A continental strategy for the National Ecological Observatory Network

One of the great realizations of the past half-century in both biological and Earth sciences is that, throughout geologic time, life has been shaping the Earth's surface and regulating the chemistry of its oceans and atmosphere (eg Berkner and Marshall 1964). In the present Anthropocene Era (Crutzen and Steffen 2003; Ruddiman 2003), humanity is directly shaping the biosphere and physical environment, triggering potentially devastating and currently unpredictable consequences (Doney and Schimel 2007). While subtle interactions between the Earth's orbit, ocean circulation, and the biosphere have dominated climate feedbacks for eons, now human perturbations to the cycles of CO_2, other trace gases, and aerosols regulate the pace of climate change. Accompanying the biogeochemical perturbations are the vast changes resulting from biodiversity loss and a profound rearrangement of the biosphere due to species movements and invasions. Scientists and managers of biological resources require a stronger basis for forecasting the consequences of such changes.

In this Special Issue of *Frontiers*, the scientific community confronts the challenge of research and environmental management in a human-dominated, increasingly connected world (Peters *et al.* p 229). Carbon dioxide, a key driver of climate change produced by a host of local and small-scale processes (eg clearing of forests, extraction and use of fossil fuels), affects the global energy balance (Marshall *et al.* p 273). Invasive species, though small from a large-scale perspective, nonetheless modify the continental biosphere (Crowl *et al.* p 238). Aquatic systems are tightly coupled to both terrestrial systems and the marine environment (Hopkinson *et al.* p 255). Flowing water not only intrinsically creates a highly connected system, but acts a transducer of climate, land-use, and invasive species effects, spreading their impacts from terrestrial and upstream centers of action downstream and into distant systems (Williamson *et al.* p 247). Human activities such as urbanization create new connections; materials, organisms, and energy flow into cities from globally distributed sources and waste products are exported back into the environment (Grimm *et al.* p 264).

All of the papers in this issue of *Frontiers* conclude that a new approach to studying the biosphere is required in the present era. In response to this challenge, with the support of the National Science Foundation (NSF), ecologists in the US are planning a National Ecological Observatory Network (NEON). The conceptual design of this network (Field *et al.* 2006) gives rise to several general questions:

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

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

NEON will enable us to answer these questions by providing data and other facilities to support the development of ecological forecasting at continental scales. Required data range spatially from the genome to the continental scale, and temporally from seconds to decades. Control of transport in, and the chemistry of, the atmosphere, modulation of the physics of land surfaces, and influence over water supply and quality emerge from the aggregated behavior of almost innumerable organisms (Hopkinson *et al.* p 255). The disparity between the scale of organisms and the scales of their effects on the global environment represents an important problem for large-scale ecological research (Hargrove and Pickering 1992). While the consequences of life for the environment occur on the largest spatial and longest temporal scales, biological processes must be understood by documenting the responses of organisms, communities, populations, and other small-scale phenomena.

To bridge this diversity of scales, NEON will approach such questions through an analysis of processes, interactions, and responses, including those mediated by transport and connectivity (Figure 1). Most environmental monitoring networks focus either on processes or responses and do not link these with key interactions and feedbacks. NEON addresses the multi-scaled nature of the biosphere. The fundamental NEON observations (the Fundamental Sentinel Unit, focused on sentinel organisms, and the Fundamental Instrument Unit,

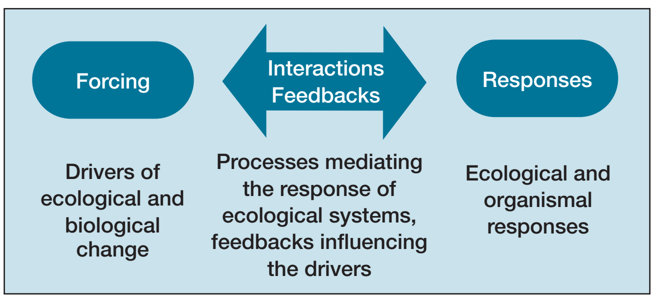

Figure 1. *NEON differs from other environmental monitoring networks because, by design, it integrates processes, interactions, and responses.*

focused on airsheds and watersheds) start at the scales of organisms, populations, and communities of organisms and directly observe biological processes (Figure 2).

