Biodiversity and Ecosystem Function – DRAFT 6 (18 Jan 2005)

I Why biodiversity and why NEON?

A grand challenge for the 21st century lies in developing – for the first time – a working knowledge of the nation's biological diversity in all its complexity so we can preserve and use these resources sustainably (Bloch et al., 1995; PCAST, 1998). This knowledge is critical to science and society—for maintaining the nation's natural resources, for growing its economy, for sustaining human health and agriculture, and for improving the quality of human life. We urgently require this knowledge as the daily conversion of natural systems to human-managed systems accelerates the decline of biological diversity and its habitats.

Forecasting the impacts of changes in biodiversity and human activities on ecosystem function/services demands understanding how the current geographic ranges of species are likely to shift/respond to changes in both anthropogenic and climatic drivers. NEON must therefore enable a full assessment of biodiversity and its reciprocal interactions with ecosystem function and human activities, as follows:

1. Census, documentation and analysis of biodiversity at the levels of:
   - genes (and genomes)
   - individuals (phenotypes and traits)
   - populations (abundance and genetic architecture)
   - species (composition and lineages)
   - species assemblages (type, size, and distribution)
   - landscapes

2. A full understanding of the ecological and evolutionary processes that determine current patterns of biological diversity.

3. How these processes will change in response to climate variability and human activities, such as land management/use.

These NEON objectives also call for *experimental studies* that:
- Target specific ecosystem functions and their taxonomic group(s).
- Provide a comprehensive continental view across habitats and biomes by integrating:
  - local and regional scale processes
  - urban to rural to wildland gradients
- Include a broad scope of taxa in both natural and managed systems.

To date, most experimental and observational studies of how variation in biodiversity affects ecosystem functions have focused on plants in temperate grasslands. Therefore, NEON's research platform will be designed to:
- expand the biodiversity focus (genomes to landscapes) and taxonomic, habitat, and biogeographic scope of scientific investigation to continental scale.

- Provide integrated analyses of the results of experimental and observational studies for regional to continental scale syntheses, which are beyond the capacity of existing networks or individual projects to achieve.

Unlike any single site or existing network (e.g., LTER), NEON will give the ecological community the potential to (a) model biodiversity at all its levels (particularly its genetic component); (b) understand how these levels are expressed across space and time; and (c) model biodiversity and ecosystem function and their reciprocal relationships with human activities from a local to regional to continental scale. As a systems approach, NEON will be designed from the outset to remove the bias of the currently limited temporal and spatial scales at which we can collect and analyze data, which has severely limited the scientific questions that can be asked and conclusions that can be drawn about how complex biodiversity, ecological, and societal systems function and interact.

Fundamental understanding of the role of diversity in ecosystems, human enterprises, and basic ecological and evolutionary processes requires wide-scale, coordinated, and synoptic measures of biodiversity, ecosystem parameters, and human activities and institutions. Only by integrating at regional and continental scales can science unravel the multitude of possible interactions and reach the level of mechanistic understanding that allows ecological forecasting.

We have increasing evidence that the temporal and spatial scale at which we collect data and conduct analysis influences our conclusions about how ecosystems function. But to translate ecological data to broader-scale management (and preservation) of natural resources requires that we acquire the ability to sample the range of variation in environmental and social drivers that occurs across the continent, linking local to regional to national patterns and processes.

The continental U.S. is a mosaic of landforms, ecoregions and habitat types, natural and managed, that vary in the ecosystem services they provide. NEON will provide the integrated and representative network of technologically advanced platforms to decipher the biodiversity and ecosystem function across these habitat types, which in turn will inform decision-making concerning the management, use, and where appropriate, restoration, of these resources.

II Specific Questions

Question 1:
How do variations in biodiversity from genes through landscapes and across space and time affect ecosystem function and human activities?

Question 2:
How do human activities affect biodiversity, from genes through landscapes, and ecosystem functions across space and time?

