The NEON Strategy

Enabling Continental Scale Ecological Forecasting

The NEON Strategy

National Ecological Observatory Network

July 2009

The National Ecological Observatory Network is a project sponsored by the National Science Foundation and managed under cooperative agreement by NEON, Inc.

NEON, Inc. is an independent 501(c)3 corporation that enables understanding and decisions in a changing environment using specific information about continental-scale ecology obtained through integrated observations and experiments.

NEON, Inc.'s mission is to design, implement, and operate continental-scale research infrastructure, including the National Ecological Observatory Network, to open new horizons in ecological science and education, and to enable ecological analyses and forecasts for the benefit of society.

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Copies available from:
NEON, Inc.
5340 Airport Boulevard
Boulder, CO 80301

Authors

Lead Authors

Dr. David Schimel

Dr. Michael Keller

Dr. Paul Duffy

Contributing Authors (in alphabetical order)

Dr. Luciana Alves

Steve Aulenbach

Dr. Brian Johnson

Ted Hehn

Dr. Tom Kampe

Dr. Becky Kao

Dr. Michele Kuester

Dr. Hank Loescher

Dr. Valerie McKenzie

Dr. Heather Powell

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National Science Foundation Science Review Panel

Dr. Alan Covich (Chair), University of Georgia
Dr. Gregory Glass, Johns Hopkins University
Dr. Lou Gross, University of Tennessee
Dr. Whendee Silver, Berkeley University
Dr. Dean Urban, Duke University
Dr. Susan L. Ustin, University of California, Davis

NEON Science, Technology, and Education Advisory Committee

Dr. Christopher Field (Chair)
Dr. Virginia Dale, Oak Ridge National Laboratory
Dr. Todd Dawson, University of California, Berkeley
Dr. Ruth DeFries, University of Maryland
Dr. Michael Donoghue, Peabody Museum of Natural History
Dr. Jack Ewel, University of Florida
Dr. Christine Goodale, Cornell University
Dr. Alan Hastings, University of California, Davis
Dr. Urs Hoelzle, Google
Dr. Ann Kinzig, Arizona State University
Dr. Gary A. Lamberti, University of Notre Dame
Dr. Halton Peters, Lazard Brothers & Company
Dr. Larry Robinson, Florida A&M University
Dr. James Tiedje, Michigan State University
Dr. Kathleen Treseder, University of California, Irvine
Dr. Steven C. Wofsy, Harvard University
Dr. Joy Zedler, University of Washington

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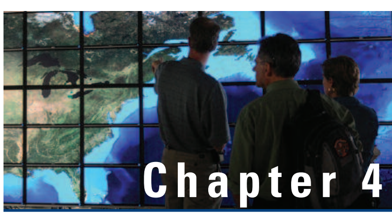


Chapter 1
Introduction

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. In an era of dramatic changes in land use and other human activities (Vitousek et al., 1997), understanding the responses of the biosphere to human drivers of environmental change is both an intellectual grand challenge and a practical necessity. Humans depend on a diverse set of biosphere services and products, including food, fiber, and fuel, and also depend on the maintenance of air and water quality (Millennium Ecosystem Assessment, 2005). These services and products are strongly affected by human drivers of change such as climate change, land use and management, air pollution, and water management. Enhancements or disruptions of these services by human-caused environmental change could alter the fundamental trajectory of the human endeavor over large parts of the world.

A wide range of biotic and physical processes link the biosphere to the geosphere, hydrosphere and atmosphere. Despite this link, our understanding of the biosphere does not match our increasingly sophisticated understanding of Earth's physical and chemical dynamics at regional, continental, and global scales. Because many Earth system processes occur at large scales, they cannot be investigated with disconnected studies on individual sites or over short periods of observation.

The National Ecological Observatory Network (NEON) is a bold effort to expand horizons in the science of large-scale ecology, building on recent progress in many fields. NEON is a continental-scale ecological observation platform for understanding and forecasting the impacts of climate change, land use change, and invasive species on ecology. NEON science focuses explicitly on questions that relate to grand challenges in environmental science, are relevant to large regions, and cannot be addressed with traditional ecological approaches (ISEP, 2006). NEON's open access approach to its data and information products will enable scientists, educators, planners and decision makers to map, understand and predict the effects of humans on the earth and understand and effectively address critical ecological questions and issues.

The design and data requirements of NEON have emerged from a decade of discussion and planning by the ecological research community. NEON partitions the United States into 20 ecoclimatic domains, using a statistical analysis of ecoclimatic state variables such as temperature, precipitation, and solar insolation. Each domain will host one fully instrumented NEON core site located in a wildland area. Collectively, the domains represent the full range of U.S. ecological and climate variability at the continental scale. Observations deployed on additional sites (known as relocatable sites), airborne sensors, and mobile ground-based observing systems will extend the reach of NEON measurements and increase the ability of the observatory to observe intensively managed ecoysystems and abrupt ecological changes.

NEON is based on a multiscaled sampling strategy, employing systematically deployed ground-based sensors, high-resolution airborne sensors, and integration with national geospatial information (Figure 1).

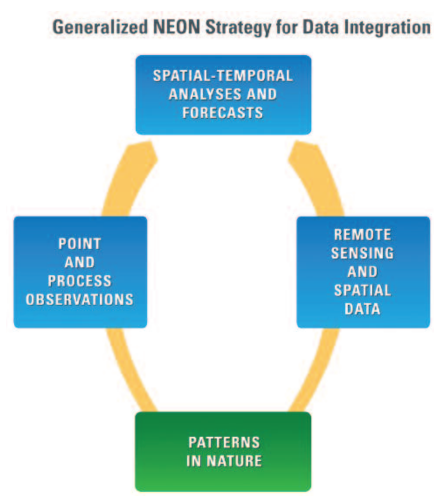


Figure 1: A general scheme showing multiscaled sampling of complex patterns in nature and their analysis via spatio-temporal models and theory.

NEON will observe both the human drivers and the biological consequences of environmental change. Environmental monitoring networks typically observe either the cause (for example, climate, air pollution, or land cover change) or the consequences (for example, phenology or avian populations). Rarely do environmental networks provide integrated observations of aspects of both cause and effect to allow increased understanding of the underlying processes. NEON is unique in that it observes both a suite of key causes of environmental change (climate, land use, invasions) and a wide range of consequences. Because NEON links cause and effect, it operates as a research system and not as an environmental monitoring program.

The National Research Council report "GRAND CHALLENGES in the Environmental Sciences" (NRC, 2001) identifies key science areas. These include:

- **Biogeochemistry:** understanding and predicting the impacts of human activities on the Earth's major biogeochemical cycles.
- Biological diversity and ecosystem functioning: understanding the regulation of biological diversity and its functional consequences for ecosystems (**biodiversity**).
- Climate variability: understanding and predicting climate variability, including directional climate change, and its impacts on natural and human systems (**climate change**).
- Hydrological forecasting: understanding and predicting changes in freshwater resources and the environment (**ecohydrology**).
- **Infectious diseases** and the environment: understanding and predicting the ecological and evolutionary aspects of infectious diseases and of the interactions among pathogens, hosts/receptors, and ecosystems.
- **Land use** dynamics: understanding and predicting changes in land use and land cover that are critical to biogeochemical cycling, ecosystem functioning and services, and human welfare.

These GRAND CHALLENGES in environmental science have been reviewed by the National Research Council, the International Geosphere-Biosphere Programme, the Millennium Ecosystem Assessment, Diversitas, and the U.S. Climate Change Science Program. From these additional reports, NEON planners identified a seventh GRAND CHALLENGE and included it in the Integrated Science and Education Plan (2006):

- **Invasive species**: Understanding and forecasting the distribution of biological invasions and their impacts on ecological processes and ecosystem services.

The phrases in boldface above indicate the consistent language that NEON documents use to refer to these GRAND CHALLENGES. NEON infrastructure targets this set of seven environmental grand challenges (hereafter referred to as the NEON challenge areas) but is strategically aimed at those aspects of the GRAND CHALLENGES for which a coordinated national program is particularly effective.

Addressing these challenges involves (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 Earth system processes, including climate and hydrology; and (3) understanding the implications of these processes and feedbacks for the human endeavor.

For network implementation and convenience, NEON groups the NEON Challenge areas into two types. First are the *drivers* of change, those forces that cause change in biological systems (ISEP, 2006). These include climate change, land use change, and invasive species. The second are the *responses*, including biodiversity, biogeochemistry, ecohydrology, and infectious disease. This grouping is not unique; depending on scale and process, any of these areas may be both cause and effect (for example, changes to vegetation structure may affect climate, and emerging diseases can dramatically change ecosystem processes).

In a special edition of *Frontiers in Ecology and the Environment* (Vol. 6, Issue 5, June 2008), a series of invited papers explored the questions that a continental-scale ecological observatory might address. Specific questions posed included:

- What is the impact of "connectivity" (local patterns and processes affecting broad-scale ecological dynamics) on the global environment? (Peters et al., 2007)
- What are the ecosystem-level causes and consequences of invasive species and infectious diseases, and what environmental measurements can predict these consequences? (Crowl et al., 2008)

- What societal/environmental factors can be used to forecast the spread of invasive species and infectious diseases on continental scales? (Crowl et al., 2008)
- What causes the variability in the success of countermeasures against invasive species? How do invasive species arrive at a new location? (Crowl et al., 2008)
- How does climate change affect the ability of invasive species to spread? (Crowl et al., 2008)
- How do climate and land use changes impact temperature and carbon cycling in lakes and streams, and what is their effect on aquatic metabolism? For example, does climate change alter organic matter loading in lakes and streams, as well as the thermal structure and extent of anoxia in lakes? (Williamson et al., 2008)
- How do changes in intensity, spatial distribution and frequency of windstorms affect ecosystem attributes? How will storm damage in inland forests (soil erosion, water retention, nutrient export) affect coastal systems? (Hopkinson et al., 2008)
- What are the ecological and socio-ecological consequences of local land use changes at regional and continental scales? (Grimm et al., 2008)

- How are pollutant source and deposition regions (connected through air and water vectors) related to patterns of land use, and how do ecosystem structure, function and services respond to changes in pollutant loadings resulting from changing land use? (Grimm et al., 2008)
- How does climate change affect mean temperature and drought severity, and what influences are predicted on species interactions, phenology, snowmelt dynamics and dust emissions? (Marshall et al., 2008)
- How will climate change-induced impacts on fuel accumulation, combustibility, and rates of ignition impact fire regimes (Marshall et al., 2008)

Using such questions (and also drawing on extensive input from prior NEON development meetings), we began to derive the design requirements for a continental-scale ecological observatory that can address the GRAND CHALLENGE science areas. The process is seen in Figure 2. The GRAND CHALLENGES link drivers of change ("Forcing," top left) to responses. They lead scientists to a diverse set of questions and hypotheses that can be investigated on continental scales, such as the examples in Figure 2. Then, it is possible to define a suite of data products that are needed to support and advance research and education related to the questions and hypotheses. Ultimately, an infrastructure and set of science facilities (packages) can be designed to provide those data products. Scenarios for infrastructure (priorities for particular observations) can be tested against a set of important questions.

Through analysis of the questions derived from the GRAND CHALLENGES, some measurements emerge as absolutely essential to the program (for example, in almost any question on climate change, soil moisture emerges as a key variable). Other measurements emerge as important supporting data across a wide range of questions (for example, phenology becomes a key variable in questions related to biogeochemistry, biodiversity, invasions, and disease). From these analyses, science requirements can be derived.

The NEON Strategy provides an overview of the development process. The following sections present:

- The NEON high-level requirements identified from the scientific and educational mission and analysis of the GRAND CHALLENGE Areas;
- The NEON infrastructure and science facility design, describing the major components of the observatory and providing links to NEON project documents that contain more detailed design specifications;
- The analysis and forecasting framework and requirements that enable the NEON observatory to support continental-scale science and ecological forecasting.

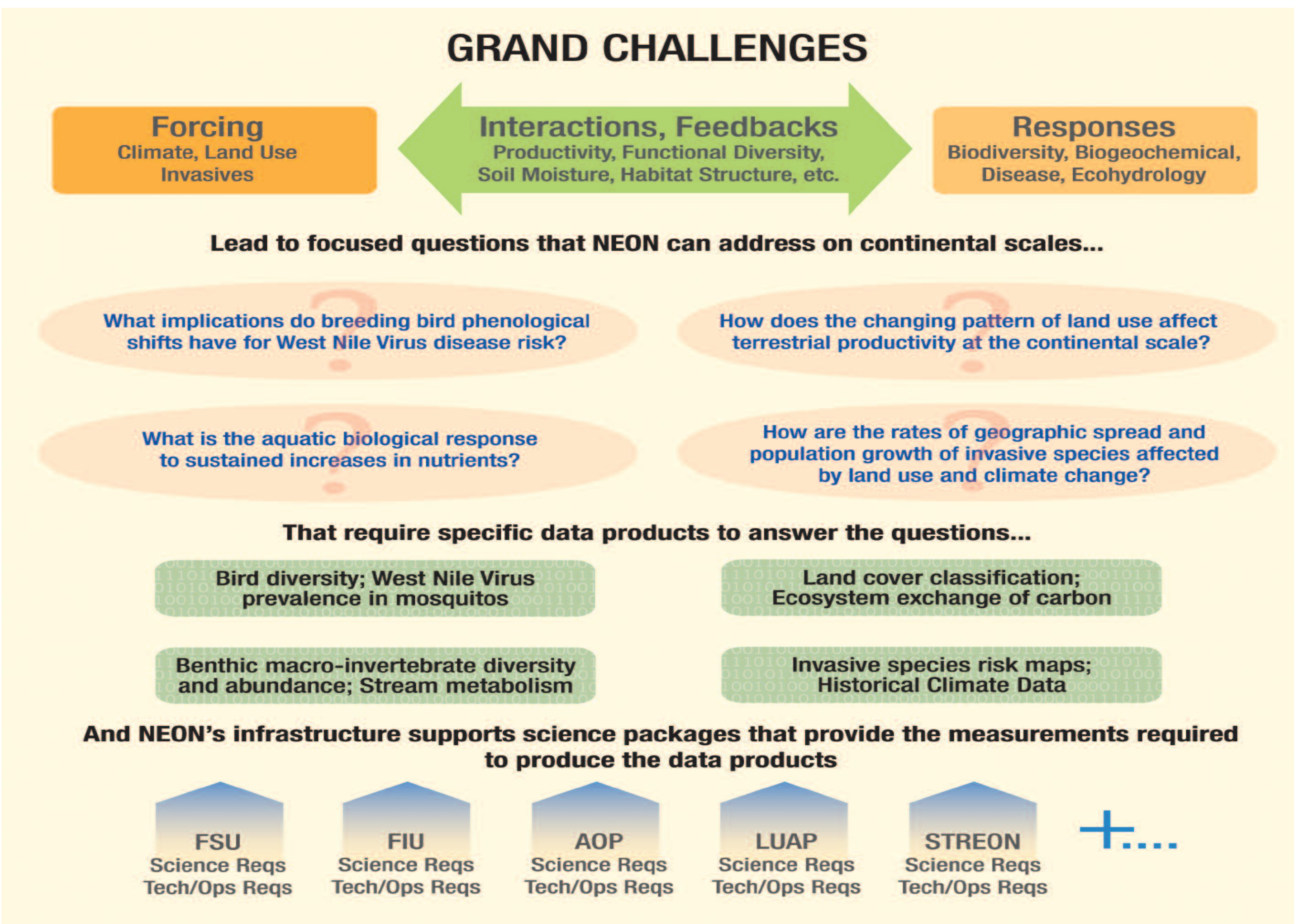
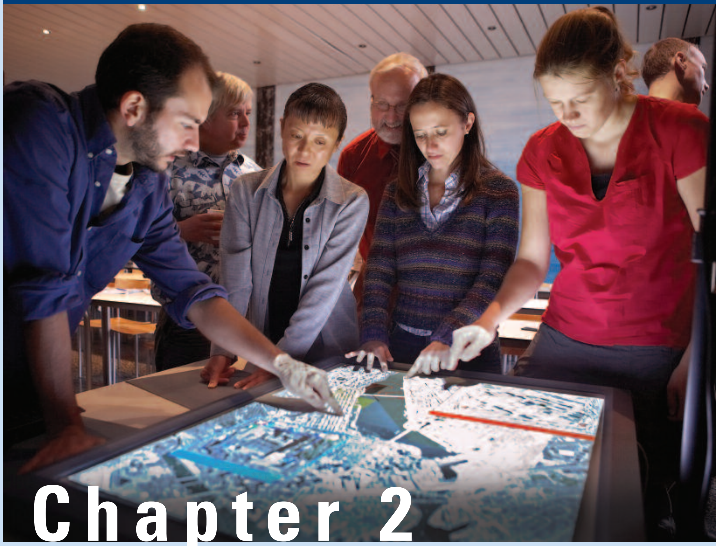


Figure 2: The NEON design process.



Chapter 2
NEON High-Level Requirements

NEON is a National Science Foundation-sponsored facility for research and education on long-term, large-scale ecological change. NEON's science mission is defined in its Integrated Science and Education Plan (ISEP, 2006).

