, we know that climate, geology, soils, past patterns of water and land use, and evolutionary history all play important roles in determining the structure, composition, and dynamics of contemporary ecosystems (Brown and Lomolino 1998). In the past 20 years scientists have also come to appreciate the critical role of disturbance, even disturbances that are rare. For example, some ecosystems may never have fully adjusted to the climates of glacial periods (Davis 1986). Fires, floods, hurricanes, and ice storms, which occur much more frequently, have major impacts on the structure, composition, and dynamics of most ecosystems (Turner et al. 2003).

Superimposed on processes like these are human-related activities. Even before Europeans settled North America, Native Americans may have significantly altered ecosystem structure, especially through their use of fire (Schullery 1989). Since European settlement, the effects of humans have become far more dramatic and pervasive. Vast areas of the country have been cleared, plowed, grazed, or logged. Wetlands have been drained. Streams and rivers have been diverted or dammed. Water and air pollution affect ecosystems throughout the United States, and invasive species increasingly are displacing native species and affecting the functioning of both aquatic and terrestrial ecosystems, often leading to the loss of the ecosystem services on which humans depend. Finally, humans have had a hand in eliminating many native species, including wolves, buffalo, elm, and chestnut, which previously were critical in defining the ecosystems of which

Box 2. Retrospective Ecology

Residing in every landscape is a complex history of changes and conditions. All areas are recovering from past environmental changes and impacts from human and natural disturbance, and their current characteristics and future responses are conditioned by this history. Consequently, retrospective studies and an interpretation of this history are as much in need for comprehensive environmental studies as the sophisticated analyses of the modern ecosystem itself.

The New England landscape yields a case in point, as revealed by investigators at the Harvard Forest. As is true of much of the East, the thickly forested region has been transformed over four centuries by changes in land use. As a consequence the modern diversity, abundance, distribution, and structure of communities of plants and animals reflect this history in great detail (Bellemare and Foster 2002, Motzkin et al. 2002). Individual forests are currently growing rapidly, following 19th century logging and subsequent farm abandonment, and the entire region serves as an immense carbon sink that figures into global carbon calculations (Aber and Driscoll 1997). Across the region wildlife populations are changing rapidly as a consequence of these changes in land cover; for example, moose, deer, bear, beaver, coyote, turkey, heron, and eagle numbers are increasing, and field birds such as bobolinks and meadowlarks are declining in number (Foster et al. 2002). The ability of these forests to absorb the high quantities of nitrogen deposited from fossil fuel combustion, as well as their susceptibility to natural disturbances including hurricanes, is determined by soil conditions and forest structure, both of which are influenced by centuries of land use (Aber et al. 1998, Ollinger et al. 2002). To attempt to understand these forests in the absence of exhaustive studies of the history of the land is folly.

they were part. Not only do these activities affect ecosystems at local scales, but they also operate at regional and continental scales, where our understanding is limited.

Identifying how historical influences shape the structure, composition, and dynamics of contemporary ecosystems in the United States requires answers to questions like these:

- What is the current and past species composition of selected ecosystems in the United States, and what are the evolutionary histories and relationships of important taxa found there?
- To what extent do differences in the structure, composition, and dynamics of ecosystems represent differences in environmental conditions versus differences in evolutionary history?
- How have ancient and recent changes in climate interacted with geology, soil, and patterns of land and water use to determine the distribution of microbes, plants, and animals?
- What factors have allowed some species to persist in the face of environmental change while others decline to extinction?
- How have infrequent natural disturbances and historical land use by humans determined the current composition and functioning of ecosystems?

Answers to these questions will help us to recognize and ameliorate stress in natural and managed systems, to restore systems that are damaged, and to manage those that are not. By providing a geographically diverse set of observatories at which historical influences on the structure, composition, and dynamics of ecosystems are well understood, NEON will provide the infrastructure necessary to answer these questions.

2.3. Forecasting the future

At the broadest level, we know that how ecosystems respond to externally imposed change, whether a change in climate or the introduction of a new species, depends on the species composition of its communities, on the web of interaction among its resident species, and how those species respond to that change (Schlesinger et al. 1990, Loreau 2000). We also know that change in ecosystems, far from being predictable by linear extrapolation, is characterized by threshold responses that can result in small, incremental changes having enormous effects. For example, a chronic rise in sea level may have a minimal effect on the distribution of salt marshes in a region if they receive a constant or increasing sediment input from rivers and streams. When rivers or streams are dammed, however, sediment input may drop below a critical threshold at which the salt marsh and its associated ecosystem services are lost. It is also becoming clear that the loss of native species from an ecosystem is a reliable indicator of ecosystem stress (Karr 1981, Flather et al. 1998).

While change has always characterized ecosystems, it is likely to be even more extreme and pervasive during this century, both because of increasing urbanization and demand for agricultural land and because global climate change will alter the distributions of species and communities and the functioning of ecosystems (Ojima et al. 1994). Ecosystems associated with deserts in the southwest and with the coasts of the southeast, the Gulf of Mexico, and California are likely to experience increases in urban, agricultural, and industrial land uses (Bartlett et al. 2000). These areas, which sustain nationally important concentrations of threatened and endangered species, include many of the most important international transportation hubs in the United States, and such hubs are commonly entry points from which introduced species invade. As a result, these areas are likely to encompass a larger proportion of human-dominated ecosystems than they do now, and those ecosystems are likely to be the most highly affected by introduced species.

Accurately forecasting how the structure, composition, dynamics, and distribution of ecosystems in the United States will change in this century requires answers to questions like these (see also Box 3):

- How can we use evolutionary changes within species and changes in the species composition of communities to predict ecosystem responses to change?

Box 3. Land Loss and Conversion and the Future of Ecosystems and Processes

Predicting the relative rates and magnitude of land cover conversion at a range of scales is critical in understanding the consequences of such change for a wide variety of ecological goods and services upon which our society depends. How well we understand the drivers, including environmental, economic, and social variables, that lead to patterns and scales of land-cover conversion will determine how accurately we can forecast potential impacts. Our understanding of these drivers will also determine how accurately we can evaluate alternatives to reduce the severity of potential impacts to biological and ecological resources. Robert Costanza and colleagues (Costanza 2000, Costanza et al. 2002) have developed a series of linked ecological and hydrological models that forecast how alternative land conversion scenarios affect basic biological, ecological, and hydrologic processes. Detailed information on these processes and their interactions within and across scales was used to create a spatially distributed model that predicts how the conversion of specific land units in a watershed affects processes such as nutrient, energy, biomass, and water fluxes. Different land conversion rates and patterns were then linked to building scenarios, such as 25%, 50%, or full development of zone areas. The results illustrated how different scenarios would affect both environmental quality and the quality of life for people living in the area. In at least one case, a board of commissioners used the results of the analysis and other quality-of-life concerns as the basis for its decision to adopt a specific land-use policy. NEON will provide the necessary linkages between biological, ecological, and hydrological processes across multiple scales for analyzing and developing management and risk-reductions strategies across the United States.

- What indicators can we use to predict when an ecosystem is near a threshold at which a small change in its structure, composition, or dynamics may have a very large effect?
- What characteristics of species and communities determine whether they will persist or perish in a changing environment?
- How will the structure, composition, and dynamics of ecosystems change in response to local, regional, and global climate change, and how will those ecosystem responses depend on differences among species in their ability to disperse or evolve in response to climate change?
- Why do ecosystems differ in their resistance to externally driven changes, and can we manage fragile systems in ways that would increase their resilience?

3. NEON Design

Answering questions about ecological processes over large spatial scales and long time periods requires a well-developed network of scientists and observatories. Building the infrastructure for this network involves planning at all levels, from anticipating the kinds of information that will be collected to determining the ultimate uses those data will serve. Developing such a large-scale observatory network requires the participation and coordination of many different sectors of the scientific community in an interdisciplinary effort of an unprecedented magnitude. For several years, the scientific community has been working to identify the component of the network and determine the best way to connect them (NEON 2000a, 2000b, 2000c, 2002a 2002b, forthcoming).

3.1. Overview

NEON will be a common science facility. Its resources will be open to all qualified users who typically will be supported by individual or team funding from scientific programs within or outside NSF. In some cases, such users simply will need access to the public data generated at one or more observatories. In other cases, researchers will need physical access to one or more observatories to conduct their own measurements, requiring scheduling of the appropriate equipment.

Several fundamental principles underlie the design of NEON's observatory network:

- To address questions concerning the impact of long-term, low-intensity, geographically widespread environmental changes, measurements of the same phenomena and of species, community, and ecosystem responses must be made at a variety of observatories in a broad range of ecosystems within the United States and Antarctica.
- To distinguish between chronic, directional change and change that is part of a long-term cycle, measurements must be made at a replicated series of sites over long periods of time.
- To investigate the physical, chemical, and biological processes that underlie environmental changes, a small number of sites must be distributed within each of the major ecosystem types and must provide highly sophisticated analytical and computational resources.
- To identify the contributions of natural and human-mediated processes to the structure, dynamics, and evolution of ecosystems, measurements and experiments must be undertaken across a gradient of environmental factors and human influences.

3.1.1. Structure

These principles suggest that each observatory in NEON will itself be a network of facilities, such as biological field stations; LTER sites; national parks; college and university campuses; marine laboratories; federal, state, and local agency field stations; and nature preserves (Figure 2). These examples represent the range of facilities that can participate in NEON, but they list is not exhaustive or prescriptive. Furthermore, observatories will cover a broad range of ecosystems types. Such a "network of networks" corresponds with the "octopus model" for NEON (NEON 2000c). Each observatory will include both a core site that is extensively instrumented and a number of satellite sites observatories that are less extensively instrumented. The core and satellite sites will also span gradients of environmental factors and human influence.