To answer these questions we will need to:

- Document the historic geographic distribution of known species and lineages from legacy databases (i.e., museums, herbaria, and culture collections), and determine the taxonomic and geographical gaps in these data.
- Assess the genetic, genomic, phenotypic, and species diversity of appropriate taxa that can serve as metrics (indicators) of changes in ecosystem functions/services across broad spatial scales at ecologically relevant time scales.
- Document species assemblages, habitat composition, and landscape structure across gradients of climate, land use/management (e.g., urban to suburban to exurban to rural to wild), and across climatic and elevational gradients as a baseline for documenting future change and, where appropriate, informing restoration.
- Acquire appropriate data on human systems (e.g., population density, land use, demographics, etc.) and attitudes.
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To conduct these activities, we will need to develop:

- Mobile labs, sensors and sensor-networks to:
    - Map the current composition, abundance, and distribution of appropriate taxa, including field-based automatic recognition systems for rapidly identifying species and higher taxa.
    - Study sudden natural disasters, perturbation,s and responses.
    - Mobile labs to assess human attitudes and social systems.
- Analytical labs (centralized or distributed) capable of very high throughput (VTHP) analyses of genetic, elemental, ionic, isotopic, and other samples.
- Tools to quantify how interactions among species change in response to alterations in biotic (e.g., herbivory, invasive species or diseases, pollination) and abiotic (e.g., climatic variables, fertility, fire) factors in the environment.
- The cyberinfrastructure, informatics, and statistical tools (elaborated below) for (a) integrating and archiving biodiversity data from genes to landscapes, (b) analyzing these data to determine biodiversity patterns and processes, and (c) synthesizing these data with data on ecosystem functions and human activities.
- A biodiversity informatics center for (a) integrating, analyzing, and visualizing NEON-generated and related legacy biodiversity data, (b) implementing and managing a national network for informatics and web-based data and analytical services (elaborated below).
- New archival facilities for processing, curating, and archiving NEON-generated samples (vouchers, tissues, genetic preparations, etc.) and their associated data.
- Field sites, appropriately sized, located, and dispersed (watershed scale), with associated support facilities to conduct short and long-term, regionally coordinated experiments to test hypotheses and observe responses to manipulations of biological composition and environmental drivers.
- Capacity to establish new experiments in response to anthropogenic and naturally produced disturbances.

III The Data

Baseline Biodiversity Data

Documenting the known biodiversity of the United States from legacy data is a fundamental starting point to implementing the biodiversity research plan. Critical here is harnessing the data associated with voucher specimens in the nation's herbaria and museums that document 200 years of the biological exploration of the nation. This encompasses two tasks, which are essential to NEON research, *but only appropriate parts of which might be part of NEON-funded infrastructure.*

- Assembling and mapping these biodiversity data, many of which are already digitally captured, georeferenced, and available over a number of biodiversity networks, such as FishNET, HerpNET, MANIS, ORNIS, APHIS, GBIF, and NatureServe.
- Digitizing and georeferencing those museum and herbarium biocollections data that have not yet been digitized, but are essential to establishing and mapping the known biodiversity of the nation. Because existing data can be used to predict and model the distribution of species of animals and plants in areas from which vouchers are unknown (by proven statistical methods), these data play a key role in maximizing the efficiency of further sampling.

Museums and herbaria will be essential partners in the NEON research enterprise in processing, managing, and archiving *new, NEON-generated biocollections, ecocollections and digital collections and their associated data* using the NEON informatics infrastructure. The transformational aspect of these collections will be their documention through physical and digital means of the presence *and absence* of biodiversity for robust modeling analyses. In turn, this will encompass automated, high-throughput identification capacity and biodiversity informatics architectures, software, and tools for dissemination and analysis.

Genes—Genetic, Genomic, and Phenotypic Diversity

Most ecologists still use species determinations based on field guides when resolving patterns of richness and abundance in the systems they are studying. Surveying and documenting genetic and genomic diversity will require the deployment of rapid high-throughput facilities and protocols. DNA-based techniques are particularly critical for soil/microbial biodiversity, where it is often impossible to culture a large fraction of the total biota, and for microarthropods from all habitats. Diversity assessment should include techniques for estimating both composition (genetic and taxonomic) and abundance.

The NEON platform must enable capture and documentation of ecological and evolutionary dynamics across extremely small temporal and spatial scales, namely, (a) the movement of individuals and divergence in subpopulations; (b) ecological and ecosystem processes that underpin incipient evolutionary changes in biodiversity; and (c) identification of relevant lineages among study species.

NEON's genomic infrastructure should accommodate techniques and facilities, including:

- DNA-based microarrays designed to survey a particular gene (or genes) across diverse taxonomic groups for identification or targeting specific genes of functional importance (e.g., genes involved in components of nitrogen cycling).