NEON's mission is to:

Enable understanding and forecasting of the impacts of climate change, land use change and invasive species on continental-scale ecology

by providing infrastructure and consistent methodologies to support research and education in these areas.

NEON provides two kinds of infrastructure:

- ***Information infrastructure:*** consistent, long-term, large-scale data sets that serve as a context for research and education.
- ***Physical infrastructure:*** a research and education platform for investigator-initiated sensors, observations and experiments providing physical infrastructure, cyberinfrastructure, learning opportunities, human resources, and expertise in program management and coordination.

Photo by Sandra van de Ven Communications & PR

The requirements for NEON infrastructure are captured in high-level statements derived from the mission statement and from analysis of the NEON Challenges via the process shown in Figure 2.

1. NEON will observe both the causes and consequences of environmental change in order to establish the link between ecological cause and effect (*understanding and forecasting the impacts…*).

2. NEON will detect and quantify ecological responses to climate, land use and biological invasion (*climate change*, *land use change*, and *invasive species*), which play out over decades.

3. NEON will provide information on all the GRAND CHALLENGE areas: biodiversity, biogeochemistry, ecohydrology, infectious diseases, biological invasion, land use change and climate change (*climate change*, *land use change*, and *invasive species on… ecology*).

4. NEON will address ecological processes at the continental scale, allow the integration of local behavior to the continent, and observe transport processes that couple ecosystems across continental scales (*continental-scale ecology*).

5. The NEON infrastructure will support experiments that accelerate changes toward anticipated future conditions (*enable … forecasting*).

6. NEON will provide usable information to scientists, educators, students, the general public, and governmental and non-governmental decision makers (*enable…*).

7. NEON will provide infrastructure to the scientific and educational communities both by providing a long-term, continental-scale data/information context for research and education, and by providing cyber infrastructure, power, and other resources needed to enable additional sensors, measurements, experiments and learning opportunities to be deployed by the community.

Taken together, these top-level requirements lead to some of the critical and fundamental aspects of NEON's design, and guide the architecture of the infrastructure. Key aspects of the design that are traceable to the above statements include:

1. NEON's measurement strategy will include coordinated and co-located measurements of drivers of environmental change (physical and chemical climate, land use, and biological invaders) and of biological responses (matter and energy fluxes, biomass and plant productivity, diversity and genomics of key organismal groups, infectious diseases and community, phenological and population indicators).

2. NEON's spatial observing design will systematically sample national variability in ecological characteristics, using systematic sampling of the nation's eco-climatic variability.

3. NEON will allow extrapolation from the observatory's local sites to the nation. NEON will integrate continental-scale data with site-based observations to facilitate extrapolation from the local measurements to the national observatory.

4. NEON will sample managed landscapes in order to understand land use effects. Relocatable sites will be selected and paired with either core sites or other relocatables to allow measurements of contrasts between different land use practices (e.g., wildland versus managed, intensively versus extensively managed).

5. NEON infrastructure and observing system signal-to-noise characteristics will be designed to observe decadal-scale changes against a background of seasonal to interannual variability over a minimum 30-year lifetime.

6. NEON observing strategies will be designed to support ecological forecasting, including requirements for state and parameter data, and timely and regular data delivery to support new and ongoing ecological forecast programs.

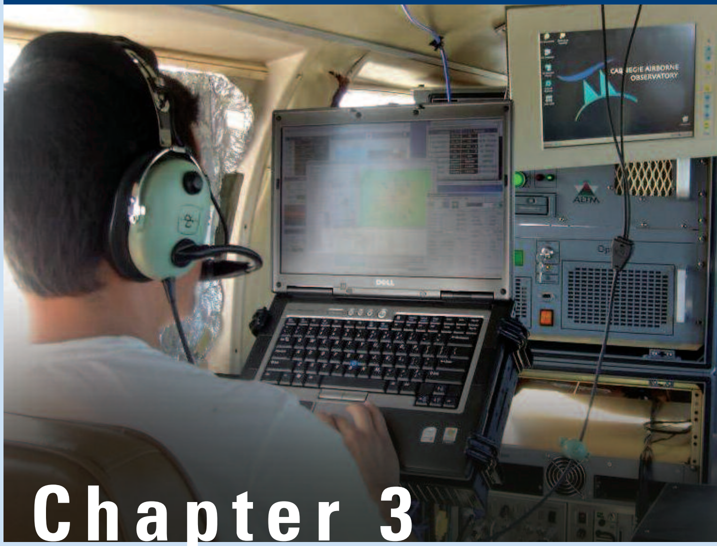
7. NEON will include a rapid-response capability to observe abrupt events triggered by long-term trends such as climate change, land use change, and biological invasions.

8. NEON will enable experiments that accelerate drivers of ecological change toward anticipated future physical, chemical, biological or other conditions to enable parameterization and testing of ecological forecast models and to deepen understanding of ecological change.

9. NEON measurements will be standardized and calibrated to allow comparison across sites and over time to enable understanding of ecological change in time and space. Calibration and standardization will also allow new sensors/measurements to be incorporated.

10. The NEON data system will be open to enable free and open exchange of scientific information. Data products will be designed to maximize the usability of the data. The NEON cyber infrastructure will be designed to be open and modular to enable the addition of new capabilities. All NEON sites will be as open as possible to new measurements and experiments to effectively provide NEON infrastructure to scientists, educators and citizens.

11. NEON will produce usable information from its observations to enable access by a wide range of scientific, educational, and environmental decision makers. NEON will convert primary observations into useful and credible derived data products and will make these data products available widely to enhance understanding and ecological forecasting.



Chapter 3

NEON Infrastructure and Science Facility Design

NEON will provide scientific infrastructure that will enable the ecological research and education communities to better understand and forecast the drivers and impacts of environmental change. As mentioned previously, this infrastructure will be of two types: (1) systematic, long-term, large-scale data sets and (2) a research and education platform for investigator-initiated sensors, observations, and experiments. NEON's facilities are designed to provide integrated, co-located measurements and infrastructure to support additional PI studies of ecological cause and effect. NEON will measure key aspects of the drivers and selected indicators of the responses (the full range of possible response variables is nearly infinite) while providing infrastructure for additional sensors, observations, experiments and learning opportunities. NEON must achieve this with continental reach and over decades, preserving the data with integrity and accessibility over these time and space scales.

The design for a continental-scale ecological observatory infrastructure that will address the GRAND CHALLENGES described in Section 1, and satisfy the high-level requirements listed in Section 2, is discussed below. Included as part of the infrastructure are several key science facilities:

- The **Fundamental Sentinel Unit (FSU)** measures key response variables in selected taxa (plants, insects, birds, small mammals, pathogens, phytoplankton, fish, microbes) and media (soil and water). Most of the FSU measurements are made in the field and analyzed in the laboratory.
- The **Fundamental Instrument Unit (FIU)** measures climate (temperature, incoming solar radiation, humidity, wind velocity, precipitation), and climate-related physical variables (soil temperature, water chemistry, streamflow, and stream temperature). The FIU also measures some biological responses (soil carbon dioxide flux, photosynthesis and transpiration, leaf area). FIU measurements are made with in situ sensors.
- **The Airborne Observation Platform (AOP)** observes land use drivers, plant canopy, and habitat structure characteristics in the region around NEON sites, using remote sensing instruments deployed on a light aircraft.
- The **Land Use Analysis Package (LUAP)** provides information on land use and land management drivers at a continental scale as well as information on land use not accessible through remote sensing (e.g., fertilizer inputs, cultivation intensity, forest rotation length). The LUAP is a gateway to a wide variety of geospatial data products, including remote sensing and statistical data, and it also provides convenient and coordinated access to other context variables such as soils maps and climate observations and projections.
- A **Mobile Deployment Platform** enables a subset of the FSU and FIU measurements to be strategically deployed in response to abrupt events, PI-driven investigations, or educational opportunities.

In the current NEON design, a community-proposed experiment is included:

- **The Stream Observation Network Experiment (STREON)** seeks to study how stream ecosystems respond to an acceleration of two of the key drivers of their structure and function: nutrient loading and loss of top consumers. STREON will consist of long-term nutrient addition and top-level consumer manipulation experiments conducted in multiple streams at NEON core and relocatable sites distributed across climate gradients in the United States and representing the dominant stream hydrologic regimes present in North America.

The education and outreach component of NEON includes a suite of products that will enable physical and virtual use of the facility by a variety of audiences, including scientists, educators, students, the general public, and decision makers. The science facilities and educational products are discussed in greater detail below.

3.1 A Continental Observatory Sampling Design

The selection of core wildland sites for NEON is driven by a set of boundary conditions that arise from NEON's overarching goal of providing infrastructure that will enable understanding and forecasting of impacts of climate change, land use change and invasive species on continental-scale ecology). The network design is the optimal solution to the constraints discussed below, which correspond to these boundary conditions. **NEON must make and facilitate observations at the level of individual organisms.** Ecological responses to climate change, land use change, and species redistributions (including the effects of invasive species) begin at the organismal level; therefore, the need to understand forcing and responses within a system concentrates many measurements at individual sites.

Stratifying the United States into relatively homogeneous domains allows for increased sampling efficiency and decreased sampling error. The observatory must systematically sample the United States in such a way as to objectively represent environmental variability. Some existing maps divide the country geographically into ecological regions (Omernik, 1987; Bailey, 1983). However, the ecological boundaries and number of subdivisions in these maps were chosen subjectively on the basis of expert knowledge.

In contrast to these maps, NEON has designed a set of domains based on a statistically rigorous analysis using national data sets for ecoclimatic variables. The statistical design is based upon algorithms for multivariate geographic clustering (MGC) (Hargrove & Hoffman, 1999, 2004). An alternative analysis using similar techniques with the Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) data set also reached the conclusion that approximately 20 domains is an appropriate solution (Figure 3) (Urban et al., personal communication). The optimized outcome of the geographical analysis results in 20 domains (Figure 4).

Diminishing returns are encountered when establishing the number of variables used to determine the subdomains because so many ecoclimatic variables are correlated. MGC techniques applied to the definition of NEON domains used nine input variables mapped across the United States at a 1 x 1 km raster resolution. Normalized variable values for each raster cell are used as coordinates to plot each map cell in a multidimensional data space. Because the plotted location of a map cell in the data space employs the combination of environmental variables within the map cell, two map cells that are plotted close to one another in data space will have similar mixtures of environmental conditions and are likely to be classified into the same region cluster. Similarity is coded as separation distance in this data space.

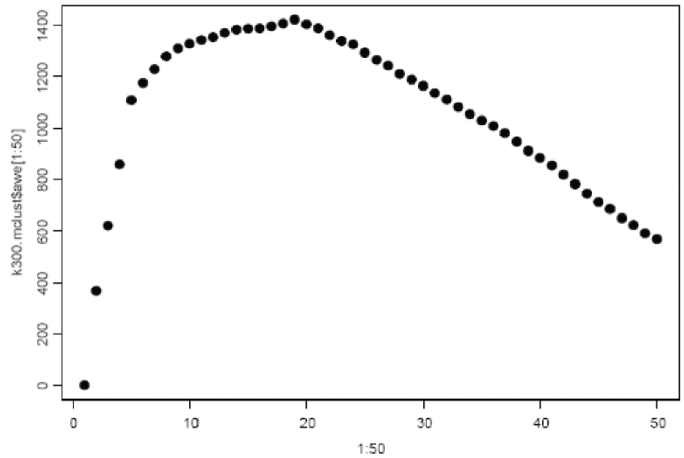


Figure 3: Results from a multivariate clustering of the United States using ecoclimatic variables. The plot shows a measure of the network's explanatory power against the number of domains. This analysis identified a region of between 17 and 25 regions as optimal.

The algorithm requires a user-specified number of region clusters, *k*, into which the map cells are to be grouped. In a single iteration, each map cell is assigned to the closest (i.e., environmentally most similar) existing cluster average, or centroid. At the end of the iteration, the coordinates of all map cells within each group are averaged to produce an adjusted centroid for each cluster, and another iteration of assigning map cells to these new centroids begins. After the grouping process has converged, the *k* regions have been statistically defined. The process is similar to unsupervised classification for remotely sensed imagery, but ecologically relevant conditions are used rather than spectral reflectances.

The network design was optimized under these conditions within an envelope of available funding. Financial constraints necessitate the identification and implementation of the most critical aspects of the design. By developing the initial design to satisfy rigorous science requirements driven by the overarching goal of NEON, and then optimizing within the financial boundary conditions, the number of sites is defined. NEON uses a parsimonious continental strategy for placement of the observational units within the United States.

The NEON domains are shown in Figure 4.

3.1.1 Selection of Observatory Sites

Once the United States was divided into 20 domains, candidate sites that best represent each domain were suggested by the scientific community in response to a request for information. Suggestions for multiple candidate sites were received for some domains, while other domains had only one suggested site. The sites were evaluated against a set of specific criteria (Table 1) and then the site best matching those criteria for each domain was identified as the candidate core site (Keller et al., 2008). The first criterion shown in Table 1 was the most important and challenging to evaluate. Alternate sites within domains were evaluated by calculating the ecological distance in ecoclimatic space (described above) between the centroid of the domain and each site. Sites were carefully located and registered to the ecoclimatic data grid in order to ensure that a fair comparison was made. NEON selected the site most representative of ecoclimatic variability within the domain.

In order to verify that this process resulted in sites that represent the nation, a map was computed that codes each grid cell in the national database according to how similar it is to the NEON candidate core site for that cell. The shading in Figure 5 represents the degree to which the ecoclimatic characteristics of the candidate core wildland sites represent environments in the conterminous United States. The figure shows that the eastern portion of the country is generally well represented. In the West, representation is more heterogeneous, particularly in the desert Southwest and in the Rocky Mountains. This occurs because of the high degree of linked climatic and biological variation related to complex topography and terrain. Sampling of orographic variability (climate dynamics related to topography) is improved by selection of relocatable sites along elevation gradients in the West.

The list of candidate core sites is shown in Table 2.

A wildland site representative of the domain (vegetation, soils/landforms, climate, ecosystem performance)
Proximity to relocatable sites that respond to regional- and continental-scale science questions including connectivity within the domain
Year-round access, permitting available, land tenure secure for 30 years, air space unimpeded for regular air survey, potential for an experimental set-aside

Table 1: Criteria for NEON candidate core sites.

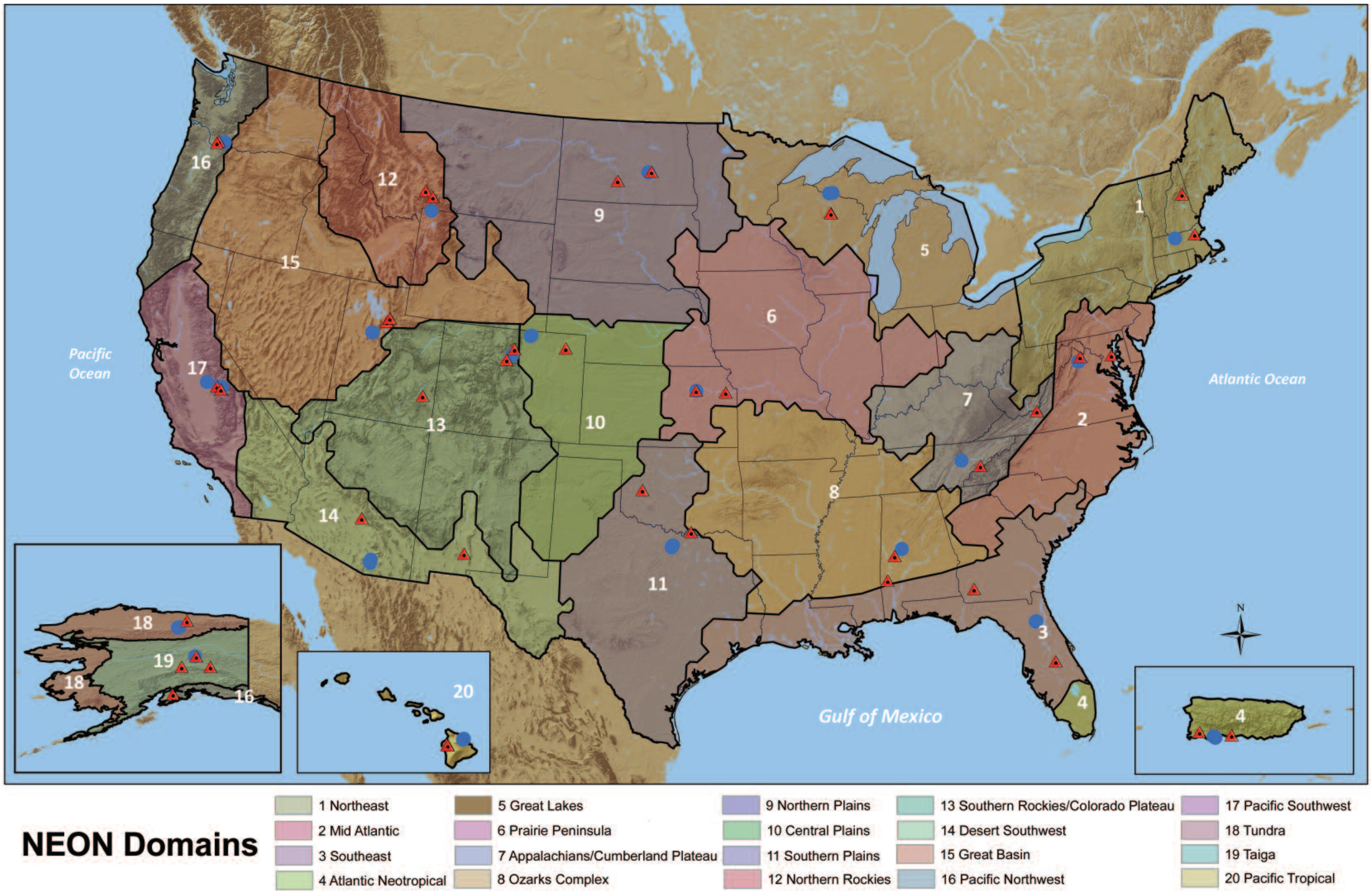


Figure 4: The NEON Domains.

