Integrated Science and Education Plan
for the
National Ecological Observatory Network

October 23, 2006

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Executive Summary

NEON and the Grand Environmental Challenges

The biosphere is the living part of planet Earth. It is one of the planet's most complex systems, with countless internal interactions among its components and external interactions with physical processes of the earth, oceanic, and atmospheric environment. This complexity leads to some of the most compelling questions in science, because the scientific challenges are so great and because humanity is an integral component of the biosphere. Humans use a diverse set of services and products of the biosphere, including food, fiber, and fuel—and depend on the air and water quality that the biosphere maintains.

NEON is a bold effort to build on recent progress in many fields to open new horizons in the science of large-scale ecology. NEON science is explicitly focused on questions that relate to the Grand Challenges in environmental science, are relevant to large regions of the United States, and cannot be addressed with traditional ecological approaches. The Observatory is specifically designed to address central scientific questions about the interactions of ecosystems, climate, and land use:

- How will ecosystems and their components respond to changes in natural- and human-induced forcings such as climate, land use, and invasive species across a range of spatial and temporal scales? And, what is the pace and pattern of the responses?

- How do the internal responses and feedbacks of biogeochemistry, biodiversity, hydroecology and biotic structure and function interact with changes in climate, land use, and invasive species? And, how do these feedbacks vary with ecological context and spatial and temporal scales?

These questions reflect a fundamental scientific curiosity about the nature of the world we live in. We would like to know the magnitude, pace, and geography of ecological changes, and to understand the underlying mechanisms and implications of such changes for species and for the provision of ecosystem services to humans. These fundamental questions are as compelling as questions about the origin of the universe, the origin of life, or the nature of consciousness; answering these ecological questions is critical to the future of human well-being.

A New Approach to Science

The science to be addressed by NEON relies on a body of theory that includes: (1) physical theory that describes the motions of the atmosphere or the partitioning of energy at the Earth's surface, (2) ecological theory that describes the process of community assembly, (3) genetic theory that describes the rate of spread and evolution of a disease organism, and (4) ecosystem theory that describes carbon and nutrient turnover. Although theory in each of these areas is relatively mature, the scientific community has limited experience integrating theory from contrasting sub-disciplines and using the products to understand and predict the response and feedbacks of interconnected systems. Developing these integrated theories will require a combination of precisely defined studies focused on details of the integration, plus broad investigations that enable tests at the level of integrated systems. Transforming ecology into a predictive science at the regional to global scale will require a coordinated program of theory development, testing, and refinement.

NEON is designed to be a continental-scale research platform for discovering and understanding the fundamental ecological principles that govern the responses of the large-scale biosphere (including responses to land use and climate change) and feedbacks with the geosphere, hydrosphere, and atmosphere. The NEON mission is to provide the capacity to forecast future states of ecological systems for the advancement of science and the benefit of society. The Observatory's network of coordinated sensors, experiments, and cyberinfrastructure will collect the ecological data needed to develop the scientific understanding and theory necessary to manage the Nation's grand ecological challenges.

NEON will embody two primary strategies for observations and experiments, both supporting the forecasting mission. First, the Observatory will be a sentinel for quantifying both gradual and sudden changes, and their causes and consequences. Second, NEON will support targeted improvements in forecasting capability through focused critical ecological measurements, experiments, and models to improve the understanding and predictability of ecological processes.

The NEON Design

NEON is based on a stratified design that combines comprehensive coverage of the United States from partnering agencies which manage space and aircraft platforms with more intense deployment of infrastructure in carefully selected representative areas, transects critical for understanding particular drivers of and responses to change, and other sites of special interest. In addition, the Observatory offers the potential for deploying networks of manipulative experiments to explore parts of the space-time domain that are inaccessible with other approaches.

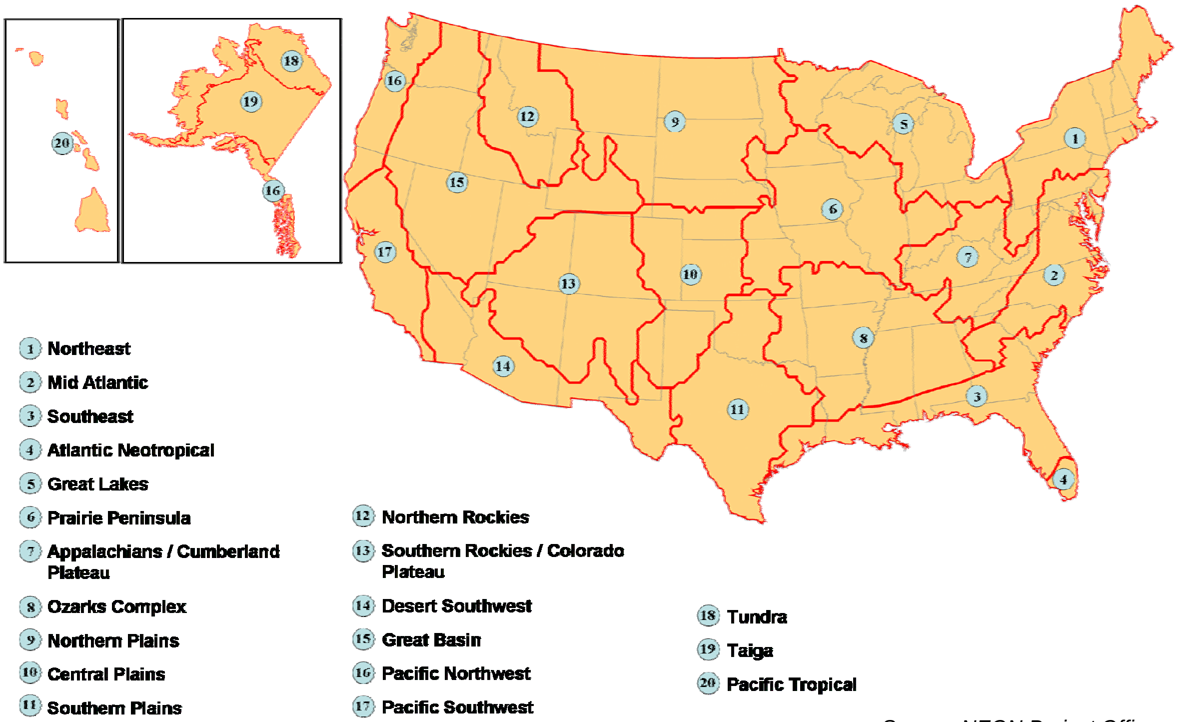
NEON will link diverse technologies and approaches in a coordinated framework that delivers standardized, high-quality measurements over an extended time period in locations and along gradients sited to provide access to the broad range of large-scale ecosystems, processes, and feedbacks. NEON will make major investments in seven interrelated aspects of its research program. These are:

1. Twenty heavily instrumented core sites, located in wildland areas selected to span the range of major US climate zones and ecosystems.

2. Airborne observatory platforms with remote sensing instruments to provide regional information for scaling and extrapolation from sites.

3. Gradient sites, serviced by mobile or relocatable systems, located to facilitate understanding through observations of ecosystems exposed to long-term differences in key environmental or human-dimension factors, such as elevation, precipitation, land use, time since disturbance, and location within a major watershed.

NEON Climate Domains



Source: NEON Project Office

NEON partitions the United States into 20 climatic domains ranging from the tropics of South Florida to the tundra of Alaska. The approach for defining climatic domains is twofold: (1) cluster analysis of climate state variables, and (2) resultant wind vectors to delineate climatic regions based on airmass seasonality.

4. Sites of opportunity served by mobile systems selected to allow detailed study of an important process, trend, or intervention, such as recovery from a major wildfire, response to an invasive species, conversion to agriculture, abandonment from agriculture, or rehabilitation of an urban watershed.

5. National scale experiments, subjected to coordinated manipulations (such as warming, altered precipitation, and reduced biodiversity) to assess large-scale controls on ecosystem responses, especially for processes where the spatial gradients are not informative.

6. Cyberinfrastructure to support diverse observations and models, and manage the data and output they produce, including autonomous sensor networks and high-resolution animal tracking systems.

7. Education and outreach programs that prepare the scientific community to use NEON to the fullest, enhance the science by enlarging and diversifying the research community, and prepare and support the public to use and benefit from NEON to better understand and effectively address critical ecological questions and issues.

The Observatory Infrastructure

NEON infrastructure includes a standard set of instruments to collect biological, biophysical, biogeochemical, and land use and land management data across the continent, as well as facilities and cyberinfrastructure. The instrumentation is organized into five instrument packages:

1. A Fundamental Instrument Unit (FIU) that provides comprehensive monitoring of climate and fluxes between ecosystems and the atmosphere, using a suite of towers and aquatic and terrestrial sensor arrays.

2. A Fundamental Sentinel Unit (FSU) that supports diverse measurements on organisms, soils, hydrology, aquatic processes.

3. A Mobile Relocatable System (MRS) that provides investigators with flexibility in the deployment of instrumented systems to collect data.

4. An Airborne Observation Platform (AOP) with remote sensing instruments to provide regional information for scaling and extrapolation from sites.

5. A Land Use Package (LUP) that supports comprehensive assessment and analysis of patterns, changes, and drivers of land use, land cover, and land management.

In addition to the integrated measurement systems, the Observatory includes facilities for physical processing, analyzing, archiving, and curating biological, water, air, and soil samples that are routinely collected.

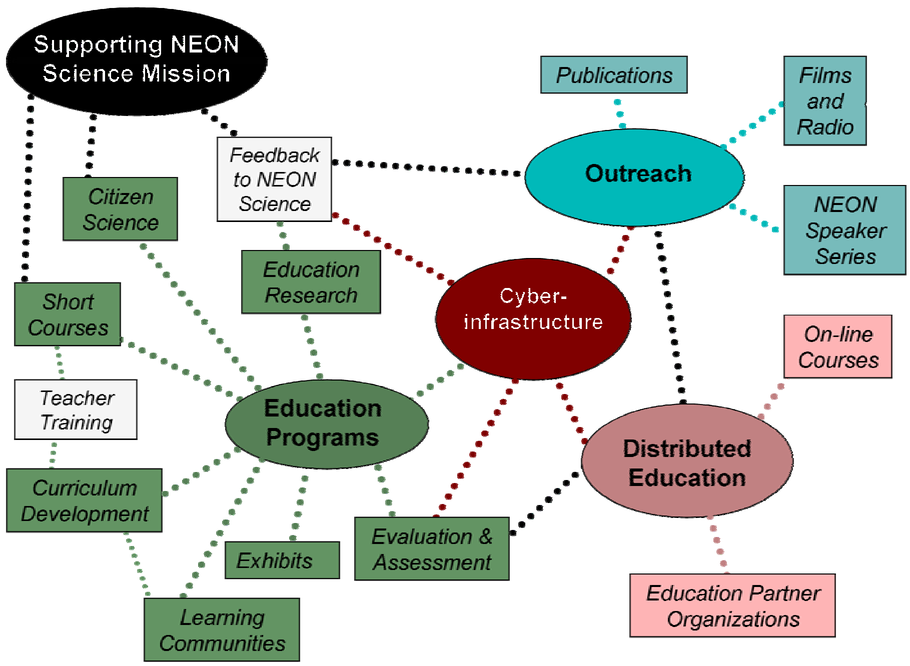
The Observatory will provide a comprehensive end-to-end cyberinfrastructure for NEON data—from the acquisition of data via field-based embedded sensors and remote sensors, through data and information processing, to the transfer of Observatory data, information, and knowledge to the NEON community. This vision of cyberinfrastructure encompasses many functions, including the rapid communication and secure preservation of high-quality data, timely dissemination of NEON data and information products, and broad-ranging support for public access and education.

Integrating Education with Science

The NEON education program is fully integrated with the Observatory science program and is designed to translate scientific data into meaningful information that citizens can understand and use; provide the environment for people to collaborate, investigate, and learn; and support the professional development opportunities that scientists and educators need to become more effective researchers and teachers. Furthermore, the Observatory offers an optimum environment for supporting education research projects that complement scientific research endeavors, and that can lead to improved methods for teaching ecological concepts and optimal approaches for delivering information to citizens.

NEON education serves learners in both formal and informal education settings. Students ranging from K-12 to undergraduate and graduate levels plus postdoctoral scholars will have unprecedented access to large databases, information, and resources that support science and technology training. These results can be attained through training and outreach activities, new curricula, and web-accessible training modules. Citizen science and school-based programs will support field data-collection activities and help create the mindset that transforms the learning paradigm for ecological

Organizational Integration of NEON Science Components with Education and Outreach Activities



Source: NEON Project Office

science from a top-down model to one built around the concept of information feedbacks. Observatory programs promote an information pathway in which learners can also produce data and information and add to the accumulated knowledge base.

An Era of Collaboration

Governed by a member-elected board of directors, NEON, Inc. will cultivate broad bottom-up participation and community input while ensuring the centralized management of the project and a clear line of accountability to NSF, the primary funding agency. During the operational phase, NEON, Inc. will coordinate the scientific planning, cyberinfrastructure development, and education and outreach efforts with input from community members participating on standing and ad hoc committees. With community-based committee recommendations filtering up to NEON management through transparent processes, NEON, Inc. will maintain open access to NEON resources, including facilities and data. In addition, appropriate committees will be formed to assess technological advances and ensure that NEON benefits from technical innovations throughout its operating lifespan.

NEON will build partnerships with the academic research community, government, and private sectors in the following areas: sensor network development; information management and delivery; resource sharing; data collection; analysis and forecasting; education and knowledge transfer; and international collaboration. Collaboration with partners will ensure that NEON is well-designed, cost-effective, and configured for interoperability and the timely dissemination of results. Furthermore, the NEON education program will develop partnerships with educational organizations such as schools, universities, and museums at national and domain levels.

Discoveries enabled by NEON will be important in public policy development. Through partnerships with organizations such as the Heinz Center for Science, Economics and the Environment, scientists and policy analysts will work together to inform the decision-making process with continuous access to the strongest and most up-to-date scientific information. Advancing international observational collaborations is also a priority because of the global nature of ecological systems. NEON will be a key and enabling US contributor to the international Global Earth Observing System of Systems (GEOSS), making significant contributions to international efforts to assess and predict the performance of key environmental systems.

Meeting a Critical Need

The Grand Challenge questions cannot be answered with a program less ambitious than NEON because the key mechanisms and feedbacks operate at continental and decadal scales. NEON establishes a new level of ecological science. It is the first ecological observatory network designed to test and develop ecological theory by detecting and forecasting ecological change at continental scales over multiple decades. Such research will enable a deep understanding of large-scale processes, feedbacks, and implications for both ecosystems and human societies. Continuous NEON data streams, made possible by state-of-the-art computing power and sensor and communications technologies, will be a national resource for ecological research.

NEON education is designed to advance ecological science literacy through new programs and activities that develop and promote scientific ways of thinking. Through formal and informal education initiatives, Observatory science educators can accurately translate scientific data into meaningful information that connects citizens with the science of their local, regional, continental, and global ecological systems.

CHAPTER 1

NEON Science:

Ecosystems in a Changing World

Chapter 1. NEON Science: Ecosystems in a Changing World

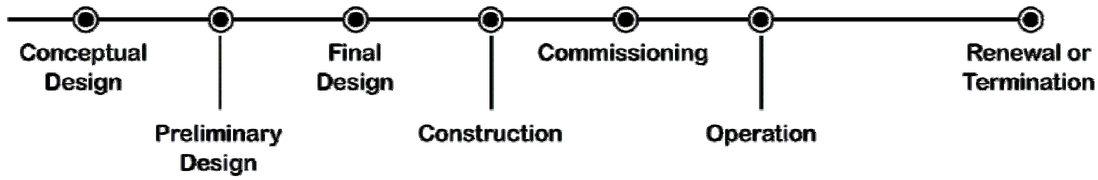
The Broader Context

The biosphere is the living part of Earth. It is one of the planet's most complex systems, with countless internal interactions among its components and external interactions with the Earth's physical processes and its oceanic and atmospheric environments. This complexity leads to some of the most compelling questions in science, in part because the scientific challenges are so great and because humanity is an integral component of the biosphere. In an era of dramatic changes in land use and other human activities, the responses of the biosphere to human activities are of much more than academic interest. Humans use a diverse set of biosphere services and products, including food, fiber, and fuel, and are dependent upon the maintenance of air and water quality. Enhancements or disruptions of these services could alter the fundamental trajectory of the human endeavor over large parts of the world.

Experimental research and derived theoretical analyses show that a wide range of biotic and physical processes link the biosphere, geosphere, hydrosphere, and atmosphere. Our understanding of the biosphere's responses, and the way these responses feed back to affect processes in the geosphere, hydrosphere, and atmosphere, does not match our increasingly sophisticated understanding of Earth's physical and chemical systems at regional, continental, and global scales. Because many of these responses and feedbacks are intrinsically scale-dependent, they cannot be investigated with studies on small plots or over short periods of observation. The National Ecological Observatory Network (NEON) is a bold effort to build on recent progress in many fields to open new horizons in the science of large-scale ecology. NEON science focuses explicitly on questions that relate to grand challenges in environmental science, are relevant to large regions of the United States, and cannot be addressed with traditional ecological approaches. Because the NEON endeavor is transformational in nature, it will be the first project from the National Science Foundation's Directorate for Biological Sciences to qualify for funding consideration through the Foundation's Major Research Equipment and Facilities Construction (MREFC) Account (Box 1.1).

The nation's Grand Challenges in environmental science have been recently reviewed by the National Research Council, the International Geosphere-Biosphere Programme, the Millennium Ecosystem Assessment, Diversitas, and the US Climate Change Science Program. These challenges span three distinct frontiers for enhancing our knowledge of the biosphere: (1) understanding and predicting the way ecosystems work and respond to changes, especially at large scales; (2) understanding how ecosystem processes feed back to alter physical processes, including climate and hydrology; and (3) understanding the implications of these processes and feedbacks for the human endeavor. The Grand Challenge areas identified by the National Research Council are biodiversity, biogeochemical cycles, climate change, hydroecology, infectious disease, invasive species, and land use (Box 1.2).

Box 1.1 NEON and the MREFC Process



Source: NEON Project Office, based on NSF 's Guidelines for Planning and Managing the Major Research Equipment and Facilities Construction (MREFC) Account, Nov 2005

NEON construction and deployment are being considered for funding through the National Science Foundation's Major Research Equipment and Facilities Construction (MREFC) Account. The purpose of this account is to provide "state-of-the-art tools that are centralized in nature, integrated systems of leading-edge instruments, and/or shared-use networked infrastructure in advancing one or more fields of scientific study" (NSF, 2005). Additionally, the MREFC account was established to provide a stable funding source for projects that would otherwise create short-term perturbations in the budgets of individual directorates and programs.

The lifespan of an MREFC project involves seven stages: Conceptual Design; Preliminary Design/ Readiness; Final Design (for National Science Board approval); Construction; Commissioning; Operation; and Renewal/Termination. The developmental phase of the project (Conceptual through Final Design) is a multi-step process of iterative refinement of scope and specifications leading to acceptance and the release of construction funds.

The NEON Integrated Science and Education Plan (ISEP) and the Networking and Informatics Baseline Design (NIBD) are both components of the Conceptual Design Stage. The purpose of these documents is to articulate the conceptual approach with respect to the scientific, technical, and programmatic components of the Observatory. The ISEP presents a vision of how NEON will be used; the NIBD describes the cyberinfrastructure that will support and enable that use.

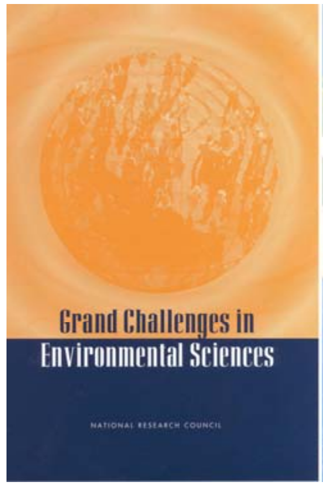
As NEON advances through the MREFC development and review process, the level of detail and the specificity of technical requirements will increase. The transition from one stage to the next will be mediated by a formal review and continued input from the community.

Box 1.2 Grand Challenges in the Environmental Sciences from the National Research Council (NRC 2001, 2003)

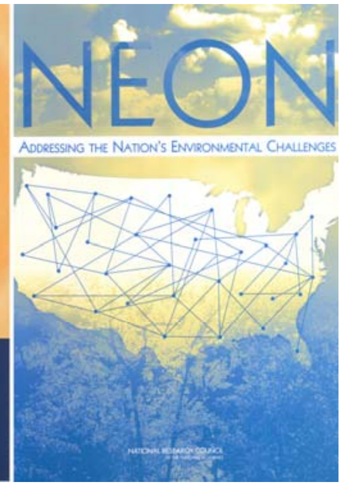
- Biodiversity: "… to improve understanding of the factors affecting biological diversity and ecosystem structure and functioning, including the role of human activity."

- Biogeochemical cycles: "… to further our understanding of the Earth's major biogeochemical cycles, evaluate how they are being perturbed by human activities, and determine how they might better be stabilized."

- Climate change: "… to increase our ability to predict climate variations, from extreme events to decadal time scales; to understand how this variability may change in the future; and to realistically assess the resulting impacts."



NRC (National Research Council). 2001. Grand Challenges in Environmental Sciences. Washington DC: National Academies Press.



NRC (National Research Council). 2003. NEON: Addressing the Nation's Environmental Challenges. Washington DC: National Academies Press.

- Hydroecology: "… to develop an improved understanding of and ability to predict changes in freshwater resources and the environment caused by floods, droughts, sedimentation, and contamination."

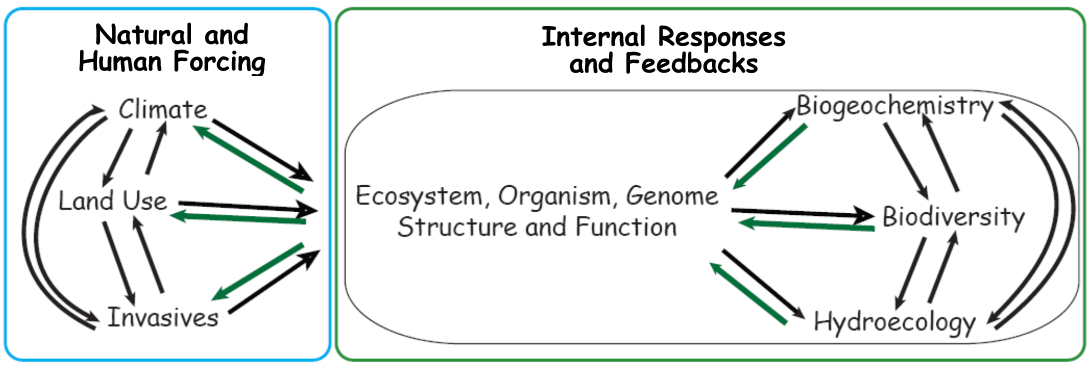
- Infectious disease: "… to understand ecological and evolutionary aspects of infectious diseases; develop an understanding of the interactions among pathogens, hosts/receptors, and the environment; and thus make it possible to prevent changes in the infectivity and virulence of organisms that threaten plant, animal, and human health at the population level."

- Invasive species: … to understand species invasion "as an ecological process sufficiently to allow forecasting of the invasiveness of species and prediction of which potential biological agents would both be effective in controlling an exotic species and have the fewest detrimental effects on natural and managed ecosystems."

- Land use: "… to develop a systematic understanding of changes in land uses and land covers that are critical to ecosystem functioning and services and human welfare."

The Grand Challenge areas span a vast extent of intellectual territory. From the perspective of the biosphere, three of the challenge areas—climate change, land use, and invasive species—start as external drivers, with ecosystems responding through changes in other grand challenge areas, especially biogeochemistry, biodiversity (including modifying effects of infectious disease), and hydroecology (Figure 1.1). Interactions among the drivers and responses, and ecosystem feedbacks give the system a staggering diversity of potential responses. In addition, these interactions can occur across a range of spatial and temporal scales, further complicating system dynamics.

Figure 1.1 The Role of Ecological Processes in the Grand Challenge Areas and their Feedbacks



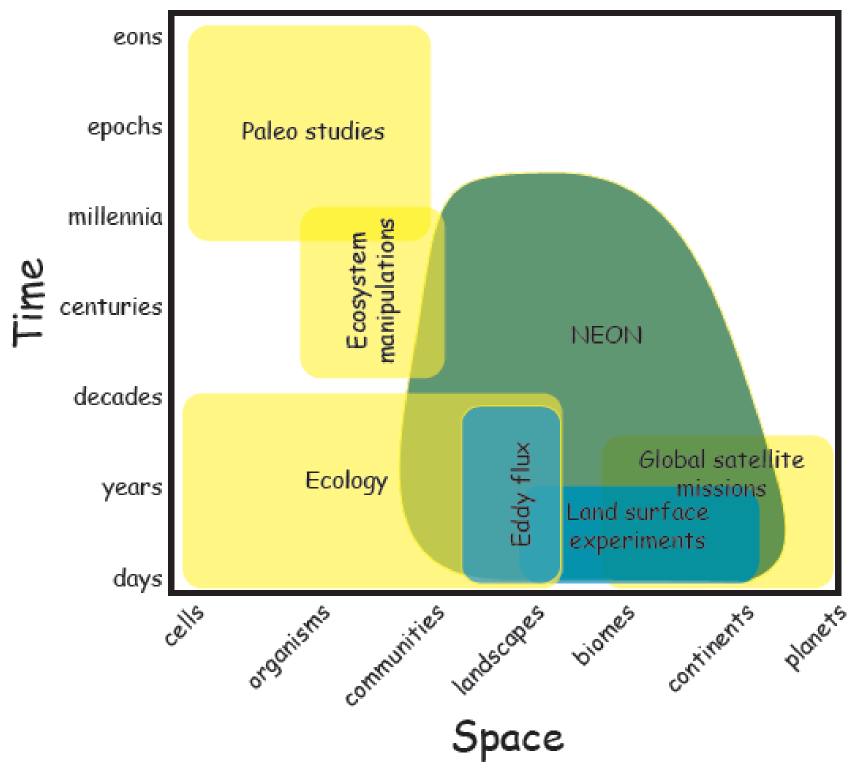
Black arrows indicate responses to the external drivers, while green arrows represent feedbacks from the ecosystem to the processes initially identified as external forcers. In this coupled system, none of the components can be fully understood except in relation to the others. The diagram includes changes influenced by humans and the reciprocal effects of ecosystem changes on human systems.