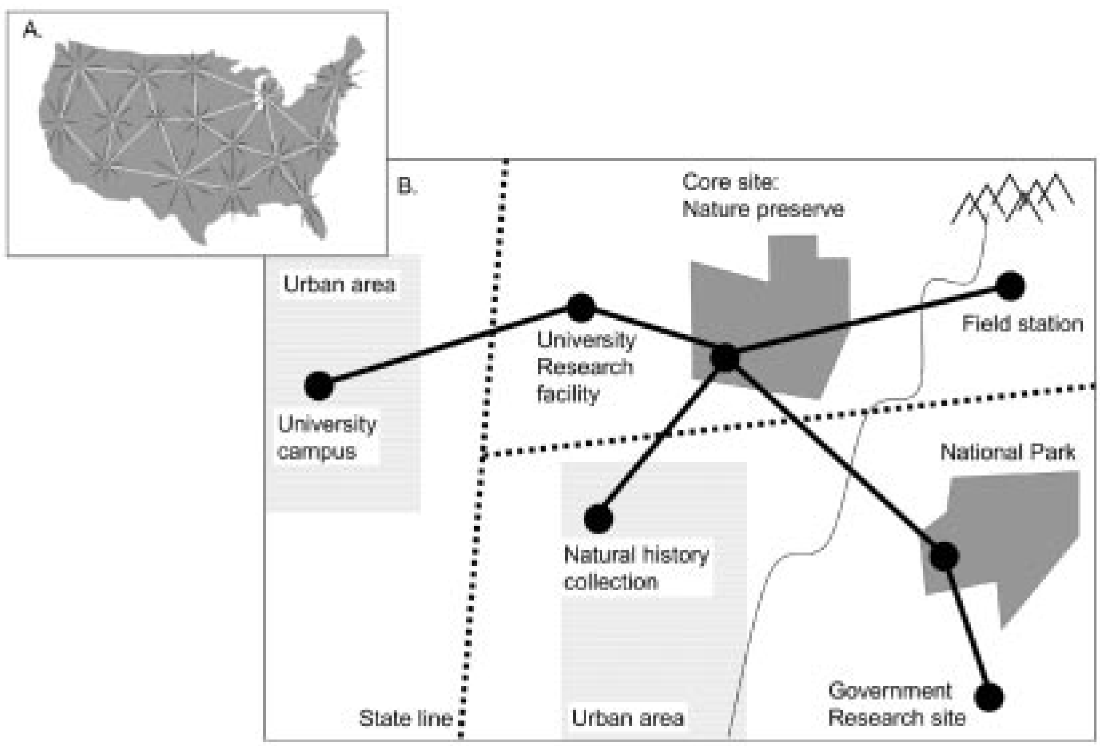

Fig. 2. National- and regional-level schematics of NEON. A. Conceptual map of fully deployed NEON. Starbursts of various size and shape represent haphazardly distributed observatories. This illustration is not intended to suggest a prescription for the geographical location of observatories in the actual network. Nor are the starbursts meant to imply a radial arrangement of satellite site around an observatory's core site. B. Hypothetical regional observatory with a footprint that spans three states and includes urban areas. In this illustration six satellite sites are associated with the core site, but neither that figure nor the specific examples of satellites are meant to exclude other arrangements.

To ensure that NEON encompasses a broad range of ecosystem types, a minimum of 17 observatories is needed, 16 in the United States and 1 in Antarctica (NSF 2002). The number of observatories needed in the United States is based on the number of biomes and ecoregions recognized by the United States Forest Service (Figure 3; Bailey 1995), but the design of individual observatories should not be required to reflect that classification. Extremely large biomes may require multiple observatories to enable adequate replication and coverage of dominant ecosystem types. In other cases, many small biomes may be encompassed by a single observatory. Each observatory should instead be designed to provide insight into ecological processes characteristic of a broad geographical region. Those processes may be understood better in the context of regions defined by large watersheds or other prominent landscape features than in terms of regions defined by dominant terrestrial vegetation. Furthermore, to provide insight into regional processes, individual observatories are likely to involve coordinated efforts over regions encompassing thousands of square miles and a broad range of ecosystems. Simply because of their size, most observatories will include a gradient of systems from the relatively unmodified to the human-dominated, such as agricultural, urban, or industrial systems.

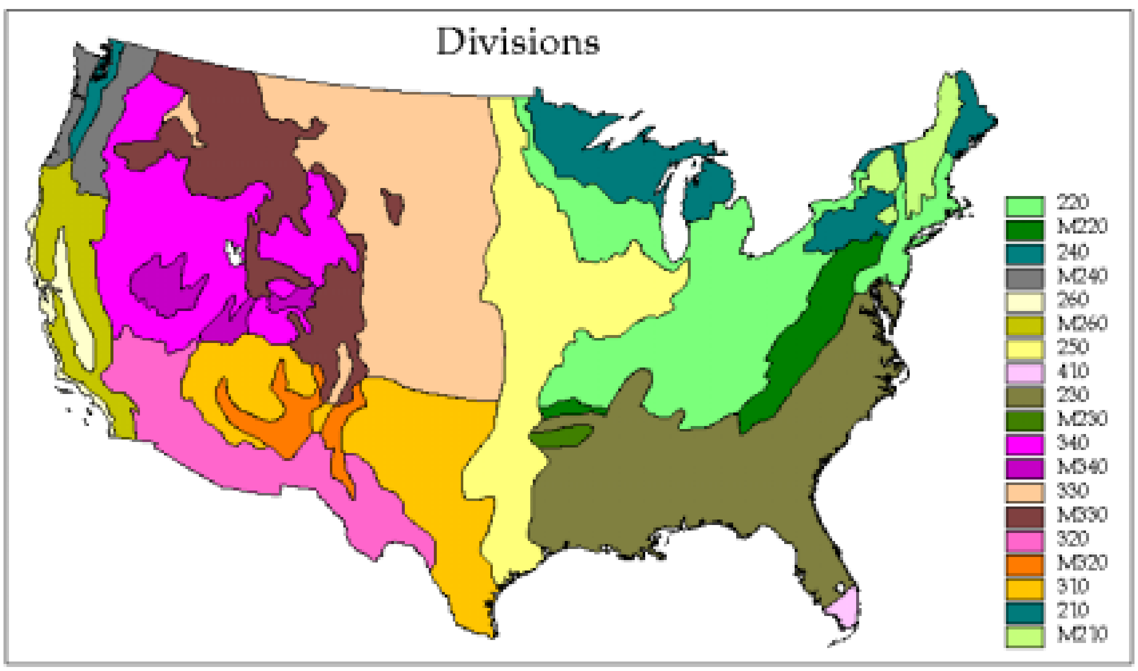

Fig. 3. Map of some US ecoregions. From US Forest Service. 1995. Descriptions of Ecoregions of the United States. *www.fs.fed.us/land/ecosysmgmt/ecoreg1_home.html.*

Highly specialized research infrastructure, including field-based sensor arrays, flux towers, stable isotope analyzers, microarray analyzers, and automated DNA sequencers, will be located at core sites. Although there will be only one core site per observatory, several institutions may share responsibility for observations at the core site. For example, a university with expertise in ecosystem ecology may be responsible for gas flux measurements, while a field station with expertise in population ecology may be responsible for vertebrate population measurements.

The relationships of satellite sites to each other and to the core site may differ among observatories, depending on the geophysical and biological context within which they are located. Some observatories may require relatively equal distribution of effort across a regional network of peer sites. Others may require disproportionate input from one lead site, supported by less intensive efforts at other sites. In some or all observatories, mobile observational, sensor, or laboratory components may be needed to respond to emerging research questions. In general, satellite sites will undertake a subset of the measurements made at core sites.

Variation among core sites gives a geographically coarse view of processes operating at a continental scale. Variation among satellite sites within an observatory allows scientists to determine how continental-scale processes influence those at the regional and local scale and to identify the causes of differences among local ecosystems within a broad ecosystem type. The combination of local-, regional-, and continental-scale observations will provide unprecedented insight into the factors that control the structure, composition, and dynamics of ecosystems.

3.1.2. Implementation

The implementation of NEON involves building observatories sequentially through a process involving competitive peer review of observatory proposals. The first round of construction will establish two observatories, with more sought in future years. This approach creates both challenges and opportunities. The first challenge lies in developing a mechanism for evaluating independent observatory proposals in a sequential series of solicitations while ensuring that a coherent national network of observatories results. Because observatories will be sequentially established, observatories that are built later in the process will be more geographically constrained than those that are built earlier. The second challenge lies in developing a mechanism for managing the network that ensures the network is able to respond to emerging scientific challenges, to accommodate the addition of new observatories, and to provide broad access to NEON facilities and data.

The process by which these challenges are addressed also provides significant opportunities. Specifically, observatories will be selected through a competitive, peer review process, allowing the final structure of NEON to capitalize on the most creative ideas from a broad spectrum of the environmental science community. To ensure that successful individual proposals produce a coherent, national network, review criteria for NEON observatories will require that proposals demonstrate the following:

- The regional focus for the proposed observatory contributes significantly to building the national network that NEON is intended to provide.
- The observatory is designed to adapt its methods and instrumentation to address emerging scientific challenges.
- The observatory provides the infrastructure needed to address NEON- and user-generated intersite and network-wide research questions.
- The observatory ensures that data are collected, maintained, archived, and disseminated according to a set of common standards.

Unlike some major research platforms such as oceanographic ships, linear accelerators, and large telescopes, NEON comprises a large number of replicated modules. Some equipment (DNA sequencers, mass spectrophotometers, field-based sensor arrays) has an expected lifetime of 5 years or less. As a result, when new instruments become available, they can be easily incorporated into some or all observatories. Thus, every observatory in the network will be continually upgraded, ensuring that consistent, replicable measurements of important environmental phenomena are available for the entire network. Moreover, measurements will be made with the most modern, precise equipment available for all of NEON's expected 30-year life span.

3.2. Management and governance structure

The management and governance structure of NEON must address certain strategic objectives. The structure should be designed to create synergies at both the national network level and the regional observatory level. At the national level, such synergies will enable scientists to work across observatories to answer the regional and national scale questions described earlier in this document. At the same time, each regional observatory must itself facilitate synergistic interactions between the entities it comprises. In addition, the management and governance structure of NEON must generate broad support from the ecological and general scientific communities.

