NEON Observatory Design

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See Configuration Management System for Approval History

Change Record

REVISION	DATE	ECO #	DESCRIPTION OF CHANGE
1	10/10/2008		Initial Version
2	01/01/2009		Revision 2
3	03/18/2009		Revision 3
4	04/16/2009		Revision 4
A	05/15/2009	NEON.MGMT.NPR.000012.CRE	Initial Release
B	07/30/2009	NEON.MGMT.NPR.000059.CRE	Revision to Sec 3.10, deletion of paragraph in Sec 4.4, changed figures
C	09/26/2011	ECO-00283	Update to new document number's/template throughout document.
D	07/20/2012	ECO-00389	Document update in all section of the document.

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1 DESCRIPTION

The NEON Science Strategy described the derivation of NEON's high level science requirements from the NEON Grand Challenges. It describes the high level science implementation, education plan and data products plan for NEON.

1.1 Purpose

The purpose of the document is to define the high level requirements and science implementation for the observatory.

1.2 Scope

The document provides a high level overview of the NEON system.

2 RELATED DOCUMENTS AND ACRONYMS

2.1 Applicable Documents

Applicable documents contain information that shall be applied in the current document. Examples are higher level requirements documents, standards, rules and regulations.

AD [01]	DOORS Requirements Database
AD [02]	
AD [03]	
AD [04]	

2.2 Reference Documents

Reference documents contain information complementing, explaining, detailing, or otherwise supporting the information included in the current document.

RD [01]	NEON.DOC.000008	NEON Acronym List
RD [02]	NEON.DOC.000243	NEON Glossary of Terms
RD [03]		
RD [04]		

2.3 Verb Convention

"Shall" is used whenever a statement expresses a convention that is binding. The verbs "should" and "may" express non-mandatory provisions. "Will" is used to express a declaration of purpose on the part of the design activity.

Thanks to all the thousands of colleagues who helped conceive, design, plan, review, and promote NEON since its inception more than ten years ago. NEON would not exist without these contributions of expertise and time and without the support of the scientific community.

The science strategy for the National Ecological Observatory Network that is outlined in this document builds upon the 2006 Integrated Science and Education Plan (ISEP) and the 2009 NEON Observatory Design (NOD).

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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3 INTRODUCTION

The biosphere, Earth's living component, is one of our planet's most complex and fascinating systems and is also the source of many vital services to humanity (Millennium Ecosystem Assessment, 2005). The biosphere influences, and is influenced by, physical, chemical, and geological processes and is arguably the least understood of these systems. The biosphere and the physical Earth System interact strongly over diurnal and seasonal cycles, but also have critical interactions over decades and centuries. Currently, the ability to observe or reconstruct long-term coupled behavior between living and nonliving components of the Earth System is limited and must be improved to support long-term ecological forecasting. Additionally, while humanity now affects nearly the entire biosphere, our understanding of how the biosphere operates in these landscapes is limited because most studies focus on organisms in pristine or minimally altered ecosystems (Vitousek et al., 1997). We must develop a better understanding of the physiology, distribution, and evolution of organisms in human-dominated landscapes.

Living systems interact with each other and with the rest of the Earth System at many scales. At a small scale, individual plants exchange energy and matter with the atmosphere to support growth. At a large scale, like that of an entire continent, exchange between biotic components, the atmosphere, and surface water affects climate and hydrology. Individual organisms interact directly with each other locally, but the movement of invasive or pathogenic species can change the biota of entire continents. Understanding the role of organisms and their biology in the Earth System requires coordinated analysis of patterns from small-scale mechanisms within cells to global-scale fluxes. Understanding the patterns of movement and distribution of organisms is also important, as is the development and coordination of methods for quantifying the various scales of biological activity.

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's goal is to improve understanding and forecasting of ecological change at continental scales.

To achieve this end, NEON has been designed as a continental-scale platform for understanding and forecasting the impacts on ecology of climate change, land use change, and invasive species. NEON science focuses explicitly on questions that relate to the Grand Challenges in environmental science (National Research Council, 2001), are relevant to large regions, and cannot be addressed with traditional ecological approaches (NEON, 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 primary effects of humans on the natural world and effectively address critical ecological questions and issues.

A decade of discussion and planning by the ecological research community has led to the design and data requirements of NEON. The resulting strategy unites point and process observations with remote sensing and spatial data in order to develop spatio-temporal analyses and forecasts.

NEON will observe both the human causes and the biological consequences of environmental change, a key feature of the project. Environmental monitoring networks typically observe either the causes of change (such as climate change, air pollution, and land cover change) or the effects of change (such as phenology and the distribution of avian populations). Rarely do environmental networks provide integrated observations of aspects of both cause and effect to allow increased understanding of the underlying processes.

The Grand Challenges

NEON is designed to allow the scientific community to address the major areas in environmental sciences, known as the Grand Challenges (Figure 1). Six of the Grand Challenges were identified in the National Research Council report, *Grand Challenges in the Environmental Sciences* (NRC, 2001). The seventh Grand Challenge, addressing invasive species, was identified by NEON planners and included in the Integrated Science and Education Plan (NEON, 2006). NEON infrastructure and data products are strategically aimed at those aspects of the Grand Challenges for which a coordinated national program of standardized observations and experiments is particularly effective.

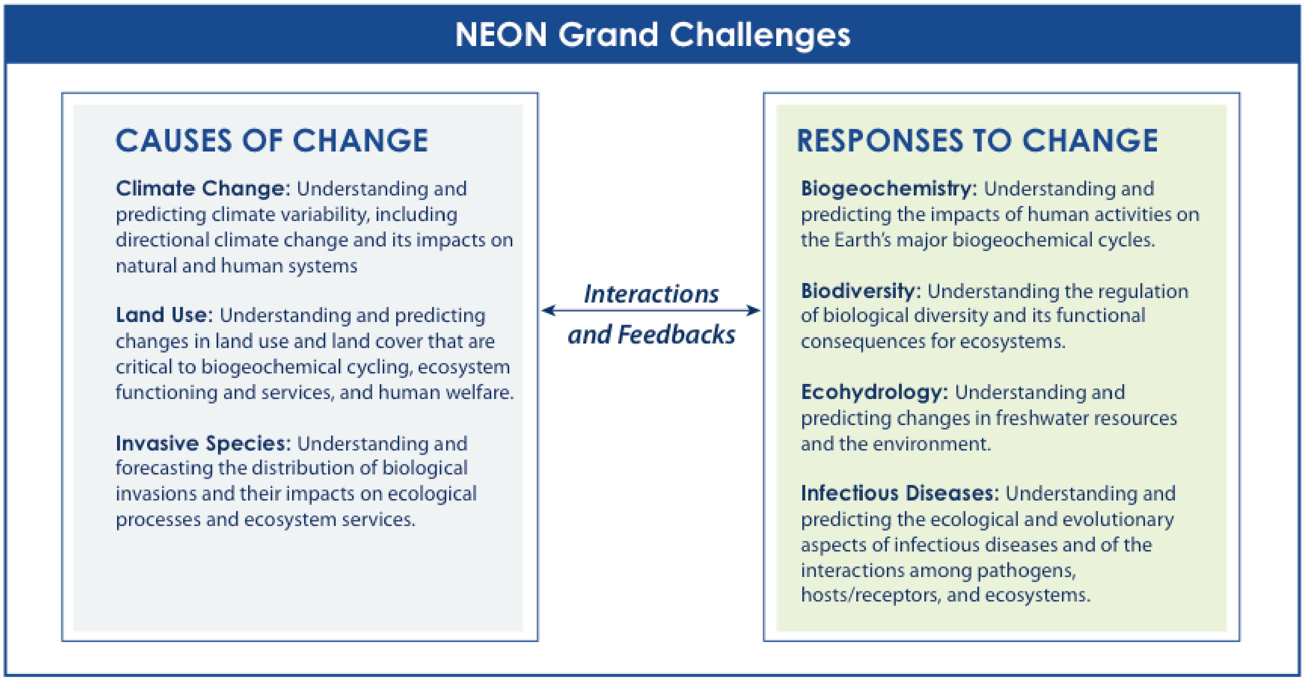

Figure 1: The seven Grand Challenges areas that NEON is designed to address, including those that cause environmental change and those that respond to change. Within NEON documents, the Grand Challenges are identified by the area of environmental science listed in bold.

NEON groups the Grand Challenges into two types (Figure 1). First are those forces that are major causes of change in biological systems (NEON, 2006). These include climate change, land use change, and invasive species. The second are those areas that respond to change. Major categories of responses include biodiversity, biogeochemistry, ecohydrology, and infectious diseases. This grouping is not mutually exclusive; 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.

A series of invited papers in a special edition of *Frontiers in Ecology and the Environment* (Vol. 6, Issue 5, June 2008) explored ecological connectivity and the questions that a continental-scale ecological observatory might address. Authors posed specific questions related to Grand Challenges, including:

Climate change

What is the impact of “connectivity” (local patterns and processes affecting broad-scale ecological dynamics) on the global environment? (Peters et al., 2007)

- How do changes in intensity, spatial distribution, and frequency of wind storms affect ecosystem attributes?
- How will storm damage in inland forests (soil erosion, water retention, nutrient export) affect coastal systems? (Hopkinson 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)
- As climate change affects fuel accumulation, combustibility, and rates of ignition, how will these changes in turn impact fire regimes? (Marshall et al., 2008)

Invasive species

- 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)

Land use

- How do climate and land use changes impact temperature and carbon cycling in lakes and streams, and what is their effect on aquatic metabolism? (Williamson 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)

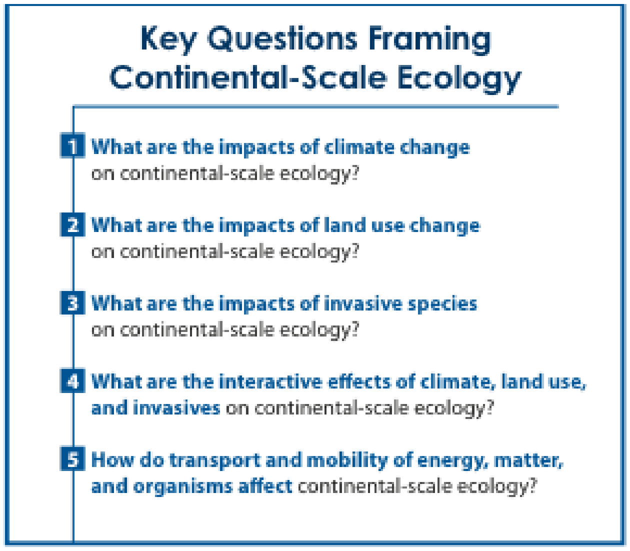

Figure 2: The five key questions that frame the study of continental-scale ecology.

The specific questions posed above lead to a common goal: to enable understanding and forecasting of the impacts of climate change, land use change, and invasive species on continental-scale ecology. Derived from this goal are five questions framing the emerging science of continental-scale ecology (Figure 2). The questions show how the Grand Challenge areas relate to each other, and provide both a basis for selecting and prioritizing specific measurements, infrastructure, sites, and analyses, and a framework to translate the Grand Challenge areas into the design of a national observatory (Figure 3).

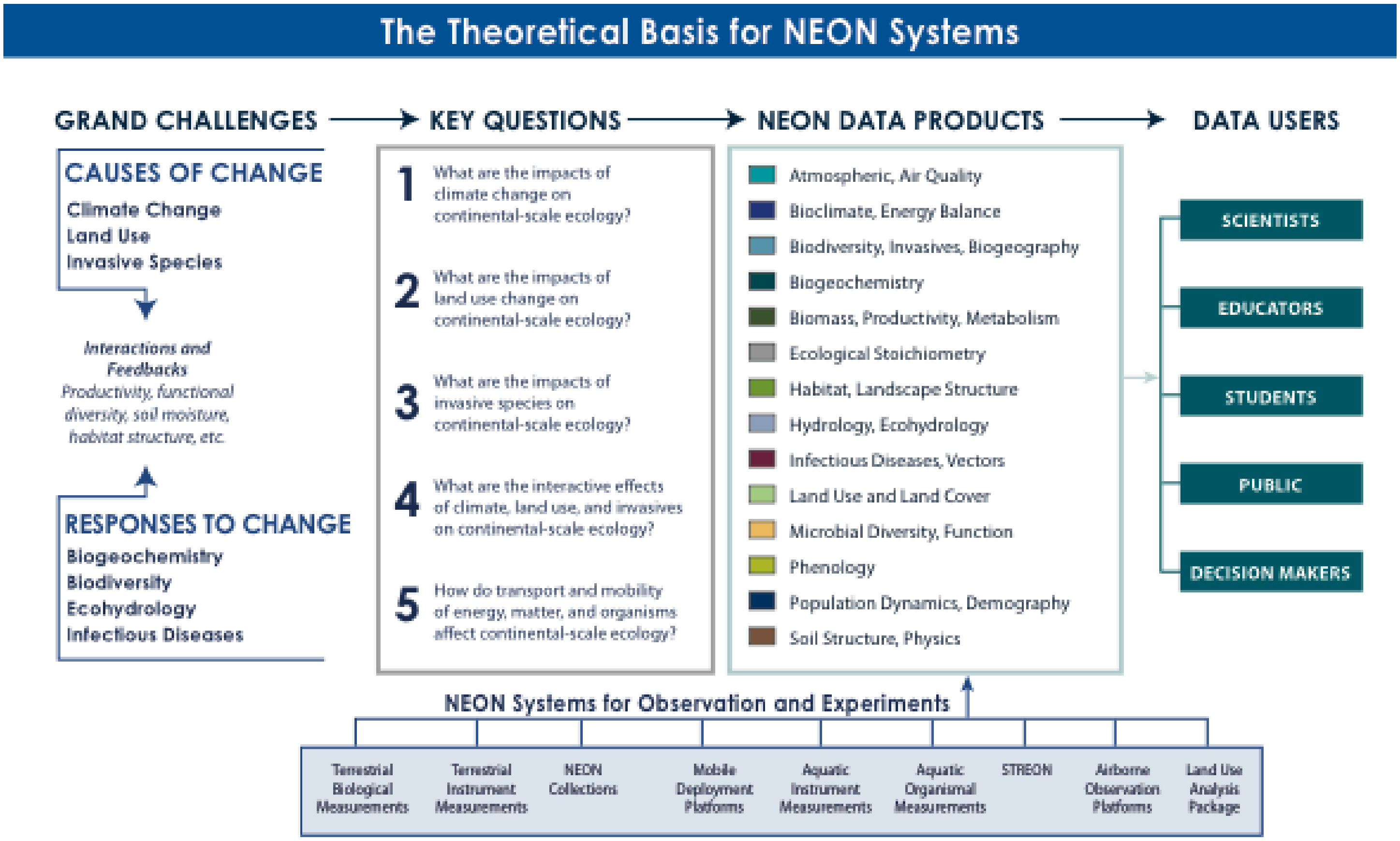

Figure 3: How the Grand Challenges translate into the five key questions and then into the data products and the required NEON systems for observation.

This NEON Science Strategy document provides an overview of how Grand Challenges and key questions were translated first into a set of requirements for the observatory, and then into an actual design. The following sections present

- **NEON requirements.** How the NEON mission is connected to high-level requirements and key aspects of the design of this continental-scale observatory;
- **NEON science infrastructure.** An overview of the design, its subsystems, and its data products;
- **Using NEON.** An overview of the strategy to get the scientific community, students, and the public involved with NEON and the role NEON can play in advancing the science and applications of ecological models, including those that forecast change.

4 NEON REQUIREMENTS

4.1 NEON Mission

NEON is a National Science Foundation-sponsored facility for research and education on long-term, large-scale ecological change. NEON's goals are derived from the Integrated Science and Education Plan.

The goals of NEON are to:

- Enable understanding and forecasting of the impacts of climate change, land use change, and invasive species on aspects of continental-scale ecology such as biodiversity, biogeochemistry, infectious diseases, and ecohydrology
- Enable society and the scientific community to use ecological information and forecasts to understand and effectively address critical ecological questions and issues
- Provide physical and information infrastructure to support research, education, and land management.

4.2 High-Level Requirements

The requirements for NEON infrastructure are captured in the high-level statements below (Table 1), derived from the mission statement and from analysis of the Grand Challenges via the process outlined in Section 3.

Table 1: Connection between NEON high level requirements and the NEON Mission

Connection between NEON high level requirements and the NEON Mission	
High-Level Requirement	**Connection to Mission**
1. NEON shall observe 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 shall detect and quantify ecological responses to and interactions between climate, land use, and biological invasion, which play out over decades.	Climate change, land use change, and invasive species

3. NEON shall 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 shall address ecological processes at the continental scale and the integration of local behavior to the continent, and shall observe transport processes that couple ecosystems across continental scales.	Continental-scale ecology
5. The NEON infrastructure shall support experiments that accelerate changes toward anticipated future conditions.	Enable … forecasting
6. NEON shall provide usable information to scientists, educators, students, the general public, and governmental and nongovernmental decision makers.	Enable understanding
7. NEON shall provide infrastructure to scientific and educational communities, by supplying long-term, continental-scale information for research and education, and by supplying resources so that additional sensors, measurements, experiments, and learning opportunities can be deployed by the community.	Providing physical and information infrastructure to support research, education and environmental management.

4.3 Key Aspects of the Design

These top-level requirements lead led to some critical and fundamental aspects of NEON's design as well as guiding the architecture of its infrastructure. These key aspects produce an additional set of requirements as described in Table 2:

Table 2: Additional requirements for NEON infrastructure

NEON's measurement strategy shall include coordinated and co-located measurements of drivers of environmental change (physical and chemical climate, land use, and biological invaders) and 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).