A finite budget limits the number and the spatial extent of the fundamental observations; therefore, NEON uses a parsimonious continental strategy for placement of the observational units. The observations must systematically sample the US in a system design that objectively represents environmental variability. Existing maps spatially divide the US into ecological regions (Bailey 1983; Omernik 1987). In contrast to these earlier maps, NEON domains are based on a new, statistically rigorous analysis using national datasets for ecoclimatic variables. The statistical design is based upon algorithms for multivariate geographic clustering (MGC; Hargrove and Hoffman 1999, 2004; WebPanel 1). The optimized outcome of the geographical analysis results in 20 domains (Figure 3).

Relocatable sites will be moved on a 3- to 5-year rotation. Candidate core wildland sites have been specifically selected to be as representative as possible of the ecoclimatic variability in each domain (Table 1; WebTable 1). Nonetheless, one may question whether 20 sites can adequately address the ecoclimatic variability in a large, diverse continental area. The shading in Figure 3 represents the degree to which the ecoclimatic characteristics of the candidate core wildland sites represents environments in the conterminous US. Inspection of the figure shows that the Eastern portion of the country is generally well-represented, although southern Florida and the Gulf Coast are somewhat less well covered than the majority of the East. Representation in these areas would probably increase if the NEON Core site for the Atlantic Neotropical domain had been included in the analysis. In the West, representation is more heterogeneous, particularly in the desert Southwest and in the Rocky mountains. This is because of the high degree of linked climatic and biological variation related to complex mountainous terrain.

The observatory design, including both permanent core sites and relocatable sites, allows for planned contrasts within domains (eg mature versus young forest, urban versus wildland) and comparisons across domains (eg urban–rural in the Northeast and Southwest, nitrogen deposition effects in forests from the Southeast to the Northeast), using a core-and-constellation strategy. Mobile systems for short deployments (weeks to months) supplement the core and relocatable sites to explore details within these sites and to study discrete events and variability in the domains. Currently, there is approximately one planned mobile system per domain. These systems may be assigned to network tasks or to calls from individuals or groups of investigators. The design is based on rigorous scientific priorities and scaled to maintain budget discipline. Present scientific questions guide the first cycle of deployment; additional questions will be implemented as the network matures.

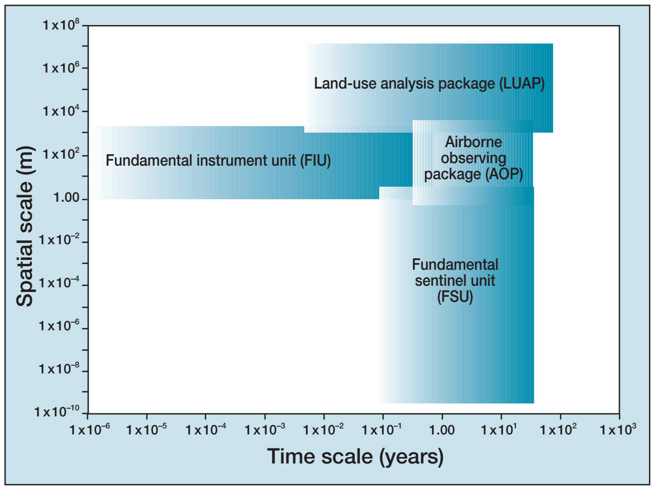

***Figure 2.** A Stommel diagram of temporal and spatial scales for the components of the observational design of NEON.*

While the set of candidate core sites provides a reasonable, static representation of the ecoclimatic variability for the continental region, scaling from point observations to the continent remains challenging. Each NEON domain observatory physically occupies a relatively small area and trades breadth of coverage for depth of insight. Modern, high-resolution, airborne remote sensing allows us to add a second strategy; the combination of imaging spectrometry (which can retrieve the chemical composition and, often, species composition of vegetation) with imaging lidar (light detection and ranging, which retrieves three-dimensional structural properties of vegetation) will provide regional coverage of key ecosystem properties. Imaging each NEON site regularly with 1.5-m resolution coverage, but expanding the scale to hundreds of square kilometers, provides a context for each site that allows the local observations of processes and responses to climate to be extended in space and generalized.