Both of these objectives—synergy and support—present challenges in terms of management and governance. A structure that promotes synergy at the national level should not unduly constrain any observatory from pursuing its regional goals and vice versa. Similarly, the structure must clearly demonstrate that although infrastructure and personnel may be concentrated at specific locations, they are nonetheless there to provide services to the greater scientific community.

Review of the management and governance structures used by many existing large scientific projects and facilities, such as Network for Earthquake Engineering Simulation, EarthScope, National Radio Astronomy Observatory, National Center for Atmospheric Research (NCAR), Laser Interferometer Gravitational-Wave Observatory, LTER Network Office, University-National Oceanographic Laboratory System, Partnerships for Advanced Computational Infrastructure, and others, reveals a wide spectrum of management and governance structures. While none presents a precise model for NEON, several clear themes emerge from the review. These themes along with others gleaned from prior NEON Planning Workshop reports will be reflected in the management and governance structure of NEON.

First, large consortia of universities and other organizations that are involved in the high-level management of facilities and coordination of scientific research programs are a prevalent feature of the facilities and programs reviewed. These consortia are usually independently incorporated, nonprofit organizations—a status that affords them a level of group autonomy apparently critical to binding individual entities into a cohesive whole. Consortia usually have a representative council or governing body, include peer review and advisory bodies, and employ a director who is key to interfacing with external funding agencies. The membership of these consortia is always broader than the few institutions that have awards or contracts under any specific program (such as NEON) and includes institutions and individuals who use facilities or are stakeholders in projects. These consortia also have the advantage of engendering broad community support of and a great sense of ownership in projects, which results in community-wide advocacy for projects rather than mere regional or sites-based advocacy.

Second, the individual institutions that are responsible for operating facilities need to recognize that, as part of a national network, the value of their own work increases, but this also imposes on each unit (here, an observatory) the mission of serving the greater scientific community. Third, coordinated observation and data collection is, in one form or another, a critical goal; data sharing and the availability of data to the public (including entities outside the program) are issues of paramount importance. Fourth, the best new ideas and solutions to problems often come from the individuals or small groups working at the facilities rather than from the top down. Fifth, successful programs are often directed or advised by strong committees that comprise users, technical experts, and administrators.

These themes suggest that the management and governance structure of NEON will overcome the challenges imposed by the strategic objectives only if the following tactical objectives are satisfied. First, the coordinating structure of the national network must be developed prior to or, at the latest, concurrently with the two initial regional observatories. Second, the entire scientific community must be invited to participate in the network-level activities and organization. Third, within broad constraints, the consortia that form regional observatories must be allowed to generate their own management structures that both reflect the size and extent of the consortium and various institutional cultures as well as emphasize scientific and managerial entrepreneurship. Finally, new ideas—both operational and programmatic—must be allowed to emerge from the individual regional observatories, with the best being implemented network-wide.

To handle the national-level organization and administration in a manner consistent with the themes and tactics described above, a NEON Coordinating Organization (NCO) is envisioned that assumes the roles of the previously defined NEON Coordinating Unit, NEON Coordinating Committee, and subcommittees (NSF 2002). The NCO will coordinate the following:

- Network-level scientific goals
- Data standards and quality
- Information management (standards, databases)
- Scheduling and prioritizing the use of facilities (especially those shared by multiple observatories)
- Training (techniques, instrumentation)
- Network-level committees and meetings
- Integration of new observatories into the national network
- Evaluations (observatory- and network-level)
- Education and public outreach (ecological knowledge base)

The NCO must formulate and implement procedures. As described above, the NCO should be an open membership-based organization—perhaps a nonprofit corporation—that includes, but is much broader than, the institutions that operate and manage the regional observatories (e.g., a consortium of universities, other relevant organizations, and individuals). A representative governing body, such as a board of directors or advisory council with appropriate officers, is needed to formulate procedures, and a professional staff is needed to see to administrative matters and work with the regional observatories to implement procedures. The NCO governing body is expected to form topical standing and ad-hoc committees as required (e.g., standing committees on information management or education, ad-hoc committees on technical issues such as net primary productivity measurement).

Any NEON management and governance structure must provide enough top-down oversight through the NCO to ensure that the overall network is adequately addressing scientific issues at the national scale while balancing the regional needs and interests of the individual observatories. Striking this balance will require excellent leadership from NSF as well as the good faith of those involved. Some additional mechanisms may be helpful in NEON management and governance, such as an external advisory group that reviews the operation of the NCO and reports to NSF, or an observatories committee that represents the individual regional observatories, although such a committee can form under the auspices of the NCO.

Both the regional observatories and the NCO will be administered through Cooperative Agreements with NSF after selection via a competitive, merit-based, peer review process. This arrangement, unlike grants and contracts, provides NSF with close oversight of the project and the ability to shape the outcome.

The framework for the management and governance of NEON described here as well as the mechanisms for forming a nation-wide consortium will be further defined during a workshop that is currently being planned for later this year as part of AIBS's IBRCS project.

3.3. Standard measurements and instrumentation

A standard suite of instruments and measurements has been selected to provide an integrated set of standardized measurements and analytical capability to address the grand challenges in ecology. The standard measurements and instrumentation will facilitate quantitative and integrative analyses of (1) climate and hydrology, (2) biodiversity and population assessment, (3) biogeochemistry, (4) biosphere–atmosphere coupling, (5) spatial analysis and remote sensing, and (6) manipulative experiments. These comprehensive measurements provide the foundation for addressing questions about biodiversity and ecosystem function, carbon dynamics, invasive species, coupling of human and natural systems, ecology of infectious diseases, and biogeochemical imbalances. No such combination of deployed instrumentation and analytical capability exists in one place anywhere. By filling this gap, NEON will provide the capability to understand the causes and consequences of biological change. Below is a summary of standard measurements and instrumentation, which has been distilled from the fourth NEON Planning Workshop report (NEON 2002a).

Data collection and instrumentation standards are fundamental to achieving NEON's goal of an integrated, national-scale research platform. Therefore, measurement and instrument standards for core data collection and analysis will be imposed from the start at all NEON observatories. To enhance data compatibility and to allow cross-site comparisons, all NEON observatories will have facilities for the basic instrumentation and analytical capabilities described in the following sections.

3.3.1. Climate and hydrology

Characterization of regional climate and hydrological systems, and evaluation of future changes in these systems, will require broad coverage using distributed networks of weather-sensing stations, surface and subsurface water flow detectors, and near-real-time processing of data. Individual NEON observatories will include the following key components: a climate mesonet, subnetworks of sun photometers and ecohydrological sensors, and a core observatory super-site.

A spatially distributed network of weather monitoring stations, a climate mesonet, will support two fundamental aims: the development and deployment of weather and ecological forecasting using the most accurate coupled biosphere–atmosphere models available, and the evaluation of climate and ecological variability at numerous time scales, including decadal trends. The exact number of individual weather stations to be included in the climate mesonet is expected to vary depending on the nature and size of the proposed observatory footprint; however, each weather station will measure radiation and heat flux components, precipitation, air and soil temperature, barometric pressure, wind speed and direction, and humidity (at a minimum of two heights).

A subnetwork of sun photometers will be co-located at some of the weather stations in the climate mesonet. This network is intended to resolve the length scale of atmospheric transmissivity (primarily affected by water vapor) for the purpose of rigorous atmospheric correction of satellite data. The presence of this subnetwork will greatly improve the ability of observatories to analyze remotely sensed images that are expected to be a critical part of the regional data archive.

A subnetwork of ecohydrologic sensors will provide the information necessary to evaluate water and nutrient transport and transformation and the role of surface and subsurface water in the regional energy budget. The subnetwork also helps characterize the dominant surface and subsurface components of the regional hydrologic cycle, which will permit the understanding of aquatic–terrestrial interactions, hydrologic flow paths, and aquatic biogeochemical dynamics. Examples of components of this subnetwork are soil moisture profiles, shallow groundwater wells, lysimeters for measurement of evaporation, soil moisture lysimeters for nutrient content analysis, stream and river gauges, subsurface gauges (hyporheic gauges), snow surveys, and remotely sensed imagery. At coastal sites, components may also include high-frequency and low-frequency tidal gauges, bathymetric surveys, optical current meters, and salinity and temperature measurements. Part of this network may already exist in observatory footprints due to activities of other organizations (e.g., US Geological Survey [USGS], Consortium of Universities for the Advancement of Hydrological Sciences, Inc.). When appropriate, observatories will work with such organizations to integrate new components of the NEON ecohydrologic network with existing components.

An intensively instrumented super-site will be located at the core observatory for the purpose of more intensive and extensive measurements than those taken at the distributed stations of the climate mesonet. Measurements to be included at the core observatory, in addition to those of the mesonet stations, are UV radiation; aerosol optical depth; diffuse versus direct radiation; boundary-layer profiling; high frequency–high accuracy atmospheric pressure (for use in atmospheric turbulence modeling); and eddy flux measurements of energy, gases, and water.

To date, no comprehensive co-located network of climate–hydrology instrumentation infrastructure exists. Thus, NEON would yield a powerful set of integrated measurements that would be replicated spatially across the network.

3.3.2. Biodiversity and population assessment

Biological sampling and analysis at the broadest taxonomic level is one of the unique opportunities of the NEON program. Assessing the distributions and abundances of organisms across the tree of life is very difficult to accomplish, yet understanding how natural and anthropogenic environmental change affects organisms is a key goal in understanding ecosystem function through time. NEON sites are platforms from which researchers will have the ability to examine biodiversity on spatial scales that range from local to transcontinental, and temporal scales that could span several decades, with all of the relevant environmental data. NEON sites should provide researchers with these tools and resources:

- Standardized sampling and preservation methods that take into consideration the potential for future molecular analysis of the samples.
- Standardized processing protocols that can be replicated by other researchers.
- Documentation of sites and ecologically relevant measurements (e.g., location, temperature, pH, salinity) at the time of sampling.
- Access to high throughput or state-of-the-art analysis facilities.
- Standardized training for the staff performing these functions.