NEON's spatial observing design shall systematically sample national variability in ecological characteristics, using an *a priori* division of the nation to allow extrapolation from limited intensive sampling of core wildland sites back to the continental scale.
NEON shall allow extrapolation from the observatory's local sites to the nation. NEON shall integrate continental-scale data (via the NEON Land Use Analysis Package) with site-based observations to facilitate extrapolation from the local measurements to the national observatory.
NEON shall sample managed landscapes in order to understand land use effects. *Relocatable* sites will be selected and paired with either core sites or other relocatable sites to allow measurements of contrasts between different land use practices (e.g., wildland versus managed, intensively versus extensively managed).
NEON infrastructure and observing system signal-to-noise characteristics shall be designed to observe decadal-scale changes against a background of seasonal-to-interannual variability over a minimum 30-year lifetime.
NEON observing strategies shall be designed to support new and ongoing ecological forecasting programs, including requirements for state and parameter data, and a timely and regular data delivery schedule.
NEON will observe abrupt events triggered by long-term trends, using mobile facilities that can be deployed in response to events. Climate change, land use change, and biological invasions trigger ecological responses on time scales best observed with stable sites (e.g., core sites), but they also cause responses that must be observed with a rapid response capability.
NEON shall 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.
NEON measurements shall 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 calibrated against the old.
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 cyberinfrastructure will be designed to be open and modular to enable the addition of new capabilities. The NEON sites (core, mobile, and relocatable) will be designed to be as open as possible to new measurements and experiments to effectively provide NEON infrastructure to scientists, educators, and citizens.
NEON shall produce information from its observations that will be accessible to a wide range of

scientific, educational, and environmental decision makers and users to facilitate understanding and ecological forecasting. NEON will convert primary observations into useful and credible derived data products and make these data products available widely.
NEON shall incorporate and use relevant ecological and climatological data from existing studies and ongoing programs outside of NEON in order to produce the most accurate and recent derived scientific data products.

4.4 Continental-Scale Observatory

Developing NEON's spatial observing design to sample national variability in ecological characteristics and to enable extrapolation from the observatory's local sites to the national scale presents major challenges. Meeting these challenges has led to a systematic national sampling design (i.e., a framework of multiscaled observations and analyses) based on theory, simulation, and analysis (Figure 4).

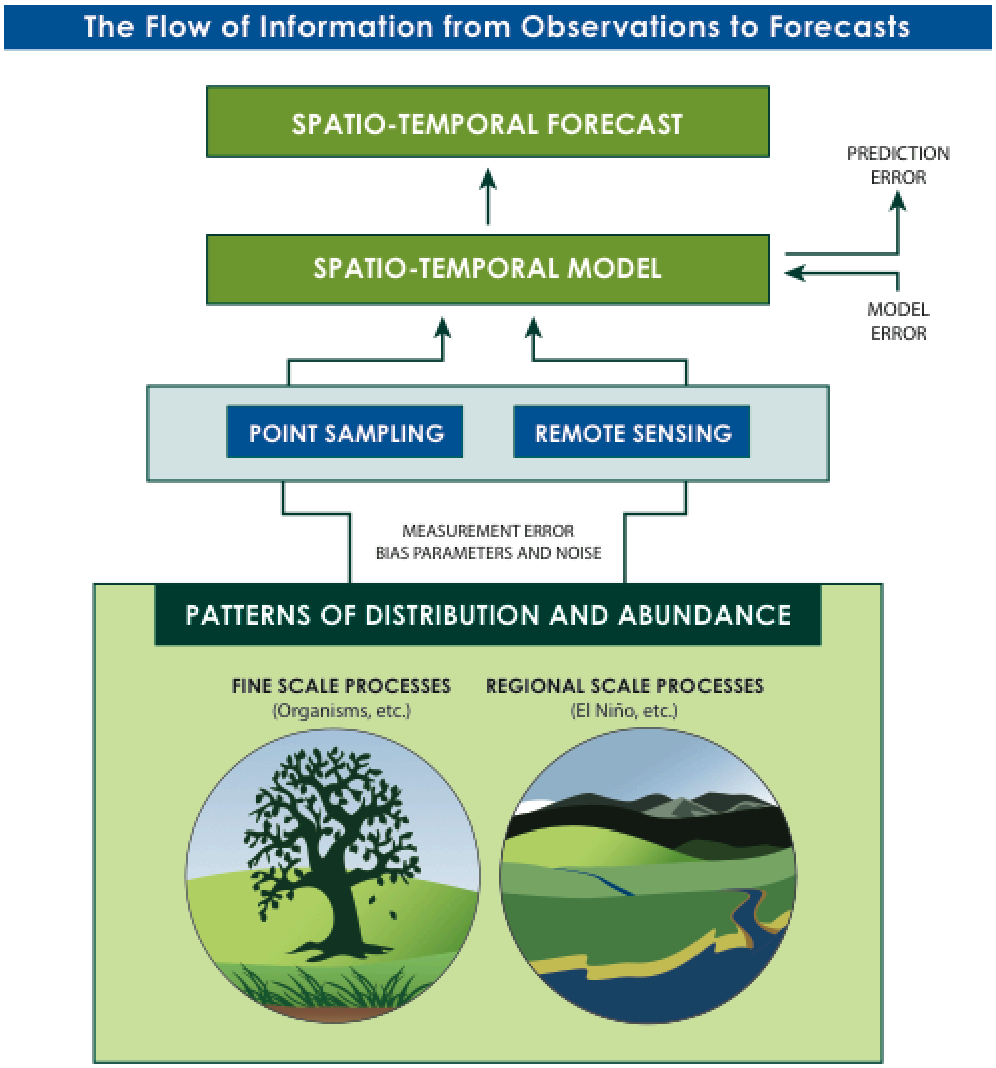

Figure 4: The flow of information from observations to forecasts. Patterns in the natural world—from fine-scale through regional-scale processes—are sampled by NEON using site-based point sampling and remote sensing. NEON will combine observations from different sampling strategies using spatio-temporal modeling to produce estimates of processes and their uncertainty in time and space. The information will be used for spatio-temporal forecasting.

NEON data will be used to extrapolate relationships between causes and ecological responses to change within areas where partial, extensively sampled, or gridded information is already available. NEON's observing strategy is designed to accomplish this by:

- Locating sampling sites that are representative of the largest possible surrounding areas
- Coordinating local site measurements with high-resolution airborne remote sensing (as described in Section 5.2.7, Airborne Observation Platform)

- Integrating measurements made at sites and measurements made with remote sensing and statistical data sets (as described in Section 5.2.8, Land Use Analysis Package)

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

- Quantifying the relationships between observations of causes of ecological change and observations of responses to change – a measure of how much variables change together and how strong the underlying mechanistic relationships are.
- Quantifying how these relationships among measurements change between sites and over time. This is the basis for extrapolating from sites to larger regions over time.
- Identifying where and when the observed patterns in cause-effect relationships are stable (i.e., stationary) or break down, indicating coherence or changes in the underlying responses to change across regions or over time.

A fundamental challenge to the statistical characterization of data that vary across space and time is change in covariance structures in both dimensions (i.e., spatio-temporal non-stationarity). The classical approaches to dealing with this challenge either rely heavily on assumptions or are computationally intensive. A statistical framework for analysis that can explicitly account for changes in spatio-temporal covariance structures when using data from multiple sources is required.

This analytical modeling framework provides important guidance for how NEON information products can address much larger regions than those directly sampled at NEON sites. The framework provides a quantitative approach for combining NEON data collected through observations and tower sensors (Section 5) with data collected remotely via airborne sensors (Section 5.2.7) and Land Use Analysis Package information (Section 5.2.8). These data, collected at different scales and using different techniques, must be readily used together and have common time and space references. Modeling provides a quantitative statistical approach in which information from separate but related field and laboratory experiments can be combined to inform regional and continental forecasts.

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, a process often referred to as model-data fusion.

4.5 Detecting and Explaining Decadal Changes in Ecosystems

To meet the high-level requirements described in Section 2.2, NEON observations require sufficient measurement accuracy, precision, sampling, and replication to allow the detection of decadal trends against the background of diurnal, seasonal, and interannual variation. Many of the measurements planned for NEON have never been deployed to detect and diagnose long-term trends. Thus, considerable work has been done, involving simulation and analysis, to provide initial estimates of measurement requirements for use in NEON's design. NEON's spatial design was optimized to quantify spatial patterns; its temporal sampling strategy was designed to detect and quantify trends over time, as well as characterizing the spatial pattern of those trends.

The ability to detect and quantify ecological trends depends on five main variables:

- **Spatial variability.** For example, temperature change over 105 years varies dramatically across the United States (Figure 5) and patterns of land use change are even more diverse.
- **Temporal variability.** For example, global average temperature shows a generally consistent warming trend (Figure 6), but processes like the El Niño/Southern Oscillation cycle cause temperature to vary widely from year to year around that trend (see Figures 4 and 5 in Wang and Schimel, 2003).

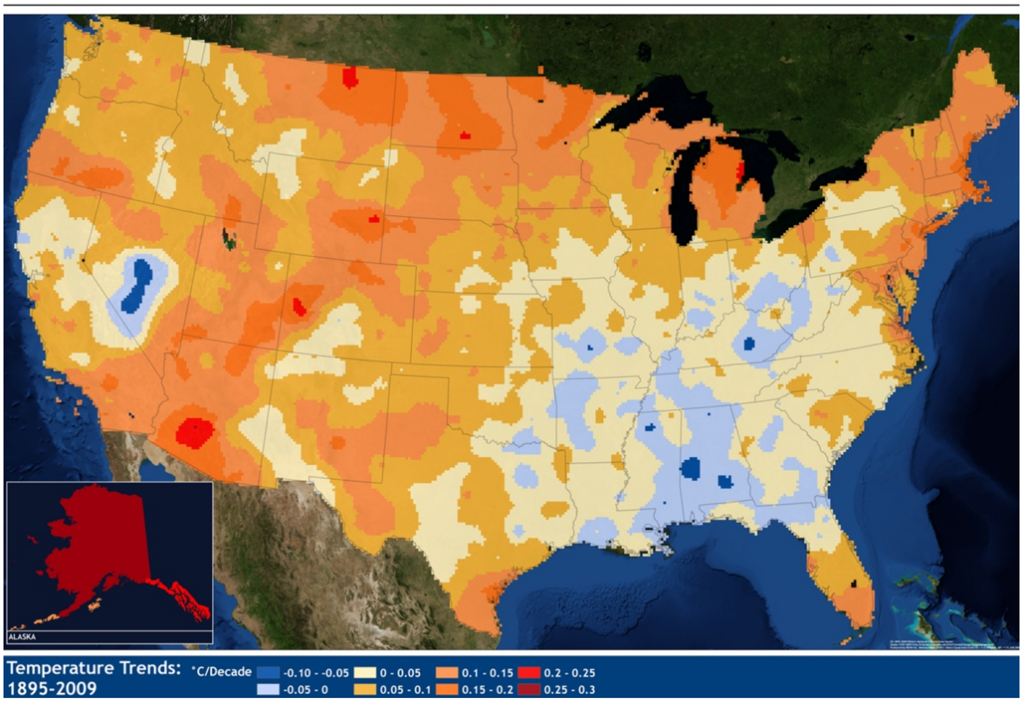

Figure 5: Change in temperature per decade over the continental United States (1895-2009, NOAA data) and Alaska (1949-2009, University of Alaska Fairbanks) showing the high spatial variability influenced by latitude, proximity to ocean, aerosol effects, and other factors.

- **Knowledge of the relationship between specific observed causes and effects within scales.** These responses may be more or less sensitive, and the form of the response may be linear or nonlinear, and may vary in space and over time.
- **Measurement uncertainty.** This includes the accuracy and precision of the measurement technique and the adequacy of sampling in time and space.
- **Number of sites** (replication) and their degree of correlation.

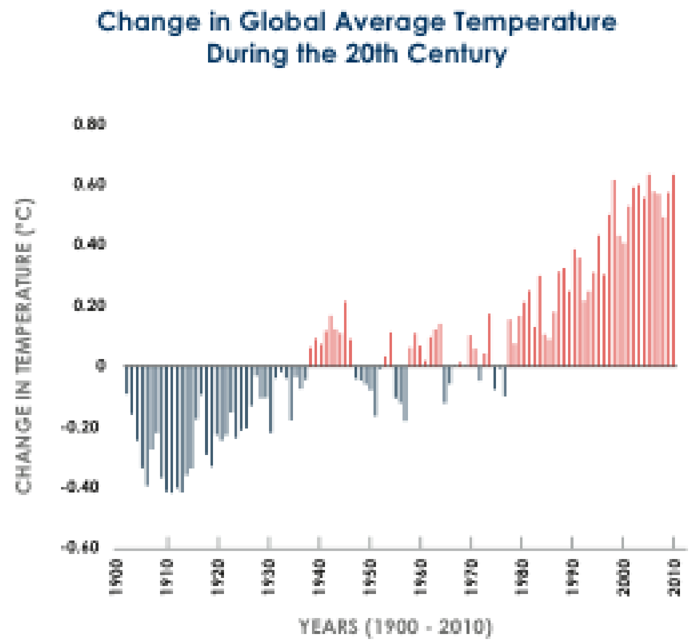

Figure 6: Change in global average temperature during the 20th century.

Simulation analyses were done to estimate the required accuracy, precision, and replication for NEON measurements. The certainty associated with the detection of trends by NEON was quantified by simulating responses under varying levels of the factors that influence observations (Table 3). The network simulations were based on data and assumptions (derived from ranges found in the literature) about the magnitude of trends, amount of interannual variability, and degree of correlation among sites. Because quantifying long-term changes is a fundamental NEON science requirement, the network sensitivity was assessed using annual time-scale information. Within the conservatively simulated ranges for magnitude of trend, interannual variability, and correlation among sites, simulation results provide a basis for bounding levels of measurement error. In this case, measurement error includes instrument or observer accuracy and precision, sampling or representativeness errors, and errors associated with data processing algorithms. This approach allows the development of requirements for measurement replication, frequency, accuracy, and precision. The simulation framework also provides a basis for tracking the propagation of error as data are collected, calibrated, and processed to higher data product levels.

Table 3: Number of years until a trend can be quantified as a function of the magnitude of that trend relative to noise, *interannual variability, and observational uncertainty*

Number of years until a trend can be quantified as a function of the magnitude of that trend relative to noise, *interannual variability, and observational uncertainty*				
	Interannual Variability (% per year)			
Magnitude of Trend (% per year)		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.

The relationship between a hypothesized cause of change and an ecological response to change was simulated to test the ability of the network to (1) detect trends in ecological responses, (2) distinguish between linear and nonlinear relationships, and (3) quantify the parameters of relationships between causes and responses. The observatory can typically detect and determine the form of complex nonlinear relationships, but the number of years required to accomplish this depends on the size of the effect and the degree of variability in the response. Quantitatively retrieving the parameters of ecological relationships is not always possible within 30 years. This has allowed us to identify areas where NEON data are necessary, but where additional observations, experiments, and analyses are also required to fully address a topic.

4.6 Designing a Decadal-Scale, Continental-Scale Observatory

The network simulation described above serves to inform the design of measurement accuracy and sampling intensity in the NEON observations and experiments. Table 3 shows that this approach does not completely specify either the required measurement accuracy and precision or the 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 suggests a protocol:

- In general, measurements are required to meet an uncertainty of 10-20% (from all sources) in the annual time scale, to allow detection and quantification of most trends within the 30-year time span of NEON.
- When the measurement characteristics corresponding to network simulation model parameters are known, this methodology will be used to define requirements for sampling intensity and tolerable measurement uncertainty.
- When the trend and interannual variability are not known, tolerable measurement uncertainty is estimated using simulation and modeling, and the impact of measurement uncertainty on detection is quantified.
- When the measurement uncertainty is not known, calibration, validation, and audit processes are required to allow the uncertainty in response variables to be quantified. Based on these processes, scientific adjustments to methodology or sampling effort can be made over time, possibly responding to changes in variability over time.

The approach described in this document is a framework that can be used to define and evaluate trends throughout the operation of the observatory. To realize the largest science return on investment, measurements must allow 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 budget. In some cases a key measurement may barely meet requirements or fall slightly short. When this occurs, the methodology allows specific areas to be targeted for research and design. This allows for an improvement of the network design as more observations are collected and analyzed.

5 NEON SCIENCE INFRASTRUCTURE

5.1 A Continental Observatory Design

The design for a continental-scale ecological observatory infrastructure that will address the Grand Challenges described in Section 3, and satisfy the high-level requirements listed in Section 4, is discussed below.

5.1.1 Continental-Scale Design

NEON's domains were defined with a statistically rigorous analysis using national data sets for ecoclimatic variables. The statistical design is based upon algorithms for multivariate geographic clustering (MGC) (Hargrove and Hoffman, 1999, 2004). In MGC, clusters are formed so that each cluster contains roughly the same fraction of the total ecoclimatic variance, and so that the centroids of the clusters lie roughly equally far apart in ecoclimatic space. Thus, selecting one core site per domain allows NEON to sample within the ecoclimatic variability of the U.S. in a roughly uniform way. Put another way, each site represents roughly the same fraction of total ecoclimatic variability, providing an equal-variance design.

MGC techniques applied to the definition of NEON domains use nine input variables mapped across the United States at a 1 x 1 km raster resolution. Those input variables are:

- Number of days above 90 degrees Fahrenheit in the growing season
- Number of days below 32 degrees Fahrenheit in the growing season
- Total precipitation in the growing season
- Total precipitation in the nongrowing season
- Number of days with measurable precipitation in the growing season
- Number of days with measurable precipitation in the nongrowing season
- Soil plant-available water holding capacity to 1.5 m depth
- Total solar insolation in the growing season
- Total solar insolation in the nongrowing season.

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. Use of additional predictor variables does not greatly alter patterns, because of the high degree of correlation among climatic, edaphic, and ecological variables, so there is a gross resemblance between the NEON domains and many other ecosystem classifications.