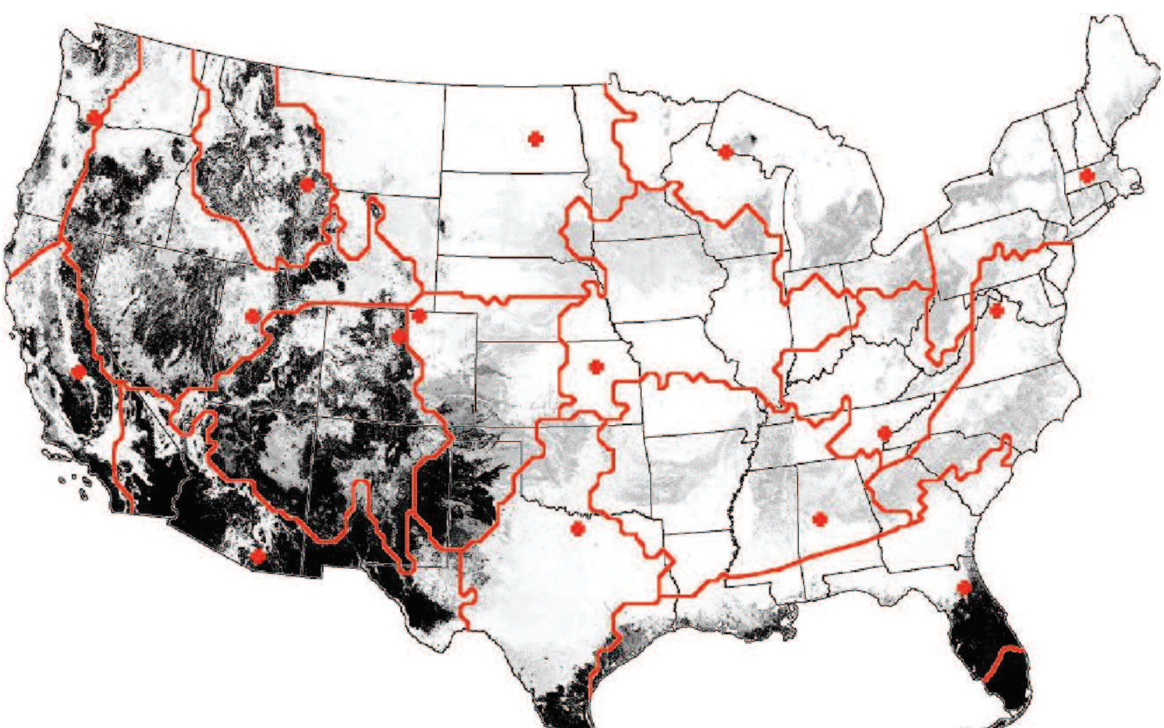


Figure 5: NEON domain representativeness.

Domain Number	Domain Name	Candidate Core Wildland Site	Latitude (N)	Longitude (W)
1	Northeast	Harvard Forest	42.4	72.3
2	Mid-Atlantic	Smithsonian Conservation Research Center	38.9	78.2
3	Southeast	Ordway-Swisher Biological Station	29.7	82.0
4	Atlantic Neotropical	Guánica Forest	18.0	66.8
5	Great Lakes	University of Notre Dame Environmental Research Center and Trout Lake Bilogical Station	46.2	89.5
6	Prairie Peninsula	Konza Prairie Biological Station	39.1	96.6
7	Appalachians/ Cumberland Plateau	Oak Ridge National Research Park	35.6	84.2
8	Ozarks Complex	Talladega National Forest	32.9	87.4
9	Northern Plains	Woodworth Field Station	47.1	99.3
10	Central Plains	Central Plains Experimental Range	40.8	104.7
11	Southern Plains	Caddo – LBJ National Grasslands	33.4	97.6
12	Northern Rockies	Yellowstone Northern Range	45.1	110.7
13	Southern Rockies	Niwot Range	40.0	105.6
14	Desert Southwest	Santa Rita Experimental Range	31.8	110.9
15	Great Basin	Onaqui-Benmore Experiment Station	40.2	112.5
16	Pacific Northwest	Wind River Experimental Forest	45.8	121.9
17	Pacific Southwest	San Joaquin Experimental Range	37.1	119.7
18	Tundra	Toolik Lake Research Natural Area	68.6	149.6
19	Taiga	Caribou-Poker Creek Research Watershed	65.2	147.5
20	Pacific Tropical	Hawaii ETF Laupahoehoe Wet Forest Unit	19.9	155.3

Table 2: Candidate core sites and locations.

3.1.2 Inferring Processes within Domains: The NEON Relocatable Sites

NEON plans to utilize relocatable sites in order to collect data on GRAND CHALLENGE questions that cannot be fully addressed by gathering data at the core wildland sites. For example, it would be difficult to gather complete data on land use utilizing just core wildland sites; more information is required. The relocatable sites can be used to create gradient or comparison studies that can address key questions, often providing critical data in 3-5 years. Themes proposed during the Request for Information (RFI) process in 2006 generated a large number of conceptual and site-specific suggestions from the ecological research community. These suggestions were evaluated during a week-long workshop in Sioux Falls, South Dakota. Several key points emerged from the Sioux Falls workshop and subsequent NEON, Inc. analyses:

- It is important to ensure that the relocatable sites preserve the "cause and effect" paradigm. In other words, each relocatable site should include organismal collection (the Fundamental Sentinel Unit or FSU), automated measurements (the Fundamental Instrument Unit or FIU) and remote sensing (the Airborne Observation Platform or AOP).
- The relocatable systems should not be minimally configured, instrumentation-only systems, as had been envisioned in some early NEON discussions. FSU staff must be allocated to relocatables, and the sites should not be too remote from the core sites to save staff travel time and expense. Unlike climate change, land use and its effects cannot be studied at the core wildland sites (by definition). As a result, land use must be a priority for relocatable deployments.
- NEON focuses on a few land use types (forest management, agriculture, and urbanization) and replicates deployments in land use types across ecoclimatic gradients.
- The overarching theoretical question of connectivity—the linkage of ecological processes across space—is relevant to all of the GRAND CHALLENGE questions. A number of relocatable deployments should address connectivity, sampling hydrological and atmospheric transport (of dust and air pollution) flowpaths. They should address not only the sources and sinks of materials, but also the way these sources and sinks may change with land use and other disturbance processes.

NEON, Inc. used the Sioux Falls recommendations to develop a conceptual implementation plan in a workshop in Boulder, Colorado. This plan identified specific science themes and suggested an assignment of the themes to particular NEON domains. In some cases, a specific site was suggested; in others, the type of site required was identified, but not an actual location. The outcome of this process was released to the community in a document entitled *Research Design Basis for the NEON Relocatable Systems,* available on the NEON, Inc. web site (http://www.neoninc.org/documents/45).

The domain site survey identified a long list of potential relocatable sites meeting the science theme requirements, which were discussed by the ecological research community and NEON, Inc. In this phase, the assignments of some themes to specific locations were found to be unworkable and had to be refined. For example, the Sioux Falls group recommended that Domain 11 have a core site as far south in Texas as possible, close to an important invasive species gateway region, and relocatable sites to study interactions between land use and invasion. However, no core site could be located in the target region that had wildland conditions, adequate size, and secure land tenure. A core site in northern Texas was identified and the science theme modified to address land use and woody plant expansion. These decisions were made in close communication with domain-based scientists, and the final assignment of themes was reviewed in a series of conference calls. Only a few such revisions were made; in general, the Sioux Falls vision is being implemented.

Once the science theme assignments were complete, NEON, Inc. staff began to identify specific sites. Prior to visiting each candidate core site, staff asked each domain point of contact (POC; generally the lead RFI respondent) to convene a committee to discuss potential relocatable sites during the site visit. The various committees represented a wide range of institutions and scientific interests within the 20 domains, and in some cases, key people outside of the domains also. The national strategy was discussed at meetings that included participation by teleconference, and a tentative plan was usually developed for relocatables. Some follow-up teleconferences were needed to refine the strategy. In exceptional cases, a relatively mature strategy had been identified during the RFI process, and candidate relocatable site visits were scheduled along with the candidate core site visit.

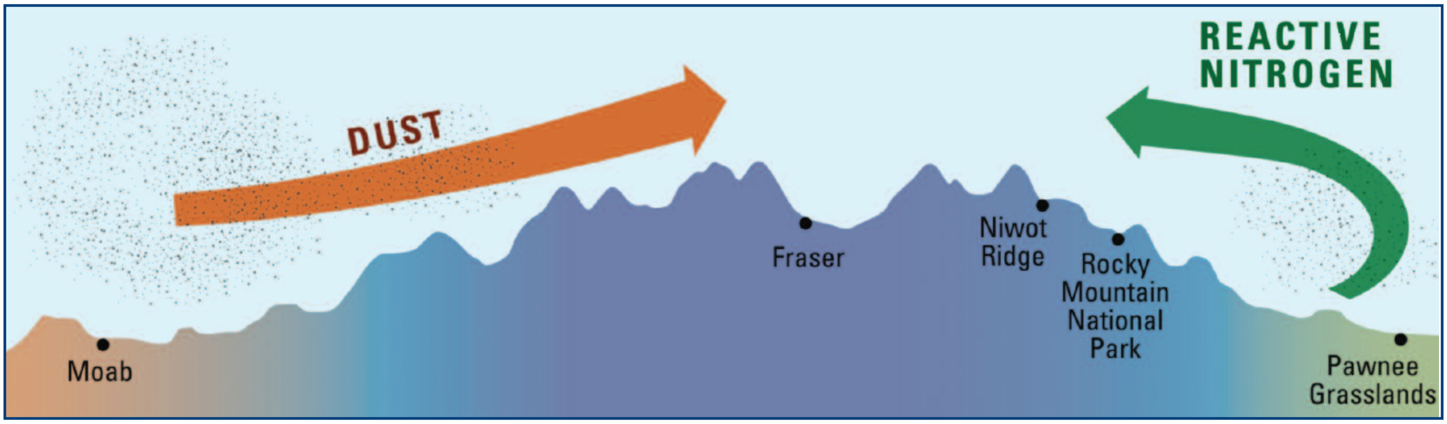


Figure 6: A simplified schematic of key atmospheric flowpaths in Domains 10, 13 and 15.

Table 3 identifies each currently planned candidate relocatable site and the science theme to which it is assigned. In addition to individual science theme assignments, several regional or multidomain themes are important:

1. Nitrogen deposition. The core and many of the relocatable sites in the Eastern Seaboard domains represent a gradient in the intensity of nitrogen deposition (and air pollution, more broadly). Relocatables in Domains 1 and 7 are specifically assigned to complete this gradient, and several other core and relocatable sites will also contribute.

2. Permafrost. The core and relocatable sites in Alaska (Domains 18 and 19) span a gradient from stable continuous permafrost through discontinuous or unstable (thawing) permafrost to permafrost-free soils. Permafrost status is a primary determinant of biological processes and community composition.

3. Land use and atmospheric transport. The core and relocatable sites in Domains 10, 13, and 15 are aligned along atmospheric flowpaths. Dust produced by land use is transported by prevailing westerly winds to receptor sites to the east in Domains 13 and 10. Reactive nitrogen is generated by agriculture and transportation in the Front Range region of Domain 10 and transported in upslope westerly winds toward Domains 13 and 15. Dust and nitrogen have dramatic effects on biogeochemistry, ecohydrology, and ultimately productivity and biodiversity.

4. Ecohydrological connectivity. In Domain 8, the core site is in the Black Warrior River watershed, on a tributary of the Tombigbee Waterway, a major river system draining southern Alabama. The core and aquatic sites are positioned to observe aquatic and terrestrial-aquatic interactions in the headwaters region of this important watershed. Relocatables are located at Armistead Selden Lock and at Choctaw National Wildlife Refuge on the Tombigee along the aquatic flowpath. The sites allow aquatic chemical and biological changes along the flowpath to be monitored. Importantly, this entire watershed experiences major precipitation pulses from tropical storms and hurricanes, so the impacts of such pulses on nutrients, organic matter, and the biota can be observed as they propagate downstream.

Domain Number	Domain Name	Site Name	Science Theme
1	Northeast	Bartlett Experimental Forest	Nitrogen Deposition
1	Northeast	Burlington, MA	Land-use/Urbanization
2	Mid-Atlantic	Smithsonian Environmental Research Center	Invasive Species
2	Mid-Atlantic	Blandy Experimental Farm	Invasive Species
3	Southeast	Disney Wilderness Preserve	Land-use/Forest management
3	Southeast	Jones Ecological Research Center	Land-use/Forest management
4	Atlantic Neotropical	Lajas Experimental Station	Land-use/Agriculture
4	Atlantic Neotropical	Ponce Metro	Land-use/Urbanization
5	Great Lakes	Steigerwald Land Services	Land-use/Forest management
5	Great Lakes	Tree Haven	Land-use/Forest management
6	Prairie Peninsula	The University of Kansas Field Station	Land-use/Agriculture
6	Prairie Peninsula	Konza Prairie Biological Station (Agricultural Lowland)	Land-use/Agriculture
7	Appalachian/Cumberland Plateaus	Mountain Lake Biological Station (SW Virginia)	Nitrogen Deposition
7	Appalachian/Cumberland Plateaus	Great Smoky Mountains National Park, Twin Creeks	Biodiversity
8	Ozarks Complex	Armistead Selden Lock	Ecohydrological connectivity
8	Ozarks Complex	Choctaw National Wildlife Refuge	Ecohydrological connectivity
9	Northern Plains	Dakota Coteau Field School	Land-use/Agriculture
9	Northern Plains	Northern Great Plains Research Laboratory	Land-use/Agriculture
10	Central Plains	North Sterling, CO	Land-use/Agriculture
10	Central Plains	Rocky Mountain National Park	Nitrogen & dust deposition
11	Southern Plains	Klemme Range Research	Invasive species
11	Southern Plains	University of Oklahoma Biological Station	Invasive species
12	Northern Rockies	Bozeman, MT (MOR)	Land-use/Urbanization
12	Northern Rockies	Loch Leven, MT	Land-use/Urbanization
13	Southern Rockies	Moab Canyonlands Ecological Research Site	Dust sources
13	Southern Rockies	Fraser Experimental Forest	Nitrogen & dust deposition
14	Desert Southwest	Jornada LTER	Climate change
14	Desert Southwest	Phoenix CAP LTER	Land-use/Urbanization
15	Great Basin	Murray, UT	Land-use/Urbanization
15	Great Basin	Red Butte Canyon	Land-use/Urbanization
16	Pacific Northwest	Good Seed Unit 2	Land-use/Forest management
16	Pacific Northwest	Thyme Unit 1	Land-use/Forest management
17	Pacific Southwest	Soaproot Saddle	Climate change/Rain-snow transition
17	Pacific Southwest	Upper Teakettle	Climate change/Rain-snow transition
18	Tundra	2nd Pump Station, Polygonal Tundra	Climate change/Permafrost
19	Taiga	Well Drained Black Spruce Forest Delta Junction (Non-permafrost)	Climate change/Permafrost
19	Taiga	Black Spruce Forest, Erickson Creek (Permafrost Gradient)	Climate change/Permafrost
19	Taiga	Eight Mile Lake, Healy AK, Alpine Tundra (Thermokarsting)	Climate change/Permafrost
20	Pacific Tropical	Puu Waa Waa-invaded	Invasive species
20	Pacific Tropical	Puu Waa Waa-uninvaded	Invasive species

Table 3: The NEON candidate relocatable sites and locations for the first round of deployment focus heavily on land use. Rapid climate change and invasive species are also well represented.