In some cases, existing databases in museums and herbaria collections may provide a historical context that will be complementary to NEON sampling. In other cases, trends and patterns of species turnover and invasion may be generated anew at NEON observatories. Both will provide invaluable information for elucidating ecosystem composition and function.

It is important to note that NEON observatories are research platforms that will enable the scope and scale of sampling necessary to acquire biodiversity information, both site-specific biotic and abiotic information and data that is comparable across sites and observatories, to test theories of ecosystem function. No single team can collect and process all of the biological data necessary for such an endeavor, but NEON will foster the collaboration needed to pursue research questions related to these issues.

All samples must be collected with the intention that molecular methods will be applied to them in the future. Each NEON observatory will be equipped to collect and process samples from all taxonomic groups, using accepted approaches for each group. The observatories are designed to serve permanent plots, observatory-wide sampling efforts, and specific research-driven objectives. In many cases, samples will be collected for baseline information on all groups of potential study organisms, and these surveys will involve collections. The collections will be archived in appropriate facilities, using appropriate storage methods, including samples for molecular analysis. All samples must be given unique sample numbers that permit tracking and archiving as well as retrieval of relevant ecological metadata. Museums are moving toward the incorporation of digital images, perhaps of the entire collection, in their archives. Thus, provision will be made for acquisition, storage, and curation of both digital and real collections.

At any NEON observatory, it is expected that surveys of organisms of ecological relevance to the site(s) will be undertaken on a regular basis. These organisms include indicators of environmental change (e.g., amphibians, lichens, aquatic organisms); invasive species; sensitive, threatened, and endangered species; and species of social relevance (e.g., disease organisms,

organisms of bioterrorism, viruses). Both traditional and molecular approaches for identification of these organisms will likely be used, and it is essential that these methods be standardized to facilitate comparisons of data across the temporal and spatial scales being studied within and between the sites in the network. The development of novel approaches is to be expected and encouraged, such as gene sequencing and ultimately microarrays. Samples will be processed at the core observatories and sent to a centralized NEON molecular laboratory for further analysis (initially, sequencing and informatics).

3.3.3. Biogeochemistry

NEON observatories will measure the inputs, internal dynamics, and outputs of carbon, nitrogen, phosphorous, and biologically important base cations across the landscape. A biogeochemical strategy will extend beyond the major element cycles, to include the characterization, fluxes, and accumulation of ecologically important pollutants, both organic and inorganic.

Each NEON observatory will include a continuous documentation of biosphere–atmosphere exchanges of carbon dioxide, water, carbonaceous trace gases, and nitrogenous gases using eddy flux techniques that are consistent with the current AmeriFlux network. These measurements will include, to the extent possible, isotopic characterization and effective landscape-scale estimates of biosphere–atmosphere exchange, including data on the vertical structure of the lower atmosphere (e.g., LIDAR [light detection and ranging]).

Eddy flux techniques will be coupled with a landscape-scale strategy to identify key components of biosphere–atmosphere exchange, such as net primary production, net ecosystem production, plant and heterotrophic respiration, and the soil flux of important chemically and radiatively active trace gases. In addition, efforts will be aimed at documenting belowground production through a coordinated use of rhizotrons to study root dynamics. Documentation of landscape-scale carbon dynamics includes regular measurements of litter fall (where appropriate), decomposition rates, and above- and belowground pools of carbon.

These ground-based strategies for documenting the carbon cycle can be coupled to remote-sensing data that provide annual, spatially resolved estimates of vegetation structure and dynamics. In addition, carbon fluxes and storage will be documented in aquatic as well as terrestrial systems; aquatic production will be analyzed using a network of datasondes. As with the eddy-flux measurements, landscape-scale data on the abundance of biogeochemical species will be complemented by isotopic characterization of such species to the maximum extent possible.

3.3.4. Biosphere–atmosphere coupling

The climate, hydrological, and biogeochemical data described above will permit study of the coupling between biosphere and atmosphere. Coupling mechanisms maintain a critical balance that supports all life. NEON will foster collaboration with atmospheric scientists from universities and other government institutions to couple land surface measurements of energy and material fluxes with atmospheric measurements. NEON observatories will support analysis of the feedback of atmosphere changes on biosphere processes and vice versa.

3.3.5. Spatial analysis and remote sensing

Regional landscape structure will be characterized for the areas encompassed by NEON observatories. This will entail a combination of remote sensing and extensive ground truth data collection. Landscape structure includes overall watershed structure, community types, and mosaic (patch) structure. Such data provide the baseline for understanding land-cover and land-use changes at multiple spatial scales.

Spatial analysis is augmented through remote-sensing analysis utilizing a variety of spectral- and spatial-scale observations. Analysis of spatial–temporal dynamics of landscape and land-use units can be evaluated at the regional scale with a combination of current satellite (MODIS, or Moderate Resolution Imaging Spectroradiometer) and aircraft observations. NEON will provide seasonal and spatial data on various ecological features by collaborating with satellite-operating entities. Seasonal dynamics of land and aquatic systems will be captured through moderate spatial resolution, high temporal resolution observations to document events such as leaf out, algal blooms, and plowing events, although these relatively simple measurements provide access to only a small number of biological variables (light utilization, phenology). Land-use and land-cover change can be derived from existing high-resolution sensors such as those from LANDSAT and IKONOS satellites.

Landscape patterns and seasonal events will eventually be augmented by development and use of high-spectral- and high-spatial-resolution sensor deployment. Current sensors exist that can define landscape-level patterns of vegetation structure and composition, disturbance events, and fine spatial-scale patterns of biological activity on land and in water. This instrumentation can be deployed via aircraft platforms. In time, NEON will need an airborne hyperspectral imaging spectrometer. Such a sensor can measure a large number of terrestrial and aquatic biological properties, at high spatial resolution. No space-based hyperspectral sensor is currently available on an operational basis. No existing airborne sensor has the flexibility to acquire data over 2–10 sites often enough to provide coverage of the seasonal cycle and interannual change.

3.3.6. Manipulative experiments

Manipulative experiments in natural ecosystems and in environmentally controlled facilities are essential approaches to study ecological mechanisms. Such a mechanistic understanding is imperative for enhancing our capacity to predict the pace and scale of biological change. Although standard experimental studies will not necessarily be imposed at all observatories, NEON will provide facilities to support manipulative experiments across multiple observatories. Examples of such studies include experimental warming across temperature and precipitation gradients, and examining changes in species composition to understand relationships between ecosystem structure and functions.

3.4. Information technology and information management

Information technology (IT) is a key infrastructural component of NEON. It must bind together the core and satellite sites of an observatory with those of other observatories across the nation, and integrate these distributed sites into a single, functional research tool. Thus, investment in and attention to IT is of paramount importance to the overall success of the NEON program. Considerable planning and documentation has been directed toward IT activities for NEON (see NEON 2000b and NEON forthcoming), and that effort is reflected here.

3.4.1. Goals

Goals of NEON with respect to information technology are to support the following:

- **End-to-end quality**—Collection and maintenance of high quality data and accompanying metadata from the field to the laboratory and through analysis and dissemination.
- **Timeliness**—Timely and broad community access to NEON data and information.
- **Relevance**—Knowledge transfer to scientists, decision-makers, and the public, such as providing customized views to make data and information accessible to these stakeholders.
- **Technology leadership**—Coordination and collaboration of the network, including instrumentation, data collection, and analytical protocols; wireless and automated data collection and processing.
- **Interoperability**—Creation of a tightly coupled national network, for which interoperability is paramount.
- **Standardization**—Design and development of data and information standards for core measurements.
- **Flexibility**—Building information management systems that are robust and extensible; this may be achieved through modularity and well-designed interfaces among components.
- **Discovery**—Enhancing the data discovery process.

- **Security**—Providing secure and long-term access to the data, with back up and mirroring.
- **Stewardship**—Creation of a national data resource that can be mined for decades to come.
- **Collaboration**—Creation of an environment for data quality that draws upon collaboration among scientists, technicians, information technologists, and all personnel engaged in the NEON enterprise.
- **Research leadership**—Collaborative research into relevant information technologies that meet NEON objectives.

3.4.2. Activities

Achievement of these goals requires a range of IT activities that address both individual observatories and the overall network, as well as user-instigated research projects. In addition, IT activities will be required that address as yet unsolved problems. The IT activities required by NEON include:

- **Data acquisition**—Acquiring data through sensors, field measurements, and other methods.
- **Quality management**—Documenting and managing the quality of input data and the curation of data collections.
- **Storage and archiving**—Implementing secure local storage and long-term archiving and caching of data.
- **Dissemination and access**—Making the data available to NEON researchers and the larger research community, including the provision to control access to data as appropriate and support for information discovery and data set management.
- **Integration and aggregation**—Making data compatible with collections and tools, for example, use of co-registration and preparation of new data products by federating multiple data sets.
- **Analysis, synthesis, and modeling**—Supporting the investigation and application of the collected data using standard analysis tools and customized NEON-specific applications.

3.4.3. Components

The information infrastructure will require a broad suite of integrated technological components, including sensors, communications devices, networks, and computing platforms. The major components of the informatics infrastructure include hardware (computer servers and workstations), network (wireless access in the field and high-speed linkage between observatories), and software (commercial off-the-shelf software whenever possible and custom software when needed). Even so, commercially available software will require some effort to interface to other elements of the infrastructure.

3.4.4. Standards

NEON creates compelling needs and opportunities for engaging scientists from computer science, biology, geology, hydrology, engineering, and other disciplines in developing standard methods and approaches for collection, management, processing, and communication of biological and environmental data. An important challenge lies in seamlessly integrating massive volumes of different types of data (chemical, physical, and biological) across scales of organization from genes to biomes. Such integration requires the adoption or, when necessary, development of standard protocols for data specification (e.g., units, methods, precision, quality assurance), data storage and dissemination, metadata specification (i.e., information that maintains the usefulness of NEON data for decades after they were collected), and data accessibility.