The importance of large-scale processes in the earth system is well-documented. The temperature patterns of the planet's ocean surfaces are linked to continental- and global-scale climatic systems such as El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and the North Atlantic Oscillation (NAO). Connections among these systems link climate patterns over vast distances. While we have a network of weather observations that can advance climate forecasting and promote understanding of global climate patterns, a similar observation network for the Earth's ecosystems does not exist. A new and innovative large-scale ecological observation network is needed to develop a basic understanding of large-scale biosphere function. There is also a need to forecast the interactions among the external forcing (from land use, climate, and invasive species) and the internal responses (of biogeochemistry, biodiversity, and hydroecology). NEON will meet these needs and allow systematic study of the full suite of linkages in biosphere dynamics.

The transformative power of NEON will come from two aspects of its design. First, it is designed to yield scientific insights to ecological processes that operate at large spatial scales. A large body of evidence documents the central role played by these large-scale mechanisms in ecosystem function, biogeochemical cycles, feedbacks between ecosystems and other parts of the Earth system and ecosystem services. Yet few of these large-scale mechanisms are understood in detail. Second, NEON will provide a balanced, integrated view of ecosystem function. Coordinated measurements of land use, biogeochemistry, community ecology, population biology, biodiversity, soil ecology, aquatic ecology, and microbial ecology will provide the foundation for understanding ecological processes at a level that is both broader and deeper than was previously possible. Coupling these two goals—scaling and integration—will provide the foundation for transforming ecology as a science.

Evidence of the importance of large-scale processes in the biosphere has been accumulating over the last few decades. For example, the role of terrestrial vegetation as an important source or sink in the carbon cycle (with feedbacks to climate) is the focus of a wide range of research programs, These include: AmeriFlux, First ISLSCP [International Satellite Land Surface Climatology Project] Field Experiment (FIFE), the Boreal Ecosystem-Atmosphere Study (BOREAS), the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA), and the North American Carbon Program (NACP). While a number of these efforts involve large-scale sampling, most ecological studies have intensively studied organism interactions and their consequences for the ecosystem at very small scales. Large-scale studies have largely ignored organism interactions and their outcomes, focusing instead on short-term feedbacks of the biosphere to the physical climate. NEON will integrate these ecological processes and their large-scale feedbacks (Figure 1.2).

Figure 1.2 The Space and Time Scales of Ecological Research



Studies shown in yellow have emphasized ecological interactions within ecosystems, while those in blue have focused mainly on short-term biosphere-atmosphere feedbacks. The NEON domain, shown in green, links theses two approaches over a large range of spatial and temporal scales.

The science to be addressed by NEON relies on a body of theory that includes: (1) physical theory that describes the motions of the atmosphere or the partitioning of energy at the Earth's surface; (2)

ecological theory that describes the process of community assembly; (3) genetic theory that describes the rate of spread and evolution of a disease organism; and (4) ecosystem theory that describes carbon and nutrient turnover. Although the theory in each of these individual areas is relatively mature, the scientific community has limited experience integrating theories from contrasting sub-disciplines and using the products to understand and predict the response and feedbacks of interconnected systems. Developing these integrated theories requires a combination of precisely defined studies focused on details of the integration, plus broad investigations that enable tests at the level of integrated systems. Transforming ecology into a predictive science at the regional-to-global scale, therefore, requires a coordinated program of theory development, testing, and refinement.

NEON will provide the observations to quantify the forces and interactions that operate across local-to-continental scales. It will also enable researchers to forecast how the biosphere will change, and how changes in the biosphere will alter Earth's geosphere, hydrosphere, and atmosphere.

NEON Vision and Mission

NEON is a continental-scale research platform for discovering and understanding the fundamental ecological principles that govern the responses of the biosphere. These include responses to land-use and climate change, and feedbacks with the geosphere, hydrosphere, and atmosphere.

The NEON mission is to provide the capacity to forecast future states of ecological systems for the advancement of science and the benefit of society. The Observatory's network of coordinated sensors, experiments, and cyberinfrastructure will collect the ecological data needed to develop the scientific understanding and theory necessary to address the Nation's grand environmental challenges.

NEON will embody two primary strategies for observations and experiments, both supporting the forecasting mission. First, the Observatory will be a sentinel for quantifying both gradual and sudden changes, and for identifying their causes and consequences. Second, NEON will support targeted improvements in forecasting capability through focused critical ecological measurements, experiments, and models to advance both understanding and the capacity to predict ecological processes.

The Observatory will enable educators to prepare society, including the scientific community, to use NEON data, information, and forecasts to understand and effectively address critical ecological questions and issues.

Fundamental NEON Science Challenges

NEON is designed to address scientific questions focused on the interactions of ecosystems, climate, and land use, including:

- How will ecosystems and their components respond to changes in natural- and human-induced forcings such as climate, land use, and invasive species across a range of spatial and temporal scales? And, what is the pace and pattern of the responses?

- How do the internal responses and feedbacks of biogeochemistry, biodiversity, hydroecology and biotic structure and function interact with changes in climate, land use, and invasive species? And, how do these feedbacks vary with ecological context and spatial and temporal scales?

These questions reflect a fundamental scientific curiosity about the nature of the world we live in. We would like to know the magnitude, pace, and geography of ecological changes, and to understand the underlying mechanisms and implications of such changes for species and for the provision of ecosystem services to humans. These fundamental questions are as compelling as those asked about the origin of the universe, the origin of life, or the nature of consciousness. Discovering the answers is critical to the future of human well-being.

Background

Ecology has a rich history of tackling and solving important problems. It is a diverse field with specialized sub-disciplines that have made huge strides in elucidating key principles within each sub-discipline. Community ecology provides a rich body of theory and observations for understanding interactions among organisms. Ecosystem ecology has developed tools and data for understanding controls on fluxes of water, carbon, and nutrients. Evolutionary ecology powerfully addresses the interaction between ecological process and changes in gene frequencies. While each of these sub-disciplines (and several more) has a strong record of accomplishment, progress in linking perspectives across sub-disciplines, especially at large spatial scales, has been uneven and rudimentary. Yet this linkage among sub-disciplines is critical for the advances that will facilitate the ecological forecasts discussed above. As the need for integrated approaches has become clear in recent years, progress has been increasingly constrained by technical and infrastructural factors. Currently, the ecological community lacks the tools necessary to move to the next level of understanding and fundamental insight, and to solve real-world problems.

NEON is designed to increase understanding of how US ecosystems and organisms respond to three key external forcers at continental scales—climate, land use, and biological invasives (Figure 1.1) —and how these responses feed back to affect other aspects of the Earth system. Dominant land-use changes that affect ecosystems and organisms include the conversion of land from wild to managed or urban, from agricultural uses to urban environments (including suburbs, exurbs, and cities), and abandonment from agriculture. Changes in land use can influence nearly all aspects of an ecosystem's function, from biodiversity to nutrient cycling to climate feedbacks. For instance, changes in land use can significantly alter air temperatures, which in turn affect a variety of ecological processes. Daily maximum temperatures increase in proportion to the impervious surfaces associated with urbanization—the buildings and surfaces that absorb and store heat. Likewise, nighttime low temperatures are not as low in urban areas as in the surrounding countryside because buildings and road surfaces release heat stored during the day. Figure 1.3 illustrates this "urban heat island" effect.

Humans are both ecosystem drivers and responders. Growing human populations drive increases in urban development and managed ecosystems, while human needs for food, fiber, commerce, and recreation have consequences for ecosystem structure and function. Changes in land use and land cover give rise to altered energy, water, and momentum balances, which in turn affect ecological processes and the ecosystem services that feed back to humans.

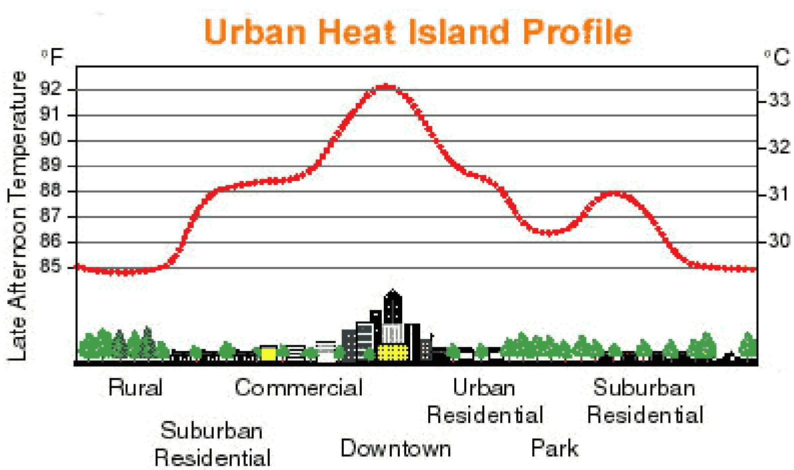
In the 20th century, land-use change was likely the strongest driver of changes in ecosystem function and biodiversity. In the 21st century, climate change and invasive species will likely be dominant drivers of changes in ecosystem structure, function, and services, including responses of primary production, wildfire, species distributions, and biodiversity. Land-use and climate change will be closely coupled in the 21st century, with many of their effects and responses amplified by changes in the abundance or distribution of invasive species.

Land use, climate change, and invasive species all share a pair of important features from the perspective of ecosystem change. Each is imposed from outside the ecosystem, but each is also subject to modulation, especially at large scales, by ecosystem processes. For example, a land-use decision to clear natural vegetation for agriculture is imposed externally, but subsequent changes in soil salinity may alter land-use options. In climate change, recent warming at high latitudes has increased the duration of the snow-free period, but the stronger absorption of solar radiation by the snow-free vegetation feeds back to amplify the warming. For invasive species, the establishment of non-native grasses in many woodland ecosystems increases susceptibility to wildfire and, consequently, increases the risk of further invasion. In each of these examples, neither the magnitude of the final effects nor the impacts on ecosystem services can be predicted without considering the ways that ecosystem processes alter the initial external forces. The impacts cannot be forecast without knowledge of the external drivers, but an accurate forecast also requires understanding the details of the ecosystem feedbacks.

The strong interactions and feedbacks among external forces and internal responses (Figure 1.1) mandate an interdisciplinary approach to NEON research and education programs. Thus, one of NEON's critical innovations will be the development of key technologies and designs to explore and better understand the drivers and feedbacks that cross the boundaries of traditional disciplines and scales of observation. For instance, climate in the NEON context needs to be specified in terms of local balances of energy, water, and momentum in order to advance scientific knowledge about the connections between ecosystems and climate, land use and climate, and ecosystems and land use (Figure 1.3).

Figure 1.3 Heat Island Effects of Cities

Urban hot spots: During the summer months, a metropolitan area can be up to 6-10° F warmer than surrounding regions. These "urban heat islands" occur because the buildings and pavement in cities absorb the sun's heat instead of reflecting it, causing a rise in temperature. At the same time, cities tend to stay warmer because they have fewer trees, shrubs, and other plants to intercept solar radiation, provide shade, and cool the air through evapotranspiration. (EPA, 2001)



Source: EPA. 2001. Heat Island Reduction Initiative. Inside the Green House (EPA-430-N-01-002). Available: http://www.epa.gov/globalwarming/greenhouse/greenhouse14/reduction.html.

The underlying drivers of ecological processes are complex. Some drivers change rapidly (at the time scale of weather systems) and require continuous, automated data collection. For other drivers, such as snow cover, soil carbon content, and species arrival and departure, data acquisition is appropriate at longer intervals. Measuring the many drivers of ecological processes is inherently complex because response variables such as decomposition and respiration are integrated over time and provide feedback to the original, more dynamic, driver variables. The NEON data acquisition plan is designed to capture both rapid and slow dynamics of these drivers of ecological change.

Ecological Theory as a Context for NEON

To be successful, NEON will need to integrate theories that address different time and space scales, and levels of biological organization. These range from Milankovich theory, which explains the progression of ice ages, to competition theory that specifies the conditions for coexistence of competing microorganisms, to theory that integrates effects of climate and land-use change in forecasting the dynamics of particular invasive species. Even within the traditional boundaries of ecology, theoretical developments from such sub-disciplines as ecosystem, population, and community ecology are incompletely integrated. Different perspectives generate distinct views of the controls on ecosystem dynamics. In the past, it has been difficult to assemble the teams and infrastructure to link diverse bodies of theory, even when it has been clear that the links are important. NEON will create the infrastructure needed to integrate multiple threads of ecological theory into a consistent framework.

The Observatory will not attempt to become a major active player in the development of economic, social, or development theory. Instead, it will interact with partner organizations, focusing on understanding the ways that environmental context alters patterns of land use and the exploitation of ecosystem services. Theory that effectively integrates human and ecological processes is a central challenge for NEON.

From Models to Forecasts

Ecological forecasting is critical to both the basic science and application of ecology. Ecosystems respond at time scales that range from milliseconds (e.g., photosynthetic response to changes in light) to thousands of years (e.g., changes in species composition as climate changes). Typically, observations and experiments addressing ecosystem responses to changes in the environment are restricted to time scales of just a few years. NEON will help extend those observations and experiments to several decades, but the very-long time scales will still be out of reach of empirical assessment. The only window available to these longer time scales is forecasting with the use of mechanistic models. Mechanistic models can simulate the connections among ecosystems components and processes to emulate the long-term functions of an ecosystem. Integral to these connections are the feedbacks that result in the long-term dynamics of the system. The advantage of a modeling approach is that the individual components and processes can usually be measured or experimentally manipulated on relatively short time scales and incorporated into the model to make forecasts of the longer-term dynamics, which involve feedbacks on time scales that are empirically unobservable.

Controls of ecological dynamics are usually multi-factorial, contingent on history (for example, species absence or presence, and evolutionary constraints) and nonlinear. As a result, relatively complex models are used in all aspects of ecology. Models that simulate processes relevant to multiple environmental stressors allow scientists to conduct multi-factorial experiments under numerous combinations of environmental conditions that simply isn't feasible through actual manipulative experiments alone. Models can also be thought of as linking theory—the conceptual basis of the science—to empiricism. The advancement of forecasting is cyclic: A forecast is made and the predicted quantities are observed and compared to the model, resulting in a new forecast. This pattern is true whether the purpose of the forecast is intellectual or practical. However, unlike the classical experiment, where a single incisive result ideally tests the hypothesis, in the forecast-analysis cycle the gain is incremental, with each cycle providing some information about the hypothesis under slightly different conditions. Engaging in a forecast-analysis cycle, with periodic re-analyses, provides both ecological forecasts and continual testing of underlying assumptions and codes, and leads to steady and sometimes dramatic progress.

Observatory data, experiments, and models will support forecasting advances. While NEON will measure many ecological variables, other desired variables will not be observed. One role for models is to forecast, on the basis of actual observations, the values of these unobserved variables. This does not imply forecasting the future, but forecasting specific quantities. Eddy covariance measures the net flux of CO_2 between ecosystems and the land surface or net ecosystem exchange. Ecologists tend to be more interested in photosynthesis (GPP), respiration (R), and net primary production (NPP). These quantities are not observed by eddy covariance, but can be estimated from eddy covariance by combining a model and observations to produce a forecast. The use of models to calculate unobserved quantities from other observations is common, and some of these calculations are so familiar that they are not thought of as modeling per se. Population parameters from mark-recapture data or intercepted photosynthetically active radiation from satellites, for example, are model analyses.

Forecasting models can go considerably beyond using observations (of climate variables, for example) to calculate outputs (such as net primary production). Forecasting models are usually “data assimilation models” in which at each time step the difference between the prediction and the observation is compared and iterated, and the model’s parameters or state variables are adjusted to improve the fit. Data assimilation uses mathematical optimization techniques to do this type of continuous error reduction, formalizing at the most basic level the forecast-analysis cycle. Such models have now been developed for a few applications in ecology and are likely to become more common as rich ecological time series data become available.

Another technique in forecasting weather and climate that can be applied to ecology is the “multi-model ensemble,” in which many models differing in subtle to fundamental ways are run with identical inputs and the results averaged. In this case, the different strengths and weaknesses of the models in some sense cancel out. An extension of this technique, the super-ensemble, uses statistical means to remove systematic biases; it is far better than just averaging models together, at least for physical problems. The multi-model ensemble technique and its more sophisticated variants are becoming increasingly important in ecology. Given the inherent complexity of ecological processes, assimilation and ensembling will have utility for ecological forecasting.

NEON data will allow existing models to run at sites and regions in conventional ways, and will facilitate the use of models to compute unobserved quantities from the observations. Because current models were developed for specific questions with defined spatial and temporal resolutions, a major challenge will be to integrate and scale these models to address regional- and continental-scale questions relevant to NEON.

The Observatory will contribute to the development and validation of these kinds of ecological models by providing the community with a set of tools (e.g., code repository, integrated data sets for a given spatial-temporal specification, a compute cluster for running computationally intensive models). NEON will facilitate and foster the development of cutting-edge models by the community with workshops at its Modeling, Forecasting, and Visualization facility (Chapter 3, “NEON

Cyberinfrastructure”). Observatory data and cyberinfrastructure will establish forecast-analysis cycling in ecology and facilitate forecasting and model evaluation using these techniques. The infrastructure will also support formal data assimilation and open many areas of ecology to these powerful time series techniques. Because considerable uncertainty will remain in ecological models for the foreseeable future, NEON must also support the inter-comparison of models and the development of multi-model ensembles and super-ensembles. The NEON Science and Technology Advisory Committee (STAC) is envisioned to provide strategic high-level guidance on these issues, as well as approve models that are supported by NEON. The STAC may also develop a list of desirable models that could form the basis for an NSF open competition. Models of any type may be developed by anyone using the Observatory’s open access data approach.

From Science to Society

NEON will develop the infrastructure for advancing the ecological understanding of the Earth’s systems, while supporting new links among scientists, land-use managers, and regulators, and creating opportunities to directly benefit society. In addition, the Observatory will provide the data needed to help shape natural resource policy in a variety of areas and applications:

- Land use and land management will strongly impact the environment and society over the next few decades—the time scale of NEON work.
- Local, state, and federal governments need to use and manage land for diverse purposes, such as minimizing environmental impacts, rehabilitating ecosystems, and delivering services to residents.
- Important aspects of NEON science—the observation and forecasting of land-use and land-management change and ecological responses—are highly relevant to local, state, and federal agencies, non-governmental organizations (NGOs), and businesses.
- The sustained, place-based character of many NEON observations creates the opportunity for well-developed research-management relationships.
- The Observatory provides an unparalleled opportunity for researchers and teachers to discover productive common ground and will promote a vision of ecological education in which scientists are educators and educators are scientists.

The ability of the NEON program to observe land use and land management and its ecological and social consequences will greatly benefit land policy, planning, and management by local, state, and federal agencies, NGOs, businesses, and private landowners. This capacity could enable close working relationships among NEON, government agencies, NGOs, businesses, and citizens. For example, changes in land management policies and practices represent powerful experiments on scales that NEON would not be able to contemplate or execute on its own. For instance, the Baltimore Ecosystem Study LTER is currently working with the City of Baltimore to assess and evaluate the City’s efforts to improve the water quality of its storm water runoff. Another effort addresses the City’s goal to double the area of its tree canopy from 19% to 38% over the next 30 years. NEON's observational network and mobile capacity are a powerful toolkit to test the hypothesis that ecological responses at the local level are correlated to changes in policy or management.

Over the lifetime of the Observatory, several iterations of observing and adjusting land use, land management, and their consequences will be powerful tests of scientific understanding and forecasting capability. This contribution benefits both science and society. These efforts could occur in explicit adaptive management programs, which involve forming hypotheses, taking management action, monitoring effects, assessing lessons, adapting management actions, and doing so iteratively. A link with natural resource policy comes when lessons learned through the work of continuing science-management partnerships are available for incorporation into policy, planning, and management. Such scientific partnerships have already been adopted at several Long-Term Ecological Research (LTER) sites.

Overview of NEON Architecture

The Observatory will link diverse technologies and approaches in a coordinated framework that delivers standardized, high-quality, long-term measurements in locations and along gradients sited to provide access to the broad range of large-scale ecosystems, processes, and feedbacks. The basic architecture is a stratified design, combining comprehensive continental data from partnering agencies that manage space and aircraft platforms (NASA, NOAA, USGS, and perhaps private sector firms), with more frequent and intense coverage of sites of special interest. These will include 20 intensively instrumented core sites (one per NEON domain), that span key continental environmental gradients. Sites that are (or are likely to become) ecological hot-spots as a result of a major disturbance or rapid change will also be supported. In addition to instrumented sites, the Observatory will provide instruments for mobile and opportunistic observations, as well as the cyberinfrastructure to let investigators gather, manage, and analyze new kinds and volumes of data. NEON will also seek community recommendations for large-scale experiments to address questions that cannot be answered through observations alone.

In the conceptual design stage of the planning process, many of the details concerning the locations of study sites and transects, strategies for selecting target of opportunity sites, coordination across long transects, and targets for experimental sites have not yet been determined. It has been determined, however, that each component of the Observatory will be designed to operate as part of an integrated network. Though NEON will deploy diverse assets to study a wide range of sites and processes, the entire deployment will be coordinated. All measurement programs will be evaluated first for their contribution to network-level questions.

In broad outline, NEON will make major investments in seven interrelated aspects of its research program:

1. Twenty heavily instrumented core sites, located in wildland areas across the continent, will be selected to represent the variability in US climate. This component will provide a wildland reference for a wide range of studies on land use and its consequences. Each core site will cover a few tens of square kilometers.

2. Airborne observatory platforms with remote sensing instruments will provide regional information for scaling and extrapolation from sites. This component will provide spatially extensive data on ecosystem structure and function, as well as land use, mapping both drivers and responses.

3. Important environmental gradients will be instrumented and serviced by mobile or relocatable measurement systems, located to facilitate understanding through observations of ecosystems exposed to long-term differences in key environmental or human-dimension factors, such as elevation, precipitation, land use, time since disturbance, and location within a major watershed. These factors will be selected in a coordinated way that lets the network function as a whole, while still addressing consequences of a wide range of environmental and land-use processes at the regional scale.

4. Sites of opportunity served by mobile systems will be selected to allow detailed study of an important process, trend, or intervention, such as recovery from a major wildfire, response to an invasive species, conversion to agriculture, abandonment from agriculture, or rehabilitation of an urban watershed. Because many important ecological processes occur in pulses or in response to extreme events, and because the Observatory cannot cover the entire nation with high-intensity fixed-in-place observations, NEON needs the flexibility to increase focus on key areas or responses to key events. For NEON to fulfill its mission, these mobile vehicle-based observations will need to be coordinated with fixed-site, transect, and spatially extensive measurements.

5. National-scale experiments, subjected to coordinated manipulations (such as warming, altered precipitation, and reduced biodiversity), will assess large-scale controls on ecosystem responses, especially for processes where the spatial gradients are not informative. Experiments, particularly multi-site experiments, coordinated with the rest of the NEON network, will provide unique tools for establishing mechanisms and testing ecological theory.

6. Cyberinfrastructure will support diverse observations and models, and manage the data and output they produce, including autonomous sensor networks and high-resolution animal tracking systems. This cyberinfrastructure will support the scientists in the field and the laboratory and serve education at all levels.

7. Education and outreach programs will prepare the scientific community to use NEON to the fullest, enhance the science by enlarging and diversifying the research community, and enable the public to use and benefit from NEON to better understand and effectively address critical ecological questions and issues.

In each of these areas, the Observatory will establish the standardization necessary to support consistent, high-quality measurements and at the same time provide support for projects proposed by consortia of research teams. Research by individuals and consortia of scientists will be supported on a competitive proposal process; selection of proposals will be based primarily on the contribution of the measurements to the integrated goals of the overall network. The design and operation of installations based on proposals from the community will be carefully coordinated with the overall network.

The Observatory will coordinate with existing data collection and other scientific infrastructure, adding value through standardization relevant to addressing large-scale NEON questions.

NEON is an observational platform for regional-to-continental ecological research. It will provide research infrastructure in many of the Nation’s most important ecosystems, as well as critically important environmental gradients, such as spatial changes in land use, elevation, biodiversity, and aridity, and the transition from terrestrial to aquatic systems.

Conclusion

The complexity of ecological processes—their interconnections, feedbacks, and tendencies for discontinuous behavior—makes it challenging to study ecosystems at a large scale. Recent advances in theory and technology, however, now make it possible to address a series of Grand Challenge questions that link external drivers and internal responses of ecosystems in a systematic way. Such research will enable a deep understanding of large-scale processes, feedbacks, and implications for both ecosystems and human societies. The key to progress is a combination of coordination and integration. Transformative science from NEON depends on the ability to examine large-scale processes in a consistent, long-term way. It also depends on the capacity to simultaneously quantify diverse kinds of drivers and ecosystem processes. Without both the coordination and the integration, the Observatory loses much of its transformational potential. The Grand Challenge questions cannot be answered with a program less ambitious than NEON because the key mechanisms and feedbacks operate at continental and decadal scales. The hierarchical design of the Observatory gives it the power to integrate mechanisms across a range of scales, linking diverse aspects of ecology.

CHAPTER 2

NEON Design:
Linking Mechanisms and Processes Across Scales

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The Hierarchy of NEON Design

NEON is based on a stratified design that combines limited coverage of the entire United States with more intense deployment of infrastructure in carefully selected representative areas, gradients critical for understanding particular drivers of and responses to change, and other sites of special interest. In addition, the Observatory offers the potential for deploying networks of manipulative experiments to explore parts of the space-time domain that are inaccessible with other approaches. The basic philosophy for NEON stratification is based on the following issues:

- Traditional ecological approaches work effectively at the local scale. There is no need for NEON to duplicate research activities that are currently underway. However, it will be important for the Observatory to build upon data and expertise from existing sites to provide a longer-term context for NEON data, and to determine how to extrapolate finer-scale information to the continental scale.

- The United States is divided into climatic areas of a common level of variability (NEON Climate Domains) (Figure 2.1) such that a relatively small number of sites within domains captures a large fraction of the variation.