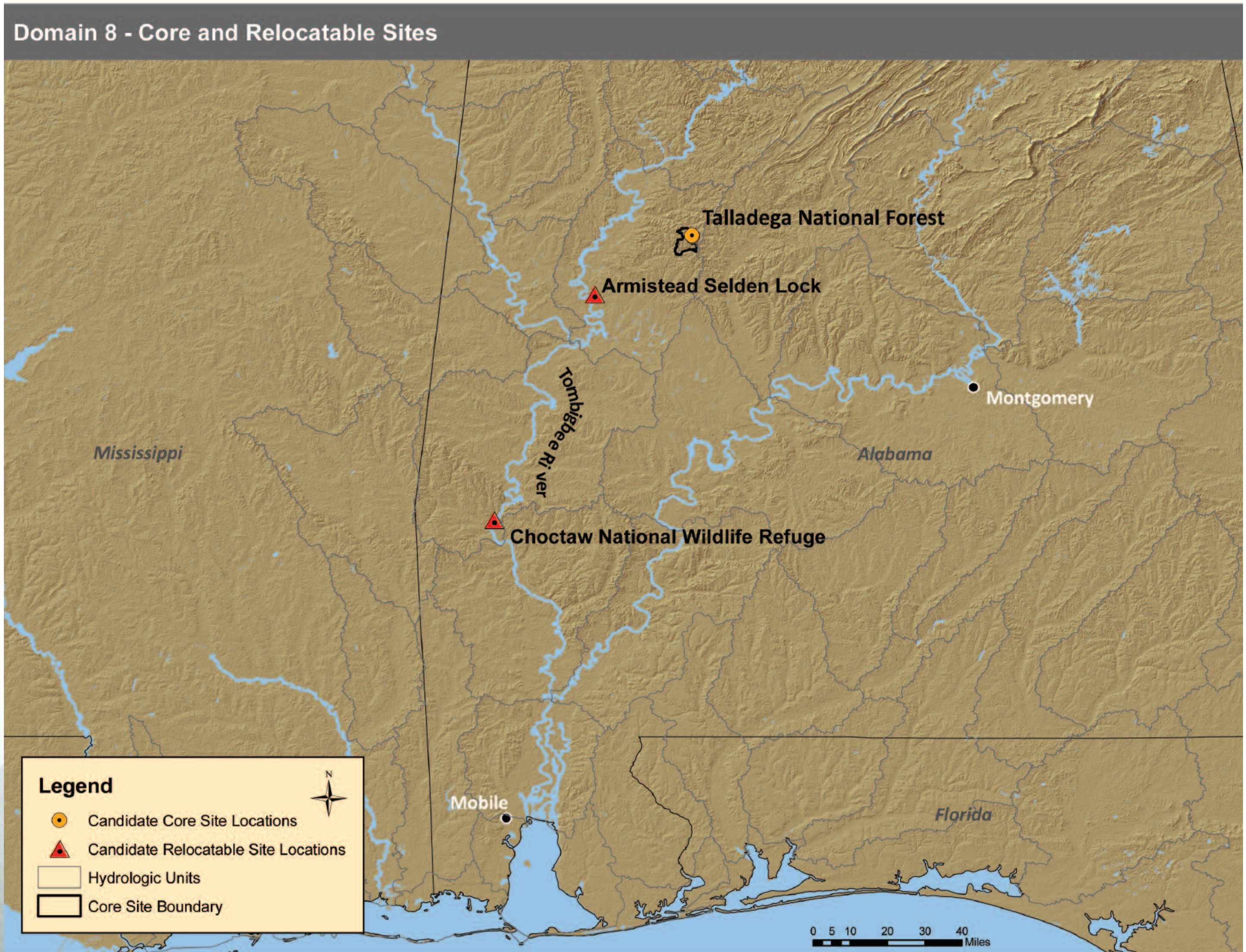


Figure 7: Map of the Domain 8 Core and relocatable sites aligned along the hydrological flowpaths down the Tombigbee waterway.

For each NEON domain, data from the core site represent a baseline or control point for ecological conditions that can be compared to potentially non-baseline conditions at the relocatable sites. These types of comparisons provide critical information that can be used to characterize impacts, especially those due to the land use change and invasive species drivers that cannot be characterized using only wildland sites. Analysis strategies for relocatable data are documented elsewhere.

3.2 Fundamental Sentinel Unit (FSU)

This component of NEON supports measurements of biodiversity and organismal responses to climate change, land use change, and invasive species. Two axes of variation define the FSU strategy. The first axis reflects a strategic selection of substrates (litter, soil, water) and taxa along a range of turnover/generation times from hours to decades. The second axis represents a hierarchy of measurable biological states and processes encompassing diversity (including genetic diversity), abundance, phenology, demography, infectious disease prevalence, ecohydrology and biogeochemistry. Both organisms and substrates must be understood to capture the dynamics of ecological forcings and responses on the interannual to decadal time scale of importance to the observatory. An economical sampling strategy is needed to obtain the data required for detection and quantification of interannual trends and continental multisite comparisons.

Understanding changes in populations and communities of organisms and their substrates requires observation and sampling in the field and analyses that are only practical in the laboratory. Some field observations (e.g., species abundance and phenology) will be rapidly available to the community following quality control. Other data will require off-site laboratory analyses of soil, water, or organismal tissues (e.g., chemical, genetic, infectious disease and isotopic analyses) to produce data products. A strategically selected portion of the carefully collected material will be stored and curated in the NEON BioArchive facilities (described below) to enable future analysis and study.

Off-site analyses will be accomplished at a limited number of FSU facilities in order to achieve economies of scale and comparability in measurements. NEON, Inc. will seek to contract the analytical and BioArchive facilities to qualified and experienced organizations. A NEON, Inc. calibration and validation laboratory will maintain quality control for the contract facilities.

A **chemical analysis facility** is necessary to quantify spatial and temporal variation in the quality of ecosystems substrates (litter, soil and water) as well as the productive component of ecosystems (leaves and algae). Monitoring carbon and major nutrient (N, P, K, Ca, Mg) biogeochemistry (both totals and labile forms) will be the focus of this facility.

An **isotopic analysis facility** is necessary to integrate ecological processes in space and time, such as the origin and movement of key elements (e.g., nitrogen) and substances (e.g., dust and water) that can directly impact ecosystem structure and function. Strong geographic patterns in isotope signature variation provide the means to trace the movement or origin of an organism, substance, or component at landscape to continental scales (Sterner and Elser, 2002). The isotope ratios of select plant and animal tissues and organic and inorganic compounds (including gases) in soil and water will be measured to represent a temporal integration of significant physiological and ecological processes on the landscape.

NEON's primary tool for understanding the microbiota (bacteria, fungi, archaea) will be a **genetic and genomic analysis facility**. Genetic analysis is revolutionizing the study of micro-organisms and organismal phylogeny (Riesenfeld et al., 2004; Tringe et al., 2005; Molloy, 2005; Delsuc et al., 2005). Previously, only organisms that could be cultured were available for study. Now, the entire microbial world can be studied. All evidence suggests that this world is far more diverse than the world of organisms that can be cultured (Tringe et al., 2005). As this is a rapidly evolving field, the aim of NEON is to enable active research linking microbial diversity to gene functioning to biogeochemical fluxes in the field. Much of microbial diversity has not been described, with multiple unknown functions and impacts remaining to be discovered. Microbes play critical roles in biogeochemical cycles of all elements and may be the key agents of some elemental transformations (Falkowski et al., 2000) (e.g., ammonia oxidation, denitrification, and nitrogen fixation). NEON will expand the temporal and spatial understanding of microbial dynamics.

A **curated collection of organisms**, key body parts of organisms, and substrates, termed the NEON BioArchive, will enable researchers to collect data that cannot be gathered with current observatory resources and to provide a record and reference collection for future studies of biological change. BioArchive samples include voucher specimens, whole organisms and tissues from invertebrate and vertebrate trapping efforts, plants, litter, soil, and water filtrates. The collected samples will provide a resource for future research efforts, enabling scientists to identify organisms, analyze archived blood and tissue samples for viruses and emerging pathogens, and perform new isotopic and biogeochemical analyses on water and soil samples. These samples will be stored in replicate and in a manner that will protect against major loss in the event of a catastrophe. Replicate samples will also allow for the destructive analysis of samples.

Examples of investigations that would use the FSU include:

- Studying *Peromyscus* demography and disease prevalence as a function of climate, productivity, and insect abundance, Forecasting future mosquito communities in response to climate change, and
- Examining the effect of climate change on nitrogen export in small streams.

3.3 Fundamental Instrument Unit (FIU)

The Fundamental Instrument Unit (FIU) will make airshed- and watershed-level observations using automated approaches from terrestrial towers and aquatic instruments. Like all NEON components, the FIU will enable the study of ecological forcings and responses. It will provide data on key local physical and chemical climate forcings including temperature, humidity, wind, precipitation, radiation, carbon dioxide, ozone and reactive nitrogen. Terrestrial and aquatic flux measurements from the FIU will provide estimates of ecosystem responses to the physical and chemical environment in the form of carbon, water, and energy fluxes where transport conditions meet measurement assumptions. In addition, the FIU will make detailed soil measurements including temperature, moisture, carbon dioxide concentration and surface carbon dioxide flux. Depending upon the ecosystem, FIU measurements will represent areas from a few hectares to hundreds of hectares.

Like the FSU, the FIU is also designed to allow detection of interannual to decadal changes. A few key ecosystem-level physiology characteristics (rates of photosynthesis, respiration, etc.) can be observed and closely linked to physical and biological controls. The insights gained through analysis of FIU data across a range of environmental and land use conditions will enable improvements in ecological forecast models for prediction of mass and energy flux responses to climate change.

The FIU will be built in three versions for deployment at the core wildland sites and in relocatable and mobile versions. Research topics that would use FIU observations include:

- Interannual variability in ecosystem productivity related to large-scale oscillations in the general circulation, and
- Biological consequences of changes in the snow-rain transition of the Sierra Nevada.

3.4 Airborne Observation Platform (AOP)

The Airborne Observation Platform (AOP) is a remote sensing instrumentation package designed to bridge from organism and stand scales to the scale of satellite-based remote sensing. The AOP will require sub-meter spatial resolution that will allow measurements at the level of individual organisms or small groups of organisms. It is designed to measure the effects of land use change and changes in vegetation state and performance, including the presence and effects of invasive species. The optimum available instrumentation to implement these capabilities is a high-fidelity shortwave infrared-to-visible spectrometer and a waveform LiDAR. Together with a high-resolution digital camera for land cover identification, an uplooking solar spectrometer will provide information needed for quantitative data processing. Respectively, these AOP instruments primarily will provide information on vegetation canopy biochemistry and structure.

The AOP will also contribute to the understanding of ecosystem forcings and responses as represented by vegetation states and processes. Invasive plants can be detected through both their spectral properties and their structural properties (Asner & Vitousek, 2005; Asner et al., 2008). Pest and pathogen outbreaks, changes in competitive relations, responses to disturbances such as wildfire, and many features of land use are also readily observed and quantified using the powerful combination of biochemical and structural information provided by spectroscopy and waveform LiDAR.

The high cost of aircraft operations will limit the frequency of AOP visits to individual NEON sites. In order to detect interannual trends, NEON will seek to overfly each core and relocatable site annually. To minimize the phenological contribution to the signal, flights will be designed to reach each site during a period of peak greenness (currently defined as the range of dates where MODIS NDVI for the site is within 90% of the site maximum). The AOP can also be deployed in response to extreme events to monitor both forcing (e.g., hurricane damage) and response (regrowth after fire) as well as other PI requests (e.g., regional surveys of invasive species or phenology).

Annual visits inevitably miss important site-level signals such as phenology. Higher-frequency data on vegetation function are available from satellite measurements at a coarser resolution. NEON needs a means to link the meter-scale AOP measurements to such satellite measurements. The need to cross scales drives AOP to observe a substantial area on the ground. We expect future satellite remote sensing to provide relatively frequent (days to weeks), moderate-resolution multispectral data at the 500 to 1000 m spatial scale.

AOP must fly a sufficiently large area for reliable comparison to satellite measurements. Currently we estimate that each AOP site mission will cover 300 km^2, a compromise between area coverage and cost. To allow for annual revisits, support of extreme events, and PI requests, three AOP systems are required for NEON.

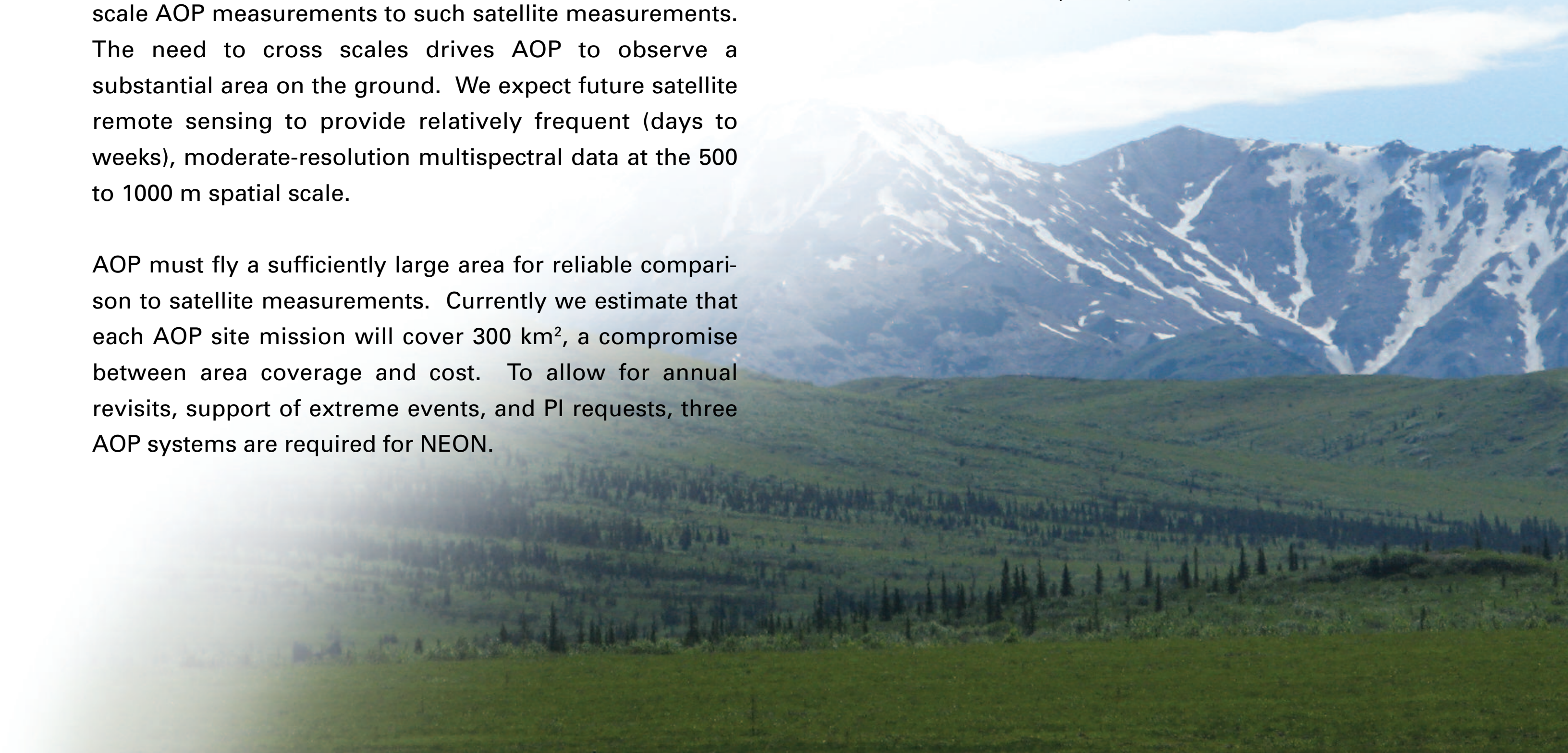
AOP will be useful in investigations such as:

- Thermokarst melting effects on trace gas emissions and vegetation composition in the Arctic,
- Dust transport in the southwestern United States and its impact on snowmelt in the Rocky Mountains, and
- Identification and tracking of invasive plant species in Hawaii at regional scales to address changes in biodiversity.

3.5 Land Use Analysis Package (LUAP)

Land use, invasive species, and climate change are all the results of human modifications of the planet. Humans directly and indirectly force ecosystem changes and also respond to ecosystem modifications. Human effects on ecosystems can be seen primarily through modifications in land cover and land use. While the AOP and satellite systems can monitor land cover, most human land use practices (e.g., fertilizer use, grazing intensity, irrigation rate) requires other types of data collection.

NEON requires land use data on the local and continental scale. These data should extend back for decades or even centuries, if possible, because the legacies of past land use can have long-term effects on ecosystem performance (e.g., Richter & Markewitz, 2001). Present and future land use



regimes encompass human dynamics that involve historical, political, economic, social, behavioral, and psychological aspects of people and their institutions.

The LUAP will provide information that ecological modelers and forecasters can use to extend their models to a continental scale. The LUAP will collate existing data, primarily through relevant federal agencies, on past and current land use practices as well as economic and social data that are useful for prediction of future land use processes. It will also compile and serve other data, including basic continental-scale data on ecosystem performance derived from satellite remote sensing, and soils and topographical data from national databases. The LUAP incorporates observations of both ecosystem forcings and responses and makes the data available for continental-scale analyses, models, and forecasts.