A great deal of coordination will be necessary to process and integrate data collected across the organizational, temporal, and spatial scales encompassed by NEON. Such coordination is necessary to relate, for example, biomass production at the scale of the plant or tree to the crop and forest productivity observed by satellite-based remote-sensing platforms. The initial efforts devoted to coordinating the structure and content of the various types of databases developed by NEON will reap enormous dividends in making those data more rapidly accessible and understood by scientists, decision-makers, and the public.

The difficulties that are associated with standardizing the data that are collected within a single region are exacerbated as the breadth of the question expands from regional to continental scales. For instance, understanding how global processes such as temperature and precipitation shifts affect plant productivity requires that we be able to interrelate biomass production of giant redwoods in California, cornfields in Michigan, and pine forests in Georgia. Such data integration requires standardized approaches for storing, organizing, retrieving, and communicating the data. Complexity will increase as we probe the causative mechanisms that account for observed effects by considering atmospheric and soils data, for example. The new scientific opportunities afforded through automated collection of biological and environmental data (through webs of sensors that are deployed in the environment) will bring with them challenges in terms of developing new ways to store, communicate, visualize, and understand the digital equivalent of libraries worth of data.

3.4.5. Network-level coordination

To meet the challenge described above—integrating and synthesizing data collected at scales ranging from field plots to the continent—significant coordination within and among NEON observatories must take place. Strong and continuous collaborations among individual observatories, the NCO, and other relevant experts and organizations, such as Partnership for Advanced Computing Infrastructure, National Center for Ecological Analysis and Synthesis, LTER, and research collection facilities, will generate the cyber-infrastructure that enables these scientific advances. Attention devoted to coordinating NEON observatories with respect to standardizing data, computational, and communication protocols will improve scientific knowledge, resource management, and decision-making throughout the nation.

In a practical sense, network-wide interoperability will proceed through automation in data acquisition and an integrated approach to the design, development, and maintenance of the information infrastructure. A network perspective and a design and development approach that emphasizes modularity and standardized interfaces will be adapted to maximize system flexibility and efficiency. The coordination between individual observatories, the NCO, and other experts will provide benefits in terms of economies of scale and quicker technology dissemination and advanced technology development, without compromising the flexibility of an individual observatory.

Balancing the autonomy of the individual observatories with network-level standardization will be a challenging task. This task will be addressed at the inception of the NEON network so that individual observatories implement compatible infrastructures. Exploring issues of inter-observatory compatibility and agreeing on common standards and procedures will greatly reduce the complexities of information management in NEON while enabling individual observatories to retain the flexibility to respond to unique site-specific issues.

3.4.6. Implementation

Implementation of the NEON information infrastructure will follow a systematic cycle of activities. This will be a continuous cycle, and there will always be ongoing development activities. Such development will be necessary to ensure that the system remains operational and capable of supporting its mission. Over the planned life of NEON, the established information infrastructure will require updating through this cycle of activities:

- Requirements assessment
- Design
- Systems integration
- Prototype development
- Deployment
- Evaluation and feedback
- Maintenance and upgrades

3.4.7. Data policies

Two types of data are collected in the NEON enterprise: core measurements collected throughout the network and experimental data collected by individuals or groups of scientists that visit observatories. An important goal for NEON is to provide timely and broad access to all data. High quality data, permanent and persistent archives, rapidly available and highly usable data stores, interoperability, standardization, and accountability are hallmarks of the NEON scientific enterprise. All data collected under the auspices of NEON shall be documented and archived on NEON information systems. Data from core NEON measurements are pre-competitive, that is, openly available and accessible to all. Furthermore, standard operating procedures shall be developed for collection and quality assurance of core measurement data; for instance, it is critical that all data transformations be fully documented. Data from other research conducted under the auspices of NEON will be made available in a timely fashion with requisite metadata. For example, data collected under the auspices of a project funded in association with NEON are to be made available prior to the termination of the project; data underpinning any scientific publication are to be made available at the time of publication.

NEON data policies should promulgate a cultural change that values data sharing. NEON user policies and agreements should, therefore, require appropriate acknowledgment and attribution for data providers and funding sources (e.g., NSF and NEON); policy should govern fair use of data by data users.

A data policy committee of scientists and technologists shall be charged with developing appropriate data use agreements (e.g., data citation and acknowledgment of data providers and funding support), developing appropriate information protocols for sample and voucher specimens, and approving exclusions (e.g., data dealing with human subjects, locations of endangered species).

Network-wide data and metadata standards shall be developed and adopted for use by NEON scientists. Emphasis shall be placed on adopting and developing community standards, enhancing analyzability of data and metadata, and accommodating well-defined legacy standards. Standards and policies (including enforcement actions) shall be developed by the NCO in conjunction with NEON observatories (and NSF, whenever appropriate). The governance structure for NEON shall be designed to promote and enforce adherence to data sharing and information management policies.

3.5. Specimen and sample management

In addition to observational data, and syntheses from these data, NEON activities will result in acquisition of objects within the physical, chemical, and biological domains. Curation of objects for current and future use requires a variety of appropriate repositories (Table 1). In turn, efficient use of the collected objects requires comprehensive tracking and inventory information.

Table 1. Summary of examples of objects to be collected at NEON observatories and the required repositories.

	Physical	Chemical	Biological
Objects	Digital records Analog records Photographs	Digital records Photographs Soil, water, and gas samples	Plant vouchers Animal vouchers Photographs Seeds Living animals Living plants Microbial cultures Microbial consortia Nucleic acid samples
Repositories	Local computers Network servers	Local computers Network servers Audio Video Solid, liquid,and gas samples	Herbaria Natural history collections Zoos Botanical gardens Aquaria Microbial and small biota collections Nucleic Acid libraries

Information on collected materials will flow into a component of the NEON information network that tracks all the collected materials including the source, disposition, replication, information derived from the study of the collected materials, and conclusions reached from the studies. The computer facilities will allow interoperable access to all data by the participants within the project and by the general scientific community. That is, we can follow the disposition and dissemination of samples of bacteria, fungi, ferns, nematodes, insects, legumes, ungulates; seed samples; insect voucher specimens; soil, water, and gas samples; and other materials. (The NEON Planning Workshop V report [NEON 2002b] contains considerable discussion and recommendations for biological collections and their tracking. The report does not consider physical and chemical objects. However, much of the report contents may well apply to the omitted categories.)

Each NEON observatory will encompass or partner with appropriate repositories such as those listed in the table. These repositories often have tracking systems and distribution and loan policies in place. The information on NEON-derived objects and the policies on their dissemination must be interoperable with the overall NEON tracking component.

By analogy with the goals stated for the overall NEON information system, the following goals apply to the curation and tracking of collected materials.

- **End-to-end quality**—Supporting collection and maintenance of high quality physical, chemical, and biological objects and accompanying annotation from the field to the laboratory and through analysis and dissemination.
- **Timeliness**—Providing timely and broad community access to NEON specimen tracking information.
- **Relevance**—Facilitating object tracking information transfer to scientists, decision-makers, and the public.
- **Interoperability**—Providing a tightly coupled tracking component of the network, for which interoperability is paramount.
- **Standardization**—Design and development of data and information standards for specimen descriptions, tracking and dissemination conventions and policies.
- **Flexibility**—Building a robust and extensible tracking component, which is best achieved through modularity appropriate to the variety of object categories.
- **Discovery**—Facilitating and enhancing the data discovery process by making known the existence of collected materials.
- **Security—**Providing secure and long-term access to the tracking information, including backup and mirroring.
- **Collaboration**—Creating an environment for specimen study that draws upon collaboration among scientists, technicians, information technologists, and all personnel engaged in the NEON enterprise and the general scientific community.

3.6. Partnerships

Partnering organizations are those organizations that share facilities, data, or expertise, but are not funded by the NEON program. Typically, Memoranda of Agreement or other vehicles (e.g., Cooperative Research and Development Agreement) for cooperation will be established with the NEON program at the national or regional level as appropriate.

NEON will promote scientific cooperation and partnerships as a way to leverage resources, expertise, and information among research universities; federal, state, and tribal agencies; and for-profit and nonprofit organizations. Partnerships can bring ongoing research and historical information to the NEON platform and can be used to reduce redundancy in data collection. Successful NEON observatories will incorporate partnerships with relevant data-gathering and research organizations. NEON proposals for individual observatories and the NCO must clearly indicate that significant partnerships have been developed and that others will be sought. A number of elements important to effective collaboration include what each partner will contribute in terms of data, facilities and staff; a realistic explanation of how goals, cultures, and time scales will mesh; and a clear picture of the synergistic value and benefits of bringing together the unique capabilities of the observatory (or observatory network) and partners. In true partnerships, both sides bring resources to the table (Box 4).

Box 4. Partnerships in Coastal Studies

The Estuaries and Great Lakes Program research centers—funded through the EPA's Science To Affect Results (STAR) program—are uncovering basic relationships between coastal biota and major stressors, such as excess nutrients, habitat degradation, and contaminants. In the process, they are developing advanced analytical approaches to investigate indicators of stressor response in coastal ecosystems. These cooperative agreements encourage university consortia to partner, without the exchange of resources, with research programs in EPA's Office of Research and Development that are developing approaches and tools for assessing conditions and diagnosing impairment in coastal ecosystems. In many instances, university and EPA projects are complimentary. Through these partnerships, problems can be examined at multiple scales: In some cases the university consortium is focused at intensive scales and EPA researchers at extensive scales, and in other cases the focus is reversed. University and government projects benefit from sharing equipment and data. Partnerships also develop intellectual capital, student training and exposure to applied aspects of research. Partners provide the research results of both parties to a broader audience, and this facilitates more rapid exchange of basic research findings with managers and stewards of coastal waters.