- Characterization of whole microbial genomes to develop assays of functional suites of genes. The current database of microbial diversity will need to be greatly expanded.
- Development of portable field-capable equipment with DNA-based identification technology.
- Documentation of all genomic and phenotypic tests with georeferenced vouchers.

Functional traits

Most of the effects of biodiversity on ecosystem processes and services are due to the functional characteristics of the organisms present. Given a certain environmental envelope, ecosystem functions can be predicted from the functional traits of the most abundant species—at least in the case of vascular plants.

A major unanswered question is whether assemblages of organisms that differ greatly in their traits lead to different magnitudes and rates of ecosystem functions than assemblages with very similar traits. Therefore, a primary objective of the NEON research platform for elucidating biodiversity and ecosystem processes is documentation of functional traits of taxa. Initially, this will require establishing which fundamental traits should be measured across the NEON network in order to predict essential ecosystem processes (e.g., nutrient cycling, plant and animal production, climate and water regulation).

Populations: Abundance and Activity (variation among and within)

Deciphering biodiversity and ecosystem function requires the ability to detect movements of individuals and populations across space, in turn allowing early detection and observation of changes in species abundance and distribution. These factors remain virtually unknown yet have profound implications for understanding the relationship between biodiversity and ecosystem function, with implications for environmental management, conservation biology, and policy issues. NEON therefore requires a nationally and regionally dispersed sensor network that incorporates the most recent advances in nano- and sensor technology to enable detection of movement of individuals and populations in specific habitats.

Species/Clades: Taxa and lineages

With the technical tools of moleculary biology (e.g., sequencing and fingerprinting) and the analytical tools of modern evolutionary systematics, biodiversity can now be characterized in the form of assemblage cladograms and lineage phylograms. NEON sensing and characterization of species and lineage diversity will require a hybrid approach. It will apply phylogenetic tools to acquired genomic, morphological, and other data on a geographic scale where feasible or essential. Otherwise, NEON will apply traditional biotic inventory and survey results to mapping species distributions on as fine as scale as possible.

Assemblages and Habitats

Populations are organized into assemblages (communities) and habitats that comprise the characteristic template of the landscape and of ecological and evolutionary processes. Yet,

there are few data that integrate genetic, phenotypic, and population-level biodiversity data with that from communities and habitats. Thus, NEON will need to provide coordinated and synoptic measures of species composition, (e.g., plants that form terrestrial habitats) at scales that intersect with genetic to landscape pattern and process.
Remote sensing can contribute to this census and mapping, but, as discussed above for genomic through species surveys, on-the-ground sampling will be critical. Therefore, NEON infrastructure will require:

- Ground-truthing of new technological survey instruments and protocols across diverse environmental conditions.
- Sensors of airborne chemicals for biochemical and isotopic identification to speed and automate assemblage mapping and observation.
- Tools and techniques to assess physiological properties of individuals or integrated indicators of whole-assemblage function, such as water use, water use efficiency, or integrated carbon fixation rates.

Species Interactions: Selected
As changes in climate and land use alter the distribution of species, historical patterns of coexistence and interaction are replaced by novel ones. Decipering the relationships between biodiversity and ecosystem function requires the ability to correlate the impacts of anthropogenic and natural disturbances with shifts in biodiversity and their cascading effects on food chains and ecosystem processes and services. For example, loss of sea otters has resulted in increased herbivore damage to kelp beds along western North America, a resource that is critical for maintainance of fisheries. It has also increased the number of shark attacks on humans as their normal prey has declined.

Tightly linked species interactions are probably highly susceptible to linkage disruptions caused by climate variability. Changes in phenology induced by climatic shifts have resulted in early arrivals of bird species when their food is unavailable, and asynchrony between flowers and their pollinators.

NEON infrastructure must include an observational network that is capable of detecting, mapping, and predicting such changes in key species interactions over a broad geographic scale, particularly species interactions involved in essential ecosystem services, such as, pollination, mycorrhizal associations, nitrogen fixation, herbivory, and regulation of herbivores by natural enemies.

Landscapes: Composition and abiotic variables [Integration with Land Use Subcommittee]
Spectral imagery can capture how changes in land management/use and natural disasters (e.g., fires, the recent tsunami) can dramatically alter vegetation and land cover. In some cases, we can use these images to track shifts in the number of abundant or spectrally-unique species or to predict how the alterations in habitat size, connectedness, or overall cover can affect the movement of species across habitats.