The MGC 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 assigns map cells to new centroids. After this grouping process has converged, the k regions become statistically defined. The process is similar to unsupervised classification for remotely sensed imagery, but ecologically relevant conditions are used rather than spectral reflectances.

The geographical analysis results in the domains, which are used to identify a given number of wildland sites that sample the maximum amount of variability (Figure 7). Using an approach that operates on individual 1 km^2 cells means that each cell is classified, and the representativeness of any site to all of the cells in a region can be quantified, allowing for a quantitative assessment of site suitability. The actual analysis is on individual cells, while the map reflects smoothing of boundaries and some other simplifications to allow the domains to be more readily visualized. An alternative analysis using similar techniques with the Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) data set also reached the conclusion that the appropriate number of domains to allow for continental-scale observation is approximately 20 (Urban et al., personal communication).

Figure 7: The 20 NEON domains and the core, relocatable, and aquatic sites.

The number of sites was defined by first satisfying rigorous science requirements driven by the overarching goals of NEON, then optimizing within an envelope of available funding. NEON uses a parsimonious continental strategy for placement of the observational units within the United States. Financial and logistical constraints necessitate the identification and implementation of the most critical aspects of the design.

The 20 NEON domains are designed to enable statistically meaningful sampling, rather than being a basis for extrapolation or analysis. The domains are not intended for direct use in extrapolation from sites to regions. Measurements taken at specific sites within a domain may apply to other locations within the domain, depending on their quantitative relevance (e.g., Figure 8). That is, measurements at a core site cannot be applied in a simple way to all cells within a domain, but each measurement's relevance can be at least partially quantified from the data used to create the domains.

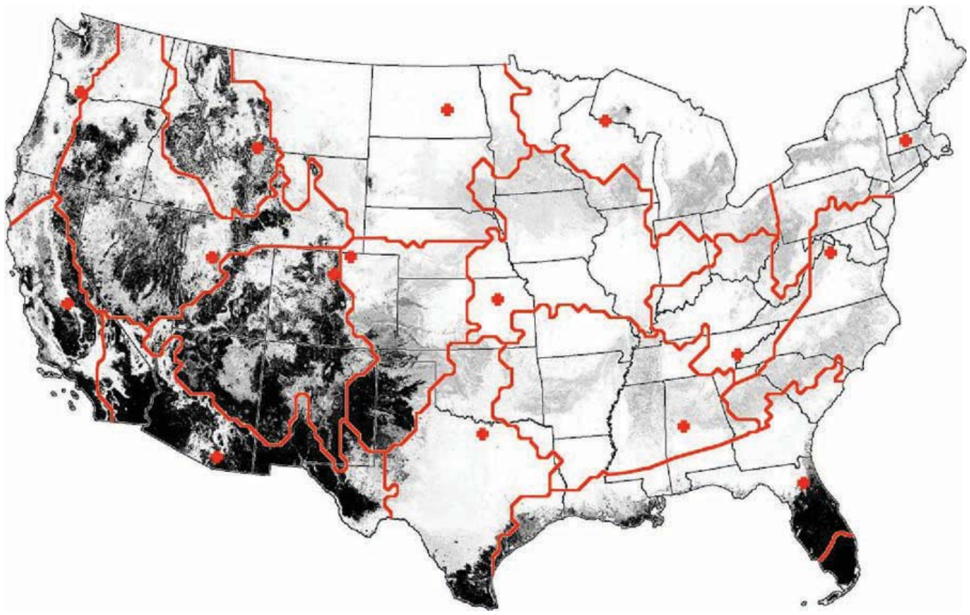

Figure 8: Map of NEON domain representativeness. Uniformly light areas indicate a high level of domain representativeness. The eastern portion of the country is generally well represented, while the West is more heterogeneous, particularly the Desert Southwest and the Rocky Mountains.

The use of multiple cell-level data sets to define the domains facilitates the development of quantitative models (statistical or simulation) to relate measurements at measured cells to conditions at unmeasured cells, in contrast to older approaches in which all cells within a type are assumed to be similar or identical for modeling purposes. Now that the core sites have been selected, the domains become primarily a basis for managing resources and logistics, not a principal basis for modeling and analysis. Key questions are often not domain based; instead, they are addressed through relocatable sites assigned to regional, multidomain gradients.

5.1.2 Validation of Design

The analysis used to define the domains provided an important criterion by which to select NEON core sites (Table 4). These sites will form a long-term baseline of observation in minimally managed, wildland systems. They also are primary locations for studies of climate impacts and reference sites for studies of other causes of change and stressors. Potential core sites within domains, which were suggested by the scientific community, were evaluated by calculating the ecological distance in ecoclimatic space (described above) between the centroid of the domain and each potential site. Potential sites were carefully located and registered to the ecoclimatic data grid in order to ensure that the site selected was the one most representative of the domain, based on quantitative comparison. The sites were evaluated against a set of specific criteria (Table 5), and the best match for each domain was identified as the core site (Keller et al., 2008).

Table 4: Terrestrial Core Sites and Locations

Terrestrial Core Sites and Locations				
Domain	Domain Name	Site Name	Lat	Long
1	Northeast	Harvard Forest	42.53690000	-72.17266000
2	Mid-Atlantic	Smithsonian Conservation Biology Institute (SCBI)	38.89292000	-78.13950000
3	Southeast	Ordway-Swisher Biological Station	29.68927000	-81.99343000
4	Atlantic Neotropical	Guanica Forest	17.96955000	-66.86870000
5	Great Lakes	UNDERC	46.23388000	-89.53725000
6	Prairie Peninsula	Konza Prairie Biological Station	39.10077000	-96.56390000
7	Appalachian/Cumberland Plateaus	Oak Ridge	35.96412000	-84.28260000
8	Ozarks Complex	Talladega National Forest	32.95046000	-87.39327000
9	Northern Plains	Woodworth	47.12802000	-99.24133000
10	Central Plains	Central Plains Experimental Range	40.81554000	-104.74543000
11	Southern Plains	Caddo/LBJ National Grassland (Unit 41)	33.40123000	-97.57000000
12	Northern Rockies	Yellowstone Northern Range (Frog Rock)	44.95350000	-110.53914000
13	Southern Rockies	Niwot Ridge/Mountain Research Station	40.05420700	-105.58217400

14	Desert Southwest	Santa Rita Experimental Range	31.9106800 0	-110.83549000
15	Great Basin	Onaqui-Ault	40.1775900 0	-112.45244000
16	Pacific Northwest	Wind River Experimental Forest	45.8204880 0	-121.95191200
17	Pacific Southwest	San Joaquin	37.1087220 0	-119.73156100
18	Tundra	Toolik Lake	68.6610900 0	-149.37047000
19	Taiga	Caribou Creek - Poker Flats Watershed	65.1540100 0	-147.5025800 0
20	Pacific Tropical	Olaa	19.5547850 0	-155.26417800

Table 5: Criteria for NEON Core Sites

Criteria for NEON Core Sites
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

In order to assess how well this process worked, a map was computed that coded each grid cell in the national database according to how similar it is to the NEON core sites. The shading in Figure 8 represents the degree to which the ecoclimatic characteristics of the 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. In the montane western United States, sampling of orographic variability (climate dynamics related to topography) was improved by selection of relocatable sites along elevation gradients (especially in Domains 10, 13, and 17) as part of addressing the science themes of those domains (See Section 5.1.3, Figure 10).

An independent, model-based analysis was also done to assess the overall design. The covariance between NEON core sites (where intensive observations will be made) and areas of North America where observations are limited to remote sensing and operational observations was done using the Community Land Model (CLM) of the National Center for Atmospheric Research. A land surface model, CLM calculates carbon, water, and energy exchanges between the biosphere and the atmosphere and is one of the models used in the periodic climate change assessments made by the Intergovernmental Panel on Climate Change (IPCC). Thirty years of model output were used to make correlations between net ecosystem exchange (NEE) of carbon between the land and the atmosphere at each NEON core site and all other geographic points in North America. In broad terms this analysis reflects the results of the geostatistical analysis that defines the domains.

Not all of the NEON domains are represented equally well (Figure 9). However, these analyses indicate that information can be extracted from NEON's intensive site-level observations and applied across geographic space via a variety of scaling methods. Further, fusing these types of observations with NEON's airborne remote sensing and LUAP will be fundamental to achieving continental-scale data products.

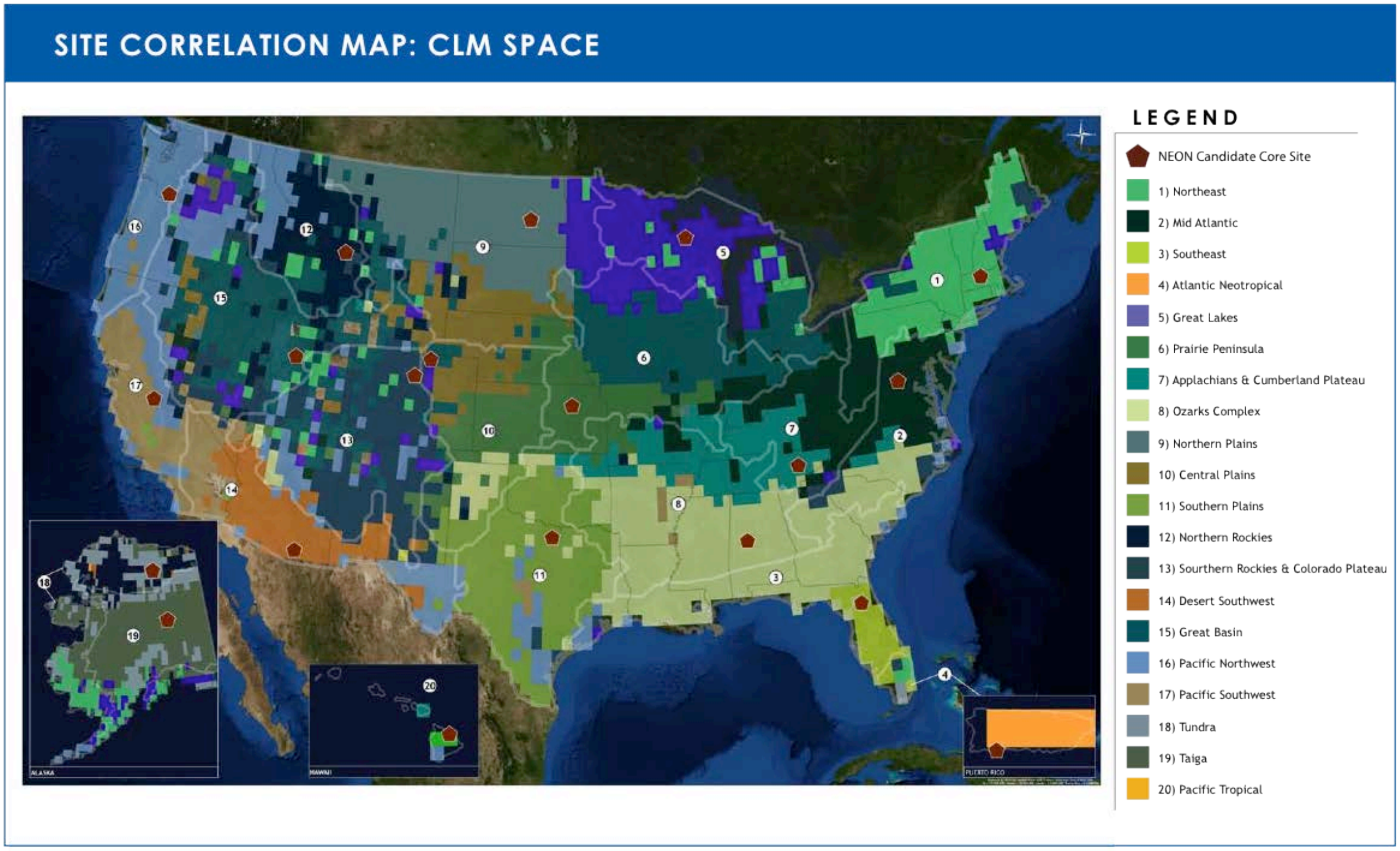

Figure 9: According to CLM analysis, information from core sites, shown in red, can be applicable to large areas where similar conditions exist and may also be applicable to smaller areas where conditions are more heterogeneous.

5.1.3 Addressing the NEON Questions through Relocatable Sites

NEON plans to use relocatable sites in order to collect data on the NEON Grand Challenges (Figure 1) that cannot be fully addressed by the core wildland sites. The maps in Figure 10 show NEON relocatable sites and their primary science themes.

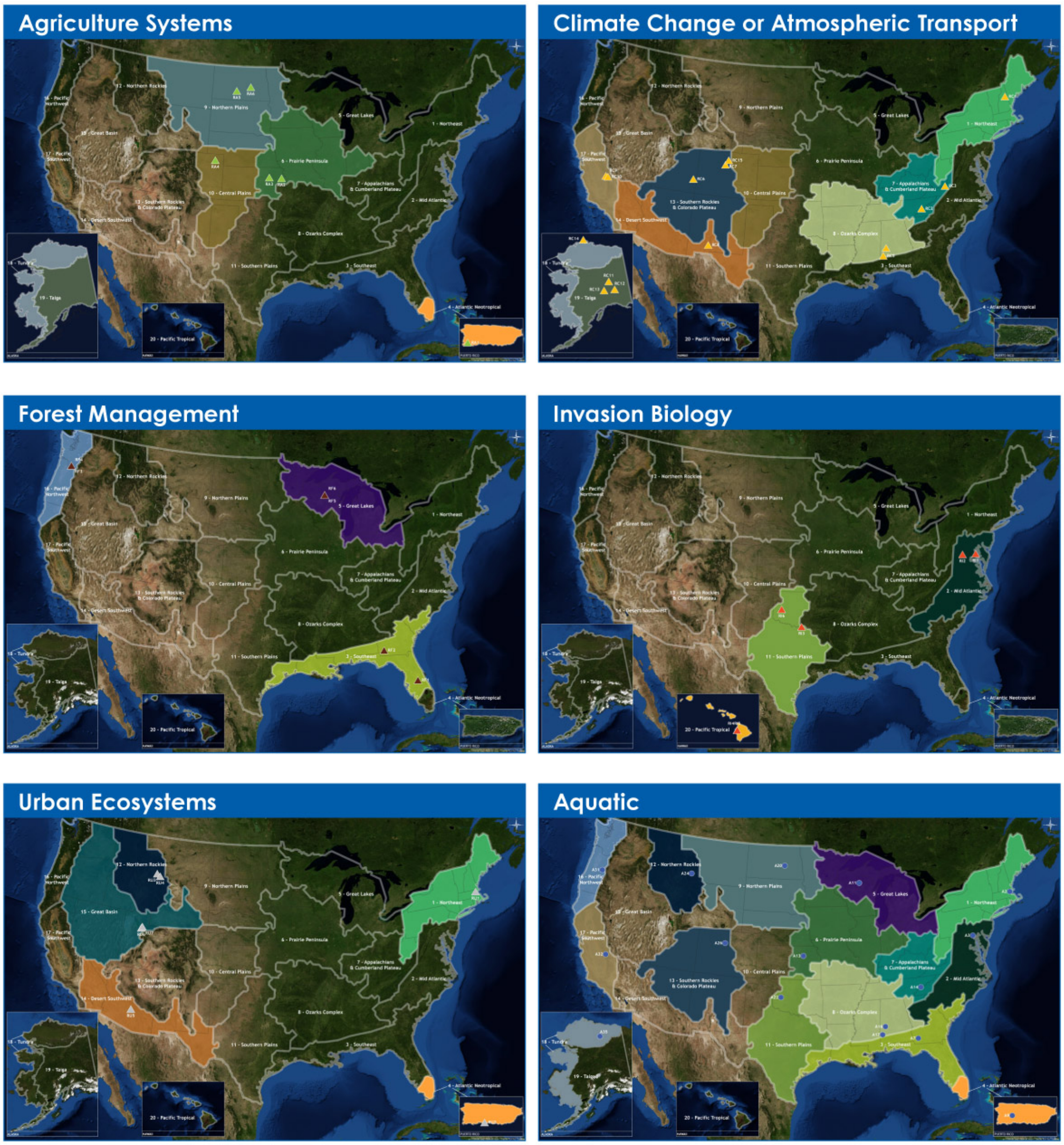

Figure 10: Relocatable site locations and the main science questions addressed by each suite of sites, plus location of sites addressing aquatic questions.

The relocatable sites are used to create question-driven gradient or comparison studies. 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 weeklong workshop and subsequent NEON analyses, allowing the following key points to emerge.

- Relocatable sites must preserve the "cause and effect" paradigm that is at the heart of NEON. This means that each relocatable site should include the same suite of sampling and monitoring as at the core sites, such as organism collection (terrestrial and aquatic biological measurements), automated measurements (terrestrial and aquatic instrument measurements), and remote sensing (the Airborne Observation Platform). The relocatable systems should not be minimally configured, instrumentation-only systems, as had been envisioned in some early NEON discussions.

- Unlike climate change, land use and its effects cannot be studied at the core sites because these are located in wildland areas. As a result, land use is often the first priority for relocatable deployments.
- In order to study interactive effects with replication, regional NEON designs also focus on a few land use types across ecoclimatic gradients rather than maximizing the diversity of land uses considered.
- The overarching theoretical question of connectivity – the linkage of ecological processes across space – is relevant to all of the NEON Grand Challenges. 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 disturbances.