4. Scientific Results and Products

NEON will be unprecedented in supporting integrated ecological research at local, regional, and continental scales on all aspects of biological change, from molecules to biomes. It will enable teams of scientists to work collaboratively on common problems at a network of ecological observatories. A well-executed NEON program will result in many difficult-to-anticipate advances in ecological science, as is true for any successful major scientific research platform. One general advance from NEON will doubtless be the explosive development of regional ecology, involving integrated understanding of flows of material, energy, nutrients, biological entities, and information through regional landscapes and watersheds. However, beyond such general statements, it is difficult to predict the specific results that will emerge from NEON. Today's major environmental issues, such as global climate change, oxygen depletion of coastal waters, limited water resources of the Colorado River system and south Florida, and problems with individual species such as the northern spotted owl and salmon in the Pacific Northwest, had not significantly emerged 20 years ago. Similarly, now it is difficult to anticipate the specific, dominant issues that will be the focus of ecological research one or two decades in the future. What we can do is identify the types of data and products that will be produced and that will enable ecologists and others to address questions about ecosystem structure and functioning that are presently impossible to address.

4.1. Types of data

The types of data the NEON will produce follow closely from the suite of instruments deployed at the observatories.

4.1.1. Climate and hydrology

NEON observatories will employ instruments and data-processing capabilities for characterizing regional climate and weather for major ecosystems of the United States over time scales ranging from near instantaneous to decadal. These data will be essential for interpreting biological data on changes in species, communities, and ecosystems.

4.1.2. Biodiversity and population assessment

Providing information on the distribution and abundance of key species of plants, animals, and microbes, both native and exotic, will be one of the most important contributions of NEON. This information is essential for understanding how natural and anthropogenic environmental change affects organisms and ecosystems.

4.1.3. Biogeochemistry

NEON observatories will have instrumentation to measure the cycles of carbon, nitrogen, phosphorous, and other nutrients, as well as contaminants. This will include measuring the exchange of materials between the atmosphere and biosphere. Quantifying these cycles is fundamental to understanding how ecosystems work. Also, these cycles are changing as a result of human activities, and these changes have implications for humans both directly and indirectly through effects on ecosystem goods and services. The unique contribution of NEON will be to provide coordinated data across a network of sites that can be utilized to detect fundamental changes in integrated ecosystem structure and functioning.

4.1.4. Spatial analysis and remote sensing

Remote-sensing technology combined with extensive ground truthing will provide data for understanding land-cover and land-use change at multiple spatial scales.

4.1.5. Manipulative experiments

In addition to providing a diverse array of physical, chemical, and biological data on US ecosystems, NEON will be a platform for ecological experiments that take advantage of the NEON structure (multiple observatories, each with molecule-to-biome coverage). Experiments complement the data-generating activities in providing data crucial for understanding mechanisms controlling ecosystem structure and functioning.

A critical feature of much of the data provided by NEON is that they will be collected according to standard protocols across the major ecosystems of the United States, so that comparisons can be made among sites and data can easily be assimilated to provide regional or national summaries. Another feature is that they will be maintained with appropriate metadata in easily accessible databases so that they are available to a wide range of potential user groups.

4.2. Other products

NEON will generate other products that advance our ability to probe the environment and convert ecological data into ecological knowledge.

4.2.1. New instruments and technologies

NEON will provide the incentive and platform for developing environmental equipment and technologies for more effectively and efficiently describing and understanding ecosystems. See Box 5 for an example of how emerging technologies are advancing our ecological knowledge base.

Box 5. James Reserve

Biologists and engineers at the Center for Embedded Networked Sensing and the James San Jacinto Mountain Reserve are developing next-generation technologies for the study of environmental systems. They are using a wireless network of instruments, coupled with video and audio recording, to measure a diverse range of environmental and biological variables; the network allows Web-based, real-time processing of information.

In one project, they focus on the response of migratory birds to seasonal variation. Small weather stations simultaneously track a variety of meteorological parameters around individual plants, across meadows, and through the forest, continuously measuring sun flecks, rainfall, snowfall, and small-scale variation in microclimates. Nest boxes, currently under construction, are being outfitted with video cameras and mounted on weighing platforms. These will allow continuous observations of bird behaviors including chick interactions, predation, and feeding. A microphone system will be installed so scientists can listen for and locate acorn woodpeckers as they move around their territory feeding, gathering food, and vocalizing. By characterizing the changing microclimates and observing and localizing bird behavior, scientists expect to gain a better understanding of how birds respond to changes in seasonality between different years.

4.2.2. Ecological models

The unique data that will be generated by NEON will in turn spawn the development of new diagnostic and prognostic ecological models. Ecological models are essential tools for integrating theories and guiding future research. Prognostic models also can be utilized for scenario analyses and to provide decision-makers with forecasts about the future responses of species and ecosystems to environmental change.

4.2.3. Data processing, summarization, and communication technologies

In molecular biology, advances in biotechnology created extraordinary amounts of data that launched a whole new field of computer science known as bioinformatics. Drawing on the

Box 6. Ecoinformatics—Defining a New Discipline

Ecoinformatics is a broad, interdisciplinary science that incorporates conceptual and practical tools for the understanding, generation, processing, and dissemination of biodiversity and ecological data and information. The emerging discipline encompasses a range of activities—project and database design, data and metadata acquisition and management, quality assurance and quality control, data archiving and dissemination, and data visualization and analysis—all of which are critical for meeting the needs of scientists, decision-makers, and the public.

Ecoinformatics.org is an open, voluntary collaboration of developers and researchers that aims to produce software, systems, publications, and services that are beneficial to the biodiversity, ecological, and environmental sciences. This active community is developing informatics solutions for the immense challenges these fields present. Such tools will become increasingly important in collaborative research efforts like NEON, as individuals and organizations can become overwhelmed with massive, real-time data streams from in situ environmental sensors, and as they incorporate disparate types of data from many scales of biological organization (i.e., from genes to biomes to global socioeconomic systems) into their analyses.

experience of biotechnology, ecologists and computer scientists are already anticipating a flood of biocomplexity data, and NEON will be a major player in generating such data. This flood of data, combined with advances in environmental and ecological technology, will enable and require the development of a new ecoinformatics. While building on the foundations of bioinformatics, ecoinformatics will generate data sets that are vastly larger and more complex than any previously created. NEON will play a key role in the development of ecoinformatics (Box 6).

4.2.4. Specimen and samples

As part the research activities, specimens and samples will be collected. These will represent a valuable resource long into the future. Specimens will be maintained and samples will be archived so that they are available to other users. Information on the existence and location of specimens and samples will be available through the NEON information network.

5. Education and Public Outreach

Education and public outreach are critical components of NEON. NEON will provide an unprecedented platform for developing new intellectual capital as well as physical infrastructure for research. For NEON to remain vibrant and effective over its life span, and for it to succeed in revolutionizing the sciences of ecology and environmental science, it must engage and involve students, scientific and nonscientific groups, and the general public at all levels. Training a new generation of scientists and increasing public scientific awareness are significant objectives of the NEON program.

5.1. Opportunities

In addition to having access to NEON resources, students at all levels will be directly involved in NEON activities, and volunteers will be encouraged to actively participate in data collection and assessment programs. NEON sites will develop programs that build on successful models of student and volunteer participation in ecological research such as the Jason Project and the Schoolyard LTER program (Boxes 7 and 8). Another key feature of NEON educational activities

Box 7. The Jason Project

The Jason Project, initiated in 1989 by the oceanographer Robert Ballard, is based on the idea that students and their teachers can do field work from the classroom. The project is a year-long, multidisciplinary course that explores the biological and geological development of our planet and allows students to interact with leading scientists. The curriculum includes a two-week virtual research expedition, during which students and teachers interact through Internet and satellite technology with a team of scientists conducting research at locations featured in the curriculum. Students learn about nature's dynamic systems, how they affect life, and what technologies are used to understand them.

The Jason Project takes its name from the eponymous Greek hero, who in Western mythology was the first great explorer to sail the seas on a ship called the Argo. Jason called his crew of navigators, shipbuilders, engineers, musicians, and warriors the Argonauts, and the Jason Project's goal is to educate the next generation of student and teacher Argonauts.

will be to enhance NSF initiatives to promote minority education and research in environmental biology. Collaborations with minority-serving institutions will be promoted, and NEON educational activities will coordinate with successful minority education programs. NEON will serve as a model of true integration of research and education. It is expected that presentations of NEON-related research at national meetings will include presentations of educational activities at NEON observatories. NSF will be able to highlight the education activities of NEON when promoting NEON research results to national media outlets.

A crucial function of NEON will be to coordinate, process, and synthesize the vast array of data continuously fed into the network. Real-time and continuous collection, analysis, synthesis, and projection of all network data will form the backbone of NEON's dynamic and user-ready knowledge base. Specialized Internet portals will be available to scientists, agencies, students, professionals, and the public and will provide access to the NEON ecological knowledge base. The value of such a dynamic and integrated resource to the teaching community and other public and private organizations will be considerable.

Box 8. Schoolyard LTER

Ecology Explorers is a K–12 education program, run by the Central Arizona–Phoenix Long-Term Ecological Research (CAP LTER) program, whose aim is to improve science literacy by engaging students and teachers in research. The program exposes students and teachers to research conducted by university-level scientists and gives students the means to conduct ecological investigations in their own schoolyards. Students enter their results into the CAP LTER database, share data with other schools, and develop hypotheses to explain their findings. The program enhances teachers' ability to design lessons and activities that use scientific inquiry and encourage interest in science.

Teachers consistently laud this program for its integration of research projects into their curriculum and for the support they receive from CAP LTER education staff. They report that students' math abilities improve after participating in Ecology Explorers, and that poster presentations enhance students' communication skills. Furthermore, the teachers themselves come away from the program with a better understanding of ecological research. Students' enthusiasm for projects is high—they feel that the projects are important because of the university connection—which results in a willingness to put in extra effort.

5.2. Organization

Like research activities, the education and public outreach activities of NEON will be organized with strong national-level programs to leverage capabilities of the full network balanced against the unique local opportunities at each observatory.