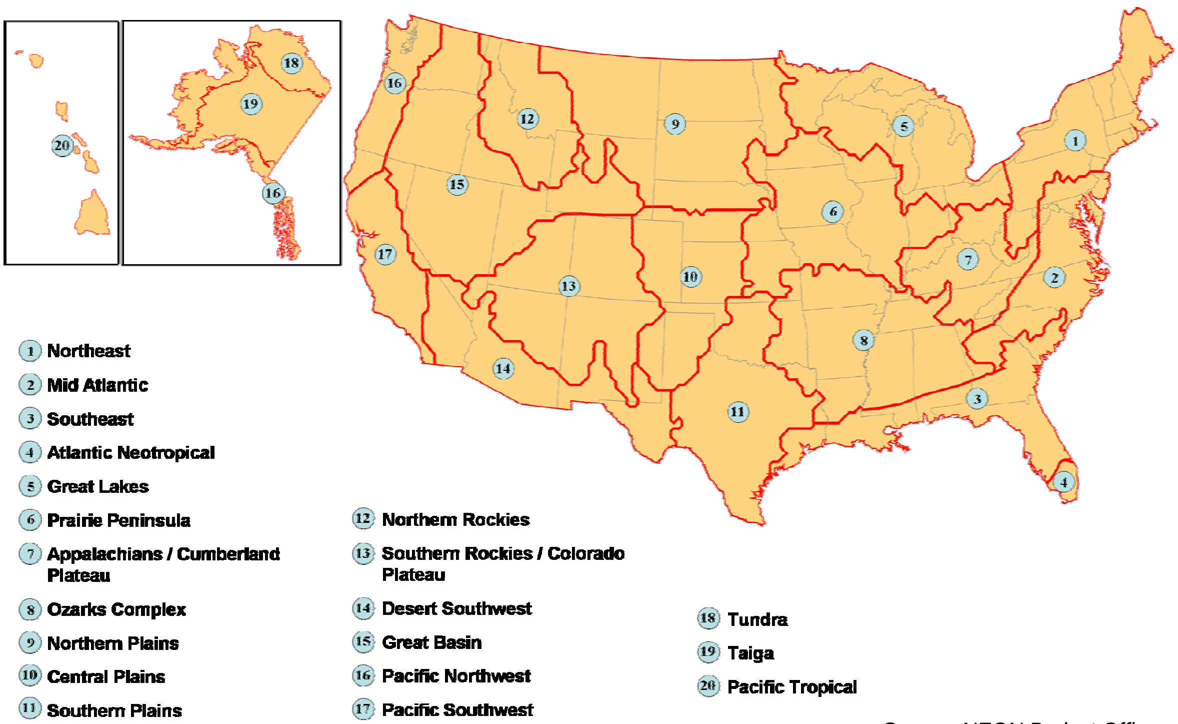
- In every part of the United States, local variations in site history (including land use and disturbance), development, soils, elevation, microclimate, and position within a watershed produce dramatic contrasts in ecosystem structure, function, and services. Still, much of this heterogeneity can be understood as variations on a regional theme.

- Permanent sites provide a powerful foundation for quantifying ecosystem changes over years to decades, and gradients can be an effective way to substitute space for time, extending the time scale. Extensive replication is critical. For some of the critical NEON questions, observations and models may not be sufficient, and definitive answers could require manipulative experiments designed to isolate interacting mechanisms.

- Critical areas of interest may emerge at unpredictable locations and times. For example, regions undergoing a biological invasion, recovering from a wildfire or hurricane, or responding to the creation of a new reservoir could offer unique research opportunities.

- Many of the nation’s existing ecological research resources (including field stations, experimental forests, research natural areas, and long-term ecological research sites) can provide information critical to NEON. Within any given domain, NEON may consider augmenting an existing instrumented site, or develop a site that has yet to be instrumented. The former helps constraint costs associated with the build-out, while the latter implies the potential for increased sampling power.

Figure 2.1 NEON Climate Domains



Source: NEON Project Office

NEON partitions the United States into 20 climatic domains ranging from the tropics of South Florida to the tundra of Alaska. The approach for defining climatic domains is twofold: (1) cluster analysis of climate state variables, and (2) resultant wind vectors to delineate climatic regions based on airmass seasonality.

- Gradients of sites, which can provide unparalleled access to processes or mechanisms that vary in space, should be arrayed at a spatial scale consistent with the mechanisms being studied. Some gradients (such as intensity of land use or time since abandonment from agriculture) might link sites over a few tens or hundreds of kilometers. Other gradients (such as hydrological position along a major river) will extend over much of the country.

- Scientific breakthroughs from NEON will depend not only on the data gathered but also on engaging a group of the Nation's scientists and empowering them to lead major aspects of the research. NEON is poised to facilitate this new capability by providing the tools to foster the creative energies of the scientific community.

The design for NEON builds on these criteria by connecting ecological elements across which analyses, modeling, and forecasting can be framed. At the continental scale, NEON defines 20 domains, selected to capture the existing variation in the Nation's climate (Figure 2.1). Within each domain, one core research site will be established in a wildland area, defined as a predominantly unmanaged ecosystem that has vegetation characteristics representative of its domain. Hargrove and Hoffman (Oak Ridge National Laboratory) have proposed a method to quantify a site's within-domain representativeness using the same variables used to delineate the 20 domains. This core site will function as a reference point for its domain. Core sites across domains will share a set of standardized measurements, although there may be minor additions and deletions to accommodate local constraints. For example, eddy covariance will not be feasible if a core site is in rugged terrain.

Each of the 20 domains will host an array of NEON sites, including a core site, gradient sites, sites of opportunity, and experimental sites. In addition, some of Observatory measurements will be spatially comprehensive over the domain. Others will be spatially extensive over gradients or other regions of the domain. Depending on focus, some of the gradients and experimental networks will likely extend across multiple domains. Others may be defined by continental-scale gradients in temperature, precipitation, soils, or land-use history. Gradients that span multiple domains may or may not be adjacent to one another. Experimental sites may also span multiple domains, if justified by the scientific questions.

Locating the core sites in largely unmanaged parts of the domain will provide reference points for diverse sites identified and developed to understand spatial processes related to each of the Grand Challenge areas and their interactions. In surveying terms, the core sites will be used as benchmarks.

Ecological theory, ecological modeling, land use, and the NEON design

The NEON spatial sampling design is based on a set of climatic attributes, delineated into domains using climate data and soil properties, capturing critical patterns of slowly changing constraints on biotic properties. While the NEON domains are mapped based on climate variables, they also capture profound aspects of the US ecology. The power of the design can be viewed as a hierarchy of constraint at different time scales. While we often think of climate as an independent variable in ecosystem studies, at the continental scale the climate variables that affect ecosystems are dependant variables. At the largest scale, the climate pattern depends in part on latitude, “continentality,” and the presence of mountain ranges (orography). However, the influence of the ocean basins that surround the continent percolates into the domain, affecting temperatures and water. At the continental scale, global patterns of variability also affect regional climates, with some areas lying in the influence of the North Atlantic Oscillation, some the El Niño, and others the Arctic Oscillation. These aspects of climate result from the structure of the Earth system, and, while dynamic, are constrained by very slowly changing boundary conditions.

Moving down in the hierarchy of control, the NEON domains also contain the continental variations in geologic and topographic properties, slope and aspect, drainage networks, and soils. The development of these constraints is in some ways correlated with climate, because geology and mountain ranges affect climate, and because soil development is influenced by slope, substrate, and climate. In other ways, the topoedaphic controls are independent of climate and reflect the longer geological evolution of the Earth. Continental patterns of climate, soils, and topography change slowly relative to many human and biological dynamics. At the next level in this rate of change hierarchy, ecosystem development reflects the climate and topoedaphic constraints, and so different species, soils, and patterns of biotic interaction exist within and (partly) as a result of the climate constraints.

Different patterns of land use, management, disturbances (such as fire or flooding), and rehabilitation also occur over this set of climatic regions and reflect in part the biogeophysical constraints. Different patterns of natural resource use and settlement tend to occur in different regions (such as forestry in forests, and agriculture in regions with ample precipitation or irrigation). While simple inferences cannot be made about the causes of human decisions about management and use of ecological resources from this design, it contains a rich set of different socio-environmental regimes in which to study these interactions.

The NEON domains provide a wide range of climatic regions within which to investigate ecological processes and human interactions. The pattern of climatic regimes yields a complex of varying boundary conditions (soils, climate), ecosystem types, and patterns of human influence across which the NEON sensors will observe system dynamics. While this type of spatio-temporal design has been utilized in the past, it has never been implemented comprehensively and uniformly across such a large area and diversity of systems. In addition, rarely have dynamics been observed as time series and, when observed, a single variable (such as net primary production) is usually reported. This type of approach has mostly been exploited along gradients where only one factor varies, not the complex set of processes NEON will observe. Spatio-temporal designs raise complicated theoretical issues for investigators trying to understand stable responses to the long-term mean pattern and dynamic responses occurring within that stable matrix. These questions will provide a fertile source of inquiry and progress within NEON.

Modern statistical and process models are now sophisticated enough to be used with this more complex regime design. The design will be used for time series observations allowing the observation of how dynamics vary in different constraint regimes, and for experiment networks, which can probe how controls operate in different regions. For example, Knapp and Smith's work (Variation Among Biomes in Temporal Dynamics of Aboveground Primary Production, *Science* 19 January 2001) on water controls on NPP suggest that changes to the rainfall regime will have different effects in different ecoclimatic regimes. The NEON design facilitates this type of direct hypothesis testing.

While the NEON design provides a template for laying out measurement and experimental sites that span climatic regions, sufficient variation remains within the domains. Thus, decisions will still have to be made about where within the domains to locate sites, measurements, and experiments. While the climatic regions provide an excellent framework for a wide range of science questions, as well as a widely distributed set of ecological indicators, criteria are needed to guide site selection for core measurements, gradient networks, and experiments. These criteria will enable scientists to identify sites for observations and experiments within the overall NEON eco-climatic domain. The goal is to harness the creativity of the scientific community to develop a final network design that balances a broad system of national coverage with a scientific focus on key aspects of the Grand Challenge questions, and the local-regional relevance of individual sites and networks, using the following criteria.

Overall criteria

1. Each core site, gradient network, or experiment must be chosen as a component of a national network and should address aspects of the Grand Challenge questions that are of national relevance.

2. Each core site, gradient network, or experiment must address one or more Grand Challenge questions. The questions as posed cannot be answered by any single network or experiment, and each question contains many testable questions and hypotheses. The link between the Grand Challenge questions and each NEON component needs to be articulated.

3. The NEON climate domains were identified based on today's climate, but specific core site locations should be selected based on the span of current climate variability and variations in anticipated changes. Similarly, gradient sites may be located in areas designed to sample

contemporary land-use type and intensity gradients, or in areas where rapid changes are expected.

4. NEON sites should not only include areas where stable conditions are expected, but also places where the goal is to observe responses to changes. Although long-term stability of access and ownership is desirable for all sites, this criterion may also apply to areas where a finite tenure on the site is expected. These could be short-term sites (five years), established with relocatable instrument systems.

Core site criteria

1. NEON must serve as a sentinel system to detect suspected and unknown aspects of ecological change in order to support national ecological forecasting and management. While not every core site will have the sentinel function as its primary purpose, the ensemble of core sites must serve this purpose, and many sites will support the sentinel function in addition to others linked to subsequent criteria.

2. NEON core sites will represent either spatially extensive or nationally critical habitat found within their climatic domain. Twenty core sites will be established in wildland areas, with one core site per NEON domain.

3. Each core site should have sufficient size to allow for a reasonable footprint of four tower systems (one Advanced BioMesonet Tower Systems, three Basic BioMesonet Tower Systems) (Box 3.2) and a set-aside experimental area with a Basic BioMesonet Tower System. The size of the site should also allow for the expression of the spatial dynamics of the organisms under study and deployment of the NEON instrument array. In many ecosystems, this can be delineated by the boundaries of a low-order watershed, which also allows for the use of the aquatic system as an integrator. In other systems (such as deserts or cities), watersheds may not provide the most logical or feasible boundaries, but a similar minimum scale of continuity (from a few to a few tens of kilometers) within the site should be sought.

4. Each NEON core site should deploy the common instrumentation to the degree reasonable. Strict interpretation might either eliminate critical sites or result in the inappropriate deployment of instruments. For example, the eddy covariance technique for using micrometeorological measurements to estimate ecosystem-atmosphere exchange does not work on sloping terrain, yet more than half of US forest area is in mountainous regions. Exceptions to the instrument manifest are permitted, but must be justified if the area is not suitable for micro-meteorological methods.

Gradient site criteria

1. Gradient sites may be established to cover a range of land use, land cover, extent of invasion, time since disturbance, elevation, precipitation, or location within a major watershed.

2. The gradients should cover a broad range of conditions (precipitation gradient, maritime/continentality gradient) and can extend across more than one NEON domain. Some sites should be placed in transition zones.

3. Fundamental instrumentation will be installed at gradient sites. Investigator-initiated research or partnerships can supplement these sites.

4. Networks located entirely within a NEON domain should be integrated and coordinated with the core site. Multi-domain networks will be scientifically integrated and coordinated, but each site in a network that spans eco-climatic domains should be coordinated with the core site of its domain for the purposes of cyberinfrastructure maintenance and operations. Experimental networks as described below should be managed similarly.

5. The time horizon of gradient studies should be specified initially (for example, “can be accomplished in a year,” or “requires a decade,” or “of interest indefinitely”). Some fraction of gradient resources should be periodically relocatable. Not all gradients or sites within a gradient should be indefinite in duration.

6. The Observatory will have a small reserve of instrumentation available to deploy opportunistically in response to abrupt events and environmental changes. These sites may become part of larger networks, adding value, for example, by defining a time-zero point in a time-since-disturbance gradient, or they may stand alone.

Experimental site criteria

1. Coordinated experiments need to be conducted at a limited but strategically chosen set of sites across domains.

2. Experiments should be designed across domains using coordinated measurements and standardized infrastructure (such as rainout shelters) to allow differences in responses across eco-climatic regimes to be observed.

3. The time horizon of experiments should be specified initially (“can be accomplished in a year,” or “requires a decade,” or “of interest indefinitely”). Not all experiments or sites should be indefinite in duration.

CHAPTER 3

NEON Deployment: Integrated Instruments, Experiments, Facilities and Cyberinfrastructure

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Overview of the NEON Scientific Infrastructure

NEON is designed to conduct long-term continental-scale ecological research. The Observatory is designed from its inception as an integrated network, making it possible for the first time to address challenging ecological questions at the scale of the continent. Observatory infrastructure will support the science needed to achieve continental-scale ecological analysis, synthesis, modeling, and forecasting. The infrastructure comprises:

1. Sites, which can be core sites, gradient sites, sites of opportunity, or experimental sites (see Chapter 2). Each core site will have a site headquarters with facilities to maintain equipment, process samples, and provide related support.

2. A standard set of instruments to collect biological, biophysical, biogeochemical, and land-use and land management data across the continent. The instrumentation is organized into five instrument packages (described in detail later):

   i. A Fundamental Instrument Unit (FIU) that provides comprehensive monitoring of climate and fluxes between ecosystems and the atmosphere.

   ii. A Fundamental Sentinel Unit (FSU) that supports diverse measurements of organisms, soils, hydrology, and aquatic processes.

   iii. A Mobile Relocatable Platform (MRP) comprised of Relocatable Tower Systems and Rapid Deployment Systems. Together, these systems provide investigators with flexibility in the deployment of instrumented systems to collect data.

   iv. An Airborne Observation Platform (AOP) with remote sensing instruments to provide regional information for scaling and extrapolation from sites.

   v. A Land Use Package (LUP) that supports comprehensive assessment and analysis of patterns, changes, and drivers of land use, land cover, and land management.

3. Outsourced facilities for archiving and curation.

4. Outsourced facilities for sample processing.

5. Cyberinfrastructure to integrate and manage the data generated from all the resources above, not only for scientists, but also for educators and lay citizens. NEON cyberinfrastructure will support automated and manual data collection in the field, as well as data and metadata streaming to network computer facilities. The cyberinfrastructure will also deliver archived data and higher-order data products to the user community.

Investigator consortia will also be given the opportunity to propose network(s) of experimental sites subjected to coordinated manipulations (such as warming, altered precipitation, and reduced biodiversity) to assess large-scale controls on ecosystem responses.

NEON resources like those above are envisioned to be centrally coordinated. The actual research programs to which resources are deployed will be largely derived from the collective contribution of the community. All Observatory research programs must be compatible with the NEON vision of being a continental-scale research platform for discovering and understanding the fundamental ecological principles that govern the responses of the large-scale biosphere and feedbacks with the geosphere, hydrosphere, and atmosphere.

Just as oceanographers submit requests to book research vessel time and resources to conduct scientific research, it is envisioned that investigator consortia will work with the NEON program to determine research needs that relate to the two NEON fundamental science challenges. Those needs will be mapped into an efficient, centrally coordinated resource allocation schedule to enable transformative research at the continental scale. Shared national resources include the Airborne Observation Platform, the Land Use Package, and analytical resources for outsourced sample archiving and processing (for example, genomics and pathogen screening). The latter largely comprises partnerships and outsourced service contracts with existing programs and facilities.

The NEON National Headquarters will facilitate the coordination of all these shared, national resources. The facility houses the management and operations staff, the national education and outreach program (training and teaching facility, staff), and components of the cyberinfrastructure (hardware, software, and staff). NEON Headquarters is designed to provide office and conference room space for the full-time employees (administrative, educational, scientific, computational, and informatics personnel). A training laboratory will offer instruction for Observatory scientists, technicians, educators, students, and computational staff from the 20 domains in the use of instruments, software, and new techniques and analytical approaches.

Continental Deployment Strategy

Instrument packages designated for deployment along gradients of interest are conceptually partitioned into two “toolboxes”: the NEON Continental Toolbox and the NEON Domain Toolbox.

NEON will offer investigator consortia the opportunity to recommend observational programs along national and large-regional gradients using instrument packages from the NEON Continental Toolbox (Box 3.1). Examples of such gradients include temperature, precipitation, and soils. Investigator consortia recommendations will be evaluated on both their scientific merit and connection to the NEON mission, in particular its continental focus. Soliciting research ideas from the community is a vehicle for unleashing the best ideas about addressing Grand Challenge questions at the continental scale.

Instrument packages in the NEON Domain Toolbox are similarly designated for continental and large-regional research designs. This toolbox comprises Relocatable Tower Systems and Rapid Deployment Systems meant for deployment along nationally standardized gradients within all or a subset of domains (Box 3.1). Examples of such gradients include a land-use gradient (such as urban to unmanaged), an environmental gradient (elevation, precipitation, edaphic factors), or other factors like vegetative structures (forest, grassland, or desert) or dynamics (rate of urbanization). This allows investigator consortia to pose questions that can only be answered by comparing observational data from all or a subset of domains collected along a common set of gradients.

Box 3.1 NEON Continental Deployment Strategy

Instrumentation arrayed along an extensive gradient

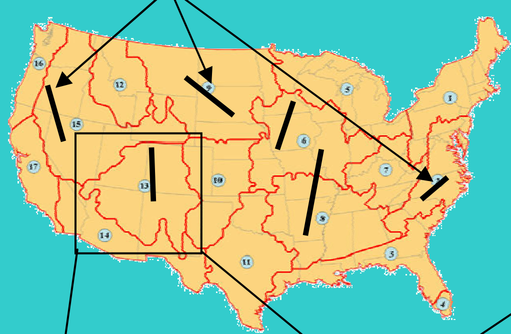
Continental Research Toolbox
Systems (○) available to consortia for deployment along extensive gradients

- Advanced BioMesoNet Tower System (10 units)
- Basic BioMesoNet Tower System (20 units)
- Relocatable Tower System (20 units)
- Rapid Deployment System (10 units)

(See Box 3.2 for definitions of the above systems)

- Fundamental Sentinel Unit Measurements

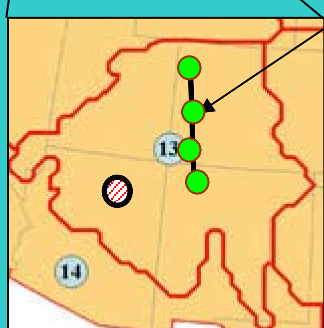
Instrumentation arrayed along gradient replicates*



Domain Research Toolbox
MRP (Mobile Relocatable Platform) (●) available for deployment along gradient replicates

- Relocatable Tower System (Average of 5 units/domain)
- Rapid Deployment Systems (Average of 0.5 units/domain)

(See Box 3.2 for definitions of the above systems)



Standard Domain Systems

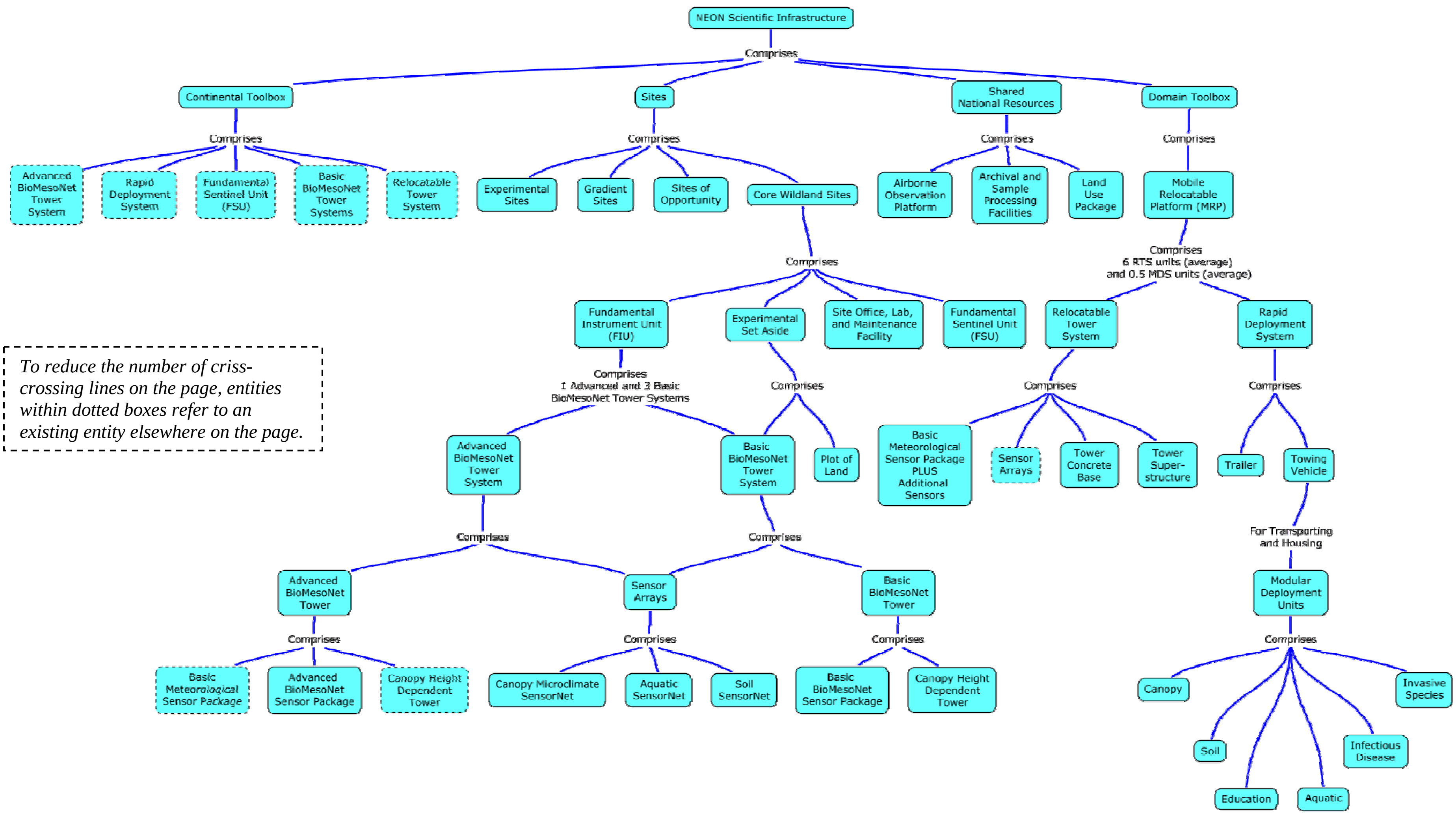
Wildland site (◎) comprising:

- FIU (Fundamental Instrument Unit)
- FSU (Fundamental Sentinel Unit)
- Experimental set-aside within wildland site and 1 Basic BioMesoNet Tower System

(See Box 3.2 and Box 3.6 for definitions of the above)

**Note: There may be one or more gradient replicates that are used to deploy instrumentation across the continent. The nature of such gradient(s) would depend on the questions being addressed.*

Box 3.2 Defining the Structural Relationship of NEON Scientific Infrastructure



To reduce the number of criss-crossing lines on the page, entities within dotted boxes refer to an existing entity elsewhere on the page.

Within each domain, the core wildland site comprises a FIU, a FSU, and an experimental set-aside area (Box 3.2). The wildland site is defined as a predominantly unmanaged ecosystem that has vegetation characteristics representative of its domain. The size of the site is expected to be at the scale of several tens of square kilometers. A site may include sites of opportunity selected to allow detailed study of an important process, trend, or intervention (such as recovery from a major wildfire, response to an invasive species, conversion to agriculture, abandonment from agriculture, or rehabilitation of an urban watershed).

Each NEON site will maintain a facility to support scientific and educational activities within its boundaries. This facility will contain office space for the scientific, educational, cyberinfrastructure, and support staff. It also provides a small laboratory and staging area for sensor maintenance, sample processing, and equipment and sample storage.

Data Integration Across NEON

In order to deliver a continent-wide set of comparable data, there will be a set of standardized system-wide NEON measurements, with little or no variation in the protocols used to collect and process the data. Regional differences may imply that certain measurements applicable elsewhere (for example, soil moisture and temperature at specific depths) will not be applicable locally; however, these measurements will be identified and agreed upon before the infrastructure is built and the NEON database is designed. Domain consortia will be given the opportunity to recommend additional measurements, beyond what is proposed in the ISEP, that will be necessary in order to answer questions that they recommend. Once these measurements are determined, they will also be subject to a strictly enforced set of measurement and data-processing standards.