Deployments were developed around the NEON Grand Challenges and are shown on the maps in Figure 10. Urbanization, perhaps the most ecologically intense and least studied of land uses, will be addressed in two transects (humid sites on the Eastern Seaboard and in Puerto Rico, and dry sites in the Intermountain West and Southwest). Managed forest sites were selected in some of the nation's major present or historical timber-producing regions, the Southeast, Upper Midwest, and Pacific Northwest. Rather than attempting to cover the immense range of U.S. agroecosystems and crops, a task beyond our reach, NEON focused on agricultural sites in the Great Plains region and in Puerto Rico to include a wide range of production systems. Several sites were selected specifically to pair invaded and uninvaded ecosystems in Hawaii, the Mid-Atlantic, and the Southern Great Plains. Climate change impacts are addressed in several deployments. 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. Table 6 identifies each currently planned relocatable site and the science theme to which it is assigned. Impacts of a changing elevation of rain/snow transition due to warming are addressed in Domain 17 (California).

Table 6: The NEON 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.

The NEON 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			
Domain	**Domain Name**	**Site Name**	**Science**
1	Northeast	Bartlett Experimental Forest	Climate Impacts

1	Northeast	Plum Island Suburban- Burlington, MA	Urbanization
2	Mid-Atlantic	Blandy Experimental Farm	Invasive Species
2	Mid-Atlantic	Smithsonian Environmental Research Center	Invasive Species
3	Southeast	Disney Wilderness Preserve	Forest Management
3	Southeast	Jones Ecological Research Center	Forest Management
4	Atlantic Neotropical	Lajas Experimental Station	Agriculture
4	Atlantic Neotropical	Ponce Metro	Urbanization
5	Great Lakes	Steigerwald Land Services	Forest Management
5	Great Lakes	Tree Haven	Forest Management
6	Prairie Peninsula	Konza Prairie Biological Station (Agricultural Lowland)	Agriculture
6	Prairie Peninsula	The University of Kansas Field Station	Agriculture
7	Appalachian/Cumberland Plateaus	Great Smoky Mountains National Park, Twin Creeks	Climate Impacts
7	Appalachian/Cumberland Plateaus	Mountain Lake Biological Station (SW Virginia)	Climate Impacts
8	Ozarks Complex	Armistead Selden Lock	Climate Impacts
8	Ozarks Complex	Choctaw National Wildlife Refuge	Climate Impacts
9	Northern Plains	Dakota Coteau Field School	Agriculture
9	Northern Plains	Northern Great Plains Research Laboratory	Agriculture
10	Central Plains	North Sterling, CO	Agriculture
10	Central Plains	RMNP, CASTNET	Climate Impacts
11	Southern Plains	Klemme Range Research Station	Invasive Species
11	Southern Plains	Northcutt Site	Invasive Species
12	Northern Rockies	Bozeman, MT (MOR)	Urbanization
12	Northern Rockies	Loch Leven, MT	Urbanization
13	Southern Rockies	Fraser Experimental Forest	Climate Impacts
13	Southern Rockies	Moab	Climate Impacts
14	Desert Southwest	CAP LTER Urban	Urbanization
14	Desert Southwest	Jornada LTER	Climate Impacts
15	Great Basin	Murray Tower (Urban)	Urbanization

15	Great Basin	Red Butte Canyon (Low Elevation-Urban Influence)	Urbanization
16	Pacific Northwest	Abby Road	Forest Management
16	Pacific Northwest	Thayer	Forest Management
17	Pacific Southwest	Soaproot Saddle	Climate Impacts
17	Pacific Southwest	Upper Teakettle	Climate Impacts
18	Tundra	Barrow Arctic Science Consortium	Climate Impacts
19	Taiga	Delta Junction	Climate Impacts
19	Taiga	Healy	Climate Impacts
19	Taiga	Poker Flats	Climate Impacts
20	Pacific Tropical	PuuWaaWaa-invaded	Invasive Species
20	Pacific Tropical	PuuWaaWaa-uninvaded	Invasive Species

Several regional or multidomain connectivity studies were established that incorporate many sites, sometimes adding connectivity as a secondary theme to relocatables that have a primary assignment to another theme:

- **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, 2, and 7 are specifically assigned to complete this gradient, and several other core and relocatable sites will also contribute.

Figure 11: Map of the Domain 8 core and relocatable sites aligned along the hydrological flowpaths down the Tombigbee waterway.

- **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 (Figure 11). The relocatable sites are located at Armistead Selden Lock and at Choctaw National Wildlife Refuge on the Tombigee along the aquatic flowpath. The core terrestrial and aquatic sites are positioned to capture chemical, physical, and biological changes in aquatic, atmospheric, and terrestrial environments. The sites are located along a river continuum, including in a small stream, a medium-sized river, and a large river. 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.

- **Dust and nitrogen.** In the Intermountain West, dust resulting from urban and agricultural land use change is transported over long distances (Figure 12). When deposited on the mountain snowpack, it alters the snow albedo, affecting snowmelt timing and altering local land surface feedbacks to climate. Sites in the Great Basin and Central Rockies-Colorado Plateau are located to examine the effects of dust. In addition, reactive nitrogen produced in the densely settled Front Range corridor of Colorado can be recirculated back to the mountains, affecting the local biogeochemistry, aquatic chemistry, and biodiversity. Sites along this flowpath are coordinated with the dust sites and form a compound transport/connectivity study.

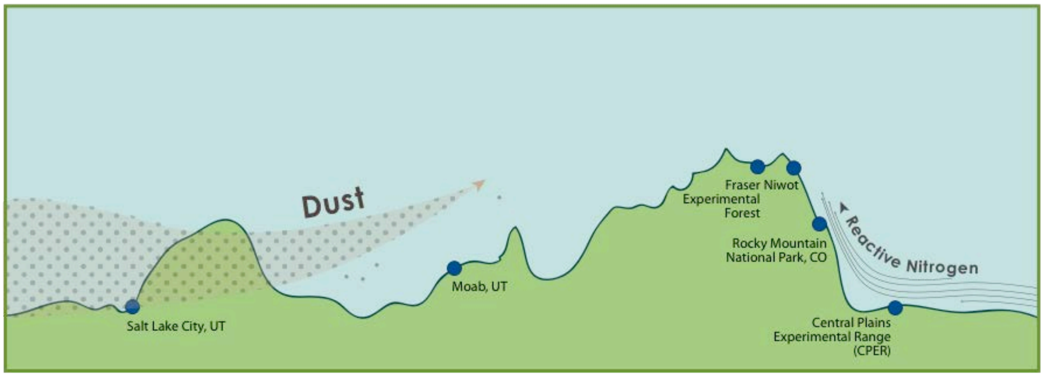

Figure 12: A simplified schematic of key atmospheric flowpaths in Domains 10, 13, and 17

For each NEON domain, data from the core site represent a baseline or control point for ecological conditions that can be compared to nonbaseline conditions at the relocatable sites. These types of comparisons provide critical information that can be used to characterize impacts, especially those due to land use change and invasive species.

5.2 Systems for Observations and Experiments

The NEON system is built around a number of subsystems, sampling differing portions of the habitat (terrestrial, aquatic and atmospheric) using different observing methods (instrumental, human field observers and laboratory analyses). The system also includes collection and curation of material. The following sections describe these subsystems.

5.2.1 Terrestrial Biological Measurements

NEON will quantify the impacts of climate change, land use, and biological invasions on terrestrial ecology by sampling key groups of organisms (sentinel taxa) and soil. The sentinel taxa were selected to include organisms with varying life spans and generation times, and wide geographic distributions to allow for standardized comparisons across the continent (Figure 13). A number of different aspects of organismal biology are captured by organismal and soil sampling, including biodiversity and phenology of native and invasive species, biomass and productivity, stoichiometry, genomics, and disease prevalence (Figure 14).

Not all of these aspects are captured for every taxon: an economical strategy is required because many of the biological observations remain labor intensive and expensive to obtain. For example, comprehensive observation of microbial phenology requires daily field collections followed by intensive lab analysis, while plant phenology can be captured with cameras and periodic, simple visual field work.

Biological measurements are made at the scale of individual organisms, and so a statistical sampling design that allows inference at regional and continental scales is essential. Plot and organism observations must be made within a sampling design that captures heterogeneity representative of the site and allows inference to the domain. Plot and organism-scale measurements will also be coordinated with the larger scale of airborne measurements (discussed in Section 5.2.7), which provide a set of synergistic biological data products at the regional scale.

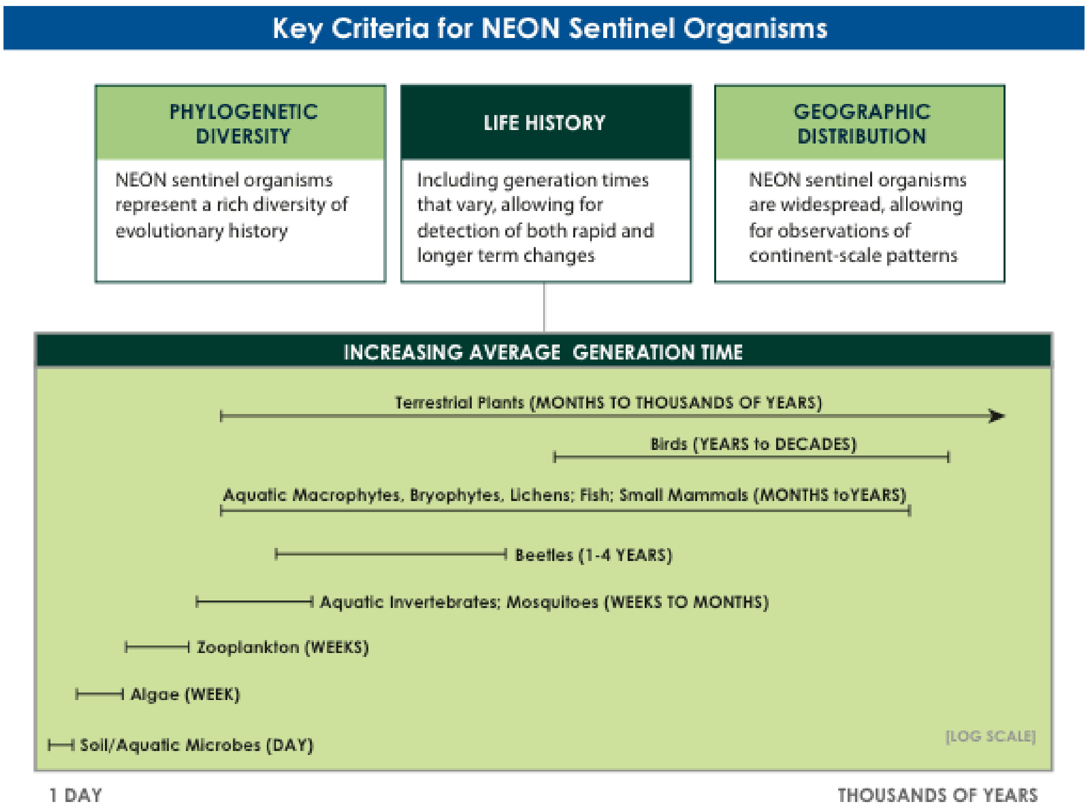

Figure 13: Typical adult lifespans for NEON sentinel organisms. Aquatic organisms are further discussed in Section 5.2.2.

A sampling design has been developed to systematically observe the sentinel taxa at NEON sites. At each site a site boundary is defined, which normally corresponds to the legal ownership boundary. In some cases a more restrictive boundary must be developed because the sites (e.g., Yellowstone National Park) are too large to be sampled with available resources. Plots are selected by randomization, stratification, and optimization of sample number.

- **Randomization.** Once the boundary is established, a very large number of potential plot locations are identified using an algorithm that incorporates spatial balance and random sampling.

- **Stratification.** The site is then subdivided according to mapped vegetation types using established national vegetation classification techniques.

- **Optimization of sampling.** From the very large number of plots identified, a smaller set is chosen to correspond to the number of plots that are logistically feasible and, according to multiple lines of evidence, can describe biological change through time.

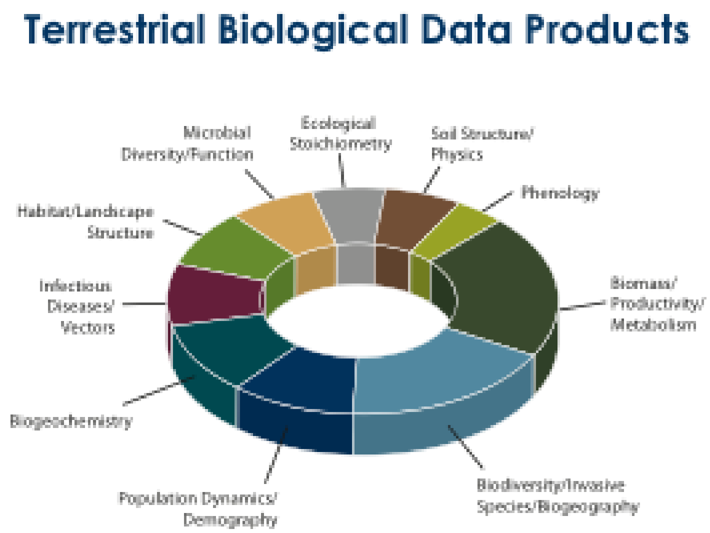

Figure 14: NEON terrestrial biological data products.

NEON attempts to provide consistent coverage of each land cover type throughout the nation,, so that, for example, all forests or grasslands have a similar number of plots per unit area to avoid large differences in sample variance between sites. In order to ensure consistent coverage, among other purposes, sites are initially oversampled. Once a feasible set of stratified random and spatially balanced plots is identified, (1) it must be field validated as lying in the system indicated in mapped resources, and (2) the managing organization must be contacted to assure that the plots are accessible and their planned use by NEON is acceptable (e.g., it does not conflict with other research). When plots fail validation, additional plots are chosen from the initial randomization. Once acceptable plots are established and data are being collected, several metrics will be computed and evaluated, and, if necessary, adjustments to sample size will be made to standardize sample statistics over the entire observatory, again drawing from the initial randomization. Plots from the initial randomization may also be used in two other ways. First, additional plots may be surveyed or photographed for later comparisons with the experimental plots so that NEON staff can evaluate the effects of sampling. Second, the unused random plots serve as a resource for NEON users who might wish to make additional measurements or conduct an experiment using the same randomization and employ the NEON plots as controls. This overall sampling design is based on sampling vegetation, and will be adapted to include the other sentinel taxa (see below) as appropriate.

NEON terrestrial biological measurements will be made on the following sentinel taxa and environmental media:

- **Plant biodiversity.** Data collected about plant biodiversity will allow better understanding of how plant species vary through seasons and over many years in the face of environmental change, and allow better understanding of the links between biodiversity and ecosystem function.
- **Plant biomass, leaf area, isotopic and chemical composition.** Observed with a combination of vegetation structure, clip harvest, canopy gap fraction data, and laboratory analyses of chemical, elemental and isotopic composition, these measurements enable calibration of remotely sensed data, allowing mapping of plant biomass and the amount of carbon and nutrients held by plants across the landscape.
- **Plant phenology.** The timing and duration of phenology events in plant communities will be monitored to record the seasonal progression of critical biological processes and the timing of ecological events.
- **Birds.** The distribution, density, and diversity of bird species will be measured at sites to understand how birds may be affected by environmental change. NEON sampling will complement other continental-scale sampling efforts such as the Breeding Bird Survey because it will be of a higher intensity (and, by necessity, at fewer sites throughout the country) and co-located with sampling of other taxa.
- **Ground beetles.** Ground beetle diversity and abundance will be sampled to capture variation throughout the year and from year to year because population or distribution shifts in ground beetle populations can indicate significant changes in the local ecological community.
- **Mosquitoes.** Mosquito diversity will be sampled because of the sensitivity of mosquitoes to climate variation and their importance as disease vectors.
- **Small mammals.** Data about small mammals (species diversity, condition, demography) will be collected to better understand how environmental changes are affecting populations over time, including the occurrence of the diseases they carry.
- **Disease.** Sampling of ticks, rodents, and mosquitoes that carry disease will improve understanding of how the prevalence of infectious agents (e.g., Lyme disease, Hantavirus, West Nile virus, and Dengue) changes over time within ecosystems.

- **Soil microorganisms.** Microbial data will allow better understanding of the environmental drivers of spatial and temporal variation in the structure and function of soil microorganism communities.

- **Soils.** Chemical, physical, isotopic and biological characterization of soils will provide context for plant and microorganism data and allow quantification of long-term changes in soil properties.

Understanding changes in populations and communities of these organisms and their substrates requires observation and sampling in the field and analyses 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 or organismal tissues (e.g., chemical, genetic, infectious diseases, and isotopic analyses) to produce data products. Collected material will be stored and curated at NEON collection facilities (described in 5.2.3) to enable future analysis and study.

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

5.2.2 Aquatic Biological and Instrumental Measurements

NEON will observe key physical, biological, and chemical drivers of ecological change, as well as responses to those factors, in freshwater systems. This will further our understanding of how aquatic systems are changing and how such changes (e.g., to water balance and nutrient fate) are linked with changes in the terrestrial environment. Aquatic sites are arrayed over broad hydrological and climatic gradients (Figure 15) and are usually co-located with NEON terrestrial instrument and biological measurements. In a few cases, for access or logistical reasons, aquatic measurements are made at some distance from the terrestrial measurements.