The LUAP would be useful for various kinds of studies, for example, a study of climate change, land use, and fire regimes in the Alaskan boreal forest.

3.6 Observing Transient Events: The Mobile Deployment Platform

NEON will observe abrupt events triggered by long-term trends using mobile facilities that can be rapidly deployed. Long-term trends such as climate change or biological invasions trigger ecological responses on a slow time scale that is best observed at a stable site (e.g., a core site), but they may also cause changes in the probability of abrupt events. For example, if a gradual rise in mean temperature crosses an ecological threshold, it can trigger rapid changes in the frequency of extreme events. These events can cause landscape-scale changes in ecological conditions, and because they have a stochastic component, the events cannot reliably be observed using fixed location sampling.

Two well-known phenomena exemplify this pattern. First, the life cycle of the mountain pine beetle is intrinsically determined by temperature, with the insect's rate of maturation depending on temperatures and mass mortality requiring 10 or more days below -35° C (Carroll et al., 2004; Taylor et al., 2006; Stahl et al., 2006). Population explosions and mass range expansion can occur if temperatures are warm enough that the insect goes from hatching one generation per summer to two generations. Population explosions can also occur if winters are warm enough that the -35° threshold is not met, eliminating winter mortality (Hicke et al., 2006; Fauria & Johnson, 2009). Both thresholds were passed for much of the western United States and Canada in the 2000s, resulting in unprecedentedly severe outbreaks and expansion of the insect's range into previously uncolonized ecosystems in boreal Canada (Logan & Powell, 2001; Kurz et al., 2008).

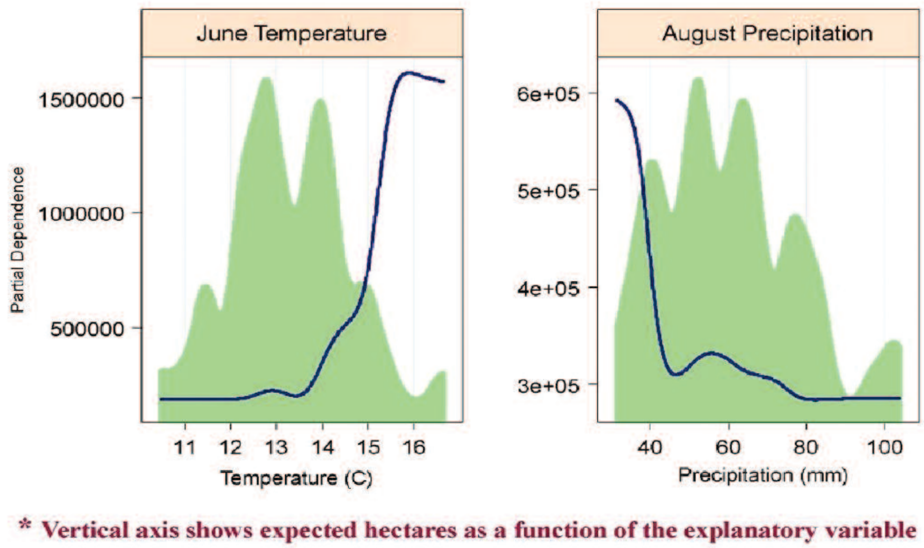


Figure 8: An example of a discontinuous ecological response to a small change in environmental conditions: the partial dependence of area burned versus June temperature and August precipitation for interior Alaska. The green backgrounds show the observed distributions of June temperatures and August precipitation.

Second, the frequency and severity of wildfires depend in a nonlinear way on climate. In Alaska, the area burned depends on spring and summer climate and particularly on temperatures and rainfall that influence subsequent fuel moisture and fire behavior (Duffy et al., in prep.). Figure 8 shows that the area burned increases abruptly when June temperatures exceed 14º or when August rainfall drops below 50 mm/month. Alaska has been warming at a very rapid rate, and these excesses have changed from occasional anomalies due to climate variability to common occurrences as mean temperatures increase (Backlund et al., 2008).

Abrupt events that occur when environmental conditions cross a threshold are thus a critical part of climate change, land use change and biological invasion impacts. NEON will provide infrastructure that can be deployed to respond to such events and observe environmental and physical conditions following the event. Two NEON facilities can address this requirement. First is the AOP, discussed above. Second are Mobile Deployment Platforms (MDPs), which provide basic FIU capabilities and FSU support in a rapidly deployable package.

Figure 8: An example of a discontinuous ecological response to a small change in environmental conditions: the partial dependence of area burned versus June temperature and August precipitation for interior Alaska. The green backgrounds show the observed distributions of June temperatures and August precipitation.

The MDPs will include a transportable laboratory containing basic working space, data communications for the sensor network and data store, and forward capability to record and secure data. They include power distribution for NEON- and investigator-supplied instruments that can be connected to line, generator, or photovoltaic systems. While the MDPs will be built using the same basic designs as the FIU as implemented at core and relocatable sites, all components will be optimized for rapid setup and takedown, to maximize research time. A main design change is that most data transfer will be wireless to decrease installation time and materials cost and to increase installation flexibility.

The mobile lab will also serve as a base for FSU activities and will include plot marking and locating equipment; small mammal, mosquito, and beetle traps; a library of FSU protocols; data entry forms; field equipment; and field data entry devices. FSU field crews on mobile lab deployments would normally be trained by NEON but staffed and funded by the requesting investigator.

Mobile labs provide the on-the-ground capability to respond to abrupt events, and will be managed to retain the flexibility to do so. When they are not being deployed for this purpose, the MDPs can be used for a variety of educational and scientific activities.

3.7 NEON Network Experiments

NEON experiments are designed to serve as "accelerators" of expected future changes of ecosystem forcing variables, eliminating the need to wait for 50 or 100 years of observations. Well-controlled, multifactor experiments that are replicated across the continent can reduce or eliminate the confounding effects of variables and thus promote a clear understanding of cause-effect relations (NRC, 2003).

Experiments fit the NEON mission in two key ways:

1. Experimental "accelerators" manipulate systems to change conditions to those resembling forecast future conditions, for example, by artificially warming temperatures, increasing CO2 concentration, or introducing potential invasive species. Accelerator experiments test and inform forecast models seeking to predict such future conditions.

2. Experiments can elucidate cause and effect for processes where observational and correlative studies are too confounded, are too complex, or occur over time scales longer than NEON's planned 30-year life span.

NEON experiments will impose new physical, chemical, or biological conditions and will use both automated instrumentation and human observers. The manipulations will be imposed, as much as possible, on ecosystems with a full complement of species. Barriers to species movement (except where such movement is a deliberate part of the experiment design) will be minimized. Experiments will be designed for a decade lifetime or more, although investigators may develop shorter-term focused experiments within the NEON infrastructure. Long-term studies allow for individual and species turnover and adjustment of long-term biogeochemical pools; these processes are often not accessible in typical PI experiments.

The ability to support both terrestrial and aquatic experiments is planned. The first NEON experiment is designed both to be scientifically important and to test technologies and management approaches for later, more ambitious experiments. A terrestrial experiment is also under consideration, and resources are being sought to prototype the technologies.

3.7.1 The Stream Observation Network Experiment (STREON)

The first NEON experiment will be the Stream Observation Network Experiment. Its primary scientific purposes are twofold: (1) to study how stream ecosystems respond to an acceleration of one of the key drivers of their structure and function (nutrient loading), and (2) to determine how loss of top consumers, singularly and interactively with increased nutrient loading, affects stream structure and function. STREON addresses the question of how the resilience and resistance of stream ecosystems are affected by chronic nitrogen and phosphorus enrichment and the simplification of food webs under conditions of hydrologic variability and expected increases in extreme events.

STREON will take place at NEON core and relocatable sites, distributed across key U.S. climate gradients and representing the dominant stream hydrologic regimes present in the Northern Hemisphere. It will allow observation of ecosystem response to the availability of a key resource and how biological structure influences that response. The primary limiting resources in stream ecosystems are photosynthetically available radiation (Hill et al., 1995; Stevenson, 1997; Roberts et al., 2007), nutrients (usually nitrogen and/or phosphorus), and organic carbon supply (Elwood et al., 1981; Peterson et al., 1985; Wallace et al., 1999). Continuous addition of inorganic N and P to streams was selected as the primary resource manipulation because these nutrients commonly limit algal and microbial growth in streams (Francoeur, 2001,; Elser et al., 2007), and because human activities involving land use and other changes often increase the supply of these nutrients to streams (Dodds, 2006). Exclusion of top-level consumers will demonstrate the effects of changes in stream food webs and how food web structure influences the way stream ecosystems respond to increased availability of resources. This design allows study of both bottom-up (abiotic resources) and top-down (consumers) control of ecosystem function, an important issue in ecosystem science (Rosemond et al., 1993; Gripenberg & Roslin, 2007). Further, extinction and extirpation of top consumers are among the most serious threats to the biotic structure and ecological integrity of aquatic ecosystems worldwide due to such factors as climate change, toxic chemicals, and invasive species.

Results from STREON will inform predictive models of stream ecosystem structure and function derived from the observational measurements. The STREON sites together with the NEON observational stream sites form an integrated experimental and observational network designed to answer key questions and develop a predictive understanding about the primary factors that drive changes in the structure and function of stream ecosystems. This experimental study will demonstrate how two of the most prominent forms of environmental change–eutrophication and species extinction/extirpation–interact to alter stream ecosystem structure and function. By conducting identical experimental manipulations across different biomes and continental gradients in climate, hydrologic regime, and nitrogen deposition, STREON will provide a transformational increase in the understanding and ability to forecast future ecological change in stream ecosystems, a critical component of the landscape representing the transition from terrestrial to aquatic systems.

3.8 Overview of NEON Observations

The NEON science subsystems will collect information relevant to each of the NEON GRAND CHALLENGES. The information can be described as falling into a number of general areas, or suites, of key parameters. NEON will provide large amounts of information on a huge number of ecosystem attributes and will deploy approximately 15,000 sensors of roughly 200 distinct types, make biological measurements on about 2000 plots distributed over 62 sites, and collect about a petabyte of information each year. The results of this data collection will be about 500 distinct primary data types (level 1 data products) and 120 types of derived ecological parameters. Samples collected by the network each year will yield 175,000 chemical, taxonomic, isotopic and genomic analyses per year, and a similar number of samples will be stored in the BioArchive for future research.

The following table provides a high-level view of the types of data NEON will collect. Basic calibrated data, or data that has been temporally or spatially rectified, will be processed using state-of-the-art algorithms and models to produce ecological information that enable the use NEON data rapidly and effectively to address ecological science, education and real-world decisions.

Data Suites	Types of parameter included:
Bioclimate Suite	• Temperature, precipitation, humidity, radiation
Biodiversity Suite	• Abundance and diversity (mosquitoes, aquatic invertebrates, beetles, fish, birds, plants, etc.) • Phenology (mosquitoes, beetles, plants) • Microbial function and diversity (functional genes, metagenomes) • Bioarchive (all taxa, substrates)
Biogeochemistry Suite	• Carbon stocks, fluxes, isotopes • Nutrient stocks, fluxes, isotopes (N, S) • Chemical climate (N-deposition, Ozone)
Ecohydrology Suite	• Water balance components (storage and fluxes)
Infectious Disease Suite	• Disease prevalence (Dengue, Hanta virus, Lyme disease, West Nile Virus)
Land Use and Land Cover Suite	• Remote sensing data (vegetation performance and structure) • Geographic data (topography, historical climate, etc.) • Statistical data (human geography)

Table 4: Overview of the types of information included by NEON

3.9 NEON Modular Enabling Design

NEON is a user facility with a 30-year lifetime. In order to a wide range of uses and to permit and anticipate ongoing upgrades throughout the duration of the observatory, its infrastructure must follow a modular and expandable design. Modularity provides the opportunity to replace every component of NEON's infrastructure, including hardware, software, and facilities such as buildings and towers. The NEON infrastructure must be designed with the ability to replace any component (plug and play) without major disruption to any other component. A key aspect of the modular design is reliance on standards that define instrument and observation interfaces to the overall NEON infrastructure. For each sensor and data type, the standards for data format and metadata will be defined, documented, and made publicly available. In addition, to the extent possible, hardware standards will be adhered to, addressing power connections, sensor mounts and other interfaces with the goal of minimizing the burden of integrating new sensors and maintaining the old.

The NEON infrastructure is also designed to be hospitable to investigators. Hardware, software, and standards are all being designed to facilitate the integration of investigator projects within the NEON infrastructure. The facilitation is intended to work in two directions. On the one hand, by developing and publishing straightforward standards and interface documents, NEON will make it as easy as possible for investigators to add sensors, observations, or experiments to the NEON backbone. On the other hand, by using a standards-based modular approach, NEON seeks to minimize its overhead associated with integrating investigators, so that the network can support the maximum amount of interaction within a stable budget. Site design will be expandable to allow the incorporation of new technology or new measurements not available or not practical in the initial implementation. The facility must accommodate new measurements implemented by the observatory operators as well as measurements implemented by outside users. Within each NEON site, components of this plan include:

- Standards for hardware physical mounting and documenting the locations free for new sensors on all towers and arrays.
- Standards for observer data and metadata formats, documentation of field data entry device requirements to link to the NEON Cyber Infrastructure.
- Standards for instrumental data formats and required metadata.
- Site maps (30 meter resolution or better) showing areas available for additional sensors, field plots, experimental set-aside areas, and detailed site ecological characteristics for planning. Site maps will also show reserved areas where additional research is not possible and transit routes to minimize disturbance.
- A clear, transparent, documented system for gaining access to NEON infrastructure for new studies via technical staff and Program Assessment Committee review.

Decisions about incorporation of new studies will be assessed for technical feasibility by NEON technical staff, and scientifically by the Program Assessment Committee (PAC). A policy for cost recovery associated with incorporation of new investigations into the infrastructure may be required, and the NEON CFO's office and PAC will be charged with developing a policy before commissioning.

3.10 Education and Public Engagement

One of the critical elements of the NEON plan is integration of ecological research with education. This project will involve thousands of scientists, educators, planners, and decision makers who will use NEON data and resources for decades to map, predict, and change human effects on the biosphere. NEON's bold aim to translate continental-scale ecological data on climate change, invasive species, and land-use into "meaningful information that citizens can understand and use" represents a commitment to providing NEON science and data products that are accessible to and usable by all communities.

The NEON platform provides extraordinary opportunities for education. The platform will support a wide range of interactions – such as between educators and scientists, students and researchers, policymakers and researchers, scientists and the general public, and students and other students. Furthermore, the integration of science and education, supported by robust cyberinfrastructure, physical infrastructure, human resources and strong partnerships, will enable facilitation of a range of innovative learning experiences that will engage a diversity of audiences as part of a broad effort to raise ecological literacy in the United States.

The focus of NEON Education is to help people think of science as a way of knowing. The NEON Education plan is organized around ways of engaging people with NEON data products and resources. NEON Education is the interface between scientific data and user communities. In this capacity, NEON Education provides tools and facilitates learning experiences that engage users with different levels of knowledge, experience and skills. These tools and learning experiences are aimed at **awareness**, **mastery** and **leadership** levels (as illustrated in Figure 9). This approach enables users to self-define their interests and abilities regardless of their affiliations (i.e., K-12 teacher, citizen scientist, family).

NEON will serve as a model for transforming science education from passively disseminating information to actively engaging learners in "doing science." As individuals take more responsibility for their own learning (Falk et al., 2009; Falk & Sheppard, 2006), it is critical that NEON facilitate ample free-choice learning opportunities where individuals can easily access, use and contribute to NEON products to meet their needs and interests. NEON Education, in partnership with stakeholder communities, will employ a variety of approaches and tools to engage individuals in the scientific process, including social media, online learning modules, citizen science projects, workshops, and informal education programs.