The deployment of infrastructure in the NEON hierarchical design supports observations at landscape to regional and continental scales, and research on specific questions derived from the NEON fundamental science challenges. The infrastructure combines terrestrial and aquatic sensor arrays for wildland sites, relocatable and rapid deployment systems for transect sites and sites of opportunity, and airborne instrument packages for extensive coverage. Advanced cyberinfrastructure will provide a framework for distributed environmental monitoring and high-speed Internet connectivity to transmit data and information to computational facilities. Near real-time access to environmental data can be provided to the research community. In addition, teachers, students at all grade levels, decision-makers, and citizen-scientists will be able to access NEON data and forecasts online and download a variety of educational modules.

Two levels of standardization are included in the Observatory design. At one level, equipment, sensors, and instruments at wildland sites within each NEON domain will be standardized, modularized, and uniformly deployed. This uniformity of sites and measurements across the continental network will be a strong foundation for comparative and time-series analyses. A second type of standardization is also transformational: all NEON domains will support observations that will be a national sentinel system for ecological change, observing properties related to all of the Grand Challenge areas across the entire nation. These questions, chosen for their national relevance and ecological priority, will be pursued throughout the network in a unified way, while providing a rich array of data to support creative and discovery-oriented research as well.

Instrument Package Overview

The Fundamental Instrument Unit (FIU) automates continuous measurements of terrestrial ecosystem properties such as temperature, precipitation, and soil conditions that provide the environmental context for many ecological studies. Each FIU will comprise one Advanced BioMesoNet Tower System and three Basic BioMesoNet Tower Systems. An additional Basic BioMesoNet Tower System will be deployed at the experiment set-aside. As illustrated in Box 3.2, each tower system comes with a canopy-height dependent tower, a sensor package, and a set of sensor arrays. The three types of sensor arrays are the aquatic, soil, and canopy microclimate sensor arrays. The aquatic sensor array will be deployed at the transitions from terrestrial to aquatic habitats. This includes lakes and streams as appropriate for the aquatic habitats at each site.

In contrast, the Fundamental Sentinel Unit (FSU) primarily measures and records ecosystem and organismal responses to external (climate, land use, and biological invasion) and internal (biogeochemistry, biodiversity, hydroecology) drivers. “Sentinel” describes that aspect of NEON instrumentation that requires waiting, watching, and sampling at critical times. Measures of ecosystem function, biodiversity, invasive organisms, and infectious diseases require a sentinel approach to sampling designs.

The Mobile Relocatable Platform (MRP) comprises Relocatable Tower Systems and Rapid Deployment Systems to augment the extent of the measurements acquired by the instruments within the core wildland sites. These represent mobile NEON capacity to capture variation across the landscape to partially address questions related to intra-domain variance. These instrument systems are also designated for deployment along extensive continental gradients to capture variation at that scale.

The Airborne Observation Platform (AOP) will complement the FIU and FSU with spatially extensive observations that provide a detailed characterization of land use (including riparian land-use of importance to aquatic ecosystems), canopy structure, and canopy chemistry over wildland sites, transects, sites of opportunity, and other areas. Spatial coverage by the AOP will be limited to a fraction of the nation’s area, with satellite remote sensing (from partnering space agencies) providing wall to wall coverage of land-use and canopy properties.

The Land Use Package will provide an information technology environment for gathering the land-use and land management data that are necessary for quantifying and understanding the human drivers of ecosystem processes. The LUP will comprise a set of hardware and software tools configured to facilitate the gathering and analysis of land-use and land management data from remote sensing imagery (with some from the AOP and some from other sources), governmental and private archives, user surveys, and direct observations.

Fundamental Instrument Unit

The wildland site in every NEON Domain will be instrumented with an FIU (Box 3.3). The FIU, through its sensing capabilities and its replication within each of the 20 domains, enables consistent sampling at the continental scale over many decades. The ecosystem driver and response variables sampled by the FIUs provide data needed to address the core NEON science questions and for constructing new models that advance ecological forecasting.

Box 3.3 BioMesoNet Measurements

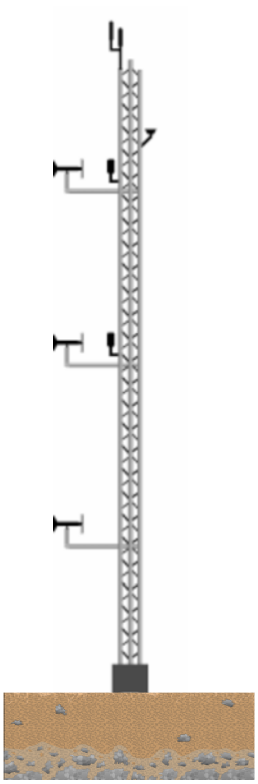


Illustration Credit: Jason C. Fisher

Basic BioMesoNet Tower

- Canopy height dependent tower
- Basic BioMesoNet Sensor Package:
  - Air temperature (at 10 m, 1.5 m, 10 cm, 0 cm)
  - Barometric pressure (at 1.5 m)
  - Relative humidity (at 10 m, 1.5 m and 2 other canopy-dependent heights)
  - Wind speed and direction (at 10 m, 1.5 m and 2 other canopy-dependent heights)
  - Precipitation (rain and snow liquid equivalent)
  - Soil moisture (at four depths from surface to rooting zone according to structural horizon, two depths of which are standardized NEON system wide)
  - Soil temperature (at depths as per soil moisture)

Advanced BioMesoNet Tower

- Canopy height dependent tower
- Advanced BioMesoNet Sensor Package
  [Basic BioMesoNet Sensor Package] plus:
  - Soil CO_2 flux
  - Incoming, reflected, total & diffuse solar radiation
  - Sensible and latent heat and CO_2 fluxes
  - CO_2 concentration (at 8-10 vertical levels from ground to above canopy)
  - H_2O vapor (at 8-10 vertical levels from ground to above canopy)
  - Stable isotopes of C and O in H_2O and CO_2
  - CO concentration
  - NO, NO_2, NOy concentrations
  - O_3 concentration
  - Airborne particles (e.g., pollen, bacteria)
  - Dry deposition of SO_4^{2-}, NO_3^-, NH_4^+, SO_2, and HNO_3
  - Wet deposition of NH_4^+, NO_3^-, o-PO_4^{3-}, SO_4^{2-}, Cl^-, Ca^{2+}, Mg^{2+}, K^+, and pH

(Note: The flux, radiation, and trace-gas concentration measurements will be placed at some uniform height above the canopy to allow for comparison across the network.)

The Basic BioMesoNet Tower tracks seasonal and long-term climate patterns and meteorological changes that are important to both ecosystem function and the growth of plants and microbes. The Advanced BioMesoNet Tower has additional capacities: To measure biologically important gases, and to monitor the chemical composition of atmospheric deposition. Such information is essential for research focused on biological responses to land use, water availability, the presence of invasive species or disease, and climate.

One Advanced BioMesoNet Tower System and four Basic BioMesoNet Tower Systems will be permanently installed at each wildland site. Three of the Basic BioMesoNet Tower Systems are meant to provide information on environmental heterogeneity within the core wildland site, and a fourth Basic BioMesoNet Tower System will be deployed at the experiment set-aside. Additional information about heterogeneity will come from a variety of sources, such as remote sensing and modeling. Each type of BioMesoNet Tower System comprises the BioMesoNet tower and its attendant sensor package, as well as a set of sensor arrays. The Basic BioMesoNet Tower includes sensors that measure fundamental atmospheric and soil properties (for example, air and soil temperatures, wind speed and direction, precipitation, barometric pressure). The Advanced BioMesoNet Tower includes additional biotic and abiotic sensors that measure photosynthetically active radiation, whole plant transpiration, wet and dry deposition chemistry, carbon dioxide and water vapor, heat flux, full range spectroscopy, stable isotopes, carbon monoxide, and ozone.

Environmental sensor arrays will be deployed in each domain. Each sensor array is designed to measure environmental diversity across the research site and includes a mix of terrestrial and aquatic sensors. These arrays, averaging one hectare or less in extent, will be deployed around the BioMesoNet towers. The locations for deployment of will be scaled appropriately to local topographic relief to ensure that variability is measured. These arrays are:

- Canopy microclimate sensor arrays (Box 3.4) complement the two types of BioMesoNet towers and provide near-ground measurements of climatic conditions affecting plant growth and biodiversity, biogeochemical cycling of nutrients, and hydrology. They measure photosynthetically active radiation, soil, air, and leaf temperatures, and climatic parameters that affect plant and canopy structure and productivity. These may be deployed with Networked Info Mechanical Systems—robotic instrument platforms that traverse wires suspended through the canopy.

- Soil sensor arrays (Box 3.4) support measurements of root and microbial growth and respiration, soil chemistry, soil temperature, and water content—factors that affect nutrient cycles and plant growth.

- Aquatic sensor arrays (Box 3.5) provide measures of parameters from which whole ecosystem metabolism and other key features can be estimated, including profiles of water temperature, dissolved oxygen (with optical sensor), pH, conductivity, light, chlorophyll, nutrients (at least nitrate, with other nutrients measured automatically as technology allows), and turbidity. Pressure transducers on each array are calibrated to stream discharge and lake water level. Automated water samplers provide samples for quantification of other key variables in the laboratory.

Box 3.4 Terrestrial Sensor Array Measurements

Canopy Microclimate Sensor Arrays

- Total, diffuse, and incident photosynthetically active radiation (PAR)
- Sunshine duration
- Air temperature (at 10 m, 1.5 m, 10 cm, and 0 cm)
- Relative humidity (at 10 m and 1.5 m)
- Precipitation (rain and snow liquid equivalent, Climate only)
- Leaf wetness (at 10 m, 1.5 m, and 2 other canopy-dependent heights)
- Leaf temperature (at heights as per leaf wetness)

Soil Sensor Array

- Root and mycorrhizae phenology
- Soil respiration (CO_2 emission)
- Soil NO_3^- concentration
- Soil O_2 concentration
- Soil pH
- Soil water potential
- Soil water volume
- Soil moisture (at four depths from surface to rooting zone according to structural horizon, two depths of which are standardized NEON system wide)
- Soil temperature (at depths as per soil moisture)
- Biological temperature (i.e., soil/leaf/canopy surface temperature)

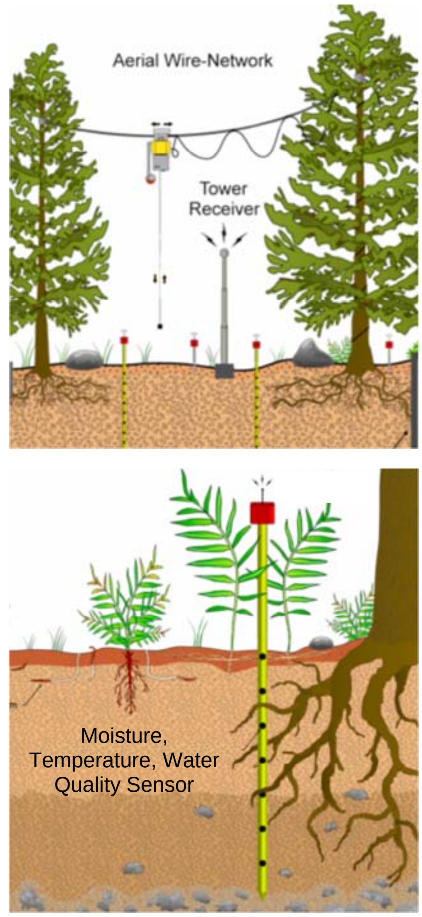
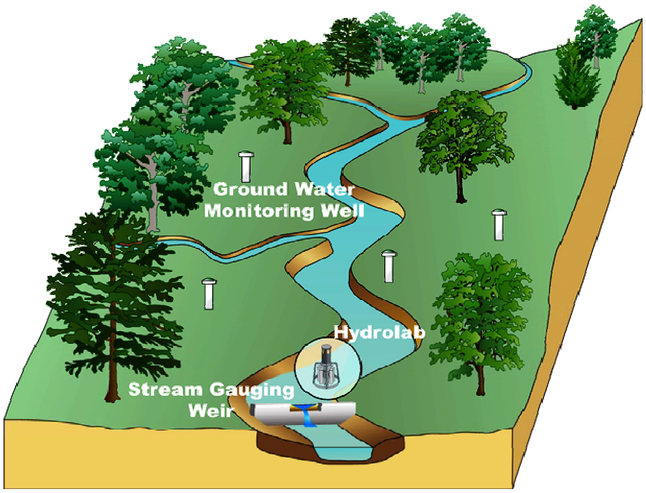


Illustration Credit: Jason C. Fisher

The canopy and climate sensor arrays determine atmospheric and meteorological conditions affecting plant growth and community composition, biogeochemical cycling of nutrients, and hydrology. The soil sensor array characterizes a suite of soil biological and chemical parameters that contribute to the biogeochemical cycling of nutrients and plant growth. These include the growth and respiration of roots and microbes, soil chemistry, temperature, and water content.

Box 3.5 Aquatic Sensor Array Measurements

- Level of groundwaters, surface waters; and discharge of flowing waters (pressure transducers)
- Soil moisture
- Dissolved organic carbon concentration
- Dissolved O_2 concentration
- Nutrient concentrations: NO_3^- (possibly NH_4^+, PO_4^{3-}, Si, as automated technology allows)
- pH
- Conductivity
- Temperature
- Turbidity
- Chlorophyll
- Surface PAR and UV
- Automated water sample collection for additional chemical profiles (NO_3^-, NH_4^+, PO_4^{3-}, Si), and biological (plankton) and isotopic measurements of groundwater and surface waters



Source: Symbols for diagrams courtesy of the Integration and Application Network (ian.umces.edu/symbols), University of Maryland Center for Environmental Science

The aquatic sensor array monitors groundwater and stream discharge, water quality, other characteristics that quantify biogeochemical cycling, and whole ecosystem metabolism of surface waters. These are essential inputs to understanding water availability and quality for managed and natural systems, plant and microbial growth, and biogeochemical cycling.

Fundamental Sentinel Unit

The FSU (Box 3.6) supports measurements of biodiversity and ecosystem responses to (and modulators of) climate and environmental change. It supports three types of observations: (1) biodiversity surveys, (2) observations of populations and behavior, and (3) observations of biogeochemical processes. The organisms monitored by the FSU share the following characteristics: they (1) are widespread in geographical distribution, (2) generally have high population turnover rates, and (3) are sentinels of changes in the environment. The spatial extent of the FSU is the same as the FIU site and is congruent so that the many measurements to be taken will have maximum scientific utility.

Box 3.6 Fundamental Sentinel Unit Measurements

Field Observation Programs

Vectors and pathogens
- Mosquito (e.g, West Nile, encephalitis, malaria)
- Deer mouse (e.g., Hanta-virus)

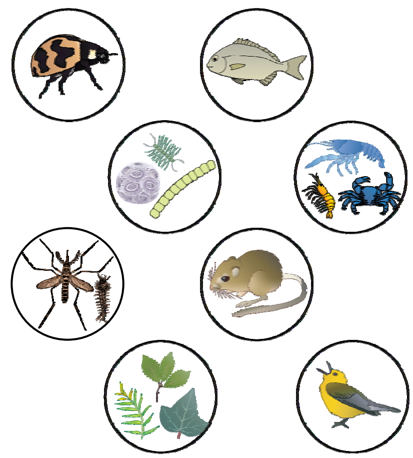
Phenology
- Standardized lilacs
- Dominant plant species
- Animals of local & national interest

Biodiversity
- Soil microbes
- Ground beetles
- Plants
- Algae
- Aquatic invertebrates
- Fish
- Breeding bird survey

Biogeochemistry
- Soil
- Aquatic

Organism Tracking System
- Deer mouse (*Peromyscus maniculatus*)

Functional Genomics
- Functional diversity
- Pathway diversity
- Genetic basis of biogeochemical fluxes
- Genetic basis of chemical transformations



Source: Symbols for diagrams courtesy of the Integration and Application Network (ian.umces.edu/symbols), University of Maryland Center for Environmental Science.

The Fundamental Sentinel Unit (FSU) tracks patterns and changes in organism movement, populations, community composition, plant cover, and phenology. FSU measurements will enable researchers to link biological indicators to changes in climate, land use, availability of water, and presence of disease or invasive species.

Monitoring the dynamics of species with the FSU approach is challenging because many key aspects of plant and animal populations and behavior do not lend themselves to automated measurement with fixed instrumental sites. Species that may be critical to include for measurement across NEON sites may consist of biological keystone species and high-impact invasive species. Long time series data can be crucial in understanding animal dynamics. Observatory sites should therefore take advantage of existing monitoring programs whenever possible and seek creative ways of coordinating NEON activities with existing programs.

Monitoring of populations is a research area where new technology could make a large difference. For many taxa, little alternative to labor-intensive field sampling and specimen collection exists. However, emerging technologies that use genomic, acoustic, and chemical sensing could make major contributions to real-time monitoring of population changes. These technologies are a high priority area for investment within NEON and in the scientific community if the NEON goal of understanding the relationship between changing community structure, ecosystem function and ecosystem services is to be met.

The Observatory proposes to undertake a system integration effort using existing commercially available off the shelf (COTS) computing hardware with customized programming. The BioPDA—a rugged, portable, field-capable computer—is envisioned to be deployable in the very near future. The unit will feature COTS modules which can be plugged into an expansion socket on a per-need basis. Examples of such modules include bar code label-generators, GPS receivers, digital cameras, and colorimeters. The BioPDA will equip scientists to efficiently record data about the environment and physical specimens that are associated with FSU programs. It will also facilitate the processing and archiving of samples collected from the field.

Biocollections, analytical, and computer support facilities will enable Fundamental Sentinel Unit biodiversity samples to be cataloged and archived for future retrospective studies. These samples include voucher specimens, tissues, microbial communities, water, soil, and a subset of biological specimens. The collected samples will provide a rich resource for future research efforts, enabling scientists to identify organisms, analyze archived blood and tissue samples for viruses and other pathogens, and perform new isotopic and biogeochemical analyses on water and soil samples. Budgetary and other logistical considerations permitting, these samples should be stored in replicate and in a manner that will protect against major loss in the event of a catastrophe (for example, in geographically different facilities, or different freezers within the same facility). Replicate samples will also allow for the destructive analysis of samples if necessary. NEON will not build these facilities, but will instead subcontract these services out to existing facilities. For example, genomic analyses will be outsourced to genomics facilities that provide standard molecular genetics laboratory infrastructure and support sequencing, fragment analysis, gene expression mapping, proteomics, and metabolomics. Likewise, existing analytical resources can provide stable isotope ratios of hydrogen, carbon, nitrogen, oxygen, and sulfur in materials sampled from aquatic, terrestrial, and atmospheric environments.

Biodiversity Survey

The NEON biodiversity program is designed to support observations of changes in the biodiversity of species and functional groups that have rapid population turnover rates (the ability to respond quickly to changing environmental conditions) and play important roles in ecosystem function. Biodiversity sampling plots and various sensor arrays should be co-located to provide the greatest interrelationship of the data streams. Sensor arrays and biodiversity sampling plots will be associated but physically separated to avoid damage to the sampling plots. The biodiversity sampling plots will include the sampling of:

- **Plants**. Vegetation will be sampled in modular quadrats that can be scaled and adapted to the dominant vegetation at each site. For example, the Carolina Vegetation Sampling Protocol uses quadrats with smaller units nested successively down to sub-meter resolution.

- **Soil microbes**. In association with each tower, a soil pit will be dug to establish initial soil chemical and physical characteristics, with a new pit dug and analyzed every ten years. In the neighborhood of each of the initial pits, three small soil cores will be taken annually and analyzed for microbial DNA and chemical characteristics.

- **Ground beetles**. Five replicate pitfall traps will be located adjacent to the vegetation plots.

- **Fish.** Where appropriate, sampling occurs at four sites in a 300 m stream reach at the base of the watershed, including multiple riffles and pools per stream.

- **Algae**. Where appropriate, four replicate sets of tiles will be placed in the 300 m stream reach where fish are sampled. At each location, an array of three unglazed quarry tiles will be placed in the stream. Periphyton will be collected and composited from the three tiles at each location at the end of a predetermined incubation period.

- **Aquatic macroinvertebrates**. Where appropriate, aquatic macroinvertebrates will be sampled at four locations in the 300 m stream reach where fish are sampled. At each location, three subsamples will be collected in a manner consistent with the USGS-NAQWA [National Water-Quality Assessment] Qualitative Multi-Habitat (WMH) sampling protocol. Flow measurements will be taken at the same time and location as the invertebrate samples.

Populations and behavior: Animals

Population surveys. The Breeding Bird Survey (BBS) is a long-term standardized protocol that provides basic information on bird populations. Each NEON wildland site should implement or intensify these protocols to tie into the national BBS. Locating sites where long-term BBS records already exist is a strength. In all possible cases, partnerships and linkages to ongoing programs should be identified and NEON should continue, expand, or enhance existing monitoring. All opportunities for transitioning measurements from labor-intensive to technology-intensive ones should be explored.

Migration and food web tracers. For birds, insects, fish, and some other taxa, Observatory infrastructure provides an important opportunity to quantify movement patterns of migratory species and changes in food webs over time. Stable isotope ratios and trace element concentrations are sensitive tracers of both movement patterns and food sources. Archived samples of such organisms should be analyzed for these constituents and will provide a unique long-term record of changes in migration and habitat use. For many organisms, a small and non-lethal sample is sufficient for analysis.

Mosquito surveys. Mosquito populations are sensitive to climate variation. They affect a diversity of hosts, which include an increasing number of invasive species (for example, *Aedes albopictus*, which is still spreading across North America). Mosquitoes also serve as a vector for various human and animal diseases. They should therefore be sampled at all sites for analysis of pathogen dynamics. In partnership with the Centers for Disease Control, NEON will track mosquito-borne pathogens (such as West Nile Virus, encephalitis, malaria, yellow fever, and Rift Valley Fever).

Organism tracking system. Mobile organisms such as birds, insects, and small mammals are ideal bio-sentinels/bio-sensors for changes in the environment. An understanding of their movements provides scientists with insights into the spread of diseases and invasive species, responses to regional and global climate variation, and population dynamics and migration patterns. The organism tracking system envisioned for NEON can track the movements of radio-collared small mammals. The deer mouse (*Peromyscus maniculatus*) has small home ranges and does not migrate. The interactions and movements of individuals can be tracked with the organism tracking system. The deer mouse is designated as a sentinel species because (1) it occurs throughout the United States, and (2) it will provide important new insights into the spread and transmission of vector-borne viruses such as Hantavirus. A plan for any keystone or critical indicator species should be developed with appropriate sampling and use of the organism tracking system if appropriate.

Populations: Plants

The NEON biodiversity program will collect data on plant community composition in biodiversity sampling plots. The NEON phenology program, on the other hand, is designed to record the seasonal progression of critical biological processes and the timing of ecological events. Phenology (a branch of science focused on relationships between climate and the seasonal timing of biological phenomena, such as bird migration and blooming dates) is one of the most sensitive and easily observed indicators of biotic response to climate variability. Phenology is affected by forces like length of growing season, timing and duration of pest infestations and disease outbreaks, water fluxes, nutrient budgets, carbon sequestration, and food availability. Because of the ease of observation and its relevance to ecological education, the phenology program is a good candidate for the citizen science program, with teachers and students, scientists and non-scientists all making observations at many sites within each NEON domain. The United States National Phenology Network (USA-NPN) works in partnership with the United States Geological Survey. To ensure comprehensive national coverage and adherence to established standards, NEON phenology observations will be aligned with those of the USA-NPN.

Populations: Microbes

The pathogen monitoring program provides an opportunity for NEON scientists to partner with the Centers for Disease Control in tracking mosquito-borne pathogens (West Nile Virus, encephalitis, malaria, yellow fever, Rift Valley Fever) and deer mouse-borne pathogens (Hantavirus, plague). Mosquitoes and deer mice (blood and tissue) will be sampled twice yearly within each domain. Representative samples will be tested for the presence of known pathogens, while remaining samples will be archived for subsequent testing for the presence of newly discovered pathogens.

The functional genomics of the micro-organisms program will provide the capacity to interpret biogeochemical processes, especially the degradation of toxic chemicals, fluxes of trace gases, and transformations of C, N, and P, in terms of the composition of soil and aquatic microbial communities. High-throughput phenotyping and physiology, as well as gene expression profiling using microarrays, will broaden ecologists' understanding of gene functioning in the field. In addition, the molecular characterization of organismal diversity and activity will enable ecologists to address important ecosystem questions. In efforts that could transform taxonomic surveys and studies of the relationship between species occurrence and ecosystem function, NEON scientists should partner wherever possible with ongoing efforts to harness emerging genetically-based technologies to more quickly detect the presence, abundance, and function of microbes (and larger organisms, such as plankton, where technology allows).

Functional Genomics: Linking Biodiversity to Ecosystem Function

As the foundation for mechanistic understanding of plant and microbial physiology, high-throughput genomic approaches should play an important role in NEON. High-throughput phenotyping and physiology, as well as gene expression profiling using microarrays, will broaden ecologists' understanding of gene functioning in the field. In addition, the molecular characterization of organismal diversity and activity will enable researchers to address important ecosystem questions, particularly microbial interactions affecting plant nutrient uptake, the degradation of toxic chemicals, and the fluxes of trace gases from soils and aquatic systems. The National Science Foundation already supports molecular surveys of microbial diversity through numerous efforts, including its Microbial Observatories and Microbial Interactions and Processes program. The research that has arisen from these efforts has significantly expanded ecological knowledge of the diversity and abundance of soil organisms. Rather than duplicating these successful efforts, the NEON focus will be to emphasize the link from gene functioning to biogeochemical fluxes in the field, connecting high-throughput genomic approaches with process-level measurements. This effort will take advantage of existing new technologies, but it also presents an opportunity for ecologists to design new tools specialized to their interests.