NEON infrastructure will incorporate sensing technology that can detect rare species or the initial occurrence of species in a landscape. Such nanotechnology is currently available to track the movements of individuals, but needs to be developed to measure movement patterns of a broader range of taxa, including those with small body sizes (e.g., insects). NEON also requires parallel technology to track the movement of elements (e.g., nitrogen) and other abiotic variables and the feedback loops between changing biodiversity, climate, and land cover.

Social: Human drivers and responses
(Information for this section to follow.)

IV Infrastructure Needs

Sensors and Sensor-Networks
NEON will spur transformational advances in both science and technology by promoting the development of sophisticated portable field sensors capable of genetic identification and referencing through real-time access to the IT structure via satellite connection. The critical advance is the ability to conduct biodiversity assessment in the context of all available data archived in the system. With this capacity, changes in the geographic distribution and abundance of invasive species and disease vectors would instantly be available and the possibility of rapid response greatly enhanced. Such technology might not be available in the next five years, but should become available during the NEON build-out phase.

Embedded sensors are underexploited as a means of estimating the presence and density of species. Many animals including birds, insects, and amphibians use sound to communicate. These sounds are often species-specific or, at least, genus- or family-specific, and can often be detected at great distance. Acoustic sensor networks offer the potential for constant observation of large areas and can be deployed with existing but underutilized technology.

Visual sensors offer comparable potential. Sensors can be used to detect movement along game trails and movement-sensitive triggers can be linked with digital cameras, coupling these records with images that can be used to identify species, and sometimes, individuals.

A third application involves the use of electronic sensors in conjunction with electronic tags (e.g., Passive Integrated Transponder (PIT) tags). This latest generation of mark and recapture technology can yield unprecedented information on habitat use and movement rates, as well as population density. When coupled with genetic sampling, movement rates can yield information on subpopulation structuring as well as indirect estimates of natural selection.

Research Infrastructure

Field sites and Experiments
NEON infrastructure should be established across explicit gradients of human activity (from urban to suburban to agricultural to rural to wild), climate (rainfall and temperature)

and geography to enable observational and experimental ("natural and designed") studies of how all components of biodiversity respond to and influence natural and anthropogenic drivers.

NEON should include experimental facilities to determine and test predictions of:

- How components of aquatic and terrestrial biodiversity (genes to landscapes) are influenced by major drivers locally (e.g., productivity/fertility, foodweb structure and disturbance) and regionally (climate, habitat diversity, landscape structure).
- which components of biodiversity influence ecosystem services at regional to continental scales.

Such facilities include greenhouses, standardized plots, and aquatic facilities with environmentally controlled laboratories and artificial ponds/streams for large-scale manipulations. NEON infrastructure should also include facilities for "rapid response" experiments in response to natural (e.g., fire or flood) or anthropogenically-driven disturbances (e.g., deforestation, mine reclamation, abandoned agriculture).

Analytical Instrumentation
Biodiversity is inherently multivariate and requires sophisticated sampling and analytical designs, i.e., a long-term commitment to state-of-the-art computational, statistical, and modeling capabilities. NEON must include capability for VHTP analyses of genetic, metabolic, elemental, biochemical, ionic and isotopic samples (of organisms, soils, air, water, etc.). For example, large or small-scale tracer isotopic studies can establish movements and source-sink relationships of organisms and ecosystem components, as well as integrate long-term organismal or ecosystem performance. Facilities to provide these analytical capabilities could be co-located or distributed-networked.

Archival Facilities
NEON will require extensive archival facilities to process, preserve, and study NEON-generated biotic samples (collections, specimens, and their preparations, such as tissues) that will document biodiversity from genes to landscapes. The size and scope of these facilities will depend on estimates of the number of samples NEON will generate in 30 years. The facilities include:

- Bricks and mortar—Museums as currently structured cannot accommodate new biological and ecological collections, digital collections, or associated data that NEON research will generate. For the most part, many of these collections will involve *new curatorial and digital protocols* that will be developed as part of NEON's information flow, and will require specifically designed faciltities to accommodate these protocols. These new buildings should be associated with museums and herbaria that are partnering with the NEON enterprise. Standards for HVAC systems, floor loading, and traditional processing laboratories are established. Specifications for handling and archiving material for digital data, automatic recognition systems, high-throughput sequencing, etc. need to be developed. Each building should be able to accommodate a minimum of 750,000 to 1M specimens and their preparations (e.g., tissues, Bacterial Artificial

Chromosome (BAC) libraries) recognizing that different taxa occupy different amounts of space. Each building must have:

  - A fire-rated pod restricted to storage of specimens in alcohol.
  - Storage equipment and curatorial material—mobile compactor units and standard specimen cases. Drawers and containers for animals and plants will be cost-effective and space-efficient. Ultracold units for long-term storage of tissue specimens and genetic preparations, either freezers or liquid N systems, each with emergency, failsafe backup systems.
  - Processing laboratories for processing incoming material, shipping and receiving loans of material to researchers, and study laboratories for visiting scholars.