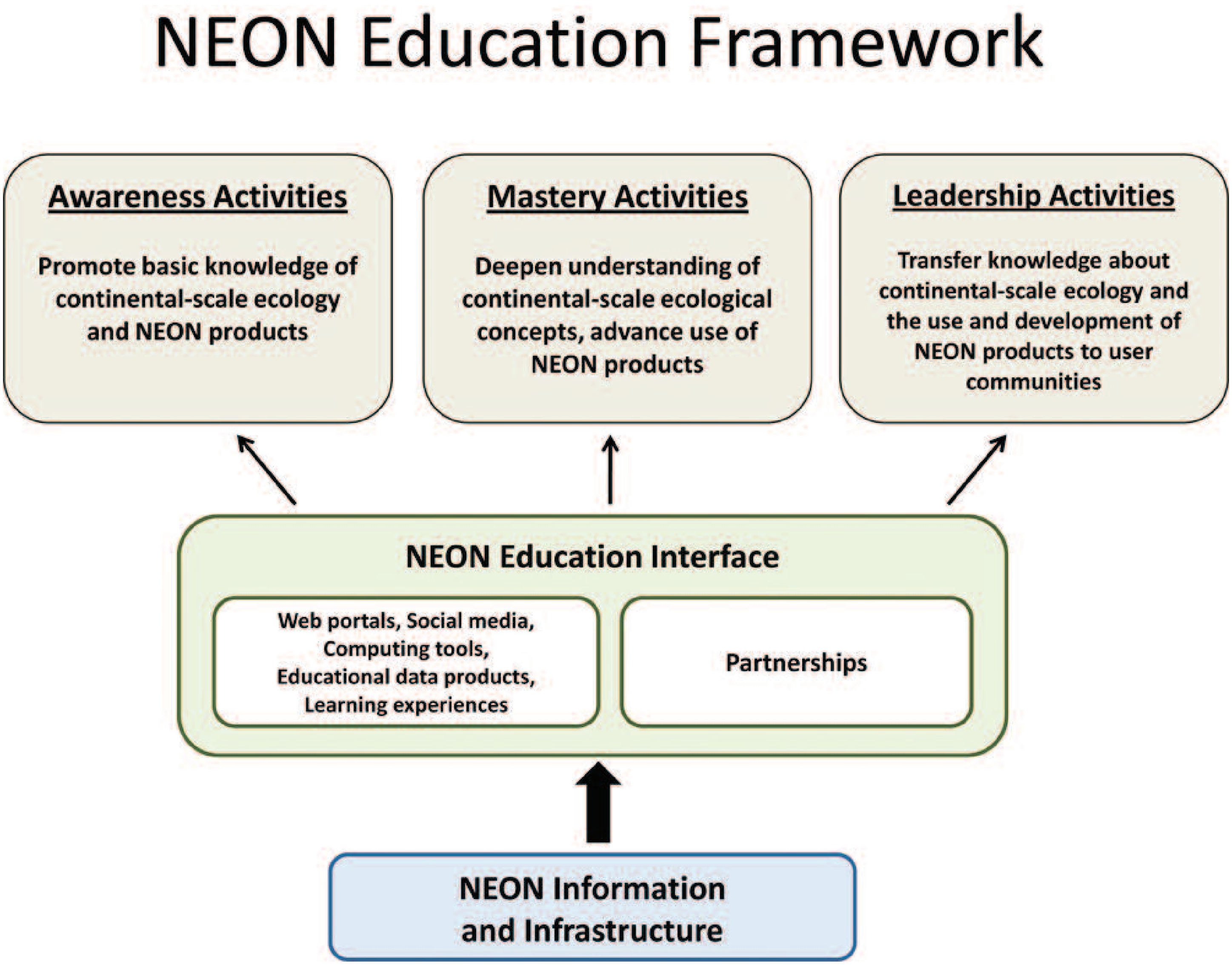
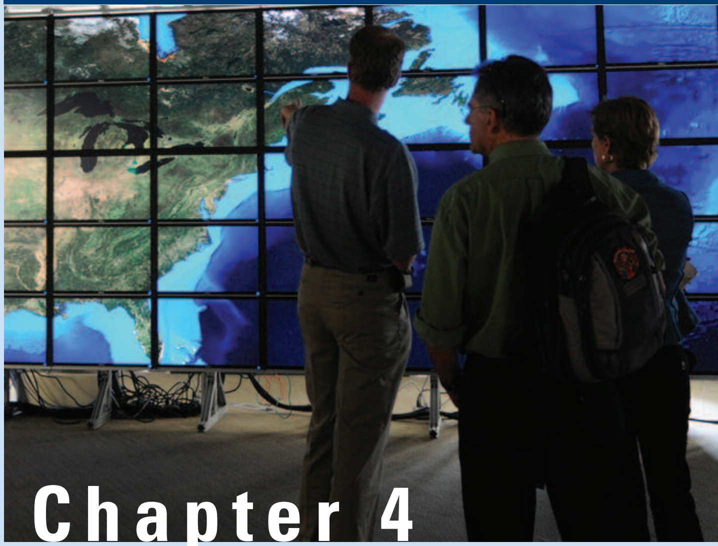


Figure 9: Representation of NEON Education as the interface between NEON science products and activities aimed at awareness, mastery and leadership.

NEON's Education and Outreach mission is to enable society and the scientific community to use ecological information and forecasts to understand and effectively address critical ecological questions and issues. NEON will include numerous physical and virtual capabilities to enable educational and public use of the facility, including:

- A citizen science program and web portal to increase awareness and educate citizen scientists about the impacts of climate change, land-use change, and invasive species on continental-scale ecological processes as well as expand NEON data collection capacity by enabling laypersons to collect, enter, analyze and visualize geographically distributed data;
- A central web portal to introduce users to NEON and provide online learning experiences, including tailored access to real data, focused on the fundamental ecological concepts associated with NEON;
- A web portal that provides tools for decision makers to use NEON data to make scientifically-based decisions related to climate change;
- A web portal that provides (1) content and learning experiences for educators to master continental-scale ecological concepts, and (2) activity modules, tools and resources to support educators as they engage students in ecological learning experiences using NEON data;
- Professional development opportunities to prepare educators to use NEON data and Education tools, provide opportunities for educators to contribute to Education product development (i.e., activity modules for web portal), and facilitate community collaboration and investment in effective ecology education;
- Research and internship opportunities for undergraduates to prepare future generations of ecological scientists and science, technology, engineering and mathematics (STEM) professionals to use NEON and other continental-scale data, and broaden participation in STEM experiences by traditionally under-represented groups;
- Workshops, seminars and courses to provide training and learning experiences for individuals to more effectively use and contribute to NEON data, tools and learning experiences;
- A NEON User Data Base to track and better understand the NEON user community, allow for ongoing assessment of NEON data and educational products, and enable educational research.

Partnerships are critical to every aspect of NEON Education. The framework for developing these products requires significant input and collaboration with stakeholder and user communities. Successful implementation of these web portals and learning experiences depends the ability of NEON to establish strong partnerships. NEON must be receptive and responsive to its potential partners and stakeholders in order to leverage NEON's resources to help transform science and science education nationally. NEON will invest considerable effort up front in building partnerships with many complimentary organizations and groups, including professional societies, federal and state agencies, formal and informal educational institutions, innovative technology developers, NSF biological synthesis centers, and community organizations, to promote broad ecological literacy and the education of the next generation of environmental scientists. With active input from partners, NEON Education can define the best opportunities and resources available and enable partners to define the programs and products that most effectively use NEON resources.



Chapter 4

NEON Analysis and Forecasting Framework

4.1 Spatial Extrapolation Strategy: From Sites to a National Ecological Forecast

For NEON to function as a continental-scale observatory, it must demonstrate that methods exist to produce continental estimates using NEON's observing strategy (e.g., analyses that have a map as output). That is, NEON must be able to extrapolate relationships between drivers (climate change, land use change, and biological invasions) and ecological consequences to areas that are not sampled by NEON facilities but where partial, extensively sampled, or gridded information is available. NEON's observing strategy is designed to accomplish this by:

- Locating site-based measurements so they represent the largest possible area,
- Coordinating local site measurements with high-resolution airborne remote sensing (AOP), and
- Integrating site and AOP measurements with national remotely observed and statistical data sets (LUAP and others).

These observations provide the raw material for continental estimates but do not define an analytical framework. This section will outline an analytical approach that can integrate measurements at multiple scales; typically, many intensive measurements from a small number of sites (NEON core and relocatable sites), a few key measurements from a large number of sites (for example, the Forest Service's Forest Inventory Analysis plots), and data from remote sensing.

Pairing intensive and extensive measurements at NEON sites allows the development and calibration of relationships between these two types of observations that can be applied elsewhere. The approach described has a fairly long heritage, but modern developments in statistics greatly increase the possibilities for spatial modeling. The framework describes just one way to combine data across scales; the availability of NEON is expected to stimulate new approaches to spatial and spatio-temporal modeling and analysis.

The framework for spatial extrapolation (and, by extension, spatio-temporal extrapolation including forecasting) is based on several principles:

1. Quantifying the covariance between measurements of ecological drivers and responses. The covariance is a measure of how much two (or more) variables change linearly together. When empirical data (from coordinated observations or experiments) are analyzed, the covariance measures the strength of the underlying mechanistic relationships, as they are expressed in the data. Most other statistical measures of relationships derive from the covariance. This concept can be generalized to consider nonlinear effects.

2. Quantifying the covariance among measurements at different sites and times to establish how variables change through both time and space. This is the basis for extrapolating from sites to larger regions over time.

3. Identifying where and when patterns in the covariance are stable (i.e., stationary) or break down, indicating coherence or changes in the underlying process between regions or over time.

A fundamental challenge to the statistical characterization of data that vary across space and time is discontinuities in covariance structures in the spatial and temporal dimensions (i.e., spatio-temporal non-stationarity). Classical approaches have developed some tools to deal with non-stationarity in either space or time, but they either rely heavily on assumptions or are computationally unable to assimilate data from multiple sources and scales. It is necessary to utilize a statistical framework for analysis that can explicitly account for non-stationary spatio-temporal covariance structures in the context of using data from multiple sources. Such a framework is outlined elsewhere in this document.

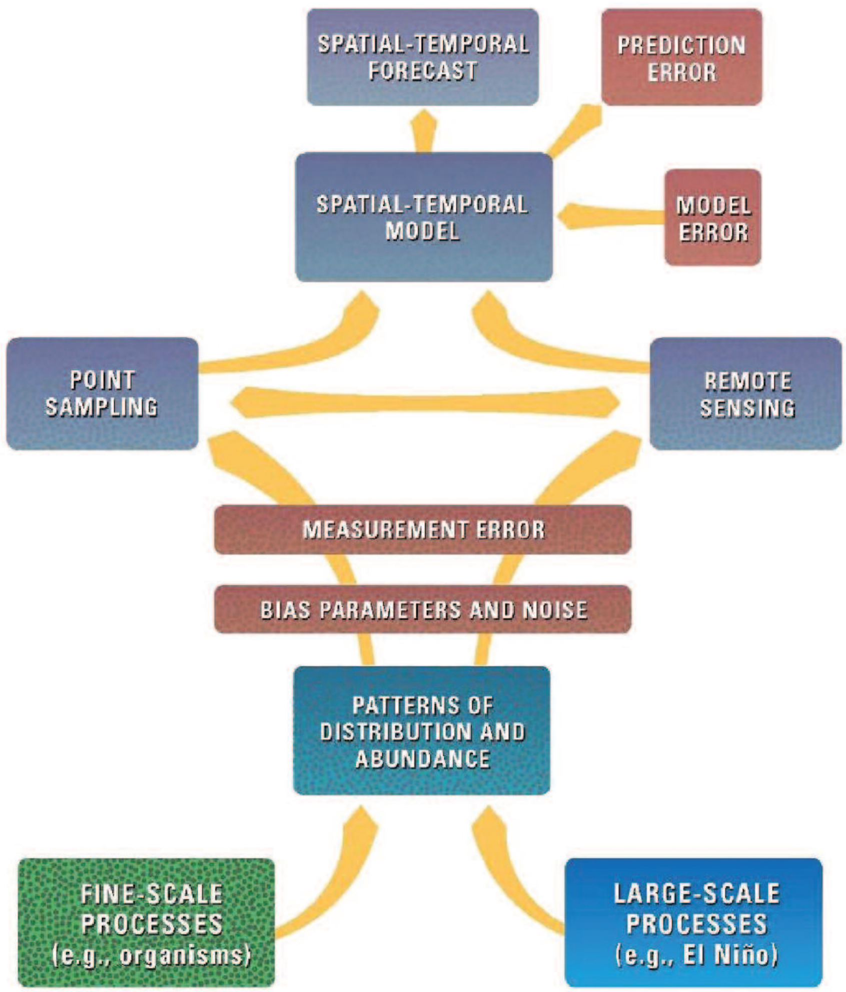


Figure 10: The flow of information from observations to forecasts. Patterns in the natural world are multiscaled (bottom of figure), from local and organism-scale processes up through coherent patterns at continental to global scales (such as droughts connected with El Niño and regional air pollution). Patterns at different scales combine to produce the systems sampled by NEON using site-based and spatially comprehensive remote sensing techniques. The NEON information system will combine observations from these different sampling strategies using spatio-temporal modeling algorithms to produce estimates of processes, and their uncertainty, in time and space.

The overall flow of information, from multiscaled processes in nature to spatio-temporal forecasts, is shown in Figure 10. This figure shows in a simplified way that ecological processes can be controlled by both coarse-scale patterns (for example, El Niño climate anomalies that affect continental-sized areas) and fine-scale patterns (for example, natural mortality of individual trees). Ecological processes may be sampled intensively at points where many variables can be measured simultaneously, or via extensive measurements such as remote sensing, where only a few variables are measured. Both of these measurement strategies introduce various types of uncertainty and bias. Spatio-temporal models can then be used to combine these various types of observations, and also to introduce more general knowledge (from other field and lab studies) via models. This process is often referred to as model-data fusion.

This modeling framework (based on geostatistics and hierarchical Bayesian model (Cressie et al., in press)) provides important guidance to NEON. It shows how NEON information products can address much larger regions than those directly sampled at core and relocatable sites. The framework provides a quantitative approach for combining FSU and FIU data with AOP and LUAP information, and it also generates the requirement that these data types be readily interoperable. It provides a quantitative statistical framework in which information from separate but related field and laboratory experiments can be combined to inform regional and continental forecasts.

Figure 10 (a)

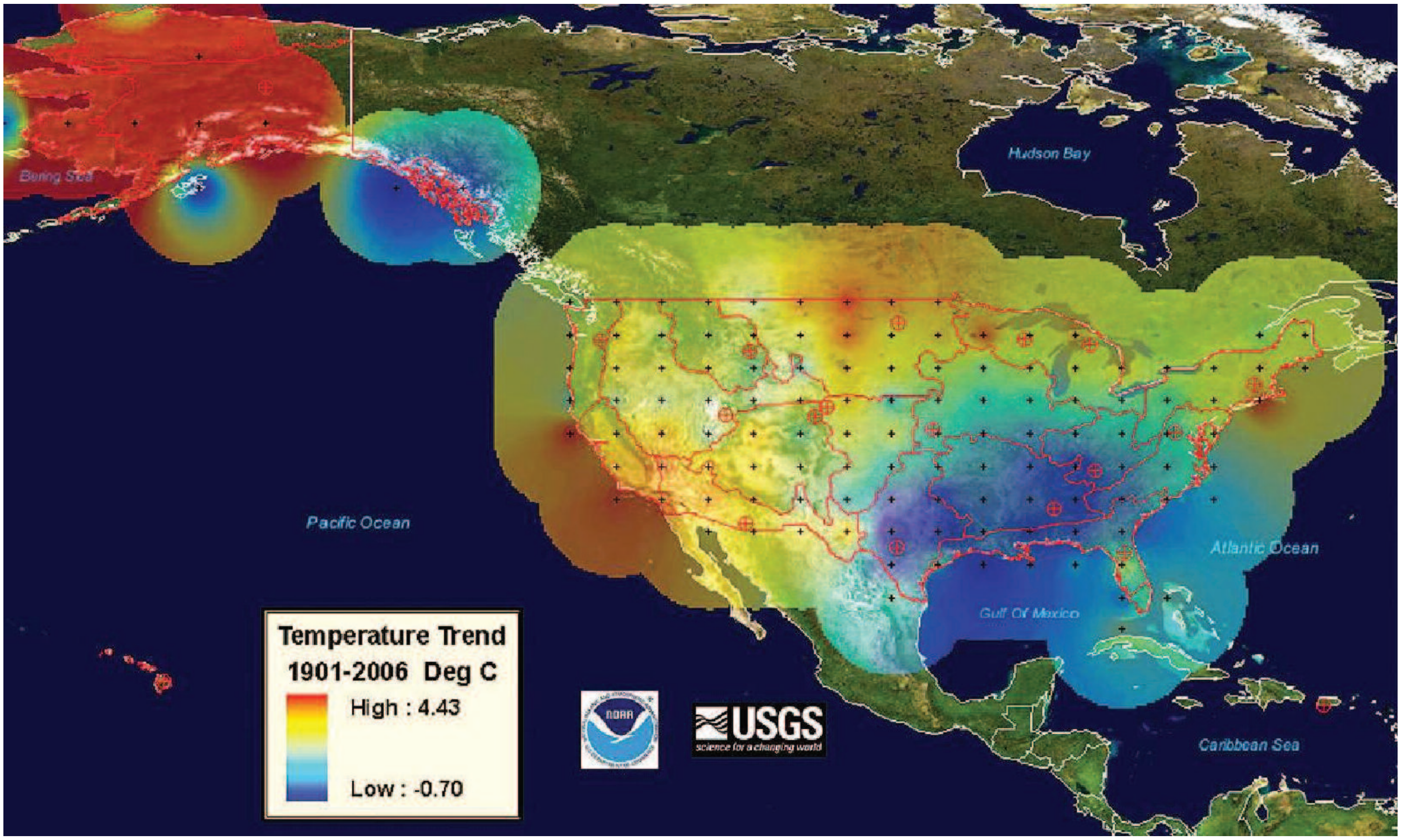


Figure 11: (a) Temperature trends over the United States, 1901–2006, showing the high spatial variability of the trend, which is influenced by latitude, proximity to the oceans, and aerosol effects. (b) Global average surface temperature anomaly with respect to the 1951–1980 climatology, based on the meteorological station analysis of the Goddard Institute for Space Studies by Hansen et al. (1999). Individual years are shown as vertical bars while the heavy solid line plots the 5-year moving average (taken from Wang and Schimel, 2003). The extent of the variability illustrates the difficulty of quantifying trends in drivers of ecological change without long time series: most ecological response variables will be at least as noisy as the drivers, or significantly more so.