As one example, the research team of Jizhong Zhou (University of Oklahoma, Norman, OK) has designed functional gene microarrays (FGAs) that encompass the variation for more than 10,000 microbial genes involved in the cycling of nitrogen, carbon, and sulfur. The biochemical processes associated with these genes include denitrification, cellulose degradation, and methane oxidation and reduction. To date, scientists have employed this technology primarily in specialized settings, particularly the bioremediation of soils. Observatory investigators should encourage partnerships with other projects and programs to accomplish NEON goals. Investigators could design and adopt standardized genomics approaches, such as simplified functional gene arrays, that allow researchers to examine the abundance and expression of key genes seasonally, diurnally, and across environmental gradients. Genomics-based approaches employed in NEON should include both DNA-based analyses to examine the abundance of genes across space and time and RNA-based techniques that provide data on gene expression. Examples of the many key genes of interest include the nos gene family for denitrification, methane monooxygenase (mmo) genes for methane metabolism, and ammnonia monooxygenase (amo) genes for nitrification. To our knowledge, no systematic survey of this kind has ever been undertaken. These genomic approaches should also play an important role in NEON manipulative experiments and gradient studies, particularly those focused on biogeochemical fluxes.

While interesting in its own right, the real power of such combined analyses would be in linking the molecular data with the process-level measurements of trace gas fluxes and nutrient transformations planned in NEON's nested scales. The Observatory provides the opportunity to monitor the abundance and expression of genes through space and time, linking this novel physiological information with data for biogeochemical fluxes.

The NEON investment will enable the ecological community to identify novel biochemical pathways in the field and the groups of organisms that perform them. For example, new evidence now suggests that archaea, rather than bacteria, are the predominant ammonia-oxidizing prokaryotes in soil (Leininger S. et al. 2006. Archaea predominate among ammonia-oxidizing prokaryotes in soils. Nature 442: 806-809). Functional gene arrays are available to examine community diversity of microbes, and genetic barcoding and other novel taxonomic approaches may be useful for linking biodiversity studies to ecosystem functioning in NEON experiments. Again, NEON investigators should encourage partnerships with other programs and efforts wherever possible. In general, genomics-based approaches integrated into the NEON plan will help ecologists link important organisms and functions with the mechanisms through which those organisms operate.

Biogeochemical Processes

The soil biogeochemistry sampling program addresses two objectives. Soil cores collected twice per year will enable scientists to develop a long-term record of organic matter accumulation—a significant component of carbon and biogeochemical cycling models. Soil cores will also be archived and analyzed to provide an historical record of past environmental and climatic conditions (a reference against which future changes can be evaluated).

The aquatic biogeochemistry sampling program will parallel the soil program. Stream, lake, and groundwater samples collected on a regular schedule, and analyzed for nutrients (including total and dissolved nitrate, nitrite, ammonium, orthophosphate, silicon, and dissolved organic matter) will enable scientists to develop a long-term record of changes in water chemistry.

Mobile Relocatable Platform (MRP)

In additional to the core network of fixed sites, NEON will deploy non-fixed assets collectively known as the Mobile Relocatable Platform (MRP) (Box 3.7). The two primary tiers to this program are Relocatable Tower Systems and the Rapid Deployment System—a suite of vehicle mounted and/or towed measurement and analytical systems.

Relocatable Tower Systems

Relocatable tower systems will be deployed on permanent concrete pads with a tower base. These assets can be considered "plug-n-play" systems. Relocatable tower systems are based on Basic BioMesoNet Towers with additional sensors, as well as the relevant sensor arrays. At predefined locations within each domain, permanent concrete pads and tower bases will be installed. Roughly half of all tower bases will be unoccupied at any one time, since the relocatable systems can be readily moved from site to site without the need to install basic infrastructure for each redeployment. Subject to budget and operational feasibility, certain baseline measurement devices may be left operating continuously in such sites.

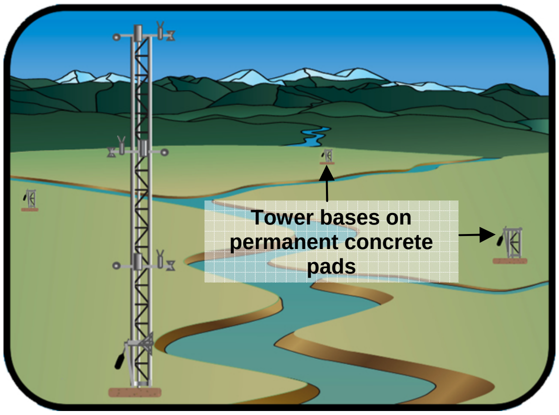
The goal of these systems is to support extended and periodic campaign deployments that expand the capacity to measure environmental variability and support observations along gradients. The expected deployment length for these systems is on the order of several months to several years.

Rapid Deployment Systems

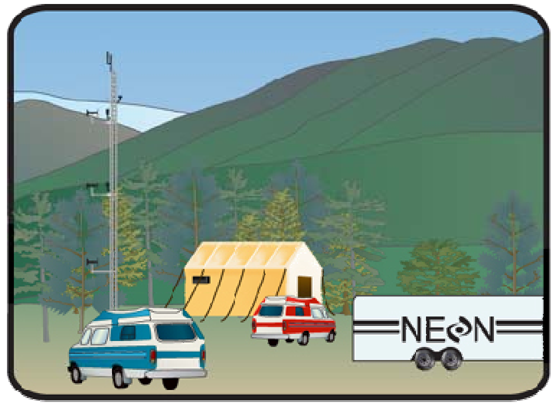
Rapid Deployment Systems are modular mobile units that collectively provide the self-sufficient capacity to deploy and conduct integrated ecosystem-level investigations / measurements in field environments. They comprise a vehicle with towing capacity, a trailer, and modules which can be loaded onto the trailer according to the particular type of campaign. Modules for the RDS include: education and social research; aquatic, soil and canopy sensor nets; and laboratory facilities to support invasive and infectious disease campaigns.

Box 3.7 Mobile Relocatable Platform (MRP)

Rapid Deployment Systems



Relocatable Tower Systems



Source: NEON Project Office

- Basic BioMesoNet Sensor Package (Box 3.3) with the following additional measurements:
  - Soil CO_2 flux (using a 4 chamber system instead of the 16 found on Advanced BioMesoNet Tower Systems)
  - Incoming, reflected, total & diffuse solar radiation (at 1.5 m)
  - O_3 concentration (at 3-5 m)
  - Airborne particles (e.g., pollen, bacteria)
  - Dry deposition of SO_4^{2-}, NO_3^-, NH_4^+, SO_2, and HNO_3
  - Wet deposition of NH_4^+, NO_3^-, o-PO_4^{3-}, SO_4^{2-}, Cl^-, Ca^{2+}, Mg^{2+}, K^+, and pH
- Soil Sensor Array (Box 3.4).
- Canopy Microclimate Sensor Array (Box 3.4).
- Aquatic Sensor Array (Box 3.5).

- Towing vehicle.
- Trailer to transport / house one or more of the following modular units:

Aquatics - Water chemistry sampling, collection and *in situ* measurement, acoustic Doppler velocimetry, biological sampling and collection, sonar imaging, boat.

Canopy - Climbing and safety gear, biological sampling and collections, canopy microclimate sensor arrays.

Climate - Basic BioMesoNet Tower sensors and trailer- mounted tower.

Invasive Species - Organism trapping and tagging, biological sampling and collections.

Education - BioPDAs, presentation equipment, abbreviated equipment set for training (e.g., mini tower with sensors).

Soils - Biological sampling and collections, soil sensor array.

Infectious Disease - Molecular genetics sampling and collection, tissue sampling and collection.

All modules would include network connectivity.

The goal of these systems is to support short-term campaigns (days to several months) that are focused on "targets of opportunity" such as wildfires, natural catastrophes, and other events that require rapid deployment to locations without an existing NEON presence. Additional uses envisioned include planned activities such as ground-truthing remote sensing systems, training, education and outreach, and data collection in areas in which a permanent NEON presence is not feasible.

The NEON program will coordinate and set the deployment schedules for the Rapid Deployment Systems based on requests from investigator consortia. Deployments would be planned using some of the principles developed with ocean research fleets. The scheduling of such resources would also take into account necessary deviations from scheduled deployments to deal with event-based deployment opportunities.

Airborne Observation Platform (AOP)

Satellite remote sensing provides unique access to large-scale ecological phenomena. It forms a critical foundation for the Observatory. NEON, however, will not deploy its own space-based platforms, but will rely on satellite sensors operated by other entities, including NASA, NOAA, and the private sector. For the immediate future, key sources of information for NEON will come from MODIS and LANDSAT, but both these sensor systems face uncertain futures. MODIS is at the end of its design life, and LANDSAT 7 is crippled off-nadir by the failure of its scan line corrector. Future missions will be critical for NEON data, though important aspects of the features and timing of upcoming US missions, including the National Polar-orbiting Operational Environmental Satellite System (NPOESS) and the NPOESS Preparatory Project (NPP), are still undecided as of mid-2006.

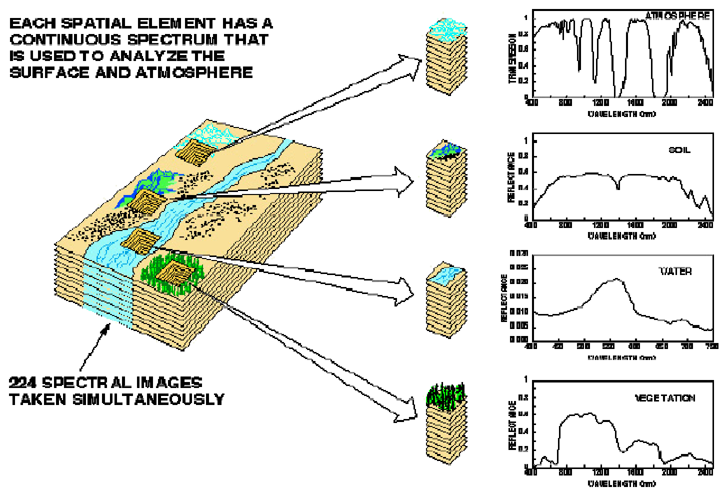
Aircraft remote sensing is an area where NEON can genuinely transform the ecological sciences (Box 3.8). Currently available technology makes it possible to mount a combined visible / near IR imaging spectrometer and wave-form LIDAR on any of a number of aircraft and provide 1 m scale resolution on a 1 km swath. Wave-form LIDAR provides access to many aspects of canopy structure and land use. Imaging spectroscopy provides access to many aspects of canopy biochemistry. Together, the two techniques form an Airborne Observation Platform that can map a wide range of ecological dynamics, including biological invasions, pest and pathogen outbreaks, changes in competitive relations, responses to disturbances like wildfire, and many features of land use. A high resolution digital camera should also be mounted to capture the visual scene for geo-referencing.

A single airborne platform can acquire data from hundreds to many thousand km^2 per day. Data can be acquired on repeat frequencies tuned to specific science questions. The high resolution of the aircraft systems will provide NEON with a highly visible capability that gives NSF a unique role in remote sensing, focused directly on ecological questions. Moreover, such high resolution data can be used to create analogous data provided by broad-band multi-spectral sensors by averaging various sets of spectral bands. This may be especially valuable in the light of the uncertainty facing the continuity of LANDSAT data.

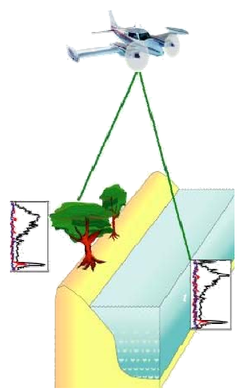
Many or most of the remote sensing questions in scaling NEON site science require multiple airborne measurements over the phenological cycle, or on even shorter time scales. Enabling phenological coverage of the network's domains will require at least two AOP sensor packages. Intensive studies, emergency responses, or long transects may require simultaneous use of two or more systems. The plan for at least two airborne packages provides sufficient capability for the core program, flexibility for targets of opportunity, and eliminates the risk of a single point of failure that exists if the program depends on a single resource. In order to optimize the deployment of this shared national resource, scheduling for data acquisition campaigns will be centrally coordinated by the NEON program.

Box 3.8 Airborne Observation Platform

High-fidelity imaging spectroscopy
- Vegetation indices
- Leaf area index
- Canopy moisture
- Canopy chemistry (terrestrial and aquatic)
- Spectral unmixing of vegetation components
- Diversity
- Canopy pigments (terrestrial and aquatic)



Wave-form LIDAR
- Vegetation height
- Ground topography
- Height distribution of structural elements
- Canopy top topography
- Biomass
- Life form diversity
- Bathymetry



The Airborne Observation Platform monitors canopy properties related to primary production, diversity, invasives, biogeochemistry, and dynamics of land-use change and recovery from disturbance.

Land Use Package (LUP)

Understanding and documenting changes in land use require sensor networks, data acquisition, and data analysis systems that capture information beyond the immediately observable characteristics of the landscape. Land-use regimes encompass human dynamics that include historical, political, economic, social, behavioral, and psychological aspects of institutions. In addition, surface ecosystems, land-cover assessments from remote sensing, and USGS digital terrain models are also initial LUP needs.

High quality land-use and land-management data, and the supporting social science that facilitates inference of past and projection of future land-use and land management, exist in an array of different formats (digital and analog) at different spatial and temporal resolutions. These data are typically characterized by disparate categories and variable definitions that follow a variety of disciplinary standards (legal, economic, demographic). Bringing political and economic data on land use into the NEON architecture will require more than cyberinfrastructure. It will require a broad set of hardware and software tools designed to build a unified database. Just as the FIU, the FSU, and the AOP collect raw data and covert it into a usable form, the LUP will undertake a massive program of data collection, sample processing, and integration. Consequently, the LUP will require hardware and software infrastructure for:

- Managing and analyzing data from moderate- to high-resolution multi- and hyper-spectral airborne and satellite sensors.
- Extracting information from web-based sources.
- Extracting data from economic and political databases.
- Supporting the collection and analysis of land-use data from surveys, observations, and experiments.
- Conducting all of its analyses under mechanisms that permit access to data that are open to researchers but under federal and state rules of use and security. The data should be linked to the counterpart data from the Census and Agriculture Census.

The Observatory aims to capture, assemble, and analyze new data to interpret and forecast the dynamics of the coupled human-environment system at regional and continental scales. NEON should take advantage of existing social science programs and seek partnerships with them, including the NSF Directorate for Social, Behavioral & Economic Sciences (SBE). Together, these programs have the capacity to transform the ecological and social sciences through meaningful contributions to policy development and ecosystem management. When scientists recognize the need to alter the assumptions underlying their models in order to incorporate fundamental changes in national, state, or local public policies (legal structures and regulations) that arise from observations originating in the NEON program, we shall fully appreciate the truly transformative aspect of NEON.

NEON Cyberinfrastructure

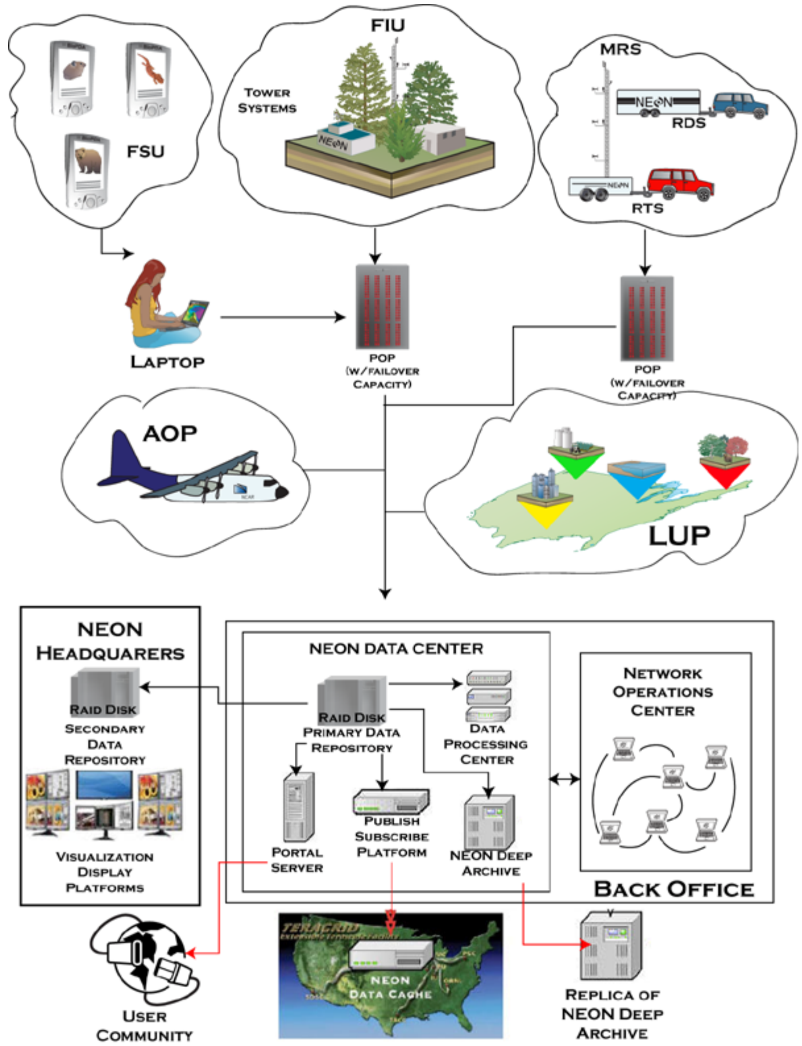
This section provides an overview of Observatory cyberinfrastructure, described more fully in the NEON Networking and Informatics Baseline Design (NIBD). The NIBD is available for download from http://www.neoninc.org/documents.

The Observatory cyberinfrastructure includes all the computing power, storage capacity, networking capability from sensor to the Web, and specialized software and hardware environments needed to conduct NEON research. The cyberinfrastructure also includes the people who operate and maintain equipment, develop and support software, create standards and best practices, and deliver security, user help-desk support, and other services.

NEON will maintain a comprehensive end-to-end cyberinfrastructure, from the acquisition of data from field-based sensors, through data and information processing, to the transfer of data, information, and knowledge to the NEON community (Box 3.9). This vision of the NEON cyberinfrastructure encompasses many functions, including the rapid communication and secure preservation of high-quality data, timely dissemination of Observatory data and information products, and broad-ranging support for public access and education.

Box 3.9 Overview of NEON Cyberinfrastructure

Every NEON site will have a uniform set of towers and sensors and standardized cyberinfrastructure hardware and software deployed in the field. One standalone server – referred to as the Point-of-Presence (PoP) – will be associated with each site. Each PoP will feature backup failover server capability. The PoP will preprocess the data and perform various data cleaning and quality assurance/quality control (QA/QC) protocols. The data will then be sent to the NEON Data Center for additional data processing via high bandwidth connections like Internet2.



Five overarching principles guide NEON planners in the development of the NEON cyberinfrastructure:

1. Provide open access to data and information.
2. Employ an open architecture in developing a robust, high-performance infrastructure.
3. Engage NEON stakeholders in cyberinfrastructure design and operation.
4. Optimally leverage with partnering organizations.
5. Design for modularity, security, simplicity, and standardization.

The software system will include a choice of appropriate cyberinfrastructure components, whether commercial off-the-shelf or open source. NEON staff will customize and integrate these components into an efficient, effective, and highly usable system, based on proven technologies and built using open systems architecture, to support extensibility and easy incorporation of new components. Essential support functions provided by NEON cyberinfrastructure are discussed below.

Distributed Instrument Control and Reliable Data Transport

A series of software components will support interface operations, data operations, and system management functions operating on the embedded sensor platform nodes. This software will provide distributed control, support taskable sensors, and ensure the security and transport of data. Networking within domains is based on a variety of approaches, including wireless, wireline, and Internet.

Data Curation and Archiving

Data curation and archiving functions will support metadata creation and management; registration of data to enable subsequent search and discovery based on spatial, temporal, and concept-based search conditions; storage and management of large data collections; and redundant, geographically dispersed archival systems for long-term data preservation.

Data Analysis and Integration

This function will support a variety of activities, including quality assurance and quality control; data filtering, post-processing of remotely sensed images, and analysis; integration of multiple data streams (including data from heterogeneous sources); and GIS mapping and visualization. Data integration includes the ability to access and integrate data from "third-party" sources, such as federal, state, and local agencies, community data repositories, and other related environmental observatories and community cyberinfrastructure projects.

Model Production and Forecasting

NEON National Headquarters will house a Modeling, Forecasting, and Visualization Facility that helps researchers to: (1) make systematic ecological predictions at the continental scale, (2) integrate forecasting capability across the domains of the network, and (3) interact closely with agency partners. The facility will be located on the National Lambda Rail / Internet2 backbone with secure high-speed connectivity to supercomputer centers and other facilities for decades to come.

Successive versions of NEON-supported models, developed and maintained by the community, will be archived and curated in order to serve the broadest possible constituency of users for the long term. The NEON Science and Technology Advisory Committee (STAC) must approve the models supported by the Observatory. These models must (1) use NEON-produced data, (2) permit forecasting of a variety of phenomena and the states of ecological systems, and (3) be easily accessed by the scientific community. In this way open access to the modeled output statistics from community models can be achieved. Both the versioned models and the model output data produced in previous model runs shall be freely available. The Observatory's institutional commitment to modeling, data archiving, and storage will create a long-lived digital data collection.

The STAC may also develop a list of desirable models that could form the basis for an NSF open competition. Models of any type may be developed by anyone using the Observatory's open access data approach. No review is necessary in such cases, though the NEON National Headquarters should be apprised of these activities.

NEON Portals

The Observatory will provide portal-based, authenticated, and role-based access to NEON resources, including data, information, tools, applications, educational resources, and collaboration spaces. The portal will be customizable in order to support different views of the collection of NEON resources, and to address audiences at different levels, from professional researchers to citizen scientists to students.

Collaboration Environments

NEON will provide support for Web-based collaborations among various Observatory components, as well as general collaboration support for scientists, educators, and students. Collaboration support will be provided for NEON staff across the 20 domains, and between the domains and the data archives and modeling facilities.

Manipulative Experiments

In an experiment, a treatment is applied and a response is observed. Manipulative experiments, when conducted with a strong design and rigorous controls, provide a unique capability for isolating driver variables and unambiguously establishing mechanisms. Manipulative experiments have played a central role in building a predictive, mechanistic ecology. A changing world further increases the motivation for manipulative experiments. When the future is likely to present novel conditions (in the composition of the atmosphere, the climate, the fragmentation of the habitat, or the composition of the biotic community), manipulative experiments provide a uniquely powerful pathway to forecasting future ecosystem responses. NEON offers exceptional opportunities to support individual and consortia-generated proposals for large-scale experiments, where access to underlying principles or trends depends on the opportunity to observe the way organisms or ecosystems respond to a set of treatments in a range of different settings.

NEON national-scale experiments will be proposed by investigator consortia via a Request for Information. The scope and scale of support for recommended Observatory experiments will be examined by NEON, Inc. and NSF. In general, NEON experiments will address questions that cannot be answered through observations alone and for which a distributed deployment adds value. Examples of possible NEON national experiments follow; these examples are illustrative, not prescriptive.

Experiments like those presented in the following four sections have been suggested by the ecological community.

1. How do water use and nitrogen deposition by humans interact and affect aquatic and terrestrial ecosystems and the linkages between them?

Two of the main effects of population growth, land-use change, and climate change are alterations of the Nation's waters and an increase in the availability of reactive nitrogen. Changing water quality and quantity are issues readily understood by society, and water quantity and quality have direct effects on personal health and well-being, the economy, agriculture, and the environment. The ramifications of an abundance of reactive nitrogen are less familiar to society, yet there is growing awareness that excess nitrogen leads to hypoxia, changing patterns of biodiversity, eutrophication, and acidification.

Even in areas where precipitation is abundant, water shortages occur, and there is increased reliance on groundwater supplies. Extraction of groundwater has profound effects on vegetation, agriculture, and society, and yet has been poorly studied. Problems of groundwater drawdown are likely to be exacerbated by anticipated changes in the timing and intensity of precipitation events that are expected as a result of ongoing climate change. Regional predictions vary from expectations of wetter climates to expectations of dryer weather patterns, but variability in precipitation is a common expectation for climate change in many parts of the country. Changes in the amount or timing of precipitation should have broad-reaching ecological impacts, in terms of direct effects on water availability to plants and to aquatic ecosystems, and indirect effects of delivery of nutrients to primary producers.

Reactive nitrogen in the atmosphere and in deposition is increasing worldwide, creating a global fertilization experiment the effects of which are becoming manifest, but remain only partly understood. The post-1950 increase in emissions of reactive nitrogen to the atmosphere, specifically ammonia and nitrogen oxides, is a major disruption of the global nitrogen cycle. Ecological ramifications, including increased forest and grassland productivity, eutrophication and acidification of freshwaters, hypoxia, and loss of biodiversity, have been documented in terrestrial, freshwater, and coastal ecosystems worldwide. Evidence is accumulating that increased nitrogen deposition may be involved in cases of major transformation of ecosystems to domination by non-native species. Yet there remain great unknowns regarding the fate of N added to ecosystems. For instance, what proportions are lost via denitrification, transported via water movement and water availability, or support vegetation and microbial growth?

To address these questions, a landscape level experiment is required in which both groundwater and nitrogen are manipulated. Manipulations of precipitation could also be nested within first order watershed scale manipulations of groundwater (wells and pumping) and nitrogen (aerial deposition by plane or helicopter). While small-scale manipulative experiments on the effects of increased nitrogen have been conducted, basin-scale experiments across terrestrial and aquatic interfaces have not been attempted. Further, we know of no experimental manipulations of groundwater. Determining the independent and interactive basin-scale effects of changes in water availability and nitrogen is truly transformational science—particularly since this could be done at a continental scale across multiple domains. The experiments will make it possible to forecast the separate and combined effects of changes in precipitation, groundwater table, and nitrogen deposition on watershed-scale export of nutrients and organic matter in streams, biogeochemical cycles, biodiversity, and invasive species.

2. How do alternative management approaches on agricultural landscapes affect nitrogen export, freshwater eutrophication, and regime shifts in inland and coastal waters?