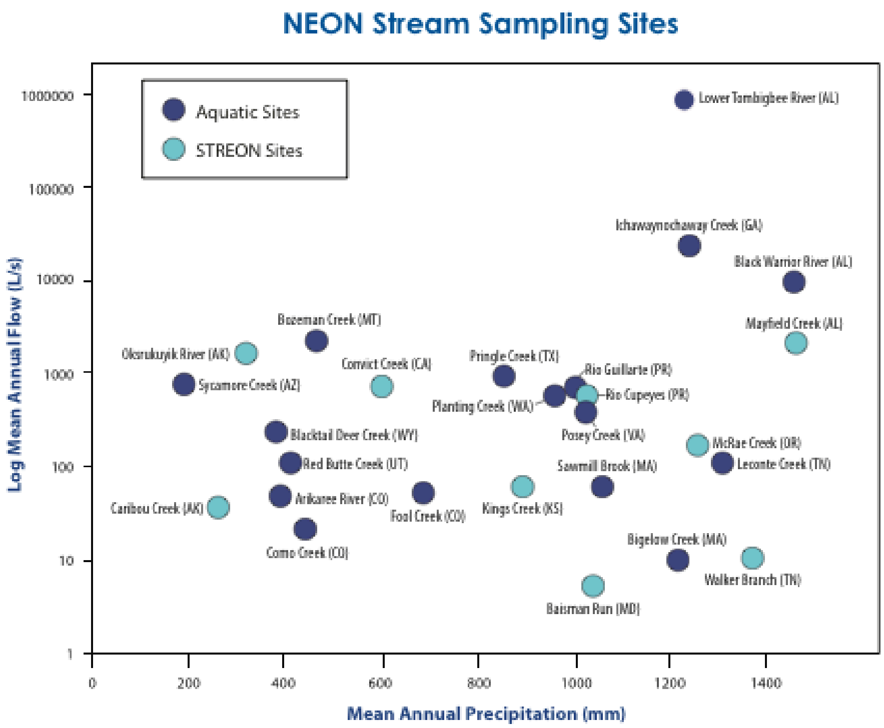

Figure 15: NEON stream sampling sites were chosen to span a wide range of hydrologic regimes. Not plotted: Providence Creek (CA) and McDowell Creek (KS).

Aquatic measurements will be made on the following sentinel taxa and media:

- **Algae.** Algae (phytoplankton and periphyton) are critical to stream primary production and are the primary organisms that perform photosynthesis. Species composition, biomass, diversity, chlorophyll, stable isotopic, and nutrient content data of algal communities will be measured.

- **Aquatic macrophytes, bryophytes, and lichens.** Aquatic plants influence habitat structure and biological processes in aquatic ecosystems. Data will be collected on the species composition and diversity and abundance of these aquatic plants.

- **Aquatic microbes.** Data about biomass, diversity (using genomic techniques), and functioning of stream and lake microbial communities will be collected.

- **Isotopes.** The isotope ratios of select organic and inorganic compounds in water and algae will be measured. Isotopes and chemical signatures aid in modeling water fate and residence time, tracing food webs, and identifying the origin of organic matter in aquatic systems.

- **Aquatic invertebrates and zooplankton.** Aquatic invertebrates are an important link in the trophic structure of aquatic ecosystems and are good indicators of aquatic ecosystem health. Invertebrates are the primary consumers of plant material entering the stream from the riparian community. Data will be collected on the species composition and diversity of aquatic invertebrates. Species composition and diversity of zooplankton will be measured in lakes.

- **Fish.** Fish are often the top consumer in aquatic ecosystems, capable of providing powerful top-down impacts on ecosystem diversity and function. Data will be collected on the number, individual weight, species composition, and diversity of fish or other top predators in lakes and streams.

- **Surface water and groundwater.** Data will be collected on the physical, chemical, and isotopic composition of surface and groundwater at each aquatic site via continuous instrumental observations and sample collection. Observations will include seasonality of flow or depth; ice cover; temperature; general chemistry perameters; dissolved oxygen, nutrients, and carbon; cation/anions; and isotopic ratios.

- **Sediment.** Data will be collected on sediment chemistry of streams and lakes, including issues of concern at impacted sites (e.g., heavy metal contaminations).

- **Aquatic habitat.** Observations will be made of stream and lake morphology, stream/lake bed composition, habitat type (pool, riffle), riparian vegetation, dead and down wood in the stream corridor, and stream microclimate (incoming solar radiation, air temperature, wind, barometric pressure).

As with terrestrial environments, understanding changes in habitats, populations, and communities requires observation and sampling in the field followed by analyses in the laboratory. And, like the terrestrial observations, some aquatic observations will be rapidly available to the community following quality control. Other data will require off-site laboratory analyses of water, sediment, or organismal tissues (e.g., taxonomic, chemical, genetic, and isotopic analyses) to produce data products. A portion of the carefully collected material will be stored and curated at a distributed network of NEON collection facilities (described in Section 5.2.3) to enable future analysis and study.

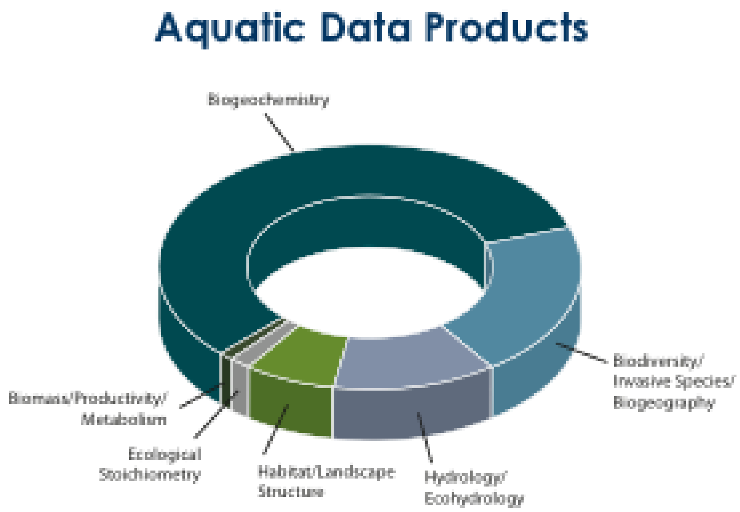

Figure 16: NEON aquatic data products.

Data products from aquatic systems include biogeochemistry, hydrology, ecohydrology, biodiversity, invasive species, genomics, and biogeography. Additional data products include habitat and landscape structure, stoichiometry, biomass, and stream metabolism (Figure 16).

Quantification of spatial and temporal variation in the data from aquatic sites will be accomplished via adherence to standardized protocols for field collection, sensor maintenance, and laboratory analysis, including rigorous quality checks and assurance on field, sensor, and lab procedures and on the data.

Taxonomic analyses of aquatic organisms include both traditional morphology-based taxonomy and utilization of modern genomic technologies to quantify organism type and quantity. NEON will build site-specific collections, which will require specialized taxonomists. The collections will be available for reference and to support genomic and other advanced taxonomy approaches.

5.2.3 Specimen and Sample Curation

A curated collection of organisms, key body parts of organisms, and substrates, termed the NEON Virtual Collection Facility, will be open to researchers for analysis, both now and in the future as new technologies emerge. Samples and specimens collected during regular annual sampling (see Sections 5.2.1, 5.2.2, and 5.2.4) will be archived in the NEON Virtual Collection Facility to provide a record and reference for future studies of biological change. Terrestrial samples to be stored include voucher specimens, whole organisms and tissues from sentinel taxa, and processed samples from analytical measurements (e.g., chemical, disease, genetic). Aquatic samples include voucher specimens, whole and unprocessed, and portions of samples from periphyton, phytoplankton, microbes, macrophytes/bryophytes/lichens, and invertebrates. Digital collections (e.g., photographs of live organisms) will also be used as an archive of sensitive or rare organisms (e.g., fish, lichens/bryophytes) that should not be removed from the sites. The archived samples will provide a resource for future research efforts, enabling scientists to identify organisms, test for the presence of pathogens, and perform new isotopic and biogeochemical analyses on organismal, plant tissue 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. Some portion of the collection will also allow for future destructive analysis of samples. The collections will be stored at partner facilities (museums and other collections) but will be centrally cataloged and available by request through NEON's cyber-archive facility.

5.2.4 Terrestrial Instrument Measurements

NEON will observe key physical and chemical climate causes of ecological change—as well as ecosystem-level responses to those causes—in terrestrial ecosystems to advance our understanding of how the structure and function of these systems are changing. NEON will also measure how these changes are linked to changes in the diversity and function of organisms in both terrestrial and aquatic systems. These measurements are made at core and relocatable sites and are fixed in space. Depending upon the structural characteristics of the ecosystem, instrument measurements will represent areas from a few hectares to hundreds of hectares.

Key measurements include:

- **Key climate inputs**. These include air temperatures, precipitation, incoming solar radiation and net radiation, aerosol optical depth, photosynthetically active radiation, and wind speed and direction.

- **Bioclimate variables**. Although largely the same physical variables as for climate, bioclimate variables are measured in biologically relevant locations (near the soil, at canopy top, vertical profiles, and within vegetated areas), not just at a fixed height in a clearing as defined for climate monitoring. These measurements are climate variables that the biota respond to and interact with. An example of such a measurement includes using automated cameras to assess changes to the canopy phenology in response to changes in light (quality and intensity) and temperature.

- **Chemical climate inputs.** Ozone, reactive nitrogen, dust, and precipitation chemistry (wet deposition) are primarily anthropogenic in nature, and these inputs also provide a temporal understanding of how changes in land use contribute to atmospheric composition and subsequently ecosystem deposition. These measurements are also tied to community-wide standards as defined by the U.S. Environmental Protection Agency, National Oceanic and Atmospheric Association (NOAA), and other groups.

- **Carbon cycle changes**. NEON will quantify the changes to terrestrial ecosystem carbon balance by using micrometeorological techniques (i.e., measuring how the whole ecosystem breathes in real time). These measurements include fast response 3D windspeeds, atmospheric carbon dioxide concentrations, soil respiration, and nutrient use efficiency. The use of change in ^{13}C (a naturally occurring stable isotope) in CO_2 assists in our ability to devolve the component fluxes, as well as determine attribution.

- **Water cycle and surface energy balance**. As with the carbon cycle measurements, micrometeorological techniques will be employed to directly estimate sensible and latent heat exchanges. The latter is also used to estimate evapotranspiration. Measurement of changes in stable isotopes, O^{18} and deuterium-hydrogen (DH) in water assists in separating evaporation from transpiration, as well as indicating changes in regional- to continental-scale source waters. The combination of these estimates with climate/bioclimate measurements provides a detailed temporal understanding of how ecosystems use water—a key data product in managing this ecosystem service.

The physical and biological responses of soils to environmental change will also be observed using instrument measurements and will include temperature, water, carbon dioxide flux (soil respiration) and root growth. Instrument soil observations complement the biological measurements described above and are coordinated using a sampling approach designed to systematically represent soil variation within the region influencing the atmospheric fluxes of carbon dioxide and water.

Soil observations include:

- **Temperature profiles**, which are a key control over soil biological activity.

- **Soil moisture profiles**, a critical measurement for understanding the link between climate, plant growth, and ecosystem function.

- **Carbon dioxide** concentrations by depth, allowing soil respiration to be quantified.

- **Root growth and phenology**, using minirhizotrons, to define the below-ground component of plant growth and seasonality.

The overall design of the terrestrial instrument system is shown in Figure 17.

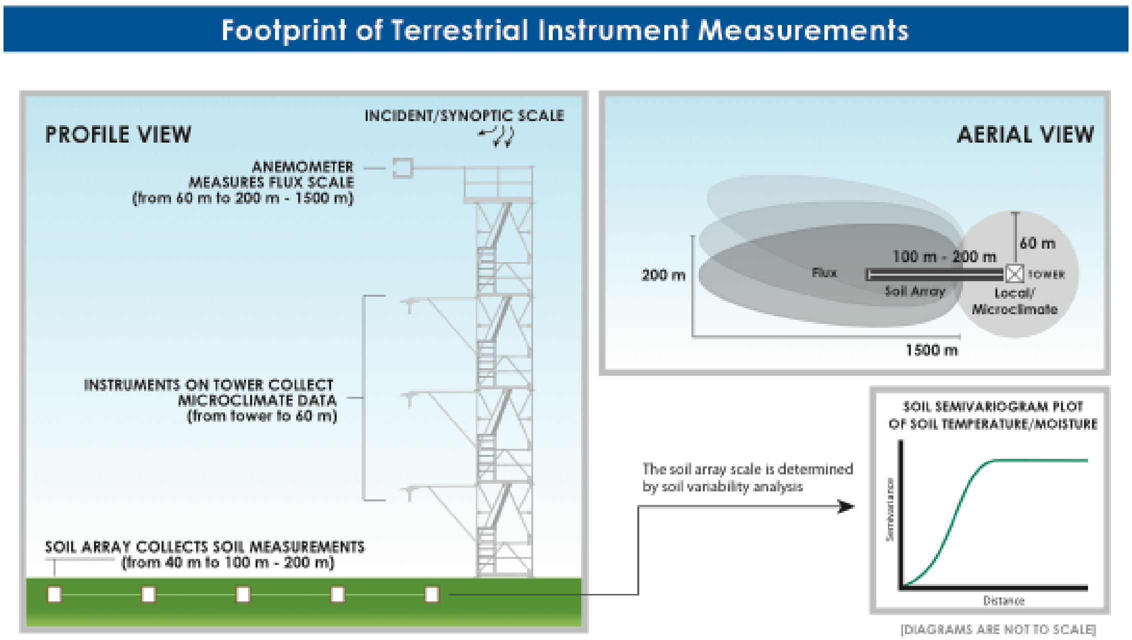

Figure 17: Design for terrestrial instrument measurements including profile view of instrumented tower and soil array, aerial view of the measurement area, and a schematic soil semivariogram plot, used to determine the spacing between soil samples.

Measurements of incoming solar radiation, aerosols, and water vapor will work synergistically with airborne measurements to ensure that biological remote sensing measurements can be corrected for the effects of atmospheric constituents (such as water vapor and aerosols), greatly increasing the accuracy and precision of airborne physical and biogeochemical observations, as well as providing key information on the abiotic drivers of ecosystem processes. Measurements of light absorption by the plant canopy in the photosynthetically active region of the spectrum will likewise help calibrate airborne estimates derived from differential spectral absorption of light.

The integration of instrument data across a range of environmental and land use conditions will enable ecological forecast models for mass and energy flux responses to climate change and other disturbances, and for forecasting land surface feedbacks to the climate system. Data products (Figure 18) will incorporate state-of-the-art, community-vetted algorithms and approaches with data quality metrics.

As with all other NEON data, terrestrial instrument measurements are made consistently across NEON sites with rigorously managed calibrations. All measurements are traceable to national or internationally recognized standards. In some instances these standards are incorporated into the first principles, and in other instances they are included in the measurement design itself (e.g., triple redundancy of air temperature as per the World Meteorological Organization

(WMO), or the double fence intercomparison reference standard for precipitation as per the NOAA U.S. Climate Reference Network). NEON's measurement approach is able to detect deteministic linear and nonlinear trends from site to continent and increases the sphere of understanding through interoperability with other research, networks, and observatories.

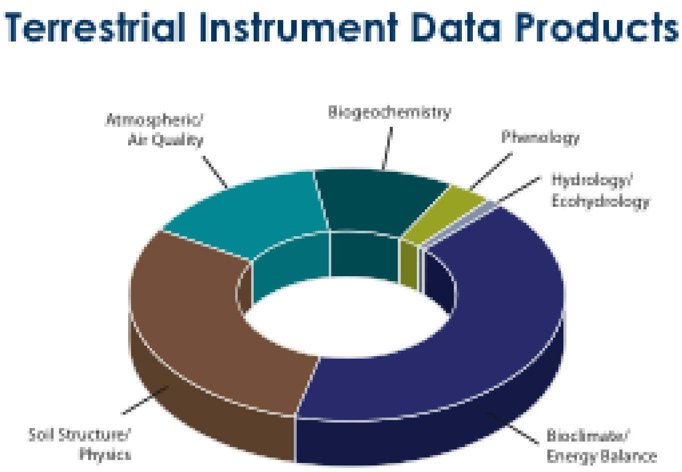

Figure 18: NEON terrestrial instrument data products.

5.2.5 The Mobile Deployment Platforms (MDP) for Observing Transient Events

The NEON core and relocatable sites can observe changes in climate and ecology over slow and moderate (several years or longer) time scales. However, changes can also occur at a faster time scale as a response to, for example, changes in the frequency of extreme events. NEON will have the capacity to observe rapid-scale events wherever they occur, using mobile facilities that can be deployed quickly.

Two well-known phenomena exemplify the types of changes that require mobile sampling. First, the life cycle of the mountain pine beetle is intrinsically determined by temperature, with the insect's rate of maturation dependent on temperature and its mass mortality requiring 10 or more days below -35 ºC (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 ºC threshold is not met, eliminating winter mortality (Hicke et al., 2006; Fauria and Johnson, 2009). Both thresholds were passed for much of the western United States and Canada in the 2000s, resulting in unequalled severe outbreaks and expansion of the insect's range into previously uncolonized ecosystems in boreal Canada (Logan and Powell, 2001; Kurz et al., 2008).

Second, the frequency and severity of wildfires often depend on the nonlinear nature of climate. In Alaska, the area burned depends on spring and summer climate, specifically, on temperatures and rainfall that influence fuel moisture and fire behavior (Duffy et al., in prep.). Figure 19 shows that the area burned increases abruptly when June temperatures exceed 14ºC or when August rainfall drops below 50 mm/month. Alaska has been warming at a very rapid rate, which has caused what were formerly occasional anomalies due to climate variability to become common occurrences as mean temperatures increase (Backlund et al., 2008).

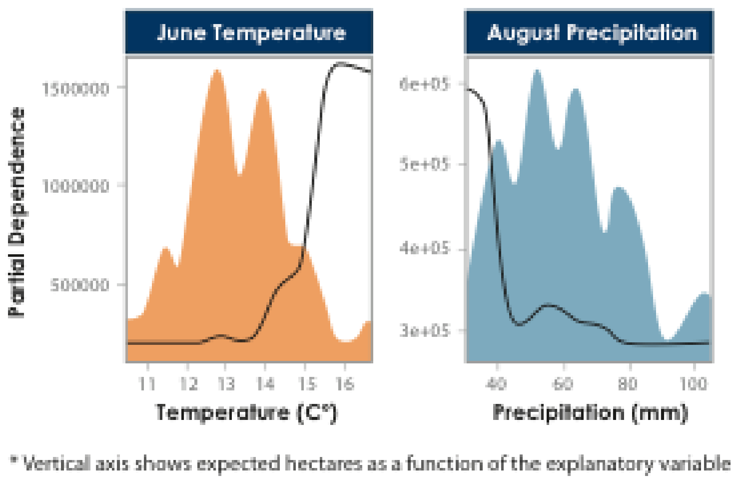

Figure 19: An example of a discontinuous ecological response to a small change in environmental conditions: the partial dependence of area burned versus June temperature (left) and August precipitation (right) for interior Alaska. The shaded backgrounds show the observed distributions of June temperatures and August precipitation. The lines indicate the area burned during each timeframe. Note that area burned varies dramatically around thresholds in temperature and precipitation.