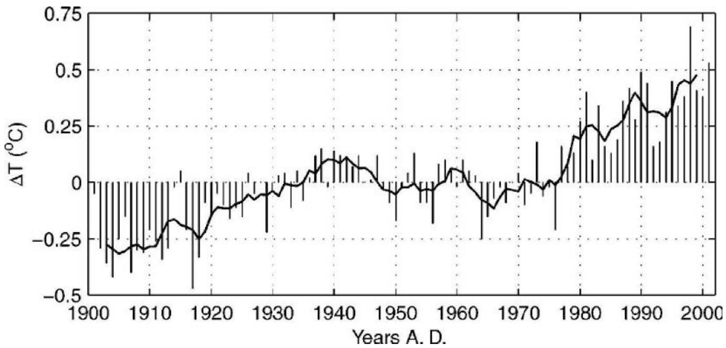
4.2 Quantification of Trends by the Observatory

NEON is designed to study climate change and other processes that occur over decades. NEON's spatial design was optimized to quantify spatial patterns; its temporal sampling strategy must equally be designed to detect and quantify trends over time, as well as characterizing the spatial pattern of those trends (for example, see Figure 11a, map of the trend in temperature).

Ecological trends can be simulated based on five main components:

1. Magnitude. For example, the temperature trend varies by a factor of four across the United States (Figure 11a), and patterns of land use change are even more diverse.
2. Intrinsic variability. For example, temperature shows a generally consistent warming trend in many regions, but processes like the El Niño/Southern Oscillation cycle cause temperature to vary widely from year to year around that trend (Figure 11b, Wang and Schimel, 2003).
3. A relationship between the forcing and the response. The response may be more or less sensitive, and the form of the response may be linear or nonlinear and may vary in space and as a function of other variables.
4. Measurement error. This includes the accuracy and precision of the measurement technique and the adequacy of sampling in time and space.
5. The number of sites (replication) and their degree of correlation.

Figure 10 (b)



	Internannual Variability			
Magnitude of Trend		Low = 0.1	Medium = 0.50	High = 1.00
	Low = 0.10	[29/29]	[>30]	[>30]
	Medium = 0.25	[14/16]	[20/21]	[23/24]
	High = 0.50	[9/10]	[12/12]	[15/15]

* Numbers in brackets represent time to detection for measurement uncertainty = 0.10 and time to detection for measurement uncertainty = 0.20. In some cases, the time to detection is not affected by measurement uncertainty, because the trend and interannual variability are both large relative to measurement uncertainty.

Table 5: Number of years until a trend can be quantified as a function of the magnitude of a trend, interannual variability, and observational uncertainty (80% likelihood is obtained for the trend versus a no-trend model). The numbers in the brackets are 10% and 20% observational uncertainty. Number of years to detect the trend is computed across 50 realizations for the model with a trend term.

The certainty associated with the detection of trends by NEON was quantified using a simulation approach. It is possible to identify potential weaknesses by simulating responses under varying levels of the factors that influence observations. The network was simulated by making assumptions about the magnitude of trends, amount of interannual variability, and degree of correlation among sites derived from ranges found in the literature. Because quantifying long-term changes is a fundamental NEON science requirement, the network sensitivity was assessed using annual time-scale information. Within the network of expected ranges for magnitude of trend, interannual variability, and correlation among sites, simulation results were analyzed for bounding levels of measurement error (Table 5). In this case, measurement error includes instrumental or observer accuracy and precision, sampling or representativeness errors, and errors associated with data processing algorithms. This approach allows us to assess the level of tolerable measurement uncertainty (due to all sources) acceptable within the network.

The relationship between a hypothesized forcing and an ecological response was simulated and simulations were created to test the ability of the network to (1) detect a trend in an ecological response, (2) identify whether the relationship between forcing and response is linear or nonlinear, and (3) determine the ability of the NEON network to estimate the parameters of the relationship between forcing and response (e.g., for $response = \alpha + \beta \epsilon^{\kappa forcing}$ where α, β and κ are parameters). The results are encouraging for the ability of the network to detect and determine the form of complex nonlinear relationships. However, quantitatively retrieving the parameters of ecological relationships is not always successful. This highlights the need for process studies and experiments linked to time-series observations.

4.3 Derivation of Requirements

This network simulation serves to inform the design of measurement accuracy and sampling intensity in the NEON observations and experiments (Table 5). The table shows that this approach does not completely specify either required measurement accuracy and precision or sampling intensity in time and space. For example, for many processes, little is known about either the trend or the temporal variability since few long time series exist. In other cases, the likely measurement uncertainty will not be known until several years of data have been gathered. Rather, this methodology establishes a protocol:

1. In general, FIU and FSU measurements will target an overall uncertainty of 10-20% in response variables at the annual time scale, to allow detection and quantification of most trends within the 30-year time span of NEON.

2. When the measurement characteristics corresponding to the network simulation model parameters are known, this methodology will be used to define requirements for sampling intensity and tolerable measurement uncertainty.

3. When the trend and interannual variability are not known, tolerable measurement uncertainty can be bracketed using the simulation and the impact of measurement uncertainty on detection quantified. This could in some cases suggest increased or decreased effort for a given measurement.

4. When the measurement uncertainty is not known, it will be established within the first several years of observation. Information can also be assumed from one site to another and adjustments to methodology or sampling effort made.

The approach described here provides a framework that can be used to define and evaluate trends throughout the operation of the observatory. In order to realize the largest science return on investment, measurements must reach a standard to meet the needs of the observatory for quantification of climate change, land use change, and invasive species impacts. If the initial measurements are insufficient, they will be improved. If they exceed the program's goals, they can be reduced to allow new measurements to be added within a constant budget. In some cases, key measurement may barely meet requirement or fall slightly short. When this occurs, the methodology allows specific areas to be targeted for Research and Design. This sort of adjustment is common on an ad hoc basis, but it will be central to NEON's management of the scientific and technical methodology. One advantage of this rigorous approach for defining and evaluating trends is that a more defensible decision (i.e., less ad hoc) about necessary adjustments to the observatory can be made. This allows for a focused, iterative optimization of the network design due to the clearly outlined metric for trend evaluation.

4.4 NEON Ecological Forecasting and the Advancement of Theory

Enabling ecological forecasting is a primary goal of NEON, but what exactly is ecological forecasting? It is a quantitative prediction that is critical for documenting and advancing scientific understanding and useful in societal application of knowledge (Katz & Murphy, 2005). Forecasting is necessary for advancing theory because it regularly confronts theory with observations via predictions. Ecological forecasting includes two closely related activities. The first is similar to a weather forecast; that is, an attempt to discern the most likely future state of an ecological system. The second activity adds an additional factor to study *the most likely future state of a system, given a decision today* (Clark et al., 2001). The first activity is often relevant for short-term forecasts where the system's own dynamics most strongly govern its change over time (for example, forecasting the likely rate of spread of an invasive species). The second comes into play when alternate management actions or scenarios are being considered (for example, forecasting the likely impacts of alternate forest fire risk mitigation practices on biodiversity). While ecological forecasting typically requires deterministic knowledge of the process being modeled, forecasts are usually probabilistic and provide an estimate of the probability of the future state, not just a point estimate of its value.

Ecological forecasting, modeling, and analysis activities are so central to NEON because the GRAND CHALLENGES, and NEON's derived mission, involve understanding and predicting across a span of environmental problems. The science vision that led to NEON's conception involved advancing the field's ability to quantitatively predict, not just to develop retroactive explanations (NRC, 2003). While qualitative forecasts may be made using models derived from first principles and theory, quantitative forecasts in complex dynamical systems require estimates of the state of the system and include parameters that must be estimated empirically (Gunderson & Holling, 2002). Initial conditions (e.g., abundance, age distribution, biomass, and size distribution) are critical and govern the subsequent trajectory of systems. In some systems, often referred to as chaotic, infinitesimal differences in initial conditions can lead to exponential divergence between trajectories (May, 2000). In chaotic systems, very complex estimation procedures may be required to stabilize forecasts. While these have not been pervasively employed in ecological systems, they are highly applicable in many systems. (See Kalnay, 2002, for a full account of forecasting in the chaotic weather system). As a result, NEON must provide measurements of key ecological state variables and parameters.

In principle, estimates of initial conditions and parameters do not require long-term, standardized observations. Within the scope of a short-term research project, initial conditions at a site can be surveyed (for example, biomass or population data) along with measurements of key rate constants, and a model can be developed and exercised. Examples of such research abound, but this type of forecasting is intrinsically limited (Clark et al., 2003).

The NEON vision is a framework of consistent, long-term observations collected on a schedule, around which PI- and project-based research can be built. The measurements in that system will gradually change over time as experience is gained through cyclic prediction-observation comparison and the analysis of factors that most strongly drive forecast errors.

Figures 12 and 13 illustrate two hypothetical applications of NEON information to specific aspects of ecological forecasting. Figure 12 shows an integrated analysis and forecast for invasive species. Invasions and susceptibility to invasion depend on processes at multiple scales, shown at the bottom of the diagram, that combine to produce multiscale patterns. NEON and non-NEON programs provide information, broadly grouped into site-based sampling and spatial surveys and remote sensing. Site-based data provide information on local processes, while surveys and remote sensing provide information on spatial processes (movement patterns) and large-scale patterns. A study of a biological invader's behavior might use a spatial, ecological niche-type model (Guisan & Zimmermann, 2000; Pulliam, 2000; Austin, 2002; Pearson & Dawson, 2003) to integrate multiscale data to produce a mapped forecast of the distribution and abundance of an invader over time.

Figure 13 shows how NEON could contribute to an estimate of the U.S. biological carbon budget through data collection, analysis and forecasting. The process begins again, with processes at different scales (from organism and molecular to continental) producing multiscale patterns of biological carbon stocks and fluxes in nature. NEON and non-NEON data provide both detailed site-based process information and spatial measures of pattern and process. These data might be integrated into a land surface model that incorporates both biophysical and biological processes (for example, the National Center for Atmospheric Research's Community Land Model) integrated with observations over time using computationally efficient data assimilation schemes such as the ensemble Kalman filter or ensemble Kalman smoother. This approach would produce estimates of ecosystem-atmosphere fluxes of carbon dioxide that could be intercompared at regional scales to similar estimates deduced from atmospheric concentration gradients using a system such as NOAA's CarbonTracker.

Potential NEON Invasive Species Analysis and Forecast

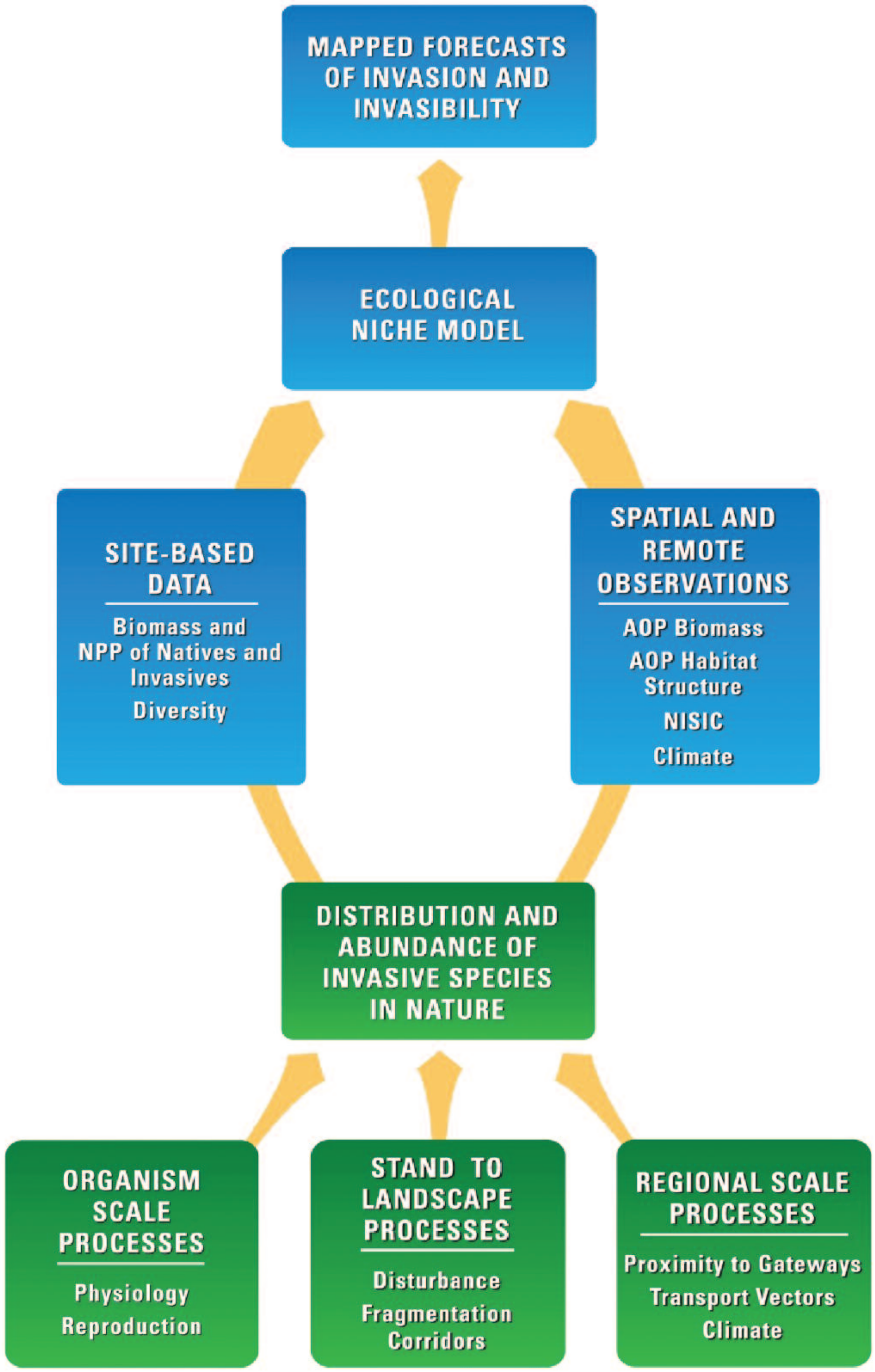


Figure 12: A conceptual time-space analysis and forecast of biological invasion using multi-scale observations and modeling. AOP = NEON's Airborne Observation Platform, NPP = net primary productivity.

Potential Spatial Analysis of US Carbon Budget using NEON and North American Carbon Program Infrastructure

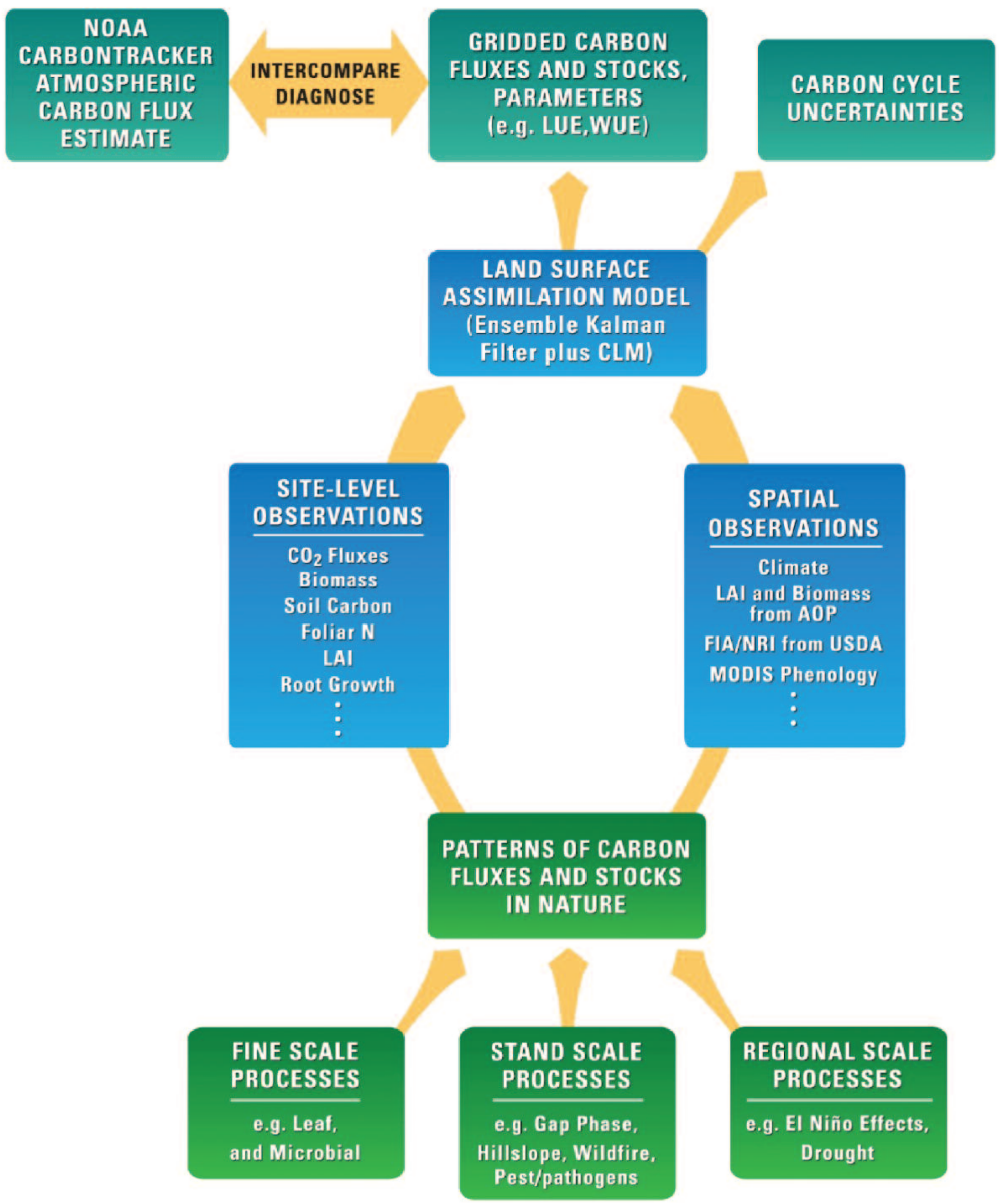


Figure 13: A conceptual analysis and forecast of the U.S. ecosystem carbon budget derived from multiscale observations and an integrated carbon assimilation model. LUE = Light use efficiency, WUE = water use efficiency, CLM = the NCAR Community Land Model (Bonan et al., 2002), LAI = leaf area index, FIA = Forest Inventory and Analysis of the USDA, NRI = Natural Resources Inventory of the USDA, MODIS = the Moderate Resolution Imaging Spectroradiometer satellite instrument, Foliar N = foliar nitrogen. CarbonTracker is a NOAA tool that estimates carbon fluxes from atmospheric CO_2 measurements and related meteorology.