The interactions involving water and nutrient budgets that were described in the previous experiment are manifest also in lakes and reservoirs, and at much larger spatial scales, including the linkages between major river basins and coastal waters. Some of the best understood ecosystem regime shifts—in which an ecosystem switches from one state to a very different state with a small change in inputs—are in lakes. Observations of the shift in temperate lakes from the desirable clear water state to the turbid state as a result of nutrient inputs have in recent years fueled rapid research in understanding and forecasting regime shifts in terrestrial and marine ecosystems. Coastal dead zones like those in the Gulf of Mexico, which have such large impacts on ecosystem goods and services including fisheries production, are increasing in number and size. They are clearly linked to export of sediments and nutrients from the terrestrial landscape via freshwater conduits, but the specific dynamics and quantitative relationship between landscape alterations and export of nutrients and organic matter are largely unknown. To measure these relationships at appropriate spatial scales would require nested hierarchies of monitoring and experimental infrastructure, coordinated across domains within NEON.

Experimental manipulations could include changes in farming practices, construction of riparian wetlands, alterations of stream channels or in-stream habitat, or other changes to enhance sediment retention, denitrification, or other processes important to watershed export of nutrients and organic matter. Such experiments would not only produce transformative understanding of interactions at large scales previously not addressed, but would also directly inform one of the most important national-scale environmental management issues. To address a question like this, NEON domains would coordinate with each other and with relevant coastal programs, such as Coastal Observing Systems (NOAA), Ocean Observing Systems (NSF), or privately funded efforts like Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO).

Similar large-scale experiments focused on lakes and reservoirs could determine the thresholds of regime shifts under treatments of different nutrient inputs (as a function of landscape alteration), different hydrological conditions, different food webs, and/or different inputs or forms of organic matter. Responses of lakes to such treatments are relevant not only to forecasting in-lake responses of biodiversity and biogeochemistry, but also to climatic feedbacks. In landscapes with abundant lakes and wetlands, exchanges of CO_2 between the aquatic ecosystem and the atmosphere are a substantial component of the atmospheric carbon budget. Indeed, whether lakes are sources or sinks of carbon may depend on the level of nutrient inputs. Without large-scale observations and experiments coordinated among domains that only NEON can support, society could not achieve the level of understanding necessary to drive future forecasting and management of surface water responses to changes in land use, climate, or invasive species.

3. How do land and water use, climate change, and changes in propagule pressure of invasive species affect the establishment, spread, and impact of invasive species?

Invasive species are one of the major external drivers of changes in biodiversity and ecosystem function. However, most previous research has focused on the later stages of invasion, especially on the spread and impacts of invasive species. Impacts, of course, are what natural resource managers and policymakers seek to reduce. Yet to forecast and prevent impacts, the earlier, invisible stages of invasion—including transport, introduction, and establishment—must be understood. Those stages of invasion, however, especially how propagule pressure predicts establishment, are little studied. This is largely because of technical difficulties associated with observations and experiments at large scales—difficulties that would be overcome with Observatory infrastructure.

At continental spatial scales, NEON airborne sensing, in concert with social science databases on human population, movements of humans and vehicles for recreation and work, and transportation infrastructure, will provide indices of propagule pressure to both terrestrial and aquatic ecosystems. These indices could in turn be linked to monitoring of the establishment and spread of species. This approach would be especially powerful to test longstanding hypotheses about the role of disturbance in enhancing invasions along changing gradients of land or water use (such as conversion of wildland or agricultural lands into urban or industrial use). Such hypotheses are central to the dynamics of communities and important to inform management of invasive species, but they cannot be tested at relevant spatial scales without NEON infrastructure.

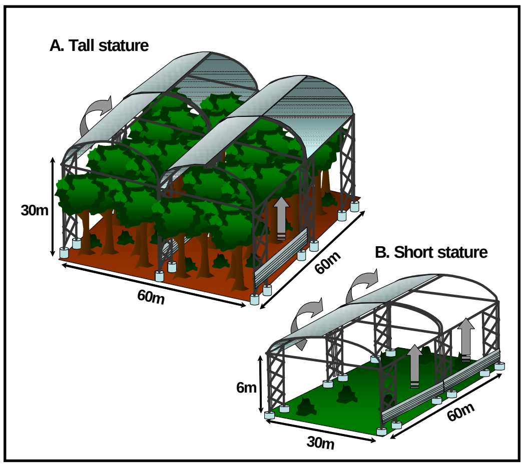
At smaller spatial scales, manipulative experiments would allow direct tests of mechanisms that may explain patterns at larger scales. Although invasive species cannot (for ethical reasons) be introduced into landscapes where they do not already occur, propagule pressure of species already present in a region could be manipulated in concert with manipulations of land cover, precipitation, nitrogen, or temperature in either terrestrial or aquatic ecosystems. Such manipulations could determine how the risk of establishment and spread relates quantitatively to the number of individual propagules released (via seeds, resting stages of invertebrates, adult organisms) or the frequency with which they are released. Such experiments would test longstanding ideas in community ecology and ecosystem succession, and would simultaneously provide insight on better managing the risks of invasive species. Experiments that are similar in design in different domains, but not necessarily on the same species, would provide general tests of theory while maximizing the regional relevance of specific results.

4. How will changes in precipitation, nitrogen loading, and nighttime temperature affect ecosystem structure and functioning?

A possible continental-scale experiment involves the construction of rainout shelters to control precipitation (Box 3.10). At the same time, the infrared energy balance of the surface would be altered by the roof structure, resulting in higher nighttime temperatures. A third treatment, nitrogen augmentation, would result in a three-way interaction experiment that would improve our understanding of three environmental changes that mirror known and projected climate variation: rainfall, minimum temperature increases, and extra nitrogen deposition.

Box 3.10 NEON Continental-Scale Experiment: Warming and N deposition

The Observatory design process included an initiative, led by Dr. Melinda D. Smith and Dr. Alan K. Knapp, to explore the idea of a NEON Core Experiment (NCE). Forecasting the future of US ecological systems in the face of unprecedented rates of global change requires a mechanistic understanding of the ways in which alterations in key environmental drivers will affect ecosystems throughout the United States (NRC 2001). The NCE would permit scientists to assess the differential sensitivities of US ecosystems to multiple global change factors and provide the predictive understanding necessary for forecasting future changes at the continental scale



Left figure. *A depiction of the NCE infrastructure of climate shelters for manipulating precipitation and temperature in (A) tall (forest) and (B) short (desert, grassland, shrubland) stature ecosystems. Key features of the infrastructure are: (1) large plots (1000 and 2000 m2 for short- and tall-stature ecosystems, respectively) in which treatments are applied at the whole-plot level to capture large-scale ecosystem dynamics and enable long-term research capacity, and (2) a retractable roof design that can exclude and redistribute rainfall and passively increase temperatures by elevating downward infrared radiation at night.* ***Right figure.*** *Retractable roof greenhouses, such as the Cravo large-scale A-frame greenhouse shown here, are commercially available and could be readily modified for the NCE infrastructure. (Illustration by M.D. Smith, photo courtesy of R. Vollebregt)*

Box 3.10 NEON Continental-Scale Experiment: Warming and N deposition

All NEON Continental-Scale Experiments should be based on a common experimental infrastructure capable of simultaneously manipulating multiple global change factors in ecosystems across the continental United States. They would focus on changes in climate (precipitation and temperature) and increased nitrogen loading. These key environmental drivers of ecological sensitivity to change are themselves undergoing significant large-scale changes as a result of human activities (Vitousek et al. 1997; IPCC 2001; NRC 2001).

Consensus is lacking among climate modelers on the magnitude and direction of temperature and precipitation alterations at any one site or region (IPCC 2001). There is agreement, however, that both nighttime temperatures (Easterling et al. 1997) and the frequency of droughts and periods of excessive rainfall are increasing and will continue to increase (IPCC 2001). Most important from a NEON perspective is that these climatic changes will occur at large spatial scales. Increased nitrogen loading in ecosystems is also a continental-scale phenomenon (Vitousek et al. 1997) related to climate. Across North America, nitrogen loading occurs in two distinct patterns: (1) background increases in nitrogen inputs due to large-scale transport of nitrogen, and (2) excessive nitrogen loading in hotspots downwind of cities, industrial areas, or intensive agricultural regions.

The NEON Core Experiment serves as a prototype for opportunistic ecological research activities that could be undertaken within NEON, after the initial elements of Observatory programs and infrastructure have been established.

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CHAPTER 4

NEON Science: Integrative Research Topics

Chapter 4. NEON Science: Integrative Research Topics

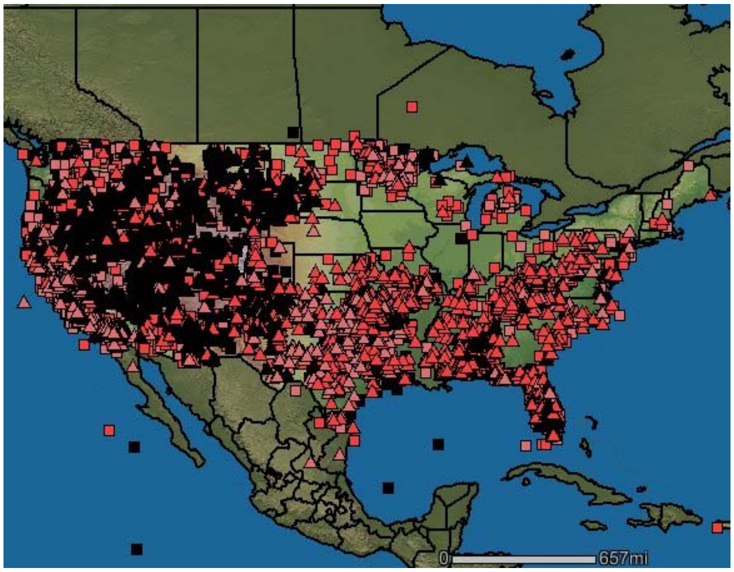
NEON will provide a platform to empower the research community to address a series of Grand Challenge questions. The power of NEON comes from its potential to unleash the creativity of the nation's leading ecologists, but its scientific potential is also strongly grounded in its ability to provide integrated measurements and approaches that address drivers and feedbacks across a wide range of processes using a variety of techniques.

This chapter introduces the kinds of integrative research topics that could take advantage of the NEON architecture. These are intended as examples only, and do not exclude other topics. Rather, they illustrate the new kinds of integration that NEON will enable and the kinds of questions that can be addressed from this new integrated perspective.

Example 1: Understanding and forecasting wildfires

Wildfires are dominant forces shaping terrestrial ecosystems including embedded and adjacent urban areas and aquatic systems throughout the US. Wildfires, like other disturbances, interact with external drivers of climate, land use, and invasive species to influence patterns and dynamics of biodiversity, biogeochemical and hydrological cycles, and infectious diseases. Humans also play a significant role because a large number of ignitions are human-caused as access to forests increases (Figure 4.1).

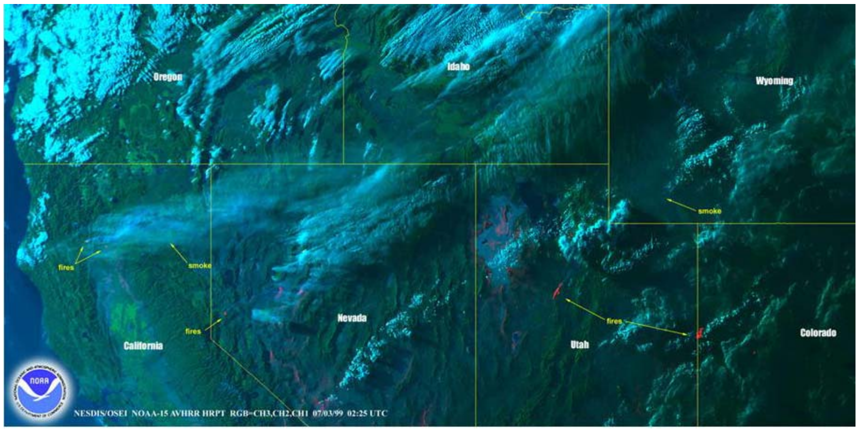
Figure 4.1 Distribution of Wildfires in the Continental United States



US wildfires 2002-2006 caused by lightning (black), humans (red), and unknown factors (pink). (http://geomac.cr.usgs.gov).

In addition, wildfire impacts occur across a range of scales. For example, wildfires affect atmospheric carbon monoxide and fine particulates with consequences for human health over more extensive areas than the actual fire (Figure 4.2). Smoke and heat from multiple fires burning simultaneously can even coalesce to influence weather (Figure 4.3).

Figure 4.2 Extent of Impact of Wildfires



Heat signatures and smoke plumes from fires burning in the western United States in 1999 (NOAA-15 POES AVHRR HRPT).

Figure 4.3 Collective Impact of Wildfires on Weather

Cluster of fires along the west coast of California on Oct. 25, 2003 affect broad-scale air circulation patterns. (http://earthobservatory.nasa.gov/NaturalHazards).

While wildfire is a natural process in many ecosystems, the presence of people and built infrastructure generates economic losses and, therefore, there is a need to manage the spread of fire. Forecasting the influences of climate variability and disturbance at the urban-wildland interface, superimposed on locations where land-use changes and land management practices bring people and property in proximity to fire, presents major scientific challenges at multiple scales of analysis.

Although research has been conducted on the ecological and economic impacts of individual wildfires, very little is known about: (1) how to forecast the rate and direction of fire spread across spatial and temporal scales for individual and multiple, coalescing fires; (2) how to forecast the regional, continental, and global impacts of wildfires, and feedbacks with broad-scale atmospheric conditions; and (3) how to minimize the ecological impacts of fires for the full range of climatic and ecological variability inherent across the country. Fire behavior across scales (including rate, direction, intensity) is difficult to predict as a result of positive feedbacks among local and regional weather (such as wind speed and direction, relative humidity), vegetation (fuel quality, quantity, and spatial distribution), and landscape features (topography, soil moisture, roads and other fire breaks). There is a clear need for forecasting fire spread using data on each variable for multiple scales combined with simulation models that dynamically update the forecast spatially. This prospect gives NEON an opportunity to contribute to basic research on wildfire, and to explore the research-to-operations transition in ecological forecasting.

Forecasting the influences of climate variability and disturbance, including land use, on fire susceptibility and ecological responses following fire requires a coordinated network of sites with sensors, acquisition of remote sensing data (for example, 30 m resolution Landsat to detect disturbance/land-use changes), and cyberinfrastructure spanning a range of spatial and temporal scales. A suite of core sites collecting centrally coordinated ecological information, combined with remote sensing imagery, geo-referenced maps, and data from existing sites that cover the United States, can provide the context for when and where a wildfire occurs. Sampling can be conducted soon after wildfires, providing “measurements of opportunity” to quantify pyrogenic emissions and carbon transformations in different fire severity classes and land management histories. Experiments altering disturbances such as insect damage and fragmentation will enable process-level understanding of fire susceptibility.

At a coarser scale across a domain, NEON can also facilitate analysis of land-use patterns, zoning and insurance policies, and land management and building practices in relation to locations susceptible to fire. For example, researchers can ask questions such as how management practices like post-fire harvest influence fire susceptibility, or how the intersection of climate and land use influences fire and how it feeds back to atmospheric CO_2 and climate. Across domains, models that incorporate process-based understanding of fire susceptibility to climate and disturbance with future land-use trajectories can generate national-level forecasting of changing patterns of fire across urban-wildland interfaces. The information can also be used to refine remote-sensing products like land-use/land-cover and disturbance history, improving inputs to biogeochemistry and atmospheric models for regional to continental applications. This information can also be used by educators in explaining the role of fire in ecological and social systems, and the ecological, economic, and cultural impacts of fire across spatial and temporal scales and social groups. Because wildfires are a common feature of ecological systems throughout the United States, information obtained from one domain can often be applied in education and outreach programs in other domains.

Example 2: Understanding and forecasting species invasions

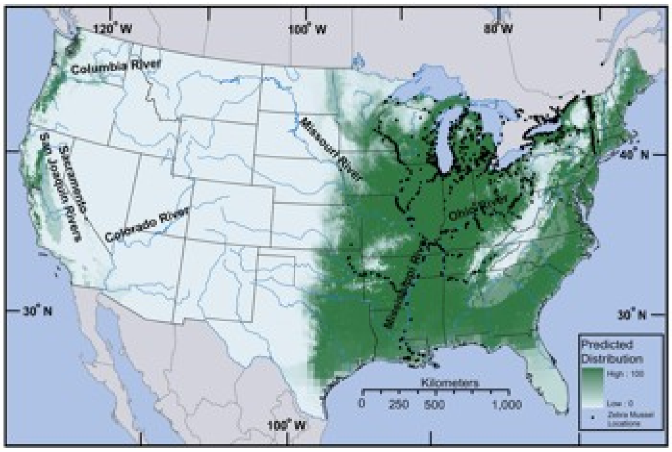
Developing the capacity to accurately forecast the introduction, establishment, spread, and impact of invasive species poses a significant scientific challenge. Such forecasting requires: (1) the expansion of the spatial scale of traditional research, (2) the acquisition of geo-referenced data on environmental characteristics and species distributions that are not now available in standard electronic formats with nationwide coverage, and (3) the incorporation of human transport of species into research.

NEON represents the first step toward answering these challenges by providing a framework for simultaneously monitoring the occurrence of organisms and collecting data on critical environmental parameters. Infrastructure and research activities coordinated across domains will allow comparisons to existing databases on species distributions and environmental parameters. When standardized, continental-scale data are combined with existing databases in a standardized format, much more accurate forecasts will be possible. NEON cyberinfrastructure is envisioned to facilitate the work of scientists to further improve the theory and application of environmental niche modeling. Monitoring changes in land use, transportation infrastructure, and movements of humans and commerce will provide indices of the anthropogenic introduction and spread of species. Such advances will support forecasts of species introduction and spread with immediate relevance to societal efforts to ameliorate the deleterious effects of invasive species.

Recent research on the spread of zebra mussel illustrates these themes. The zebra mussel is a Eurasian bivalve, introduced into the Great Lakes in ballast water of ships from Europe, that imposes high financial damage to industrial water users, large changes in ecosystem function in lakes and rivers, and losses of native aquatic biodiversity. From its initial discovery in the Great Lakes in the mid 1980s, zebra mussel spread within a few years down the Mississippi River via the Chicago Ship and Sanitary Canal and to many unconnected lakes via recreational boaters. Recent analyses of suitable habitat in the United States indicate that the species could thrive in many economically and ecologically important waterways in which it is not yet established (Figure 4.4).

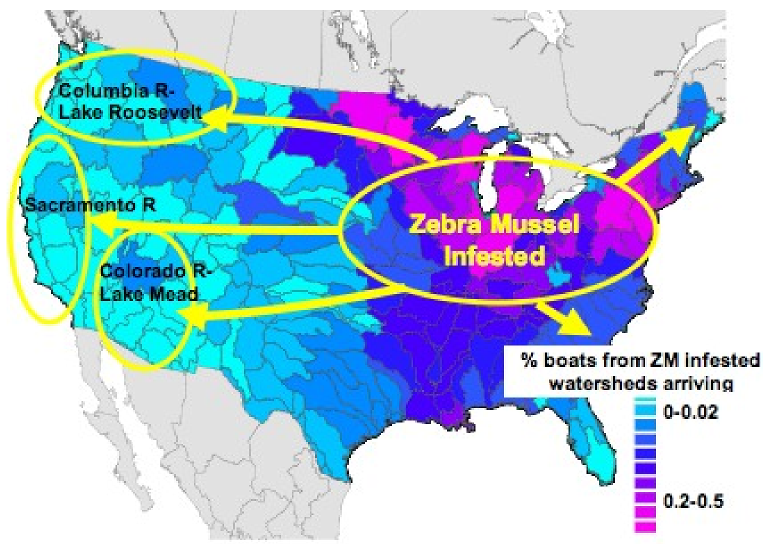
Recreational boaters continue to spread zebra mussel unintentionally to other waterways, including those that are surprisingly distant from currently infested waterways (Figure 4.5). Such analyses are based not only on the characteristics of the species of interest and the features of the natural environment, but also on human behavior and how it is influenced by transportation corridors and other infrastructure. These science-based forecasts require a strong interface with the datasets on landscape features and indices of human activity. The results in turn can inform efforts like those by the US Fish & Wildlife Service to contain zebra mussel to the east of the 100th meridian by educating boaters and inspecting boats in transit.

Figure 4.4 Prediction of Zebra Mussel Distribution



Forecast of the potential distribution of zebra mussel (green), with black dots illustrating current distribution (Drake, JM and JM, The Potential Distribution of Zebra Mussels. October 2004. BioScience 54:931-941). Zebra mussels were first discovered in Lake St. Clair (between lakes Huron and Erie). The accuracy of such analyses for both terrestrial and aquatic species is currently limited because of limited availability of geo-referenced data for relevant environmental parameters.

Figure 4.5 Forecast of Zebra Mussel Spread via Recreational Boaters



Forecast of the relative risk for uninfested waterways to future introduction of zebra mussel via recreational boaters (from Bossenbroek, Johnson, Peters & Lodge, in press, Conservation Biology). Purple and darker colors indicate greater risk of invasion. Comparison with the previous figure of suitable habitat indicates that many US waterways that are not now infested with zebra mussel are at high risk of becoming invaded unless education and management of boaters increases. High risk areas include the southeastern United States, which is a global center of aquatic biodiversity, and western waterways, which support many endangered aquatic species and highly valuable navigation and irrigation infrastructure that would be damaged by zebra mussel.

Approaches such as those described for zebra mussels would apply equally to many other aquatic and terrestrial invasive species, including weeds, plant diseases, and harmful insects. Such forecasts are at the cutting edge of current scientific capacity. Data collected from the Fundamental Instrument Unit, the Fundamental Sentinel Unit, the Airborne Observation Platform, and the Land Use Package provide a set of high-quality, highly-resolved, long-term data on the occurrence of selected species and environmental features for the NEON sites. These data, when combined with other data sets that are of greater extent but of lower spatial resolution (such as USGS data on occurrence of invasive species and aquatic water quality), will enable a multi-scale understanding of invasion patterns and processes. Local forecasts (based on NEON data alone) and national forecasts (based on combinations of NEON and other data sources) will provide essential quantitative guidance to agencies and NGOs charged with protecting ecosystems and human activities from invasive species.

Example 3: Understanding and forecasting fluxes of carbon and water

Ecologists have made significant progress in measuring and predicting ecosystem-scale carbon and water exchange. Historically, net primary productivity was measured, with ecosystem-scale carbon balance inferred or modeled at most sites. Eddy covariance technology is now employed widely across the continental United States and elsewhere to measure net fluxes of carbon dioxide between the atmosphere and ecosystems. This allows for canopy scale integration and measurements of net carbon budgets. Ecosystem models are beginning to incorporate information from these measurements about processes on time scales from the sub-daily to the inter-annual, using both traditional modeling techniques and new statistical modeling and data fusion approaches. Eddy covariance measurements are used to infer the net photosynthetic and respiratory fluxes and the climate sensitivity of the separate fluxes. Robust techniques for inferring these quantities are continuing to mature rapidly. This results in models that are better able to (1) assess how major ecosystem types across the continent will function under future eco-climatic and land use regimes, and (2) forecast how environmental change will affect the ability of ecosystems to provide critical services.

An established program exists for analyzing and modeling eddy covariance measurements and model predictions of ecosystem carbon balances at specific, well-studied sites. NEON will significantly augment this capability by providing benchmark measurements in the 20 domains and over systematic transects. The capacity to “scale up” models and forecasts to larger regions is still in development and in many cases lacks the necessary data to model the effects of climatic, chemical, biological, and human drivers. For example, concentrations of ozone (a stressor that damages photosynthetic tissues) and nitrous oxide (NO_x, an ozone precursor and a potential source of nitrogen “fertilizer”) are increasing in the lower atmosphere, and are highly dependent on air mass sources. In addition, disturbance regimes are changing (insects and wildfire, for example) and many ecosystems are changing their species composition as a result of biological invasions. NEON data will provide systematic measurement fluxes across critical environmental gradients and integrated data on physical, chemical and biological drivers.

Forecasting the effects of climate, land use, and disturbance on US carbon balances will require a coordinated set of measurements at core sites and strategic transects. For example, measurements of the response of carbon exchange to time-since-disturbance have only been made in a few ecosystem types. Yet, modeling studies and NPP measurements suggest that more measurements across more ecosystem types are necessary. Similarly, chemical gradients (ozone, reactive nitrogen) exist within many eco-climatic regimes, presumably causing differential effects. But again, few of these gradients have been sampled. Since many environmental drivers affect both photosynthesis and respiration, in principal they could cause carbon uptake to increase or decrease, depending on subtle differences in the sensitivity of photosynthesis and respiration. The scientific community will need to develop robust techniques to partition the net flux into its process-level components, estimate the environmental sensitivities of the separate fluxes, and incorporate those sensitivities into forecasts using models. Further, those sensitivities will need to be "mapped" over ecosystem types, and the strength of the drivers (chemical, climatic, biological) likewise mapped. These efforts could provide an unprecedented data synthesis involving strategic transects to measure fluxes and drivers, airborne remote sensing to measure relevant ecosystem characteristics at high spatial resolution and broader scale patterns, and modeling and interpolation of the drivers. All these data must be integrated using NEON cyberinfrastructure and provided as inputs to model-data fusion systems, model inter-comparisons, and ultimately converted into forecasts. The NEON system will facilitate this type of comprehensive capability.

Example 4: Understanding and forecasting zoonotic and vector-borne diseases

Three quarters of today’s emerging human diseases, and many historically important ones, are caused by zoonotic pathogens. Zoonotic pathogens are defined as those transferred from vertebrates to humans, either through direct contact with an infected animal or when transported by an intermediate species. For instance, a dog bite can transfer the rabies virus to a human. In other cases, a parasite such as a tick, louse, or mosquito transfers the pathogen. Diseases transmitted in this way include plague (caused by a bacterium transferred from rodents by fleas) and malaria (caused by a single-celled organism transferred by mosquitoes). Animal pathogens spread from local to regional scales and move across continents—the scale of NEON science. Species interactions are at the heart of zoonotic diseases, and ecology provides the knowledge to help track and prevent them.