Abrupt events that occur when environmental conditions cross a threshold are thus a critical process often driven by climate change, land use change, and biological invasions. NEON will provide infrastructure that can be deployed to respond to such events and, possibly as ecological forecasting matures, in advance of abrupt events (Carpenter and Brock, 2010) so that investigators can observe environmental and physical conditions following the event. Two NEON facilities can address this requirement: the Airborne Observation Platform (discussed in Section 5.2.7) and the Mobile Deployment Platforms or MDPs.

MDPs provide basic capabilities for terrestrial instrument measurements and support for biological measurements in a rapidly deployable package. Individual researchers or teams of researchers will be able to request use of this infrastructure.

The MDPs will include a transportable laboratory containing basic working space, sensor instruments, data communications for the sensor network and data storage, and capability to record and secure data. They include power distribution for NEON- and investigator-supplied instruments that can be connected to line or generator power. While the MDPs will be built using the same basic designs as those for terrestrial instrument measurements at core and relocatable sites, all components will be designed for rapid setup and takedown, to maximize research time. A main design change is that the tower will be an antenna style, and the platform on which all other supporting infrastructure sits will be mobile.

The mobile lab will also serve as a base for biological sampling activities and will include plot marking and locating equipment; small mammal, mosquito, and beetle traps; a library of NEON sampling protocols; data entry forms; field equipment; and field data entry devices.

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, outreach, and other scientific activities. Field crews working with the mobile lab deployments would typically be funded by the requesting investigator but trained by NEON staff on the use of the MDP.

5.2.6 STREON: The First NEON Experiment

NEON experiments are designed to serve as accelerators of expected future changes in the variables that cause change in ecosystems. Experimental accelerators manipulate systems to create conditions that resemble forecast futures. For example, by artificially warming temperatures, increasing CO_2 concentration, or reducing species diversity via removal, experiments can explore the impacts of these changes on ecosystems. Accelerator experiments test and inform forecast models seeking to predict such future conditions. 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 to assess responses. 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 species turnover and ecosystem adjustment to long-term biogeochemical perturbations. Replicating across the continent can reduce or eliminate the confounding effects of variables and thus promote a clear understanding of cause-effect relations (National Research Council, 2003).

The first NEON experiment will be the Stream Experimental Observatory Network (STREON). Its scientific goals are (1) to learn how stream ecosystems respond to an acceleration in nutrient loading and (2) to determine how loss of top consumers, singularly and interactively with increased nutrient loading, affects stream ecosystem structure and function.

STREON will take place downstream from 10 NEON aquatic sites, which will serve as controls for the experiment. Sites are distributed across U.S. stream nutrient gradients and represent the dominant stream hydrologic regimes across the Northern Hemisphere. The experiment will assess ecosystem response to the availability of key resources and the influence of biological structure on that response. Primary limiting resources in stream ecosystems are nutrients and organic carbon supply (Elwood et al., 1981; Peterson et al., 1985; Wallace et al., 1999). The STREON experiment will focus on chronic nutrient enrichment by adding nitrogen and phosphorus to streams because they are a common limiting factor in algal and microbial production (Francoeur, 2001; Elser et al., 2007), and human activities often increase the supply of these nutrients to streams (Figure 14) (Dodds, 2006). The experiment will also simplify the food web by excluding the top-level consumers. This will allow researchers to assess how food web structure influences the response of stream ecosystems to increased availability of resources. This design allows study of both bottom-up (abiotic resources) and top-down (biotic) control of ecosystem function, an important issue in ecosystem science (Rosemond et al., 1993; Gripenberg and Roslin, 2007).

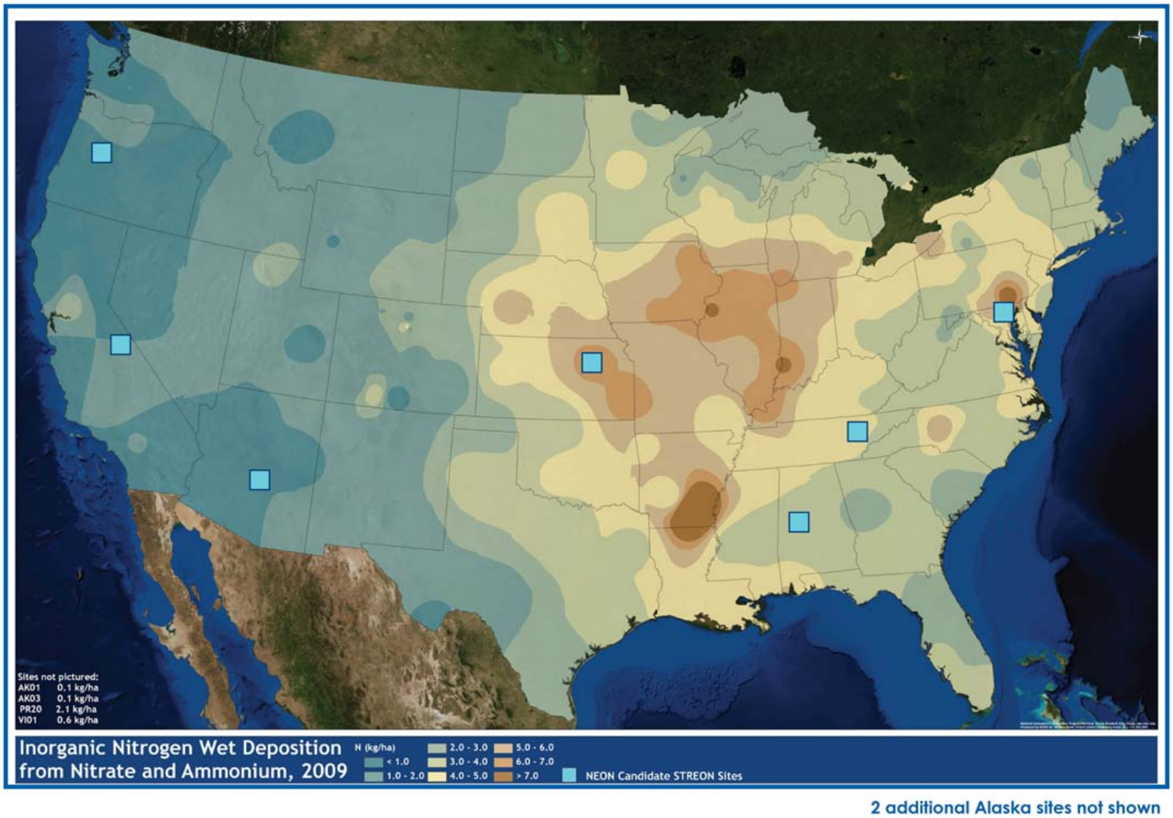

Figure 20: STREON sites (blue squares) were selected in order to span much of the range of in-stream nitrogen levels and stream flow conditions, which vary over the U.S. according to data from the National Atmospheric Deposition Program/National Trends Network. Several STREON are also located in Alaska (not shown).

Results from STREON will inform predictive models of stream ecosystem structure and function derived from the observational measurements in both control and treatment reaches. This integrated approach will allow the community to address fundamental questions and develop a predictive understanding of the primary factors driving changes in the structure and function of aquatic ecosystems. By using consistent methodologies and instrumentation across different sites that span the continent, the STREON experiment will provide a transformational increase in the understanding and ability to forecast future ecological change in stream ecosystems, which serve as critical transitional links between terrestrial to aquatic ecosystems.

5.2.7 Airborne Observation Platform

The Airborne Observation Platform (AOP) is a remote sensing instrumentation package designed to bridge scales from that of individual plants and stands, captured by plot and tower observations, to that of satellite-based remote sensing. The AOP will survey each NEON site annually, building a robust time series of landscape-scale changes. The AOP will provide meter-scale spatial resolution that will allow measurements at the level of individual organisms or small groups of organisms. It is designed to measure land use change; vegetation canopy biochemistry, structure, and heterogeneity; and changes in vegetation state and performance, including the presence and effects of invasive vegetative species (Figure

21). The direct measurements from the AOP system are spectral radiances, LiDAR returns, and photogrammetric images. However, these data can be analyzed to produce a set of low-high level data products:

- **Canopy chemistry** of individual trees and small (1-2 m) swards of herbaceous vegetation, including many of the direct correlates of photosynthesis and growth, such as nitrogen, chlorophyll, and leaf thickness.
- **Canopy moisture**, which can be estimated because water in plants has a different spectral response than atmospheric water, and which can provide a spatial perspective on water stress.
- **Leaf area** for each tree or small sward, directly estimated from the LiDAR and leaf area distribution, and the vertical distribution of leaf area, estimated from the LiDAR's waveform response.
- **Canopy and landscape structure**, from the three-dimensional distribution of individual trees and herbaceous swards, as well as from leaf area, including both its vertical distribution and its horizontal heterogeneity.
- **Canopy height**, and tree height, allowing allometric estimation of biomass in woody ecosystems and, in many cases, for individual trees.
- **Land cover** and aspects of land use, from interpretation of photogrammetric images and spectral/LiDAR imagery.
- **Diversity**, obtained by measuring the distinctive chemical and structural signatures of species or at least functional types. When LiDAR and spectral data are combined, in many cases aspects of biodiversity, including distribution of plant invaders, may be determined.
- **Disturbance**, detected from spatial patterns (such as canopy gaps) and their change over time. In some cases, disturbances may be detected directly. For example, oil from Deepwater Horizon was mapped using spectral data at sea and in the coastal zone.

The optimal suite of instruments available to provide these capabilities is a high-fidelity visible to shortwave-infrared imaging spectrometer and a waveform LiDAR. These are supported by a high-resolution digital camera to provide information on land use, including roads, impervious surfaces, and human structures.

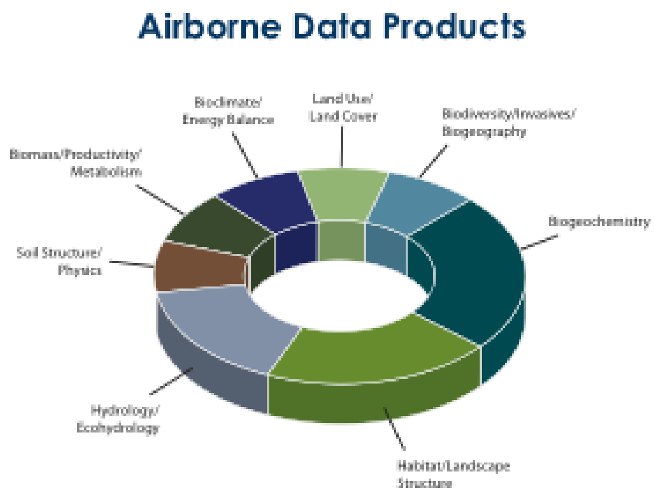

Figure 21: NEON Airborne Observation Platform science data user products.

The AOP will also contribute to the understanding of the causes and effects of change in ecosystems as represented by vegetation states and processes. Invasive plants can be detected through both their spectral properties and their structural properties (Asner and 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.

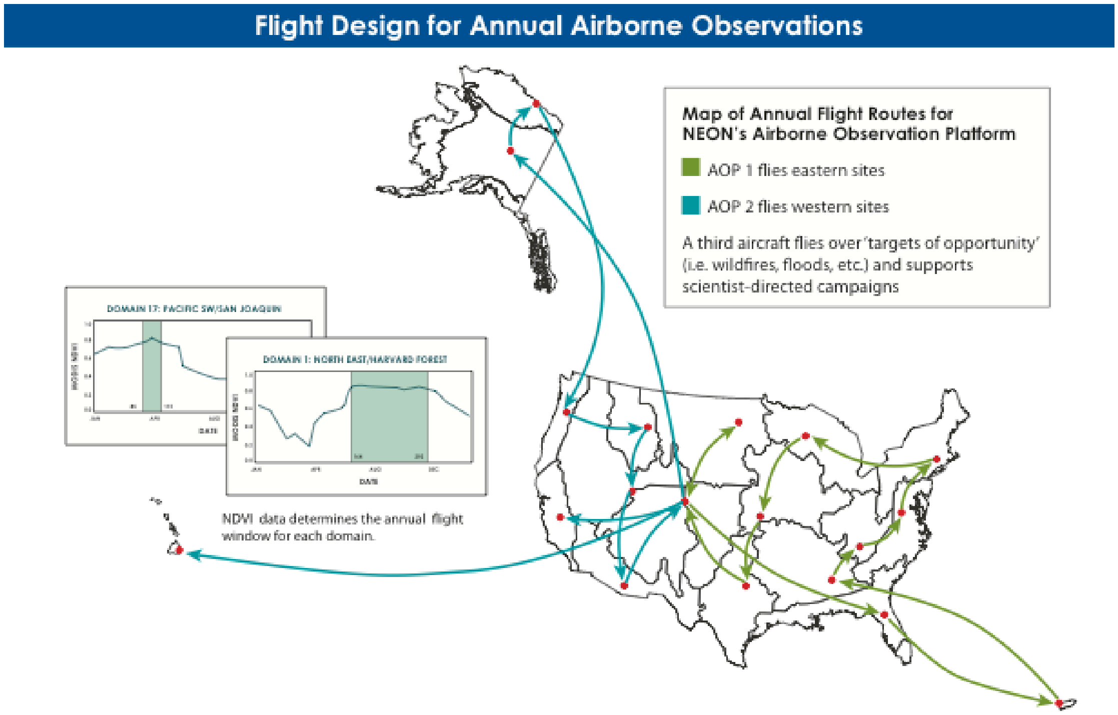

Figure 22: Baseline annual AOP flight operations are represented on the map. One AOP platform (AOP-1) targets the eastern U.S., while AOP-2 will fly the western NEON sites, including Alaska and Hawaii. Flight operations are expected to run from March to October of each year. Red points represent takeoff locations in each domain.

The high cost of aircraft operations will limit the frequency of AOP visits to individual NEON sites. Two airborne platforms will be dedicated to the annual survey of NEON sites. In order to detect interannual trends, NEON will seek to overfly each core and relocatable site annually (Figure 22). 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, that is, the normalized difference vegetation index as measured by the Moderate Resolution Imaging Spectroradiometer instrument, is within 90% of the site maximum). A third airborne platform will be available for deployment in response to extreme events to monitor both causes of change and responses (e.g., hurricane damage and the following regrowth) as well as to support PI requests (e.g., regional surveys of invasive species or phenology).

Annual visits inevitably miss important site-level signals such as phenology. Extending airborne observations to the continental scale will require a linkage from the meter-scale regional measurements to satellite measurements. The need to cross scales drives the AOP to observe a substantial area on the ground surrounding each site. Currently we estimate that each AOP site mission will cover approximately 300 km^2, a compromise between area coverage and cost. To support studies at the continental scale, the airborne data will be assimilated into ecological models along with higher-frequency multispectral satellite data, albeit at coarser spatial resolution, as well as data from national databases and the other NEON observational components.

5.3 Integrating Required External Datasets: The Land Use Analysis Package

Human modifications of the planet affect ecosystems and 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) require other types of data collection.

NEON requires land use data on the local and continental scale that 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 and 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. Data related to land use from outside the NEON observatory is provided via the Land Use Analysis Package (LUAP).

The LUAP will provide integrated, interoperable information that ecological modelers and forecasters can use to extend their models to a continental scale. The LUAP will collate existing datasets (Table 7), primarily from 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 datasets, 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 causes of change in ecosystems and responses to change and makes the data available for continental-scale analyses, models, and forecasts.