5.2.1. National level

To manage and promote NEON resources to users at all levels, effective and full-service education and public outreach programs will be maintained as integral and highly centralized parts of the NEON structure. Education and public outreach committees will guide the NEON education and public outreach missions and formulate strategic plans, which address implementation and rigorous evaluation. The education committee will explore all areas of formal and informal education, specifically focusing on the K–12 and undergraduate levels, but also including continuing education and special programs targeting underrepresented groups. Professional staff in the NCO education and public outreach offices will implement the education and public outreach strategic plans and coordinate programs with regional observatories. In addition, NCO staff will manage national-level activities and initiatives, such as interfacing with national organizations and conducting broad-scale initiatives involving large geographic regions.

The NCO education office will cooperate with schools, organizations, and education groups at the local and national level to develop curricular materials for classrooms and other programs. Educational programs will emphasize research and collaboration with NEON programs (e.g., Research Experiences for Undergraduates, graduate thesis fellowships), and materials that are developed will include standards-based curricula that incorporate NEON-specific research through on-site, classroom, and Internet-based instruction. Mechanisms for evaluating outcomes and program effectiveness will also be developed. All sectors of education will be engaged, including K–12, undergraduate, graduate, continuing, public, private, minority, and tribal. NEON will build collaborations with national education organizations and with institutions, such as tribal and historically black colleges and universities, and organizations representing groups underrepresented in science.

Examples of national education programs with potential for NEON partnership:

- Alliances for Graduate Education and the Professoriate (AGEP)
- NSF's Alliances for Minority Participation (AMP) and Undergraduate Mentoring in Environmental Biology (UMEB)

- Ecological Society of America's SEEDS program
- AIBS's Diversity Scholars program.
- Environmental Protection Agency's Tribal Science Council
- National Education Association
- National Association of Biology Teachers
- Association of College and University Biology Educators
- BioQUEST Curriculum Consortium

This office will also develop independent NEON-based education programs to be offered at NEON facilities, national and state parks, museums, education centers, and other venues. If an observatory develops a program of excellence in one of these educational areas, it may be used as models for other sites. Workshops and training programs will be designed and implemented that make use of observatories for undergraduate and graduate students and provide professional development for teachers.

The public outreach office will actively promote NEON resources and opportunities to the public. It will interface with print and broadcast media to facilitate articles and programs to which NEON facilities, research programs, or staff and research personnel can contribute (e.g., popular science magazines, radio and television programs). Another of its responsibilities will be to publish newsletters and disseminate press releases announcing facility or research program accomplishments and items of popular, scientific, or agency interest (e.g., print, graphic, multimedia, or Web based). The public outreach office will coordinate closely with the education office and enact relevant recommendations from the public outreach committee. Public faces of NEON, such as visitor centers, tours, interpretive trails, natural areas, Web sites, publications, and so on, will be developed and promoted. Public participation at NEON observatories will be fostered, by means of open houses, activity days, volunteer and docent programs, and community-driven projects and initiatives. Special efforts will be made to reach sectors of society traditionally underrepresented in science and environmental programs. Duties of the public outreach office may be distributed among observatories and may be efficiently incorporated into existing public outreach programs at partner institutions, such as museums, field stations, and national parks.

The public outreach office will hold regional and national forums to disseminate information and solicit new cooperation. It will cooperate with public outreach efforts of federal agencies (e.g., National Park Service, state parks), as well as manage Internet resources for agency, nontechnical, and public use. In addition, this office may develop and manage donor, membership, volunteer, and docent programs to enhance public involvement in observatory activities, including direct participation in observational efforts, and serve as a development office for special projects and donor management.

5.2.2. Observatory level

Each regional observatory will maintain active and integrated education and public outreach programs that pursue local and regional initiatives by interfacing with local programs and organizations. In addition, regional observatories will cooperate through the NCO offices, and participate in national education and outreach initiatives. The US Department of Agriculture's Cooperative State Research, Education, and Extension Service (CSREES) offers very good examples of outreach and education projects, and their overall structure is a good model for the NEON network.

6. Benefits and Applications

NEON generated data and research will provide a wide array of benefits to the research community, natural resource managers, and the public at large.

6.1. Benefits to the scientific community

NEON will provide critical infrastructure to support NSF research programs such as Biocomplexity in the Environment, which is designed to address questions such as these: How do systems with living components respond and adapt to stress? Are biological adaptation and change predictable in a changing environment? How will climate change affect species' ranges across multiple trophic levels? Can we forecast the combined effects of climatic and socioeconomic change? How does diversity (species, genetic, or cultural) affect ecosystem sustainability? These major research challenges cannot be adequately addressed with the current infrastructure available for instrumentation, data integration, and information management.

In a January 2003 report, the NSF Advisory Committee for Environmental Research and Education recommended increased research focus on three interrelated areas: coupled human and natural systems research, coupled biological and physical systems, and people and technology. Coupled human and natural systems research integrates population, ecosystem, and socioeconomic models to understand issues such as landscape fragmentation, spread of pathogens, human impacts on aquatic ecosystems, and economic valuation of ecosystem services. Coupled biological and physical systems research addresses questions related to biogeochemical cycles, climate change, and the relationship between biodiversity and ecosystem dynamics. Research in people and technology seeks to understand how individuals and institutions interact with the environment, how they use resources and respond to change, and how they create and implement new technologies. NEON will provide the platform for performing research in these areas, as well as data integration across all relevant scales and rapid information synthesis and management.

NEON-supported data and facilities will offer a cost-effective platform for both observational and experimental research by scientists from the full spectrum of research institutions. The NEON program can fill a significant gap in infrastructure for researchers from smaller institutions who want to conduct large-scale ecosystem research. Long-term spatial and temporal trends in biological diversity provided by NEON will aid researchers in understanding and predicting the distribution and abundance of many types of organisms. NEON sites will serve both as a hub for information storage and retrieval and as a synthesis center for large-scale patterns. The NEON infrastructure will allow us to see patterns that smaller, localized studies cannot elucidate, such as a widespread signal in decline of genetic diversity in biota or a subtle but consistent long-term change in biogeochemical processes. The effort to integrate data from diverse disciplines will facilitate new syntheses in understanding ecosystem dynamics. It is expected that significant advances will be made in developing new instruments for ecosystem analysis. Implementation of the NEON program will promote novel approaches to studying the ecosystem, as scientists refine the array of instruments that are developed and deployed, the measurements that are taken, and the information that is synthesized. This synergy of new tools and approaches will advance the frontiers of knowledge and research capacity in ecology and will produce new perspectives in ecosystem science.

6.2. Benefits to natural resource managers

The NEON infrastructure will encourage collaboration between the research community, environmental monitoring programs, and the natural resource management community. NEON units will serve as a hub to attract collaborative research among scientists in the academic community, agency scientists, and other investigators. NEON units can provide data to support national programs. These collaborations will yield rich benefits to all partners. Biological and ecological information from NEON sites will help a wide array of scientists involved with national and regional monitoring programs.

Examples of national natural science programs with potential for NEON partnership:

- Efforts associated with the Global Change Research Program
- National Report on Sustainable Forests, US Forest Service
- AmeriFlux program
- National Biological Information Infrastructure, USGS
- State of the Nation's Ecosystems, Heinz Center
- Environmental Monitoring and Assessment Program, EPA
- Natural Resources Inventory, USDA
- National Forest Health Monitoring Programs, US Forest Service
- North American Breeding Bird Survey, USGS
- Chesapeake Bay Program, EPA
- Great Lakes Program, EPA
- Gap Analysis Program, USGS
- National Water Quality Assessment, USGS
- National Atmospheric Deposition Program

The location and design of the NEON sites will help establish regional reference points for biological and ecological indicators of ecosystem function. State and federal agencies are attempting to establish regional biological and environmental criteria in setting goals for environmental management and protection. One example is the EPA's efforts to develop nutrient criteria for water by ecoregion. The NEON program can provide a theoretical basis for selection and application of these indicators. NEON sites will also provide valuable information on natural variation in biota and ecological processes that form the basis for many of the indicators deployed by regional- and national-scale monitoring programs. Although many of these programs have identified the need for intensive site studies (Figure 4), they lack information on seasonal and yearly variability, which makes interpretation of indicator results difficult.

Data emerging from NEON research sites will help inform decisions regarding management of the nation's natural resources. Land and water managers with tribal, county, state, federal, and nonprofit organizations will benefit from access to specific databases and from regional NEON

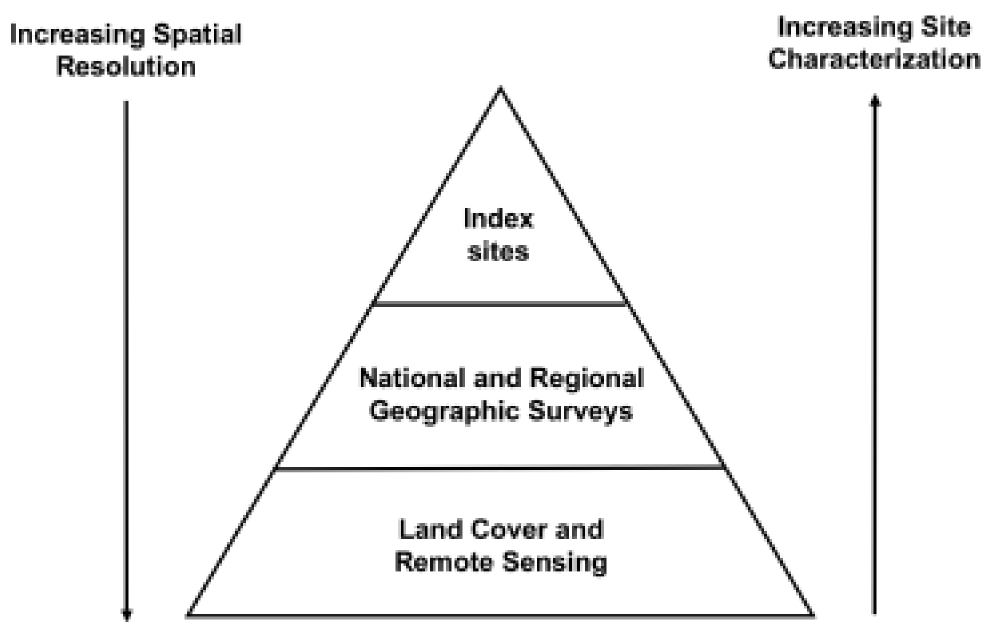

Fig 4. The tiered monitoring approach used by the Environmental Monitoring and Assessment Program. Redrawn from US Environmental Protection Agency. 2002. Research Strategy Environmental Monitoring and Assessment Program. EPA 620/R-02/002. Office of Research and Development. Washington, DC: US Environmental Protection Agency.

data summaries. Managers of parks, refuges, reserves, and other natural areas will benefit from access to regional biological and environmental data to compare with their local trends. Improvement in biological and ecological models will increase the ability of natural resource managers to interpret and predict conditions, changes, and trends over extensive spatial and temporal scales. Detailed information on seasonal and yearly variation in population level processes will contribute to the development of robust habitat conservation plans for threatened and endangered species and will improve models and estimates of species' distributions that form the basis for programs like the USGS Gap Analysis Program.