The limitations of linking forecasting to short-term or episodic data collection arise as a consequence of the lack of stationarity that exists in dynamic ecological systems. The range of values for both proximal explanatory variables and response variables changes due to changing species composition, adaptation and evolution. *Iterative* or *cyclic* forecasting provides a more powerful approach that, in a general way, accommodates the lack of stationarity. In cyclic forecasting, a model is initialized with observations, integrated forward to produce a forecast, compared again to observations, re-initialized, and again integrated forward (Figure 14).

A model developed over a single forecast cycle tends to explore a small subregion of the solution space, whereas models that are developed iteratively through updating can characterize a much larger region of the solution space. Iterative/cyclic forecasting can reveal patterns of error that are not evident in a single forecast cycle. For example, a model may perform well at low population densities but fail or exhibit biased behavior as higher densities are reached. NEON must collect and make available data on a regular schedule to enable iterative comparison of model predictions and observations, leading to an orderly forecast evaluation/update/improvement cycle.

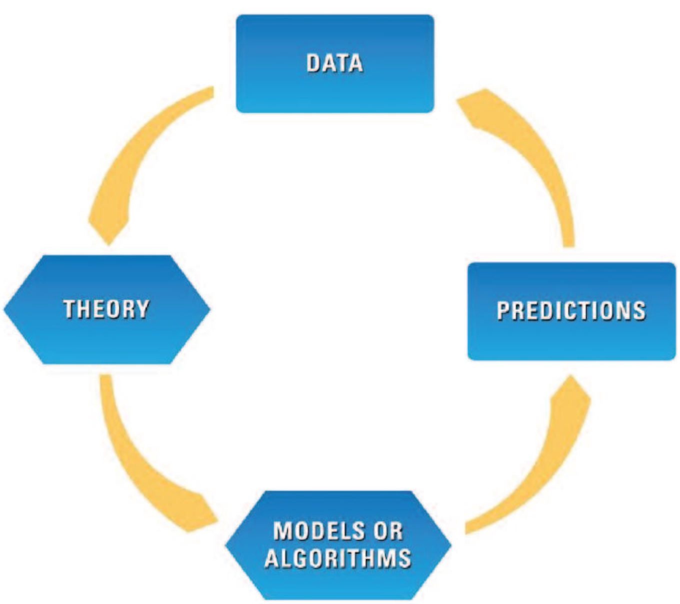


Figure 14: The iterative confrontation of observations and theory via predictions

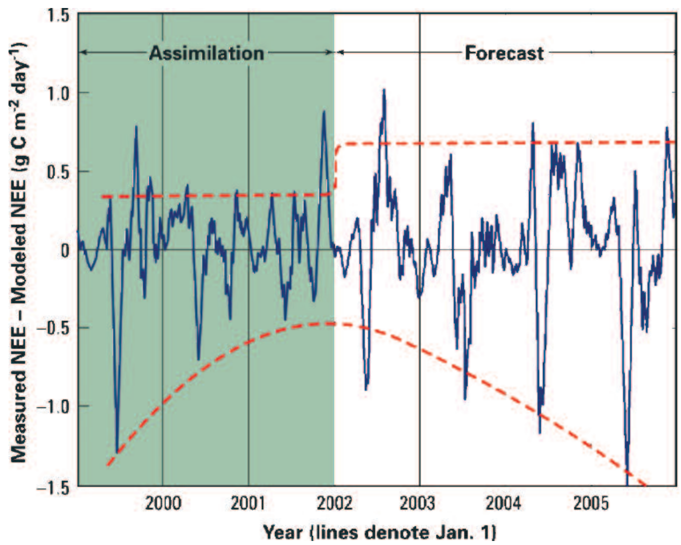


Figure 15: Comparison of twice-daily (sunlight and dark periods) predicted and observed net ecosystem exchange (NEE) of carbon. The grey-shaded years are the period during which states and parameters were estimated. The unshaded years are thus a forecast of carbon exchange given observed climate. Negative excursions are errors in carbon uptake from the atmosphere, that is, photosynthesis (A). Positive excursions are errors in nightime respiration (R). Note that the negative errors concentrated at high values of A and R tend to grow gradually after the estimation period, while the positive (respiration) errors stay constant (Zobitz et al., 2008).

The predictive accuracy of a model may drift as biological processes (physiological adaptation, community composition, or evolution) cause state or parameter values to change (Figure 15) (Zobitz et al., 2008). Sequential evaluation of the model against data, along with careful consideration and modeling of the error structure, will detect when these changes are large enough to affect the model's prediction and will provide insight into processes that only become significant at longer time scales (Sacks et al., 2007).

The requirements of ecological forecasting motivate a research strategy that includes long-term observations, such as NEON provides. A single dedicated researcher may generate a few time series suitable for long-term forecasting studies, but these will inevitably fall short of enabling forecasting at the continental scale. As recently noted in a recent U.S. government assessment, "existing monitoring networks, while useful for many purposes, are not optimized for detecting the *impacts* of climate change on ecosystems" (Backlund et al., 2008). In fact, most of the existing networks observe either drivers of change (climate, land use) or a single or small number of response variables, but not drivers and responses in a coordinated fashion.

The skill of ecological forecasts will itself evolve over time. Improvements in predictive accuracy will change as fundamental theory advances, as techniques for estimation of states and parameters improve, and as system behavior is observed under a wider range of conditions (with more parameter space characterized by observations). The phenomenon of incremental improvement in predictive ability is well known in meteorology; Figure 16 shows the improvement in the ability to forecast variations in atmospheric pressure 36 hours in advance in the U.S. operational forecast model. The overall trend is surprisingly steady given the changes to satellite observations and computing power and advances in knowledge from the 1950s to the 2000s. It highlights the fact that quantitative models should not be evaluated in a binary fashion (right versus wrong). Errors must be measured and assigned to weaknesses in theory, and then simulations or observations (or some of each) and targeted efforts must be made to improve the identified problems. Identifying and resolving inconsistencies in theory, models, and data are easier when large, systematically collected data sets are available.

Great efficiency in data collection can be realized when forecast errors that are due to weaknesses in observations lead to targeted improvements in observations. If error in a certain ecosystem variable leads to large forecast errors, as identified in an error analysis, that state variable should be targeted for improved measurement

In summary, progress in ecological forecasting of responses to drivers that play out over decades (climate change, land use change, biological invasions) requires a new and more systematic approach to observations. Conceptually, new observations need to provide information on the state of the system and parameters to enable quantitative forecasts. Key observations of cause and effect are needed over time and must be selected to stabilize state-dependent forecasts and estimate key parameters. The observing system must be able to cyclically challenge predictions with new observations to detect fundamental model error and long-term evolution of the system (through changes in processes as species adapt, change, or evolve) and quantify the forecast model skill under a wide variety of conditions. To enable forecasting at the continental scale, observations must be made in a standardized way systematically across the continent's ecological variability, or else the outcome will be highly local forecasts with variable reliability.

Figure 16: The decadal trend in the ability of weather forecast models to predict variation in atmospheric pressure. The decadal improvements result from the iterative development of improved models and observations, driven by the regular evaluation of forecasts against data. This trend reflects increases and decreases (in the 1980s and 1990s) in the number of surface observations, the advent of satellite and radar data, and many developments in forecast models and computing.

4.5 Data Product Production

NEON data from observations and experiments will need to be processed in sophisticated ways. These may range from averaging or smoothing for easy visualization of meaningful time steps to processing through models for inference of parameters or unobserved quantities. Data product production will require (1) retention of data provenance, QA/QC, and calibration information; (2) association of algorithm version and provenance information; (3) calculation of appropriate uncertainties; (4) documentation of the algorithm and process flow; and (5) identification of the critical output quantities and their uncertainties. Efficiently operating an algorithm requires a workflow combining input data, metadata, and the algorithm(s), as well as the capacity to capture the output data and metadata. In addition, efficient numerical methods, software engineering, and I/O are needed, especially for algorithms that are data or computationally intensive and/or are operated frequently.

An example may help to illustrate this. The FIU measures a wide variety of water, carbon, and energy budget components at high temporal frequency. However, observations may be missing when instruments fail or conditions do not meet required assumptions, causing data gaps. In addition, many quantities desired must be computed or inferred from the measurements made. Data processing steps for biophysical data typically involve:

1. Calculation of basic physical quantities from measurements (for example, carbon flux is computed from CO_2 concentration and wind data).

2. Calculation of key quantities during data gaps using statistical models to allow calculation of temporal averages of integrals (e.g., monthly or annual totals).

3. Calculation of desired quantities from basic quantities. For example evaporation and transpiration may be inferred from their sum; the latent heat flux and photosynthesis and respiration may be inferred from net ecosystem exchange.

4. Inference of parametric information from calculated quantities. For example, once photosynthesis and transpiration have been estimated, water use efficiency may be computed. Using respiration and temperature, the temperature dependence (Q_{10}) of respiration may be computed.

5. Estimation of process controls from observed, calculated, and parametric quantities. For example, the effect of drought on water use efficiency between statistically normal and dry years can be estimated from interannual variations in precipitation, soil moisture, transpiration, and photosynthesis.

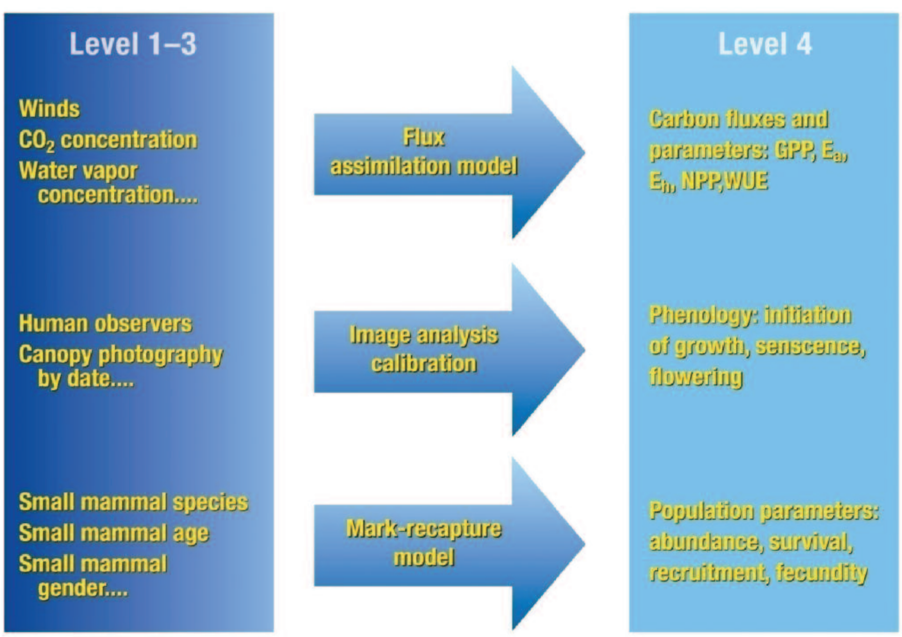


Figure 17: NEON will collect basic data through a combination of instrumentation and human observers. Basic calibrated data (Level 1) or data that have been temporally or spatially rectified (Levels 2 and 3) will be processed using state-of-the-art algorithms and models to produce synthetic data products (Level 4) that both specialist and non-specialist scientists can use to rapidly and effectively to address ecological problems. GPP = gross primary productivity, NPP = net primary productivity, E_a is plant respiration and E_h is microbial respiration.

<table>
<tr>
<td rowspan="4">Product Title:
Biodiversity_007

Sub-products:
Biodiversity_007.1
Biodiversity_007.2
Biodiversity_007.3
Biodiversity_007.4
Biodiversity_007.5
Biodiversity_007.6</td>
<td colspan="2">Product Title: Peromyscus species demography
Biodiversity_007.1 = Body size
Biodiversity_007.2 = Mass
Biodiversity_007.3 = Sex ratio
Biodiversity_007.4 = Reproductive status
Biodiversity_007.5 = Age Structure
Biodiversity_007.6 = Recapture rate</td>
<td rowspan="4">Effort: B
Priority: 1</td>
</tr>
<tr>
<td>Product Title: 4</td>
<td>Temporal resolution: 1 year</td>
</tr>
<tr>
<td>Replicates: 60</td>
<td>Spatial Extent: Site</td>
</tr>
<tr>
<td>Replicated at: Core and Relocatable sites</td>
<td>Spatial Resolution: NA</td>
</tr>
<tr>
<td colspan="4">Product Description: Small mammal demographic data inform population models and enable monitoring of responses to environmental factors such as climate and productivity. Understanding the population demography and variability inter-annually will allow better predictions of disease outbreaks, such as the delayed density dependent outbreaks of hantavirus observed in Montana (Madhav, et al., 2007). Three times per year, demographic information on small mammal (especially Peromyscus species) populations will be collected including body size, mass, sex, reproductive status, population age structure (proportion of adults versus juveniles), and mark-recapture measurements. These data will be summarized as means (averaged across transects for a trapping period with standard error). Graphical summaries of time series (spring, summer, and fall trapping periods) will be provided to visualize changes in population demographics over the course of a breeding season (e.g., (Nupp & Swihart, 1996; Zwolak & Foresman, 2008)).</td>
</tr>
</table>

Figure 18: NEON is developing a catalog of high-level scientific data products that will provide synthesized information to ecologists, educators, citizens, and decision makers. While all levels of collected and processed data will be available to users, the high-level data products will be accessible to a broader scientific audience (as opposed to technical specialists) in order to make NEON results more readily available for broad comparative and interdisciplinary studies. The Peromyscus demography data product illustrated here will integrate data from a small mammal trapping program conducted at all active NEON sites.

Analogous processing flows will be followed for other data types. For example, population estimates will be computed from small-mammal data using mark-recapture models. Population parameters (fecundity, mortality, etc.) will be calculated from population estimates. Different sorts of NEON users will be interested in different levels of data. A research biophysicist might be interested in data from the earlier steps in the FIU example given above, whereas an agricultural economist might need the sensitivity estimated in step 5 for including in a forecast of climate change impacts on the farm sector.

Producing NEON high-level data products will require:

1. Identifying and retrieving large numbers of data sets,
2. Associating calibration and QA/QC information with these data sets,
3. Passing the data sets through algorithms,
4. Storing and documenting the outputs, and
5. Repeating steps 1-4 to produce higher-level data products (e.g., parametric results).

Developing the NEON high-level data production procedures will require coordinating:

1. Algorithm science (identifying and validating the models used),
2. Applied mathematics and statistics (identifying and validating the solution or estimation procedures),
3. Computational science (identifying and optimizing the computational procedures used), and
4. Informatics (documenting and curating the information produced).

The NEON data products group will identify the initial suite of data products, the candidate algorithms for producing them, and the mathematical, statistical, and computational issues and requirements for computing them. The group will then codify the requirements for documenting, curating, and disseminating information products. This process is shown in Figure 17. The algorithms themselves will be developed in the scientific community as a natural part of research activities. This process will include appropriate community-based approaches for selecting, peer reviewing, and documenting data product production algorithms. An example from the NEON Data Catalog is shown in Figure 18.

Chapter 5
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