Table 7: Land Use Analysis Package datasets

Land Use Analysis Package datasets		
	LUAP Dataset	**Temporal Extent**
Satellite remote sensing	U.S. Geological Survey Land Processes Distribulted Active Archive Center (USGS LP DAAC) MODIS MCD43 B1: Bidirectional reflectance distribution function (BRDF) Albedo Model Parameters	16 day
	USGS LP DAAC MODIS MCD43 B2: BRDF Albedo Quality	16 day
	USGS LP DAAC MODIS MCD43 B3: Combined Albedo	16 day
	USGS LP DAAC MODIS MCD43 B4: Nadir BRDF adjusted reflectance	16 day
	USGS LP DAAC MODIS MOD09 A1: Surface reflectance	8 day
	USGS LP DAAC MODIS MOD11 A2: Land surface temperature and emissivity	8 day
	USGS LP DAAC MODIS MOD12 Q1: Land cover	1 year
	USGS LP DAAC MODIS MOD12 Q2: Land cover dynamics	1 year
	USGS LP DAAC MODIS MOD15 A2: LAI and fPAR	8 day
	USGS LP DAAC MODIS MYD09 A1: Surface reflectance	8 day
	USGS LP DAAC MODIS MYD15 A2: Leaf area index (LAI) and fraction of abosorbed photosynthetically active radiation (fPAR)	8 day
Physical geographic information	Protected Areas Database of the United States (PAD-US)	Variable
	FEMA National Flood Hazard Layer (NFHL)	Variable
	Kuchler Potential Natural Vegetation map	Single collection
	Multi-Resolution Land Characteristics Consortium (MRLC) National Land Cover Dataset (NLCD 2001)	Variable
	National Atmospheric Deposition Program National Trends Program (NADP/NTN)	1 Week
	North American Bird Breeding Survey (BBS)	1 year
	National Transportation Atlas Database 2008 (NTAD) Roads	Variable
	NTAD Airports	Variable
	NTAD Ports	Variable
	NTAD Railroads	Variable

Land Use Analysis Package datasets		
	LUAP Dataset	**Temporal Extent**
	Global Historical Climatology Network - Daily (GHCN-Daily)	Variable
	U.S. Department of Agriculture National Resources Conservation Service National Map Unit Interpretation Record (USDA NRCS MUIR) database	Variable
	USDA NRCS SIR database	Variable
	USDA NRCS Soil Survey Geographical (SSURGO) database	Variable
	USDA NRCS State Soil Geographic (STATSGO2) database	Variable
	USFWA National Wetlands Inventory (NWI)	Variable
	USGS Elevation Derivatives for National Applications (EDNA)	Variable
	USGS National Atlas/USACE National Inventory of Dams (NID)	Variable
	USGS National Elevation Dataset (NED)	Variable
	USGS National Hydrography/Watershed Boundaries Dataset (NHD)	Variable
	USGS Quadrangle maps (U.S.Topo)	Variable
	USGS HYDRO1k	Single collection
	USGS National Map Forest Cover Types	Single collection
Human geographic information	U.S. Bureau of Census Data	10 year
	USDA National Agricultural Census	5 year
	EPA AIRS Database Facility Subsystem	Variable
	USDA Forest Inventory Analysis (FIA)	5 year

5.4 NEON Data Analysis and Data Products

NEON data will provide empirical or inferential insight into the fundamental processes governing the relationships between the causes of environmental change and the impacts of environmental change over time and across ecoclimatic domains. NEON is designed to support the collection, curation, and dissemination of data. Integral in this process is the concept of data products, and the infrastructure supporting their development and dissemination.

NEON is committed to providing openly accessible, quality controlled, and assured data to the community, from raw, field-collected data to a set of integrative, multidisciplinary data products that address high-level challenge questions. These data products will be produced through an analysis and modeling framework. The creation of both raw data and data products relies on an extensible set of product and protocol definitions, statistical and computational software tools, and open standards to ensure that their utility is maximized and their provenance fully tracked.

5.4.1 Overview of NEON Observations

NEON will provide large amounts of information on a huge number of ecosystem attributes by deploying approximately 17,000 sensors of roughly 200 distinct types, and making biological measurements on about 2000 plots distributed over 60 sites. The results of this data collection will be about 500 distinct primary data types (known as Level 1 data products) and 120 types of derived ecological parameters (known as Level 4 data products). Samples collected by the network will yield 175,000 chemical, taxonomic, isotopic, and genomic analyses per year, and a similar number of samples will be stored annually in the NEON Virtual Collection Facility for future research.

Figure 23 provides a high-level view of the types of data NEON will collect. Basic calibrated data,or data that have been temporally or spatially rectified, will be processed using state-of-the-art algorithms and models to produce ecological information that enables the use of NEON data to rapidly and effectively address ecological science, education, and policy questions and issues.

Data Products by Category and Geographic Scale

	LOCAL (SITES)	REGIONAL (AOP)	NATIONAL (LUAP)	NATIONAL (DATA + MODELS)
Biomass/Productivity/Metabolism	✓	✓	✓	✓
Soil Structure/Physics	✓	✓	✓	✓
Bioclimate/Energy Balance	✓	✓	✓	✓
Hydrology/Ecohydrology	✓	✓	✓	✓
Habitat/Landscape Structure	✓	✓	✓	✓
Biodiversity/Invasive Species/Biogeography	✓	✓		✓
Population Dynamics/Demography	✓		✓	✓
Land Use Land Cover		✓	✓	✓
Biogeochemistry	✓	✓		
Microbial Diversity/Function	✓			✓
Atmospheric/Air Quality	✓		✓	
Phenology	✓			
Infectious Diseases/Vectors	✓			
Ecological Stoichiometry	✓			

Figure 23: The distribution of NEON data products by category and data suite, shown at different geographic scales.

5.4.2 Data Product Philosophy and Needs

There are two parallel philosophical considerations implemented in NEON's concept of data products, and the analyses producing them: (1) the data are sampled in space and time, and (2) NEON samples many physical and biological variables in a coordinated way.

- **Sampling in time and space**. Because NEON seeks to monitor the impacts of environmental change on ecological processes, data are collected and maintained such that trends can be robustly detected. This is facilitated by optimized spatio-temporal sampling designs. For instance, the spatio-temporal dynamics of leaf area require the integration of fixed-location observations at high temporal resolution via terrestrial instrument measurements (Section 5.2.4), distributed periodic observations via terrestrial biological measurements (Section 5.2.1), and annual observations of leaf area over tens of kilometers via the Airborne Observation Platform (Section 5.2.7), thus integrating complementary co-located data to maximize information retrieval.

- **Integrative measurements of physical and biological variables**. While individual data streams are inherently useful, analysis of trends in multiple biological and physical NEON data types will deepen our understanding of ecology. For example, meteorological observations, vegetation structure, land use change, plant productivity, or disease prevalence may be of interest in isolation, but integrated data on all these factors could provide information on mammalian habitat suitability, food availability, survival, and fecundity.

5.4.3 Data Levels and Cataloging

In order to maintain the large array of information NEON gathers, its data products are organized into a set of five product levels. These levels, defined in Table 8, are derived from and are roughly consistent with the National Research Council's Committee on Data Management and Computation (CODMAC) standard for archiving NASA data, and serve partly to delineate low-level, raw data, from the types of integrative data products described above.

Table 8: NEON Data Product Level Definitions

NEON Data Product Level Definitions	
Level 0	Raw data from instrument or human-made observations.
Level 1	Calibrated data generally from a single instrument, observer, or field sampling area. These data may include information on data quality.
Level 2	Combinations of level 1 data used to create a gap-filled data stream that may replace a level 1 product. Generally, products at this level will reflect a stream from a single instrument, observer, or field sampling area. Annotations will indicate the gap filling approach employed.
Level 3	Level 1 and/or 2 data mapped on a uniform space-time grid.
Level 4	Derived products using levels 1, 2 and/or 3 data. Products at this level may combine observations from more than one instrument, observer, and/or sampling area.

For example, three platinum resistance thermometers and an aspirated fan, mounted together, are used to collect WMO air temperature measurements every second as voltage readings; these readings are the raw, Level 0 data. The readings are converted into physical units via a well-defined set of calibration coefficients and the data from the three thermometers are averaged via an algorithm to produce Level 1 data, with data gaps annotated. The gaps are filled to produce Level 2 data. There is no need of a Level 3 product here, but one may define monthly or yearly averages of this one-second data as a derived, Level 4 data product.

Data products falling into these levels are organized into data product catalogs, which contain descriptions of the context and extent to which the measurements and/or observations are made. All of NEON's higher-level, derived products are categorized into suites that address NEON Grand Challenges. The catalog listing also includes information on the spatio-temporal extent of the data product, and a description often citing literature describing its usefulness.

5.4.4 Data Product Development

The process for creating data products from instrument and observational measurements will require collaboration of NEON engineering, computing, and science staff, often in concert with community stakeholders who will provide guidance and input. Data products derive from data gathered in accordance with established protocols, are influenced by NEON Grand Challenges (Figure 1), and are recorded with standard metadata that trace provenance. Each data product is associated with data quality metrics and the algorithms used to produce it, as well as any derived or estimated uncertainties.

Data processing steps may involve:

- Calculation of basic physical quantities from measurements
- Calculation of key quantities during data gaps using statistical models to allow calculation of temporal averages of integrals (e.g., monthly or annual totals)
- Calculation of desired quantities from basic quantities
- Inference of parametric information from calculated quantities
- Estimation of process controls from observed, calculated, and parametric quantities.

A schematic outline of data processing methodology is shown in Figure 24.

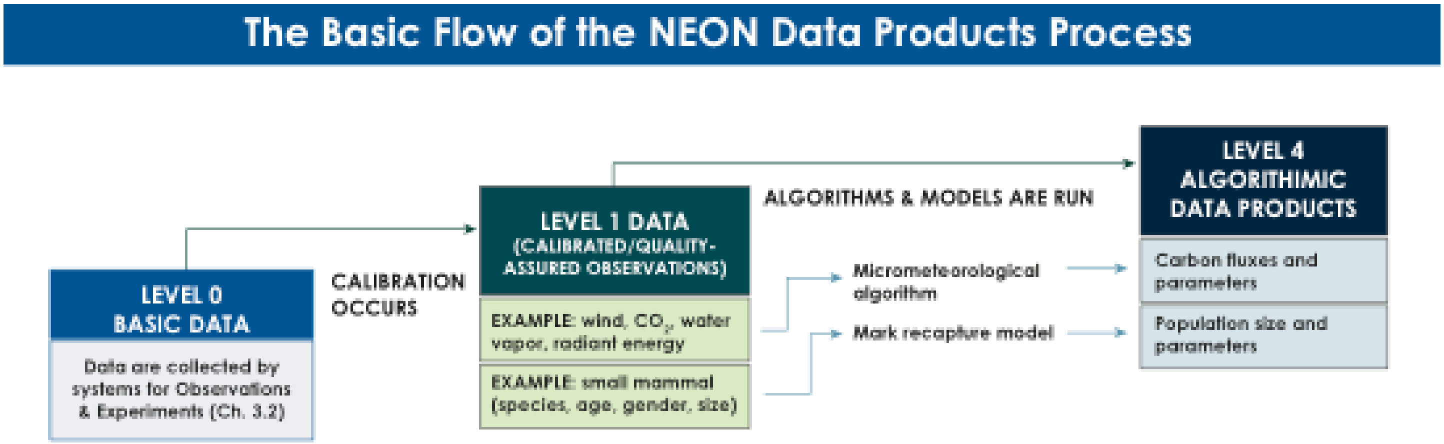

Figure 24: NEON will collect basic data through a combination of instrumentation and human observers. Basic calibrated data (Level 1) or data that have been temporally or spatially rectified (Levels 2 and 3) will be processed using state-of-the-art algorithms and models to produce synthetic data products (Level 4) that both specialist and nonspecialist scientists can use to rapidly and effectively address ecological problems.

6 USING NEON: EDUCATIONAL RESOURCES, ECOLOGICAL FORECASTING, AND THE ADVANCEMENT OF THEORY

The vision for NEON is to advance our understanding of ecological systems in an integrated way. It is intended to transform ecological science and education. The following sections describe a framework for use of NEON for educational purposes and use of NEON for ecological forecasting and the advancement of theory.

6.1 NEON Education and Public Engagement

NEON educational resources are broadly designed to help people think of science, and the data it depends on, as a way of knowing. NEON provides extraordinary opportunities for learning and public engagement, including (1) opportunities for a wide range of interactions – such as between educators and scientists, students and researchers, policy makers and researchers, scientists and the general public, and students and other students; and (2) web-based tools allowing decision makers, educators, students, scientists, and the public to access and contribute to scientific data products, visualizations, and eventually forecasts. The integration of scientific data products and educational resources that use these data, supported by robust cyberinfrastructure, physical infrastructure, human resources, and strategic partnerships, will enable facilitation of a range of innovative learning experiences that will engage a diversity of audiences in the process of scientific discovery and interpretation. This approach supports the broad effort to raise scientific literacy in the United States.

NEON, 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 educational programs and courses. As the interface between scientific data and many user communities, the NEON education and outreach team will facilitate participation in educational programs and the use of NEON products to meet community needs. Successful engagement depends on a rigorous program development process where NEON educational, scientific, engineering and informatic staff, depending on the audience, actively collaborate with target audiences and stakeholders to assess their needs and develops innovative tools and learning experiences for partners. NEON is investing considerable effort up front in building partnerships with many complementary 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 environmental literacy and the education of the next generation of environmental scientists. Furthermore, all NEON tools and learning experiences are designed using interfaces that are modular and can easily evolve with technological advances, user needs, and public interest. This flexibility and up-front investment is critical to keep NEON educational resources relevant, innovative, and poised to significantly impact science education and public engagement into the future.

The educational goals for NEON are:

- Promote and facilitate public understanding of environmental science (i.e., scientific literacy), including fundamental ecological principles. Through innovative tools and learning experiences developed in partnership with many communities, NEON will help build a model of decentralized learning centered on the collection and consumption of environmental data. NEON is committed to providing widely accessible and usable data and learning experiences to promote public understanding of continental-scale ecology and its relevance to everyday life.

- Educate the next generation of ecologists to understand complex ecological systems and their associated changes, and apply this integrated knowledge to societal needs. Synthetic research with NEON data will require new statistical analyses and approaches to mathematical modeling, simulation, and digital mapping of complex ecological phenomena. Future ecologists will be trained as students to use large datasets to examine larger spatial and temporal scales and conduct collaborative, cross-domain analyses. This approach will be the norm for future scientists, as they master new sensors, large-scale ecological transects, and rapid mobilization of sensor units for early detection of ecological change.

- Enhance diversity of the ecological research community by disseminating NEON science and education resources to all segments of the population, including people from groups that are traditionally underrepresented within the field. The NEON user community will include a broad array of partnerships enabling educational institutions, community groups, and citizen scientists to learn from and contribute to continental-scale environmental data. An increasingly diverse mix of people will join forces to learn about and address national and global environmental challenges.

- Provide tools for students, educators, scientists, and decision makers to use NEON data to make informed decisions about environmental issues. The extensive data products generated through NEON will transform ecosystem research and enhance our ability to make environmental predictions for future decision making. NEON will collaborate with user communities to define and develop user-friendly tools to make NEON data accessible to a wide diversity of users. NEON will encourage a meaningful dialogue among scientists, educators, citizens, and decision makers to foster collaboration to develop the tools that will benefit all groups of users.

As the interface between scientific data and user communities, the NEON education and public engagement team provides tools and facilitates learning experiences that engage users with different levels of knowledge, experience and skills. To guide development of these tools and learning experiences, NEON uses the following principles:

- NEON products are based on the creation and consumption of data.
- NEON products must be freely and widely accessible.
- The relationship between science and education is synergistic and reciprocal.
- NEON educational resources are strategic and leverage existing programs and resources.
- NEON educational resources are authentic and meaningful to the people involved.
- NEON educational resources contribute to national science and education efforts.

NEON tools and learning experiences are aimed at awareness, mastery, and leadership levels (Figure 25). This approach enables users to self-define their interests and abilities regardless of their affiliations (e.g., K-12 teacher, citizen scientist, family). As individuals take more responsibility and control of their own learning (Falk et al., 2009; Falk and 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 will include numerous physical and virtual capabilities to enable educational and public use of the facility.

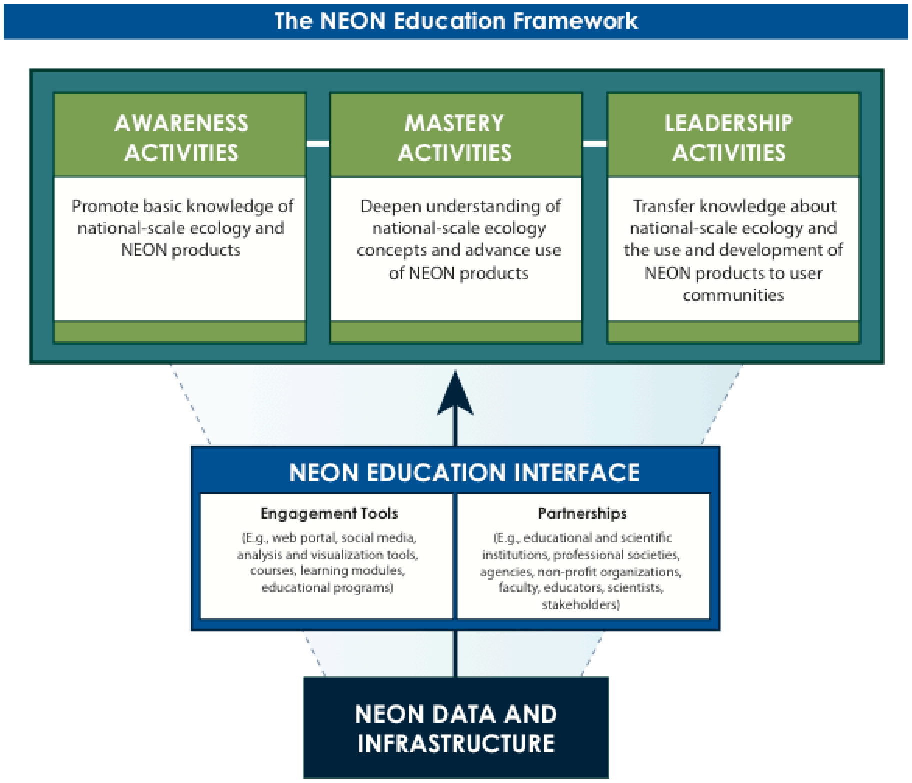

Figure 25: The NEON educational framework.

6.1.1 The NEON Web Portal

The NEON web portal will be a resource for many users as well as the external face of NEON. It will also serve as a user point of contact with NEON and a vehicle for user contributions to NEON. Thus, the web portal will function to deliver and disseminate information as well as collect it. The portal will feature the following areas:

- **Citizen science area** to enable citizen scientists to collect, contribute, interpret, and visualize scientific data, as well as provide training modules, collection protocols, and access to targeted learning experiences related to citizen science project topics.
- **General area** to introduce users to NEON and provide online learning experiences focused on the fundamental ecological concepts associated with NEON.
- **Decision-support area** that provides tools for decision makers to use NEON data to make scientifically based decisions and educates decision makers on content related to NEON data and science.

- **Educator area** 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.

- **Data products area** that provides access to NEON data products and metadata.