NEON sites will also support extensive research on molecular phylogenetics and phylogeography of plants and animals. Federal and state agencies are increasing their use of molecular and systematic data (e.g., Evolutionarily Significant Units) to establish conservation priorities for animal and plant populations. Molecular and systematic data are also used to assess the potential consequences of human activities on threatened, endangered, candidate, and sensitive species (NMFS 1997). NEON sites will serve as a source of efficient and consistent data collection, integration, and synthesis that will benefit environmental managers and scientists who are trying to make decisions about conservation and management of populations and species.

6.3. Benefits to society

NEON will benefit society by improving our understanding of the implications of ecosystem change for human welfare. Healthy ecosystems provide many goods and services that are essential underpinnings of our nation's economy. Ecosystem services include drought and flood control, pollination of crops, purification of air and water, pest and weed control, carbon storage, and decomposition of wastes, while goods include food, fiber, and pharmaceuticals. The NEON program will allow us to understand the dynamic and complex interactions that maintain healthy ecosystems and to forecast the response of ecosystems to global change.

The NEON program will complement existing land- and satellite-based networks that study and predict the ecological effects of major meteorological and geological events such as hurricanes and volcanic eruptions. When meteorological networks predict the location, force, and timing of a hurricane, data from NEON can be used to predict the ecosystem responses to this event. NEON research will help us to predict and understand responses to hurricanes, such as impacts to estuaries and fresh water systems from nutrients and pollutants that run off land, impacts to soil and terrestrial ecosystems due to flooding, impacts to forest ecosystems caused by gaps created by windthrow, and impacts to marine ecosystems caused by coastal erosion.

In addition to forecasting the ecological and environmental effects of extreme natural events like fire, floods, droughts, and storms, the NEON program will allow us to assess ecosystem response to human-induced stresses such as acid rain and global warming. Understanding ecosystem responses to such global or regional phenomena requires the ability to integrate data across multiple scales and to relate large-scale biogeochemical and climatic changes to population-level changes. For example, Pacific salmon populations are likely to decrease or shift northward in response to global warming because they prefer cold-water habitats. Decline of Pacific salmon will have an economic impact on salmon fisheries and a cultural impact on tribal communities. In addition to the human impacts, there will be significant ecological impacts because salmon are an important link in the food chain and they convey nutrients from marine ecosystems to the headwaters of rivers, where they die after spawning (Gende et al. 2002, Schindler et al. 2003)

Although ecologists have long recognized that healthy ecosystems require a complex web of interactions among species, many questions remain about how biodiversity influences ecosystem dynamics. NEON will provide the infrastructure necessary to unravel the relationships between species and their interactions and the physical environment. Understanding these relationships will provide us with the tools to explain and address the widespread decline of species such as many amphibians and native pollinators. NEON research will significantly improve efforts to conserve threatened and endangered species through the development of effective habitat conservation plans. In addition, the NEON program will help society discover the wealth of biological diversity that remains to be catalogued and described by taxonomists. The discovery of a new species can provide monumental benefits for society. For example, the discovery of a bacterial species that flourishes in the hot acid springs of Yellowstone National Park led to the purification of an enzyme that enabled scientists to develop the polymerase chain reaction (PCR) technique necessary for sequencing genes (Brock 1967, 1997). The ensuing revolution in molecular genetics has provided a host of medical and scientific benefits to society, including the Human Genome Project.

The multi-scale patterns that emerge from the NEON program will substantially improve our ability to predict and respond to wildfires, outbreaks of insect pests, and harmful algal blooms. Wildfires and insect outbreaks have strong economic impacts on agriculture and forestry and can harm recreational and tourist industries. Harmful algal blooms create public health concerns and cause economic harm to fisheries. The NEON infrastructure will also provide powerful analytical tools for understanding the ecological factors that promote outbreaks of Lyme disease, hantavirus, West Nile virus, and other emerging infectious diseases. The links between pathogen outbreaks and environmental conditions is well illustrated in the 1993 discovery of Hantavirus Pulmonary Syndrome in the Four Corners area of southwestern United States. High snow and rainfall in 1993 followed several years of drought in the region. A dramatic increase in rodent populations occurred because food sources were plentiful. The likelihood of disease transmission from infected rodents to humans soared (Yates et al. 2002). Recent studies have shown that hantavirus infects rodents across the continent in every habitat type from deserts to alpine tundra (CDC 2002). NEON sites will serve as a platform for research on population dynamics of rodents and other vectors of disease such as deer ticks (Lyme disease) and mosquitoes (West Nile virus). Even more importantly, NEON sites can search for wide scale temporal and spatial patterns in climate, vegetation, and animal populations that relate to outbreaks of these diseases.

A report from the Congressional Research Service (Corn et al. 2002) identifies invasive non-native species as a serious threat to our nation's economy. Seventy-nine species (out of 4,500 known non-native species) caused $97 billion in damage between 1906 and 1991 (OTA 1993). As new species invade and the range of invasive species increases, costs increase. Recent reports estimate that there are currently 50,000 non-native species in the United States resulting in losses of $137 billion annually (Pimentel et al. 2000). Non-native plants such a cheatgrass, yellow star thistle, purple loosestrife, and kudzu harm rangelands, wetlands, and aquatic systems. Invasive insects such as fire ants, Africanized honeybees, Asian long-horned beetles, and the Mediterranean fruit fly harm agriculture, livestock, and the timber industry. Aquatic species such as European green crabs, zebra mussels, and Asian river clams disrupt aquatic food chains and interfere with power plants and industrial water systems. NEON is a powerful research tool for discovering and identifying new introductions of non-native species and investigating their ecological impacts.

Discovering the nature and pace of ecological change at varied spatial and temporal scales will help us to better understand how human activities interact with natural ecosystems. Documenting multi-level interactions requires the technological and informational infrastructure that NEON will provide. Society will benefit from understanding complex linkages such as the link between farm fertilizers and the hypoxic zone in the Gulf of Mexico (Rabalais et al. 2002a, 2002b), and the effects of ozone depletion on marine food chains (Worrest and Häder 1989, Smith et al. 1992). The connections between NEON sites will allow us to decipher the interactions between environmental stresses such as pollution and land degradation and the spread of invasive species over regional to continental spatial scales. In a similar fashion, the connections between NEON sites will allow us to track global climate change effects and understand the impact of events such as El Niño over short- and long-term temporal scales.

Finally, as described in the preceding section, NEON will provide substantial and far-reaching educational opportunities to our nation. The NEON program will boost scientific literacy and aid in development of a well-trained professional and technical work force. NEON will serve as a model for similar programs under development worldwide, and it will provide critical data for international global change and ecosystem assessment programs.

7. Conclusion

The forefront of ecological research is headed evermore toward a focus on questions and concepts that are relevant over large geographical regions, and this highlights the need for coordinated scientific infrastructure that is itself spread over large regions. Ongoing advances in our technical capability permit the development of networks of people and tools that can meet that need. NEON has been designed by the scientific community to capitalize on such capabilities and to enable discoveries about our nation's ecosystems that until now have been impossible to address. By fostering collaboration, the development of new tools and technologies, and the study of regional- and continental-scale questions, NEON will produce new perspectives in ecosystem science and thus public benefits, both anticipated and unforeseeable.

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Sources of Public Comment

IBRCS/NEON Town Meetings

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The IBRCS Project

The IBRCS Project, an effort by the American Institute of Biological Sciences (AIBS), launched in August 2002 with support from the National Science Foundation. The following are the project's goals:

- Help the biological and the larger scientific community—within and beyond the AIBS membership—to determine the needs and means for increased physical infrastructure and connectivity in observational platforms, data collection and analysis, and database networking in both field biology and other more general areas of biology and science.

- Provide for communications within this community and with NSF regarding the development and focus of relevant infrastructure and data-networking projects.

- Facilitate the synergistic connection of diverse researchers and research organizations that can exploit the power of a large-scale biological observatory program.

- Disseminate information about biological observatory programs and other relevant infrastructure and data-networking projects to the scientific community, the public policy community, the media, and the general public.

The project is led by a working group comprising biologists elected from the AIBS membership of scientific societies and organizations and appointed from the scientific community at-large. It is assisted by Jeffrey Goldman, the project manager on the AIBS staff, and various technical advisors. The working group was assembled during the summer and fall of 2002.

The project has a special focus on the National Ecological Observatory Network (NEON) program, which is a major NSF initiative to establish a national platform for integrated studies and monitoring of natural processes at all spatial scales, time scales, and levels of biological organization. Funding for the NEON program has been proposed in the FY 2004 NSF budget, but Congress has not yet approved the expenditure.

Jeffrey Goldman, PhD, is the IBRCS project manager. Principal investigator under the grant is Richard O'Grady, PhD, AIBS executive director. Additional information is available at *http://ibrcs.aibs.org*

ibrcs.aibs.org

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