Avian influenza (avian flu), a family of zoonotic diseases, provides an example of the kind of integrating issue that NEON can help address. Avian flu is caused by highly contagious viruses transmitted through the saliva and feces of birds. Most of these viruses affect wild birds to a mild extent, but they often cause stronger symptoms in domesticated birds, which are the most common vector for human infections. When a weaker strain of the virus suddenly mutates into a more virulent one, infected chickens, ducks, and turkeys can die within days, often with mortalities as high as 90 percent. Since 2003, the H5N1 strain of the virus has killed hundreds of millions of poultry and more than 150 people through contact with infected birds. If the virus evolves the ability to spread easily from person to person, millions of people could die, as in earlier epidemics of avian influenza.

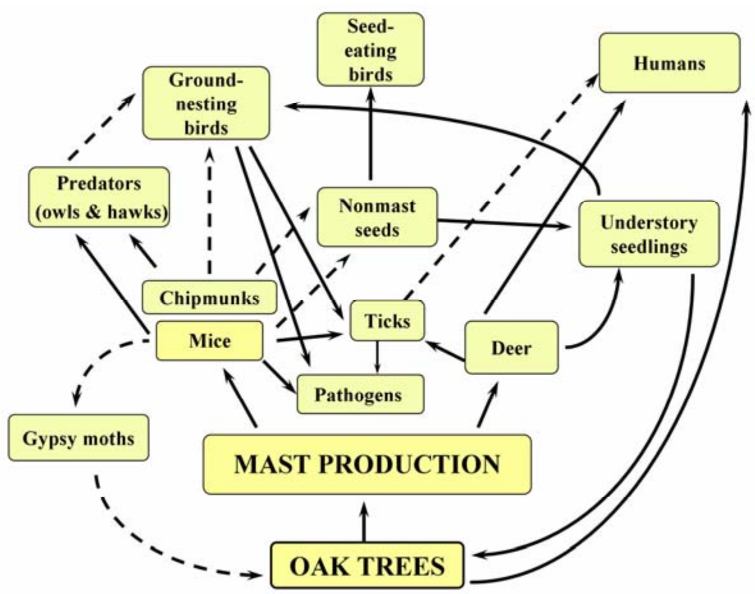
The H5N1 virus spreads when humans transport infected birds or when infected wild birds migrate. From 2003 to 2006, it spread rapidly from southeast Asia into Europe and Africa, but had not yet appeared in Australia or in the Americas. The most likely place for infected wild birds to enter the Americas is Alaska, where ducks, geese, and shorebirds from Asia migrate across the Bering Sea each year. Ecologists there are studying the potential spread of the virus by trapping and testing migrating birds. These ecological detectives are trying to catch the first wave of the disease entering North America.

Ecological knowledge provides the foundation for understanding the life cycles of pathogens and their interactions with hosts. Pathogen interactions are greatly influenced by changes in the environment around them, particularly land-use change. To control pathogens successfully, scientists need an intimate knowledge of how the pathogens interact with other species and with their environment across a range of spatial and temporal scales. This cross-scale ecosystem perspective is the hallmark of NEON.

NEON infrastructure provides measures of the key variables expected to affect biodiversity and the spread of invasive species and infectious diseases. These include climate variables (shifts in temperature and precipitation recorded by the Advanced and Basic BioMesoNet towers), land-use variables (type, distribution, and measures of primary production derived from airborne hyperspectral imagery), soil variables (soil moisture, recorded by soil sensornets), and risk factors for different human populations. Furthermore, the organism tracking system is envisioned to provide continuous tracking of targeted deer mouse populations. The deer mouse has a continental distribution and is known to carry Lyme disease and Hantavirus (Figure 4.6).

Figure 4.6 Complex Relationships of Lyme Disease

This conceptual model shows the taxa within oak forests that interact to determine outcomes such as Lyme disease risk to people, the probability of a gypsy moth outbreak, and abundance of ground-nesting songbirds [1]. Key organisms are placed within boxes, which are connected by arrows that represent interactions between taxa. For instance, an arrow goes from mast production to mice because mast production affects mouse abundance (rather than vice versa). Solid arrows represent a positive effect of one organism on another (e.g., more mice means more ticks), whereas a dashed arrow represents a negative effect of one organism on another (e.g., more mice means fewer gypsy moths).



Source: Updated and modified from Ostfeld et al. 1996 [1]

Reference:

[1] Ostfeld, R.S., Jones, C.G. and Wolff, J.O. (1996) Of mice and mast: ecological connections in eastern deciduous forests, BioScience 46, 323-329.

The tracking system will provide information about how deer mouse populations respond to changing climatic conditions and the associated availability of food. The Fundamental Sentinel Unit offers an important subset of relevant biological response measurements. These include: (1) seasonal to annual measurements of the pathogens present in mosquitoes (sampled seasonally to reflect changes in community composition through the year, pooled and analyzed for likely pathogens); (2) samples of the blood and tissues of deer mice; (3) routine biodiversity surveys of species, such as plants and ground-dwelling beetles; and (4) routine biodiversity surveys of functional groups that are sensitive indicators of environmental changes, such as nematodes and soil microbes. In addition, the measures of ecosystem function described previously will also be important for understanding the effects of altered biodiversity in relation to ecological function and the provision of ecosystem services.

Implications for Ecological Modeling and Forecasts

Ecologists and biodiversity scientists increasingly use ecological niche models to predict where invasive species may become established, and where diseases like West Nile Virus may emerge. GARP is one of many such models that require climate, soil, water quality, and other physical parameters to characterize the environmental space (or ecological niche) that a given species occupies, or has occupied in the past. Scientists then project the results of niche models to new or altered environments in order to identify new places that may be suitable for that species.

Although these models have been successful in making such predictions, many shortcomings must be addressed. First, ecological niche models rely on well-distributed observations of species and environmental conditions that are largely unavailable at the continental scale. Second, there are few systematic observation programs at the continental scale that can assess the accuracy of resulting predictions and forecasts. Third, because these models are typically calibrated against spatial patterns rather than observed time series, they provide limited information on rates. Scientists need better observations in order to improve ecological models, and resource managers need them to inform mitigation efforts.

NEON supplies the infrastructure and data necessary to better understand the spread of vector-borne diseases. For example, if we want to understand the dynamics of St. Louis encephalitis, we might first ask what the incidence of St. Louis encephalitis is in mosquito populations in urban, managed, and wildland settings. Secondly, we might also be interested in forecasting the locations of potential outbreaks of this encephalitis at the continental scale, the results of which are depicted in a map showing encephalitis "hotspots"—the places where it might be expected to appear next.

The incidence data for this example are determined from blood samples from mosquitoes collected at CO_2 traps. Climate data will be available from the same locations, while land-use and land-cover data in the vicinity can be extracted from the Airborne Observation Platform and the Land Use Package. Forecasting can unfold in two stages. At the most fundamental level, a forecast can be derived from an ecological niche model based on climate and land-cover characteristics of habitats occupied by the mosquito vector. The data necessary to develop, verify, and improve such a model would be routinely collected via Observatory infrastructure. A more sophisticated forecast might consider spatial contagion, based on new understanding of how mosquitoes (or the virus, its intermediate hosts, or passive reservoirs) move across the landscape. This more sophisticated model would also rely on NEON data and infrastructure, but would also likely benefit from new, continental-scale ecology research programs that develop in conjunction with NEON.

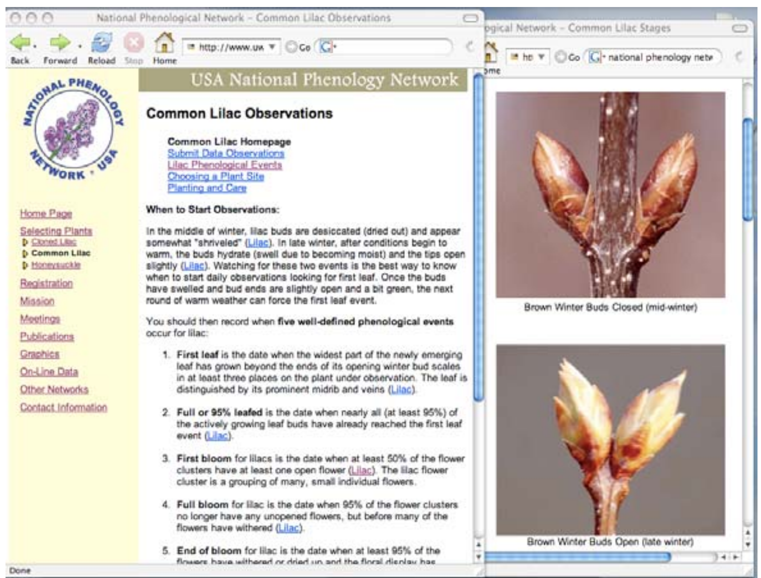
Links to Education

Education programs can supplement an observation-based learning program that has been successfully implemented in many public school systems. For example, student sampling of weather data, water quality, and water quantity has proven to be a very effective learning tool. The experiences of collecting samples, combined with subsequent analysis and the goal of reaching evidence-based conclusions, often meet educational standards of learning requirements. Access to NEON terrestrial and stream data will contribute new resources to hands-on classroom science in the schoolyard.

Many of the ecological responses to climate variation are predicted to occur at regional to continental scales and to affect a host of seasonal phenomena, such as leaf-out, bud burst, and bird nesting and migration patterns. The prospect of collecting and analyzing data related to these responses at regional and continental scales will be engaging to many people. For example, education portals will enable citizen scientists and students to contribute phenological observations to NEON science programs, which will, in turn, be linked to national and international observation networks such as the USA National Phenology Network (Box 4.1).

Box 4.1 USA National Phenology Network

Phenological observations provide key insights about unfolding ecological processes and can be contributed by citizen scientists as well as research professionals. The USA National Phenology Network (USA-NPN) facilitates systematic collection and free dissemination of phenological data from across the United States. This effort primarily supports scientific research concerning interactions among plants, animals, and the lower atmosphere, especially the long-term impacts of climate variability.



NPN helps individuals, including citizen scientists and research scientists, select and observe appropriate species at their locations, and then encourages them to register and submit the data they collect each year over the Internet. At this time, the program includes indicator plants (principally lilacs) that facilitate comparisons between sites, and native plants suited to each region.

(Text reprinted from www.npn.uwm.edu, courtesy Dr. Mark D. Schwartz, University Of Wisconsin-Milwaukee.)

The linkages between scientific research and education culminate in graduate education, especially as they support training of the next generation of doctoral students, who will in turn advance science for their future. NEON continental-scale infrastructure fosters the development of fundamentally new capabilities in young researchers as they work across unprecedented scales in space and time. Regional- to continental-scale inquiries will be supported by Observatory infrastructure and by the research programs that will gravitate to NEON sites. Funding for much of the educational component will be built into research proposals and their budgets. Undergraduates will benefit from Observatory resources as NEON science is integrated into the curriculum and as inspired students initiate research studies. Postdoctoral scientists and educators will receive early-career benefit from the community resource of NEON infrastructure, data streams, and information archives.

CHAPTER 5

NEON Education:
Translating Science Into Meaning

Chapter 5. NEON Education: Translating Science Into Meaning

Introduction

In 1804, the explorers Meriwether Lewis and William Clark began an ecological transect across what is now a major part of the continental United States. Sampling organisms and making observations from St. Louis, Missouri, to the Oregon coast, their expedition established a baseline for observational ecology for the new Nation. In 1845, Henry David Thoreau began to record one of the first observational sets of measures in a single place over time, at Walden Pond, near Concord, Massachusetts. More recently, technological advances in sensing, computing, and communication have enabled ecologists to expand their observations to include broader temporal and spatial scales and multiple scales of biological organization, ranging from molecules to landscapes.

NEON establishes a new level of ecological science. It is the first ecological observatory network designed to test and develop ecological theory by detecting and forecasting ecological change at continental scales over multiple decades. Continuous NEON data streams, made possible by state-of-the-art computing power and sensor and communications technologies, will be a national resource for ecological research.

The Observatory will also include a national level education program integrated into a suite of ecological research programs. Integration of NEON science and education enables researchers and teachers to discover productive common ground and promotes a vision of ecological education in which scientists are educators and educators are scientists. Successful, long-term integration of science and education, building on the education infrastructure and programs and activities described in the remainder of this chapter, will help create an informed citizenry that can respond to critical national ecological issues and from which a new generation of ecological researchers can emerge.

The Education Mission

The overarching mission of NEON education is to train the next generation of ecological researchers while translating scientific data into meaning for all citizens. Five fundamental ecological principles form the basis for Observatory education programs and activities:

- Ecology progresses as a science by evidence-based reasoning and hypothesis testing.
- Climate variation and evolutionary and geological processes, occurring at both short and long time scales, influence ecological systems.
- Ecosystems provide valuable services for society.
- Humans are part of ecosystems. Understanding ecology and ecological change are important to our livelihoods and well-being.
- Ecological change occurs at different scales of space and time, bringing risks, benefits, and uncertainty. NEON information and knowledge can help society forecast ecological change and plan informed responses or adaptations to future change.

Education programs and activities focus on accomplishing four specific objectives. First, science educators will translate the Observatory's data resources into information-rich products and learning experiences that promote public understanding of ecological science, including the fundamental principles listed above. Second, programs will be developed to enlarge and diversify the ecological research community. Third, materials and activities will be designed to enable students, educators, and decision-makers to optimally use NEON as a tool for making informed decisions about ecological issues. Fourth, the Observatory will be a place for training future generations of researchers through programs for undergraduate and graduate students as well as postdoctoral associates.

Education Infrastructure

The Observatory education program is designed to provide: the environment for people to collaborate, investigate, and learn; tools to help learners access and understand scientific data and information; program resources and data to develop instructional models and curricula; and professional development opportunities so that scientists and educators can be more effective researchers and teachers.

Two principal infrastructure elements support these education activities. First, cyberinfrastructure enables scientists, students, and the public to access data and information, data visualizations and ecological forecasts, curricula, and other educational resources via Internet portals. Conversely, Internet portals also allow citizen scientists to contribute data to science programs. Second, the NEON Education Headquarters and District Education Facilities provide focal points for program development, training and education, outreach activities, and education research.

NEON Cyberinfrastructure

A comprehensive description of NEON cyberinfrastructure—hardware, software, network communications and facilities, and personnel—is included in the NEON Networking and

Informatics Baseline Design, a companion to this document. Specific cyberinfrastructure components that support education include:

- level- or audience-specific portals that provide access to ecological and educational data sets;
- virtual collaboration spaces for educational researchers to share approaches and results, and for teachers to distribute learning and assessment tools and collaborative software to participating schools;
- data archives of educational resources and research that are searchable by audience, topic, or objective; and
- conferencing and distributed learning facilities at NEON education headquarters, enabling collaboration and delivery of education and research resources over the Internet.

NEON Education Headquarters and District Education Facilities

National and District-based education facilities establish the physical infrastructure needed to coordinate and host science education and outreach activities and to provide access to NEON educational resources. Classroom/lecture hall space, office space, and cyberinfrastructure will be associated with both types of facilities. The NEON education headquarters will be co-located with the overall NEON headquarters to facilitate interactions among Observatory scientists, educators, and students. Likewise, District education support facilities are likely to be co-located with a centralized support facility, museum, or other learning center in each of the 20 climatic domains. These facilities will serve as a focal point for regional education and outreach activities, as well as for communication and coordination (e.g., facilitating short-term graduate student or researcher visits to coordinating K-12 ecological activities).

The NEON education headquarters will play a central role in developing national citizen science initiatives and coordinating formative evaluation of NEON and its related education programs. For the first time, ecology educational research data will be centrally archived and made easily accessible to the research community to support comparative studies of education approaches. Physical and virtual collaboration facilities will enhance the interactions of decision-makers and scientists in articulating and evaluating NEON forecasts, and support the overall scientific mission—to produce scientific understanding and ecological forecasts that benefit society.

Education Programs

NEON education is designed to advance ecological science literacy through new programs and activities that develop and promote scientific ways of thinking (Box 5.1). Through formal and informal education initiatives, Observatory science educators can accurately translate scientific data into meaningful information that connects citizens with the science of their local, regional, continental, and global ecological systems.

Box 5.1 NEON Education Promotes Scientific Ways of Thinking

Scientific thinking. NEON science involves a challenging but important mix of the major approaches in ecology and the kinds of evidence involved. Learners should come to understand the relative strengths and limitations of (1) experimentation, (2) large-scale monitoring (e.g., remote sensing, distributed sampling devices), (3) making "natural" comparisons (e.g., comparisons across and among NEON sites), and (4) modeling and the role of uncertainty. As recommended by the National Research Council *(National Science Education Standards*, National Academies Press, 1996), NEON Education will provide firsthand experience with these concepts, through independent investigations at local scales in the schoolyard or campus and through guided investigations with NEON data.

Temporal thinking. The Observatory poses several critical questions about responses over time, such as thresholds, lags and legacies, and linear or complex responses. As a learning goal, people should develop their "temporal imagination," the ability to see fast-moving processes "slowed-down" and slow processes "speeded up," so the processes can be more fully appreciated. Key to temporal thinking is understanding why lags, thresholds, and complex responses are so important in ecological systems, knowing what rules govern them, and anticipating their occurrences and consequences.

Spatial thinking. NEON education programs foster the essential skills of geographic literacy and "spatial imagination." An understanding of ecological processes at different scales of resolution is especially important because small changes at the local level can have broad impacts across landscapes.

Transdisciplinary thinking. One focus of NEON education is to identify key learning objectives at the interface between the social and the biophysical disciplines. The network's education programs will identify concepts that overlap (e.g., ecosystem services, ecological economics, environmental ethics) in order to develop the facility for learning across a variety of disciplines.

Systems thinking. A key challenge in ecology education is to convey the concepts of conservation of mass and energy and how those concepts unfold in real ecological systems. NEON education programs include curricular models to help learners visualize and comprehend phenomena and physical structures such as atoms, molecules, elements, microbes, and energy, which cannot be seen with the naked eye. Understanding such invisible structures and processes along with how they flow through ecosystems in space and time is essential for understanding how elements introduced into ecosystems by human and natural means cycle through our environment.

Quantitative and probabilistic thinking. NEON education will help people become more capable of evaluating data and understanding the uncertainty inherent in statistical analysis. By directly addressing computational literacy and how conclusions are drawn in the face of uncertainty and natural complexity, NEON will build the public's understanding of science.

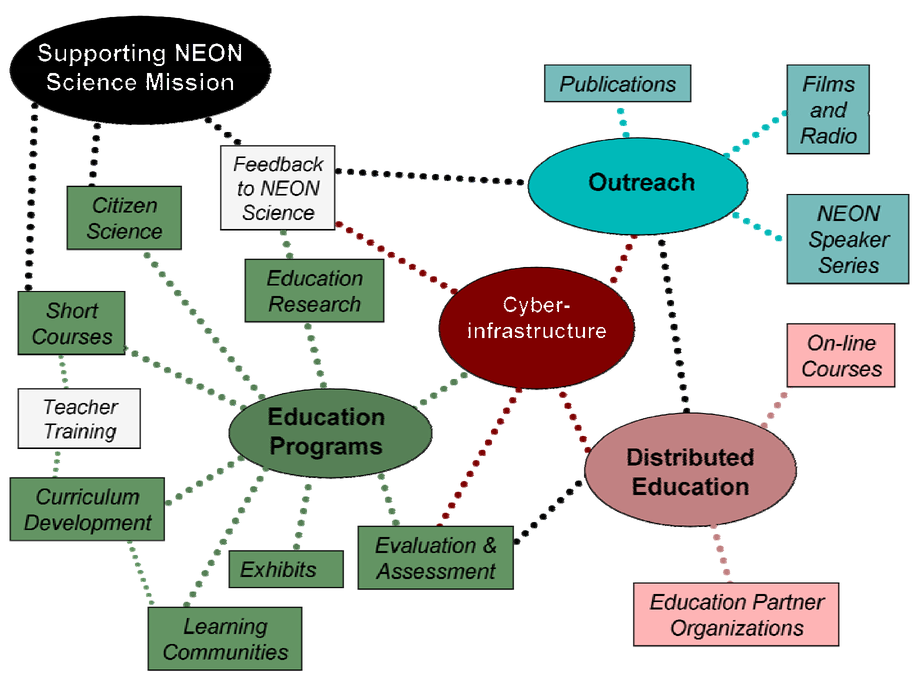
Berkowitz, A., M. Ford, and C.A. Brewer. 2005. A framework for integrating ecological literacy, civics literacy and environmental citizenship in environmental education. In, Johnson, E.A. and M.J. Mappin (eds.), Environmental Education or Advocacy: Perspectives of Ecology and Education in Environmental Education. Cambridge University Press. New York. Pp 227-266.

Science educators, via NEON education programs and partnerships, will be poised to:

- transform the teaching of ecology at all levels to prepare the next generation of ecologists;
- provide opportunities for a broad and diverse population of citizens to interact with NEON scientists, data, and ecological forecasts;
- enable scientists, students, and citizens to become familiar with the technologies that drive ecological research;
- clarify the components and functions of ecological systems for decision-makers, so they can link environmental changes to human health and well-being; and
- enrich public awareness of how ecosystem services affect daily life.

These results can be attained through training and outreach activities, new curricula and web-accessible training modules, and novel citizen science programs and other proven approaches. The relationships among the education and outreach activities and NEON science are illustrated in Figure 5.1 and described in more detail below. Furthermore, the Observatory offers an optimum environment for supporting education research projects that complement scientific research endeavors, and that can lead to improved methods for teaching ecological concepts and

Figure 5.1 Organizational Integration of NEON Science Components with Education and Outreach Activities



Source: NEON Project Office

optimal approaches for delivering information to citizens.

Training and Outreach

Short courses and workshops on ecology and education, as well as on methods and analytical techniques, will provide effective professional development for scientists, students, and educators. Throughout the lifetime of NEON, for example, workshops will be essential for training scientists and students in the use of equipment and standard analytical procedures. Box 5.2 provides one example of how focused workshops can build the necessary scientific capacity.

Modern computational and communication technologies can now support an array of distributed learning activities. Through NEON, students will communicate directly with scientists who are working in remote settings, discuss ongoing research, and, in many cases, virtually participate in data collection and analysis. The NEON education headquarters and District education facilities will be equipped with the capacity to create live feeds of scientists working in the Observatory sites and to support “live chats” among ecologists and educational groups around the country.

The potential for NEON science to inform citizens on environmental issues also depends on new visualization approaches and Web-based tools that display complex scientific data and maps, and convey an understanding of processes essential to forecast models. NEON-based education programs can provide local and regional information and advisories about rapidly unfolding ecological changes, including natural catastrophes. An “educational rapid response” to such events may include:

- timely scientific explanations about what is occurring and why;
- scenarios addressing what to expect in various time frames;
- lessons learned during similar events (at different times or places), and advice on how to respond as a current event develops; and
- forecasts of local and regional consequences (short- and long-term).

Effective education about newsworthy ecological events requires more than just making experts available for interviews; the public needs access to stories. Webcasting and podcasting are emerging as forms of mass communication that can rapidly provide the public with “the news it can use.”

NEON education programs can explore these emerging communication technologies and take advantage of new opportunities to provide the news media with “the pieces” necessary to tell stories about ecological science—not just the press releases, but the interviews, footage, and graphics needed to package a story, as well as edited stories that news stations need to cover ecological topics, much like a wire service.

Virtual and physical education exhibits that are made available to schools, museums, and other learning centers can provide cost-effective means to communicate ecosystem information to a broad audience. Such exhibits may represent the first opportunity for citizens to encounter NEON science and view data visualizations and ecological forecasts.

Box 5.2 Building Capacity to Use NEON – A Model Short Course on Stable Isotopes

Non-radioactive "stable" isotopes in plant, animal, and microbial tissues vary in abundances within ecosystems. Knowledge of stable isotope abundance can provide valuable integrated information on the structure, function, and dynamics of terrestrial and aquatic ecosystems. NEON stable isotope facilities provide for comprehensive, multidisciplinary training and education programs that stimulate innovative, interdisciplinary applications of stable isotope measurements in the environmental sciences. Short courses on stable isotope theory and practice build intellectual capacity within the ecological research community.

Stable Isotope Ecology, taught by Dr. James Ehleringer and colleagues at the University of Utah each summer, is an example of the type of transformational, multidisciplinary graduate education and training courses offered by NEON. This annual course brings together 25 students from across the nation and around the world for an intensive, two-week lecture and laboratory experience taught by 15 instructors, who also come from around the nation. With lectures spanning a diverse range of topics, from animal physiology and ecosystem nutrient cycles to geochemistry and oceanography, students are introduced to the ways that stable isotopes can be used to trace, record, integrate, and provide attribution to organic and inorganic molecules and organisms as they move through ecosystems. From eight in the morning until eight in the evening students are fully immersed in this "isotope camp." Typically, the mornings are devoted to lectures, while the afternoons are dedicated to laboratory training and group projects.

Building contacts for future research collaborations is also a critical component of this intensive short course. Each year, 10 current faculty members from outside institutions are invited to attend the lectures, with the expectation that ideas from this interdisciplinary course will spread into many other curricula. The program also provides an opportunity for students and researchers to work together, for this "next generation" to be matriculated into the current network of researchers.

Short course participants learn to process samples and analyze data in the Stable Isotope Short Course at the University of Utah. Photos courtesy of Dr. James Ehleringer (University of Utah).

Curricula

NEON scientists will need expertise with sophisticated instrumentation, advanced statistical analysis, visualization approaches, and simulation and forecasting techniques, as well as the ability to collaborate with a diverse array of environmental and social scientists. Observatory education programs will build these skill sets through higher education curricula that prepare students to use the network's instrumentation and data sets to integrate and synthesize new conceptual knowledge across disciplines.

NEON education programs will create innovative curricula that promote learning through local investigations, and through distributed collaborations nationwide that are compatible with local school requirements. Web portals and Web resources will open the doors to distance-learning opportunities. New and innovative opportunities for K-12 teachers will emerge, broadening teachers' experience with problem-based learning, case studies, and data-based activities.