6.1.2 NEON Educational Programs

NEON learning experiences are designed to facilitate active science learning. During operations, NEON will work closely with interested partners to implement many of these programs. NEON educational programs feature:

Citizen science projects 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 geographically distributed data. These projects will use the citizen science area of the NEON web portal as the interface to data collection and dissemination.

Professional development opportunities to prepare educators to use NEON data and tools, provide opportunities for educators to contribute to resource development (e.g., activities for the educator area of the web portal), and facilitate community collaboration and investment in effective science education.

Research and internship opportunities for undergraduates to prepare future generations of ecological scientists and science, technology, engineering, and math (STEM) professionals to use NEON and other continental-scale data, and broaden participation in STEM experiences by traditionally under-represented groups.

A competitive field and analysis course for graduate students to prepare the next generation of ecologists to use NEON data and tools to increase our understanding of the effects of climate change, land use change, and invasive species on continental-scale processes;

NEON museum projects to increase public awareness of continental-scale ecological issues, educate visitors about scientific strategies for researching and forecasting ecological change, and engage visitors in scientific discovery using sensors, computer modules and other NEON-inspired tools,

Postdoctoral research opportunities to prepare scientists to design, lead, and participate in continental-scale ecological research initiatives and infrastructure design and construction,

Workshops, seminars, and courses to provide training and learning experiences for individuals to more effectively use and contribute to NEON data, tools and programs.

6.1.3 Developing Educational Resources

NEON educational products are derived from the NEON mission, goals, requirements, and conceptual framework. However, the specific tools and programs will certainly change over time as new user needs are identified, new technology provides different tools, and opportunities arise due to partnerships, new funding, or societal trends. The planning framework and procedures that form the structure of NEON education must be responsive to the needs of user communities and stakeholders as well as attuned to current issues and trends. Effective communication is critical to building NEON user communities, collecting input and feedback from stakeholders, and building awareness of NEON opportunities among communities not actively engaged with NEON. Furthermore, advisory committees composed of members of the user communities and NEON stakeholders will provide input to help NEON stay abreast of the cutting edge of science education and public engagement. For its educational resources to remain successful for the life of the project, NEON must always be developing the next generation of educational tools and learning experiences in close collaboration with many partners.

The NEON educational conception framework organizes educational resources by levels of understanding (i.e., awareness, mastery, leadership). Table 9 depicts the educational resources by level of understanding, with the caveat that some products will be used in activities that fall in more than one level of understanding. For example, the citizen science projects will include all three levels of understanding, where participants can increase their knowledge, experiences, and skills as they engage in additional components of the projects.

Table 9: Summary of NEON educational resources within the conceptual framework

	Awareness	Mastery	Leadership
Citizen science	X	X	X
General web portal	X		
Decision-support web portal		X	X
Educator web portal		X	X
Professional development		X	X
Undergraduate research	X	X	
Undergraduate internships	X	X	
Graduate course		X	X
Museum projects	X		
Postdoctoral research		X	X
Workshops, seminars, courses		X	X

Using this framework and the guiding principles described earlier, NEON educational resources will help people think of science as a way of knowing, and encourage people to use NEON data products to better understand continental-scale ecology.

6.2 Ecological Forecasting

Ecological forecasting includes two closely related activities. The first is similar to a weather forecast; that is, predicting the most likely future state of an ecological system. The second activity is predicting 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 on biodiversity of alternate practices for forest fire risk mitigation). 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 is critical for documenting and advancing scientific understanding and is useful in societal application of knowledge (Katz and Murphy, 2005). Forecasting is necessary for advancing theory because it confronts theory with observations via predictions. Enabling ecological forecasting is a part of NEON's mission, and the first two formal requirements for the observatory call for the required infrastructure to enable forecasting.

Ecological forecasting, modeling, and analysis activities are central to the NEON vision. 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). NEON must provide empirical measurements of key ecological state variables and parameters that are important for development of quantitative forecasts in complex dynamic systems (Gunderson and 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, 2003, for a full account of forecasting in the chaotic weather system). As a result, NEON must provide consistent measurements of key ecological state variables and parameters across time and space.

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), key rate constants can be measured, and a model can be developed and exercised. Examples of such research abound, but this type of forecasting is limited by a dearth of long ecological time series (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 made by NEON will be evaluated over time as experience is gained through cyclic prediction-observation comparison and the analysis of factors that most strongly drive forecast errors. This will help ensure the data remain relevant, effective and efficient in a changing environment.

Aspects of ecological forecasting such as forecasts for invasive species (Figure 26) and forecasting the biological carbon budget (Figure 27) illustrate two potential applications of NEON information.

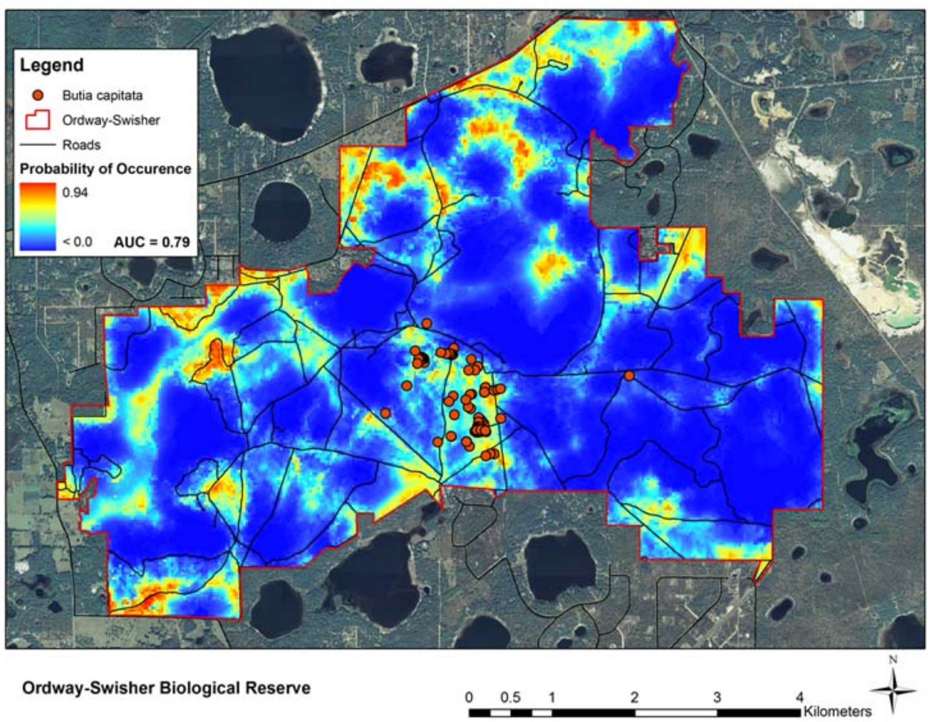

Figure 26: Predicted distribution of Pindo Palm (Butia capitata) within the Ordway-Swisher Biological Reserve (FL) according to a habitat suitability model. Red and yellow colors indicate a high probability of occurrence of this invasive species, while blue indicates a low probability of occurrence.

- **Invasive species forecasting.** Invasions and susceptibility to invasion depend on processes at multiple scales. NEON and non-NEON programs provide information, broadly grouped into site-based sampling, 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 and Zimmermann, 2000; Pulliam, 2000; Austin, 2002; Pearson and Dawson, 2003) to integrate multiscale data to produce a mapped forecast of the distribution and abundance of an invader over time. Figure 26 shows an example of how the distribution of an invasive species (Pindo Palm) can be predicted using a habitat suitability model.

- **Carbon budget forecasting**. Data collected through NEON and used for analysis and forecasts could also contribute to an estimate of the U.S. biological carbon budget (Figure 27), starting with processes at different scales (from molecular and organismal to continental) that produce 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 will be integrated into a land surface model that incorporates both biophysical and biological processes (the NEON prototype is based on the NCAR CLM) integrated with observations over time using data assimilation schemes such as the ensemble Kalman filter or ensemble Kalman smoother. This approach will produce estimates of ecosystem-atmosphere fluxes of CO_2 that can be compared at regional scales to similar estimates deduced from atmospheric concentration gradients using a system such as NOAA's CarbonTracker.

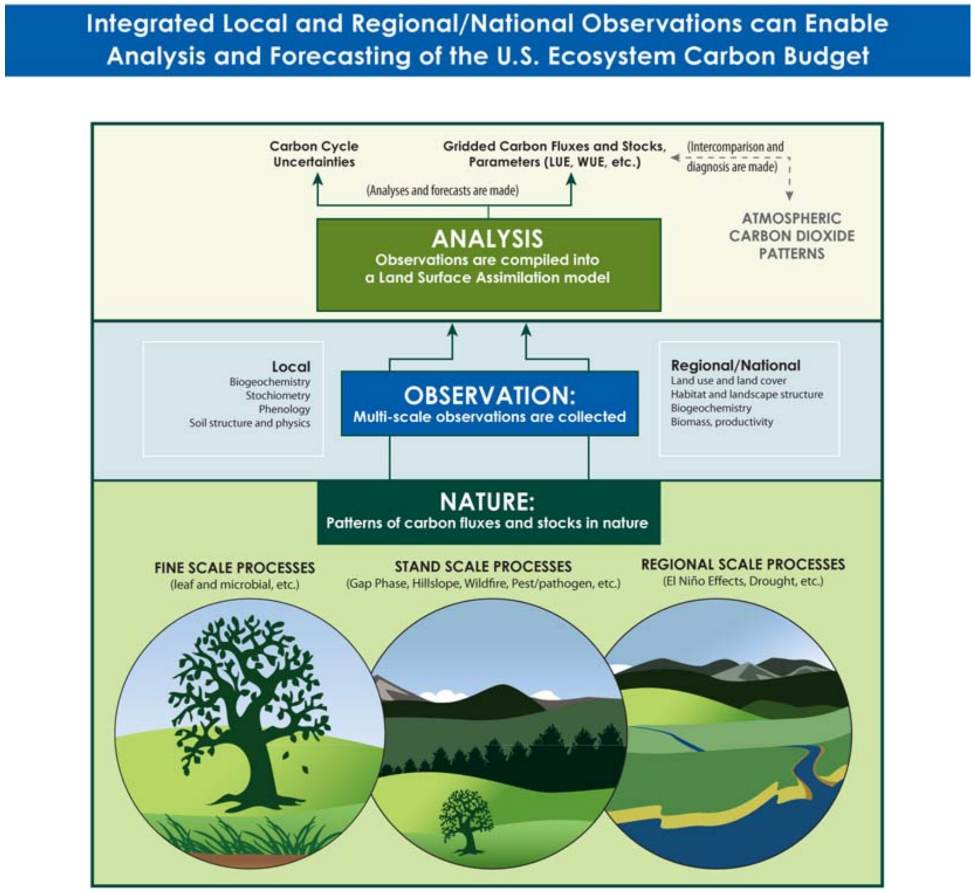

Figure 27: A conceptual analysis and forecast of the U.S. ecosystem carbon budget derived from multiscale observations of natural processes and analyzed with a land assimilation model. Acronyms include light use efficiency (LUE) and water use efficiency (WUE).

The limitations of linking forecasting to short-term or episodic data collection arise as a consequence of the nature of dynamic ecological systems. The range of values for both proximal explanatory variables and response variables changes due to changing species composition, acclimatization, and evolution. Iterative or cyclic forecasting provides a more powerful approach that, in a general way, accommodates the continually changing nature of ecosystems. 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. This approach has allowed meteorological forecast skill to evolve over time since the 1950s (Figure 28). The overall trend in ability to forecast variations in atmospheric pressure 36 hours in advance in the U.S. operational forecast model is surprisingly steady given the changes to satellite observations, computing power, and advances in knowledge. It highlights the fact that quantitative models should not be evaluated in a binary fashion (right versus wrong). For ecological forecasting, 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, i.e., with NEON data).

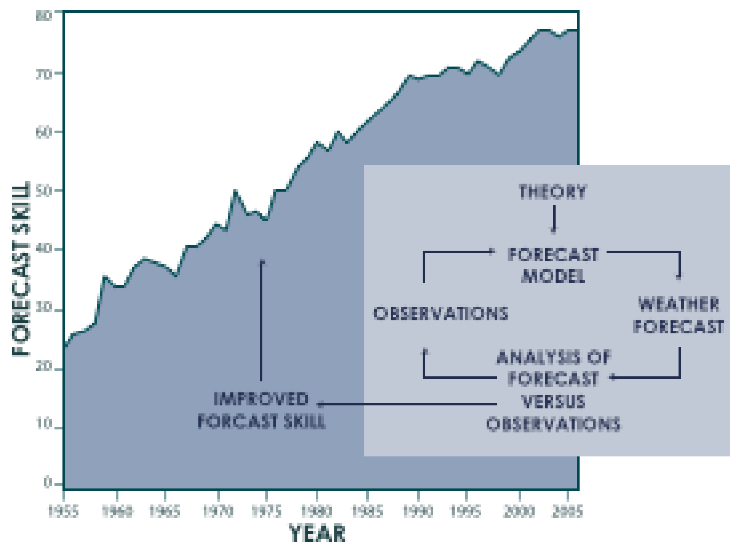

Figure 28: The ability of weather forecast models to predict variation in atmospheric pressure (forecast skill) improved over time as a result of the iterative development of improved forecast models and observations, driven by the regular analysis of weather forecasts against observations. This trend 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 theory, forecast models, and computing.

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.

The predictive accuracy of a model may drift as biological processes (physiological acclimatization, change in community composition, or evolution) cause state or parameter values to change (Figure 29; 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).

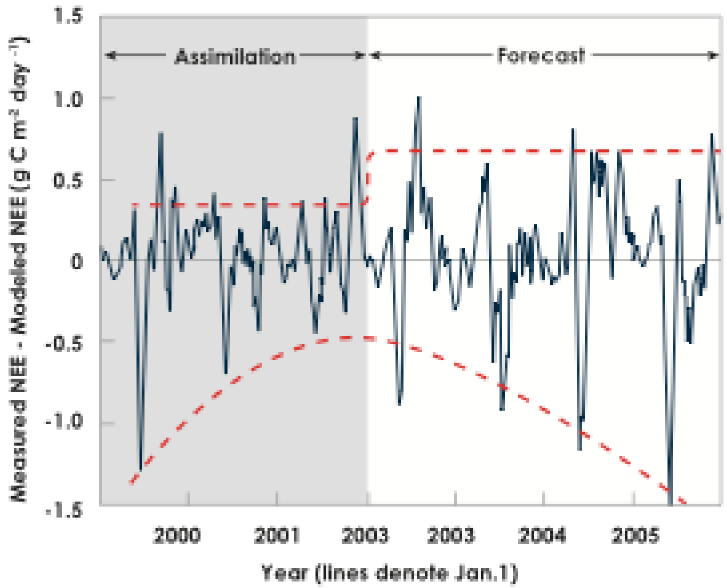

Figure 29: Comparison of twice-daily (sunlight and dark periods) predicted and observed net ecosystem exchange (NEE) of carbon. The shaded years are the period during which states and parameters were estimated. The unshaded years are thus a forecast of carbon exchange given observed climate. Negative excursions are errors in carbon uptake from the atmosphere, that is, photosynthesis (A). Positive excursions are errors in nighttime 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).

Ecological forecasting requires a research strategy including 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 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 causes of change (climate, land use) or a single or small number of response variables, but not causes and responses in a coordinated and consistent fashion.

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, then state variables should be targeted for improved measurement. NEON measurements and data products will be evaluated to ensure their effectiveness as experience is gained in modeling and forecasting, and as new needs and technologies emerge.

In summary, progress in ecological forecasting of responses to causes of environmental change 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 composition changes or species 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. The NEON design and the data products it produces will satisfy this requirement.

7 THE NEED FOR OBSERVATIONS IN A CHANGING WORLD

The earth's environment for biology is changing rapidly, and ecological responses are accelerating, putting critical ecosystems at risk. These biotic changes impact ecosystem services and biodiversity and may dominate future terrestrial carbon feedbacks. As rates of climate change exceed rates at which species can adapt or adjust their ranges, complex responses are likely to occur that have no direct analog in the past or present biosphere. Rapid climate and land use changes undermine the assumption of steady-state conditions. Ecologists use environmental variation in space as a surrogate for observing change over time, but this is misleading under changing conditions.

As climate and other environmental factors change, forecasting becomes intrinsically more difficult. As systems move further from a steady state, complex dynamics become more and more likely. Different models exist for this type of disruptive climate impact but few datasets exist to allow scientists to distinguish between alternate hypotheses, and insufficient data exist to tell which models of change are most generally applicable.

Where techniques exist for ecological forecasting in complex systems in some situations, the actual future trajectory of a system may be forecast. In other situations, however, only the likelihood of a dramatic change may be quantifiable. A consistently collected baseline of critical data, obtained soon, will provide information that will gain in value for forecasting over the coming decades.

Technological solutions to collecting ecological data are increasingly important, and are actually necessary to capture detailed time series, because traditional field approaches may fail to observe processes that change rapidly. Remote sensing methods have already been transformative in this regard, and the emerging remote sensing technologies deployed by NEON will further transform the field with the new measurements and scales they observe.

The comprehensive coverage and diversity of data from NEON provide measurements of biological variability that are required to understand the complex processes of the biosphere in transition. The world will experience an era of rapid biological change as a result of human development. Ecology must collect the vast amounts of global data needed to understand, forecast, and ultimately manage the changing biosphere and the services it provides.

The advent of continental-scale research will lead to changes in ecological science itself, including its related infrastructure, culture, and training. NEON provides data and infrastructure for decadal and continental-scale science, and will join an emerging global network of environmental observatories. Together, these facilities will provide information on the causes and consequences of environmental change. Adapting the methods and approaches of ecology to understanding the dynamics of vast areas, change over long periods of time, and the impacts of increasing connectivity will require career-long investments based at these observatories, in the same way that astronomers are linked to telescopes and oceanographers are to ships.

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