- Informatics equipment and software tools:
  - A comprehensive model (building on existing models and applications) to handle *all* classes of biological objects and their tracking, status, disposition, location, preparation, genetic sequence information, etc.
  - A modular architecture in order to plug in new management modules as needed for different/new functions, components, etc.
  - Design specifications for the data model based on a community requirements analysis and task studies.
  - Based on the data model, software designed, developed, tested, maintained, and supported @ 5-10 people/year.

Cyberinfrastructure: IT, Informatics, and Communications

NEON will require:

1. *Field cyberinfrastructure*
   - Biodiversity sensor arrays
     - A sensor informatics architecture and standardized interface to connect all biodiversity sensors into a network.
     - Command and control architecture to monitor on/off and health of all sensors.
     - Plug and play protocols to enable new sensors to be plugged into the network.
2. *Site cyberinfrastructure*
   - Continental network of NEON sites via high performance network such as Internet II or Lamda Rail.
   - Ability to manage sensors and instruments remotely.
3. *Data informatics*
   - Web-enabled ability to obtain streaming raw data and structured data through the web or via application programs for analysis.
     - Standards to document network APIs.
     - Standards for data schemas.
     - Standardization for data-emitting sensors.
4. *Analysis informatics*
   - Web-based analysis and synthesis portal for ad hoc modeling and analysis, integration of abiotic and biotic modeling regimes (e.g., SEEK project

products), and an architecture that allows alternative modeling algorithms and programs to analyze the same data sets in different ways

V Deployment

The geographic deployment of NEON must (1) be continental in scale, (2) be sufficiently dense, (3) be aligned along sufficient natural and human gradients (e.g., land use, climate), and (4) incorporate sufficient landscape units of biological and physical processes (e.g.,watersheds) to relate biodiversity and ecosystem function and address emerging issues across all areas of the nation. Human activities are important drivers of environmental change. NEON must provide the scope and scale to explicitly address how these environmental changes affect biodiversity and ecosystem function, and how they can be managed to maximize the valuable ecosystem goods and services and minimize the costs/losses associated with these activities.

VI Why is this transformational?

This proposed scientific research program for biodiversity and ecosystem function within NEON is transformational because it enables:

- Deciphering and vertical integration of all components of biodiversity from genes to landscapes.
- Mapping and analysis of all components of biodiversity to ecosystem function and human activities at a broad range of geographic and temporal scales.
- Predicting and testing of reciprocal effects among biodiversity, ecosystem functions, and human activities across these multiple scales.
- Forecasting of ecosystem and societal consequences of changes in biodiversity, including their interrelated responses to climate and land use.
- Mechanistic integration of ecological science with social science to address environmental concerns at the levels of detail that are required for useful regional and national forecasting.

Table 1: Instrumentation and Infrastructure

Instrumentation	Fixed or Mobile	Available Now	In progress (1-4 yrs)	Not Likely (R&D source	Used for?
Acoustic sensors	Fixed		XXX	XXX	Species ID / Abundance
Chemical Sensors (Sniffers)	Fixed		XXX	XXX	Species ID / Abundance
Optical Sensors	Fixed		XXX	XXX	Species ID / Abundance
Microchips/Readers	Portable	X	XXX		Species ID
Mobile (Portable) labs for genetic, morphological, phylogenetic research	Mobile	X	XXX	XXX	Species ID
Mobile labs for rapid response research efforts (expt's and observations)	Mobile				
Mobile lab for "virtual attitude assessment"			X		Scenario assessment for changes in BD
Datalogger (Realtime, High Bandwidth, satellite or spreadband capable)	Portable	X	xxx		Data Input and Analysis; Species/habitat reference
Barcoding (genetic screening)	Portable		XXX	XXX	Survey and Inventory
VHTP Sequencer	Fixed		XXX		Genetic Analysis