The NEON education headquarters will serve as the central repository for resources and tools that support collaborative development of educational projects for use by professional curriculum developers (e.g., the Earth Exploration Toolkit of the National Science Digital Library and Digital Library for Earth System Education collection). Professional development will also be linked to data generated from Observatory educational research programs to ensure that assessment is connected to classroom practice. Such growth in professional knowledge and skills will foster effective integration of best practices in teaching ecological science.

Citizen Science

Citizen science programs provide the capacity for students and interested laypersons to actively participate in scientific research. Such programs are important not only from an educational perspective but because they also enable scientists to broaden the geographic and temporal scale of their observations (Box 5.3). Observatory education facilities and programs can support the "toolkits" necessary for developing novel research programs using tested citizen-science techniques, including online instruction and tutorial materials. NEON cyberinfrastructure provides the portal to citizen science projects and resources, including online identification guides and citizen science journals.

Education Research

Because the Observatory engages a broad range of learners focused on a common enterprise, it will become a unique subject for scholarly research. Education research scientists interested in "learning how learners learn" can use NEON to help answer such questions as: How do people come to understand ecological systems? How does this influence their attitudes toward their environment and the ecosystem benefits they derive?

Using the network as a resource for education research requires collaboration across such disciplines as cognitive psychology, anthropology, education, and sociology (including socio-economic research). Data about education programs in general, and the process of learning itself, properly archived and curated with metadata included and freely available in as near real time as possible, serves the NEON education research mission.

Box 5.3 Expanding NEON Through Citizen Science

Citizen science connects researchers with members of the public who collect data following defined research protocols. Citizen science programs have collected information at local, regional, and continental scales to answer diverse questions in the environmental sciences.

Citizen science began in North America more than 100 years ago with the first Christmas Bird Count (CBC). The CBC started when a small group of scientists in New York City sought to count birds instead of hunt them. To survey birds across a wide area, the researchers enlisted the help of the public. Over the last century this effort has grown into a continent-wide program with formal protocols. The CBC provides the longest-term data set available for monitoring bird populations in North America. Data from CBC efforts have been used in hundreds of scientific publications, and summary reports are readily available on the Internet.

Why is citizen science central to the Observatory? Transformational NEON science often will require investigations at vast spatial and temporal scales. Citizen science is amenable to rapidly acquiring large amounts of data from a geographically distributed population of human sensors. For example, NEON citizen scientists could detect and report first occurrences of an invasive species in their locales. Or, they could provide important ground-truthing capabilities for satellite data. Recognizing the need for a greater alliance between researchers and interested laypersons in investigating complex environmental issues, NEON will develop and support a multi-tiered, continental-scale venue to promote a Citizen Science Gateway.

Beneficiaries of Education Programs

NEON education serves learners in both formal and informal education settings. Students ranging from K-12 to undergraduate and graduate levels plus postdoctoral scholars will have unprecedented access to large databases, information, and resources that support science and technology training. Citizen science and school-based programs will support field data-collection activities and help create the mindset that transforms the learning paradigm for ecological science from a top-down model to one built around the concept of information feedbacks. Observatory programs promote an information pathway in which learners can also produce data and information and add to the accumulated knowledge base.

K-12 Students: Students will participate in NEON-related activities in schoolyard and local study sites by using common measurement approaches and cyberinfrastructure that connects them to research sites across the nation. Citizen science and distributed learning programs enable teachers to coordinate ecological investigations at schools with research sites throughout the United States.

Undergraduate and Graduate Students and Postdoctoral Associates: The next generation of ecologists will gain the theoretical, conceptual, logistical, and analytical skills needed to address important ecological questions at broad spatial and temporal scales.

Ecological and Environmental Researchers: Scientists and educators will be provided with professional development opportunities that enable them to use Observatory sensors, technologies, data streams, and educational resources.

The Public: Education programs will make science both challenging and enjoyable by engaging citizens as partners in discovery and detective work literally in their own back yards. New science-based initiatives can introduce technology and innovation in public science programs, clarify environmental responses to change, help forecast outcomes and, ultimately, increase public understanding of the links between ecosystem health and human health.

Decision-makers: The Observatory will provide fact sheets and clear summaries of ecological issues based on sound science. As NEON generates ecological forecasts, decision-makers will benefit from improved communication about how models are developed, the kinds of assumptions made, and how the models contribute to ecological predictions.

Partnership Opportunities

The NEON education mission is to train the next generation of researchers while preparing society to use data, information, and forecasts to understand and effectively address critical ecological questions. The term “society” encompasses the broad spectrum of gender, cultural, racial, economic, and geographic groups represented in the United States. The goal is a diverse NEON user community that includes minorities, retirees, differently enabled, and young people.

Collaboration with programs such as Girls Incorporated, Operation Smart, Girls in Science, and Women in Engineering Programs and Advocates Network will promote gender diversification within NEON. The Strategies for Ecology Education, Development, and Sustainability (SEEDS)—an Ecological Society of America program, begun in 1996—is an excellent model for how partnerships between NEON science educators and professional societies will be developed to increase the number of minorities in ecology. SEEDS field trips and fellowships stimulate student interest in pursuing ecology careers by providing training, illustrating career options, and building peer connections.

Institutionally, historically black colleges and universities, Hispanic serving institutions, and tribal colleges and communities will participate in NEON research, education, and governance. “Ease with technology” will be watchwords for the network’s educational activities; differently enabled learners require a seat at the table to ensure participation, including the opportunity to collect data in the field when possible.

Science and education programs will attract a variety of science partners. Members of retirement communities and groups such as Elderhostel will access NEON data sets and record local ecological measurements. School classrooms, college laboratories, and after-school programs will link to Observatory resources. Professional scientific and education societies, such as the Ecological Society of America’s Teaching Issues and Experiments in Ecology, will make NEON research and forecasting projects accessible to classrooms. Groups such as Earthwatch and Project Wet, as well as museums, national parks, and nature centers, will collaborate with NEON to create new opportunities for citizens to increase their science literacy.

Mutually beneficial partnerships with scientists and educators from NOAA, NASA, USGS, and other government agencies are critical to effective NEON education. National Science Foundation projects for undergraduates, graduate students, postdoctoral scholars, and faculty research and training will augment their current education opportunities under the Observatory science umbrella.

NEON Education: Translating Ecological Science

The Observatory’s education programs are crafted to translate NEON science into meaning for all citizens. When fully deployed, NEON will engage thousands of scientists and educators in co-creating a high national standard of ecological education and public science. Millions of students, citizens, and decision-makers will have access to comprehensive ecological data to help them build their science literacy and make informed lifestyle choices. NEON education programs will provide the capacity to transform the way we train students while looking at our planet’s ecosystem dynamics, human inhabitants, and the ecological processes that define the biosphere.

CHAPTER 6

NEON Coordination and Partnerships

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Project Management and Governance

The complex, distributed nature of NEON requires robust management approaches tuned to match the phases of the project: design, implementation, and operation. Each phase is guided by best practices in project management as described in the NSF Facilities Management and Oversight Guide. Detailed project management plans are being defined for the implementation and operation phases of NEON.

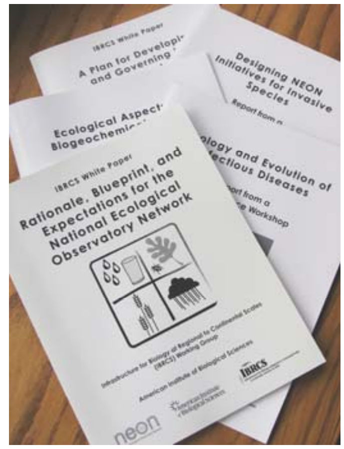
Design Phase

Thousands of ecologists, environmental and biological scientists, engineers and computer scientists, and educators have worked for years to create NEON (Box 6.1). In the fall of 2004, that effort took on new significance when the NEON Design Consortium (NDC), a team of approximately 160 experts across a range of disciplines, was selected from more than 600 nominees to participate in a systematic effort to design the network. The group’s task was multidimensional: to reflect on ecological grand challenges identified by the National Research Council and determine the novel research foci that would meet them; to build a complementary educational program; to identify technologies to enable these new research and educational opportunities; and to develop a structure and process for operating the program in an open and equitable manner for the scientific and educational communities.

Using formal tools and approaches to project design, participants specified the required system components based on research and educational goals. The process included several steps. First, participants identified central questions to guide the physical design. Next, contributors specified the project’s observational programs, including science requirements such as the optimum range and precision of sensor-based measurement systems. Using these requirements as a foundation, designers then specified the technical requirements of the instrumented systems, sub-systems, and the computational and networking backbone of the Observatory.

Box 6.1 Conceptualizing NEON

The process by which scientific communities assemble to conceive, design, and use large research platforms and facilities—such as particle accelerators, radio telescope arrays, and oceanographic research vessels—are complex and varied. Despite project-specific differences, the development of all such projects depends on broad community support over many years. The history of NEON is no different.



Source: American Institute of Biological Sciences

The conceptual birth of the Observatory occurred in the late 1990s. Early visions were the product of several community-based workshops that initiated discussion about objectives, standard measurements, infrastructure, biological archives, information management, and operational considerations.

Planning workshops continued during the ensuing years under the umbrella of the Infrastructure for Biology at Regional to Continental Scales (IBRCS) project at the American Institute of Biological Sciences. The IBRCS project was led by a 20-member working group and convened nearly a dozen workshops and other meetings aimed at informing the ecological science community and maturing the NEON concept.

As the profile of NEON grew in the scientific community, geographically-based groups of scientists organized in another effort to broaden community support, elaborate on the evolving NEON design, and assess existing resources that have the potential to complement and enhance NEON. The group's organizing body—the Consortium of Regional Ecological Observatories—provides a mechanism for communication among the various groups, the designers, and NSF. Combined, the groups cover the entire United States, with over 1,800 stakeholders from academic, government, and private sectors.

The NEON Integrated Science and Education Plan builds on the ideas and contributions of hundreds of individuals, most of whom volunteered their time and effort in the service of ecological sciences. It is these contributors and their students who will use NEON in the decades ahead to advance our understanding of the nation's ecological systems.

The NEON design phase is marked by four primary goals: delivery of (1) an Integrated Science and Education Plan (this document) and (2) a Networking and Informatics Baseline Design, which together constitute the Reference (or Conceptual) Design of NEON. In addition, the design phase will (3) produce a Project Execution Plan (PEP) that describes NEON's major infrastructure systems (with details of their cost and construction schedule) and includes the project management plan. Finally, (4) in December 2005, NEON, Inc. was legally established as a not-for-profit corporation to oversee the subsequent implementation and construction phases, and serve as the single institutional point of contact with the NSF.

Management and administration of the design phase, including the process described above, is directed by a Senior Management Team composed of scientific experts from a variety of institutions and disciplines. The combined breadth of experience of this volunteer group matches the broad scope of NEON (See NDC Membership, Appendix 1)**.** In addition, the NEON Project Office, currently a division of the American Institute of Biological Sciences, maintains co-directors, a project manager, and professional scientific and administrative staff members who provide scientific and organizational support to the project.

Implementation Phase

Plans for community participation and governance of Observatory facilities, instruments, and resources flow from NEON, Inc. The corporation will have the ultimate authority and responsibility for NEON. Governed by a member-elected board of directors, NEON, Inc. will maintain a dedicated staff devoted to the sound management of all aspects of the construction and operation of the Observatory. Any scientific, educational, or research institution that is approved by the board of directors is eligible for membership—a status that conveys the right to vote on organizational matters, including elections to the board of directors. This organizational structure is intended to cultivate broad bottom-up participation and community input while ensuring the centralized management of the project and a clear and direct line of accountability to NSF, the primary funding agency.

NEON, Inc. will work closely with a variety of NEON partners at many levels, establishing appropriate sub-awards, contracts, and other agreements during implementation and operation phases. Once subsumed by NEON, Inc., the Project Office will be responsible for the coordination and management of construction. At that time, the Project Office will include a project manager, project engineer, and systems engineers, as well as procurement, accounting, and project management control systems specialists.

Successful completion of the implementation phase on schedule and on budget requires the use of a Project Management Control System (PMCS), a set of planning, budgeting, performance measurement, and cost collection tools. The PMCS enables the analysis, reporting, and communication of project status to the project manager, NEON, Inc., and NSF. A PMCS includes a Document Control Center Database, the official repository for project documents such as specifications, plans, procedures, procurements, and technical interfaces. Oversight of the database is performed by a change control board, which ensures that the current document versions define the official and current work scope and specifications of the Observatory. A Cost Estimate Database tracks “bottom up” cost estimates, organized according to the project work breakdown structure and including the “basis of estimates” and other supporting cost documentation.

In order to oversee these specialized management aspects of project implementation and operations and to help develop internal expertise in program management within the corporation, NEON works with Triad Project Management Services, Inc. (Pasadena, CA). Triad expertise includes defining project management control system specifications, developing and managing complex schedules, budget planning and forecasting, and implementing earned value management reporting systems.

The Project Office, working with Triad personnel, will develop an integrated project schedule that meets critical path method standards and identifies the critical path and project milestones for tracking and reporting progress.

Operations Phase

As construction, testing, and commissioning conclude and operations begin, NEON, Inc. will maintain authority and responsibility for managing the network. Some aspects of NEON operations will be delegated via agreements to institutions or groups of institutions within NEON domains. During this phase, NEON, Inc. will coordinate the scientific planning, cyberinfrastructure development, and education and outreach efforts with input from community members participating on standing and ad hoc committees. With community-based committee recommendations filtering up to NEON management through transparent processes, NEON, Inc. will maintain open access to NEON resources, including facilities and data. In addition, appropriate committees will be formed to assess technological advances and ensure that NEON benefits from technical innovations throughout its operating lifespan.

Creating NEON Partnerships

The NEON design described in this document is focused on identifying patterns and relationships in the functioning of US ecosystems, and thereby providing the capacity to forecast the future states of ecological systems. However, it would be imprudent to envision a successful Observatory without recognizing NEON's connections with existing long-term investments in science and technology. NEON will build on and contribute to these investments through partnerships with the academic research community, government, and private sectors in the following areas: sensor network development; information management and delivery; resource sharing; data collection; analysis and forecasting; education and knowledge transfer; and international collaboration. Examples of prospective and existing partnerships in government, academic, and private sectors are described below and in Box 4.2. Collaboration with partners will ensure that NEON is well-designed, cost-effective, and configured for interoperability and the timely dissemination of results.

Developing the Sensor Network

A cornerstone of NEON design is the capability to make and compare observations at multiple scales. At the finer end of the measurement scale are concentrated, local observations enabled by the development of dense, low power, configurable networks of sensors embedded within specific ecosystems. A hub for development and testing of such sensor networks is the NSF-funded Center for Embedded Networked Sensing (CENS) at the University of California, Los Angeles. The CENS faculty became involved in the design of NEON early in its conception, and the partnership has created an effective dialogue in the interplay between scientific needs and technical possibilities, which has advanced both engineering and environmental science and will lead to many new and innovative sensing technologies.

Managing and Delivering Information

Much of the power of the Observatory lies in the large volume of data that will be generated and the capacity to manage and deliver those data to NEON stakeholders. This requirement transcends NEON and applies to a broad spectrum of scientific disciplines and other areas of society. Leading the development of data management and data delivery solutions are the Nation's supercomputer centers. Researchers from the San Diego Supercomputer Center and the National Center for Supercomputing Applications have brought advanced technologies, developed in conjunction with large-scale projects such as the Geosciences Network, Science Environment for Ecological Knowledge, and the Network for Earthquake Engineering Simulations that have informed the NEON design. In the environmental realm, the NSF-funded Long Term Ecological Research (LTER) Network and the USGS National Biological Information Infrastructure (NBII) have systems for handling the diverse data types associated with biological and environmental data. The USGS Center for Earth Resources Observation and Science is a source of expertise in the processing and distribution of high-resolution remotely sensed imagery and a potential partner with NEON. All of the partnerships related to the cyberinfrastructure components of NEON will yield returns not only for NEON, but also for other programs and networks via interoperability and the ability to seamlessly access complementary data from diverse sources.

Resource Sharing

NEON is a resource-intensive endeavor, but by capitalizing on effective associations with related programs, resource savings will be realized and value added to existing efforts. Secure access to land for the deployment of instrument systems is one area in which partnerships will be extremely effective. Government land holdings dedicated to conservation or research, such as Experimental Forests associated with the USDA Forest Service, offer long-term, secure access to research sites. In addition, private and university-owned research field stations (e.g., members of the Organization of Biological Field Stations or the LTER Network) will provide similar access. Deployment of Observatory research infrastructure on these lands will likewise benefit the landholders through access to environmental information. Aircraft operated by the NSF-funded National Center for Atmospheric Research are another resource that will be shared as part of NEON remote sensing activities. In addition, the nation's bio-collections (i.e., natural history museums and herbaria) will provide the capacity and expertise to curate NEON specimens and samples for contemporary analyses, and create a legacy of data for future studies using analytical techniques that are yet to be developed. Likewise, the university and private laboratories specializing in genomic and stable isotope analyses will be significant partners in realizing the NEON mission.

Data Collection

Environmental observations are routinely made across the continent each year. Although no system currently provides the broad-scale view of US ecosystem functioning that is promised by NEON, pre-established data sources will enhance (and be enhanced by) the Observatory. One example of these programs is the AmeriFlux network, which coordinates long-term measurement of gas, water, and energy exchange. Coordinating NEON protocols and data systems with AmeriFlux will enhance both programs for the benefit of the environmental sciences, and serve as a model for other state and Federal data-sharing partnerships.

By adding continental-scale ecological data, NEON will be a key and enabling US contributor to the international Global Earth Observing System of Systems (GEOSS). Other developing environmental research networks—the Collaborative Large-Scale Engineering Analysis Network for Environmental Research (CLEANER), the Consortium of Universities for the Advancement of Hydrologic Science Inc. (CUAHSI), and the Ocean Research Interactive Observatory Networks (ORION)— will also offer complementary links to other dimensions of environmental science, such as the ocean sciences, environmental engineering, and hydrological sciences. CLEANER and CUAHSI propose to better understand complex and human-stressed environmental systems by deploying a data-collecting infrastructure that will address environmental problems in our nation's waterways. ORION will become an integral part of the proposed Integrated Ocean Observing System (IOOS), which will provide the US ocean sciences research community with access to the basic infrastructure required to make sustained, long-term, and adaptive measurements in the oceans, and which can be analyzed in conjunction with NEON terrestrial climate data. Data from environmental observing systems like

CLEANER, CUAHSI, and ORION as well as data from other Federal agency efforts (e.g., NOAA, NASA, and USDA) will be integrated into forecasting models developed by NEON for more robust predictions, just as NEON data will be shared with these networks for sophisticated data mining and modeling to yield new insights that often come from the multi-disciplinary discourse and collaboration between diverse scientific communities.

Analysis and Forecasting

NEON analyses and forecasts will benefit from coordination with diverse institutions that have significant and related experience with environmental data analysis, synthesis, and forecasting. Two NSF-supported centers—the National Center for Ecological Analysis and Synthesis (NCEAS) and the National Evolutionary Synthesis Center (NESCent)—are particularly relevant to synthesis of ecological and biodiversity data. NEON will provide a rich source of diverse data and information that will be combined with data from other research programs and used in both NCEAS and NESCent activities, leading to significant advances in our understanding and new theory. Likewise, NEON can benefit from partnerships with the National Climatic Data Center and the National Center for Atmospheric Research, two institutions that have played a central role in advancing the prediction and forecasting of environmental phenomena.

Education and Knowledge Transfer

The NEON education program will develop partnerships with educational organizations such as schools, universities, and museums at the national and domain levels. Programs created with these partners will bring Observatory information to students and the public to develop an appreciation of science in general and the importance of ecology in particular.

Furthermore, discoveries enabled by NEON will be important in public policy development. Through partnerships with organizations such as the Heinz Center for Science, Economics and the Environment, scientists and policy analysts will work together to inform the decision-making process with continuous access to the strongest and most up-to-date scientific information.

International Science Collaboration

The initial implementation of NEON spans the continent from east to west, but does not include sites in Mexico and Canada. To achieve a true continental scope in North America requires partnerships with these countries. Fortunately, both Canada and Mexico have active environmental science communities and governments engaged in developing a greater understanding of ecological systems. To facilitate connections in Canada and Mexico, environmental scientists from both countries serve on the NEON Advisory Committee. Additional discussions about opportunities to extend the reach of ecological observing to the entire North American continent will continue as NEON develops.

Advancing international observational collaborations is a priority because of the global nature of ecological systems. With the Integrated Earth Observing Systems (IEOS), the United States is contributing to GEOSS. NEON will develop the capacity to make ecological forecasts—one of the nine societal benefit areas of the IEOS (http://ostp.gov/html/EOCStrategic_Plan.pdf)—and will be a significant contributor to this major international effort to assess and predict the performance of key environmental systems.

Exploring potential partnerships

The process by which scientific communities assemble to conceive, design, and use large research platforms and facilities—such as particle accelerators, radio telescope arrays, and oceanographic research vessels—are complex and varied. Despite project-specific differences, the development of all such projects depends on the broad community support over many years. The history of NEON is no different.

The partnership examples provided in this chapter highlight easily recognizable and pertinent organizations and institutions that are obvious fits to NEON's resource sharing, data collaboration and analysis needs; however, they are representative of only a small fraction of the potential partners that NEON will both benefit from, and provide value to, as a major environmental observatory in the United States.

Box 6.2 Examples of Partnership Opportunities

The US Department of Agriculture Forest Service experimental forests occur in many different ecosystem types and are potential sites for NEON infrastructure. These forests provide opportunities for landscape-scale experimentation and access to significant historical ecological data.

CENS researches and develops tools that are integral to the implementation and management of NEON: wireless self-organizing environmental sensor networks, new enabling technologies, and novel scientific and educational applications.

AmeriFlux is a network of instrumented towers that continuously monitor ecosystem-level exchanges of CO_2, water, energy, and momentum. Partnering with AmeriFlux enables the development of common measurement and data protocols to increase understanding of national and global CO_2 budgets.

The US Geological Survey Earth Resources Observation and Science (EROS) Data Center provides a data gateway and visualization technologies for remotely sensed imagery. Integration of NEON data with existing data sets, such as the National Biological Information Infrastructure (NBII), will allow large-scale, long-term trend analysis and pattern detection.

The National Aeronautics and Space Administration is the nation's primary source for remote sensing technologies. Instruments like the Advanced Spaceborne Thermal Emission and Reflection (ASTER) on NASA's Terra satellite, for example, provides high resolution images that is used to better understand the effects of urbanization on the local ecology, a topic which is of concern to NEON science.

The National Center for Ecological Analysis and Synthesis (NCEAS) develops data analysis and synthesis approaches to advance ecological knowledge through the identification of patterns and principles. Collaborating with NCEAS' exceptional scientific support and computing facilities will enable complex analyses of NEON datasets.

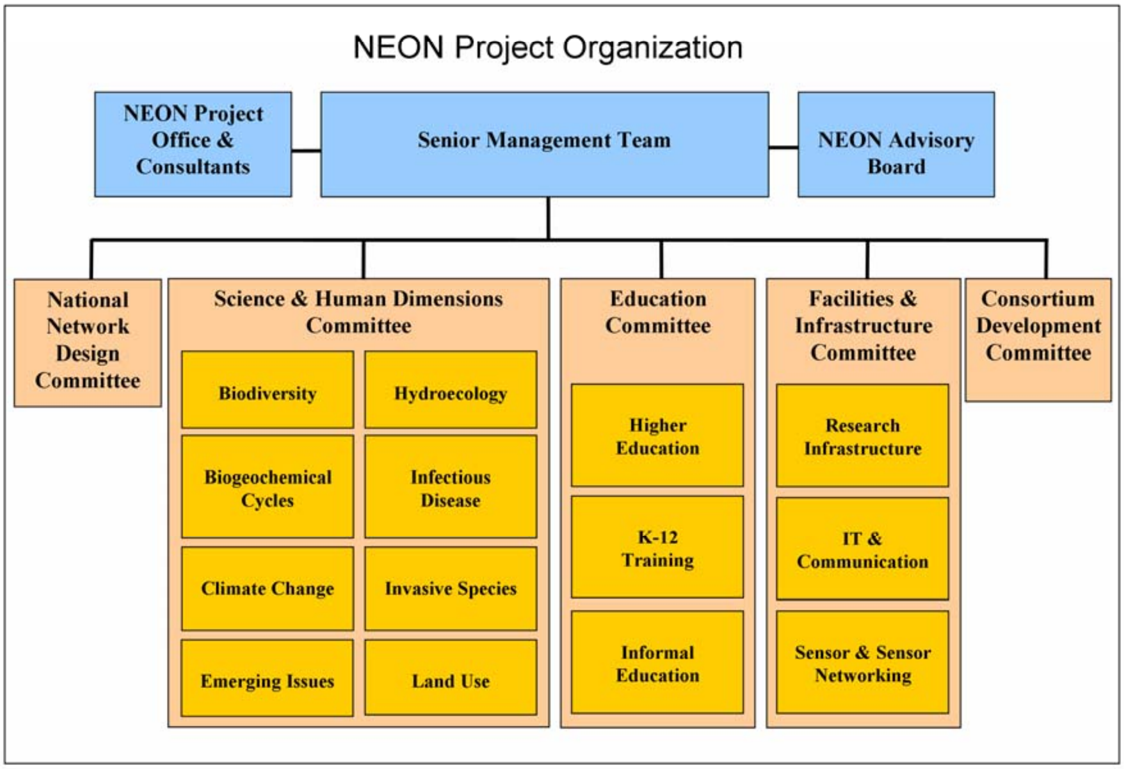
The Long Term Ecological Research (LTER) network is a source of long-term ecological data and provides potential sites for NEON infrastructure. Coordination between NEON and LTER will enable the development of novel experimental approaches.

NEON partners with the Global Earth Observation System of Systems (GEOSS) to develop the capacity to make global ecological forecasts. Working in conjunction with scientists worldwide, NEON will aid in the development and testing of targeted observing strategies and advances societal and economic use of ecosystem and climate-based intelligence.

In collaboration with industry, government, academia, and environmental organizations, the Heinz Center works to improve the scientific and economic foundation for environmental policy. NEON will provide measurements of core environmental indicators important for future Center reports on the Nation's ecosystems.

APPENDIX 1

NEON Design Consortium Participants



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