NEON data products will integrate the local and

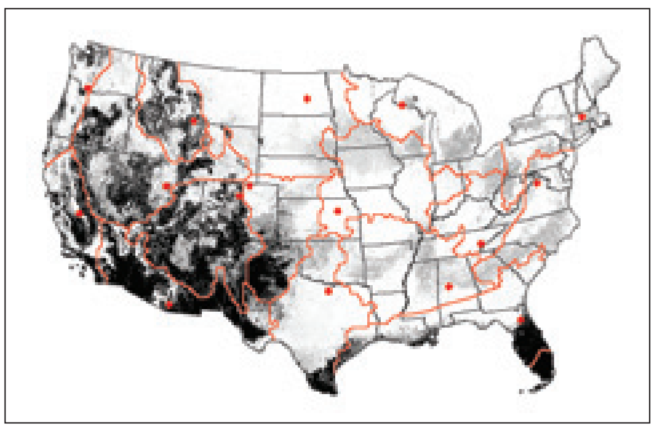

***Figure 3.** NEON domain boundaries for the conterminous US (in red) determined using the procedure described in WebPanel 1. Locations of candidate core sites (Table 2) are represented by red symbols. The shading from white (well-represented) to black indicates the quality of representation for a given area, based on the set of candidate core sites.*

Table 1. Criteria for NEON candidate core sites

(1) A wildland[1] site representative of the domain (vegetation, soils/landforms, climate, ecosystem performance)

(2) Provides access to relocatable sites that respond to regional- and continental-scale science questions[2,3], including connectivity[4] within the domain

(3) Year-round access, permitting available land tenure secure for 30 years, air space unimpeded for regular air survey, potential for an experimental set-aside

Notes: [1]Wildland is defined as "a predominantly unmanaged ecosystem that has vegetation characteristics representative of its domain" (Field *et al.* 2006). [2]Science questions posed at the continental and domain scale:

- Land-use theme: what are the within-domain contrasts that can be studied with this site?
- Biodiversity–invasives–disease theme: what are the within-domain contrasts?
- Climate change–ecohydrology–biogeochemistry theme: what are the within-domain contrasts?
- Climate change–ecohydrology–biogeochemistry theme: what are the across-domain contrasts?

[3]Relocatable sites should generally be located within three hours' travel time of the core site. [4]Connectivity is defined by NEON as "the linkage of ecological processes across space" (see www.neoninc.org/documents/NEONDESIGN-0001vA.pdf).

regional measurements to quantify how processes are responding to climate, land use, and species changes across each NEON domain. The combined site data and airborne remote sensing data extend NEON observations of ecological processes and responses to scales large enough to correspond to space-borne remote sensing and other geographic data collected operationally (Figure 2). The NEON information system is structured with time–space coordinates that allow a natural merger between NEON's local and regional observations and national-scale satellite observations, to systematically link detailed ecological observations with global surveillance.

The NEON observing strategy provides strategic, critical biological and physical observations, distributed over the landscape via a statistical observing design, so that, together, the observatories constitute a single, virtual instrument sampling the entire US. This virtual instrument can not only determine average changes over the whole country (through its sampling, scaling, and observing design) but, like a telescope, can observe the critical texture within the country and distinguish among regions with different drivers of change, or different responses to change, as well as sampling vectors for transport of materials, organisms, and energy. NEON strategically addresses gaps in the scales of our current observing systems by recognizing that biology is both a global and a highly local phenomenon, and reconciling the scale-observing requirements of these two aspects of life. While the NEON design cannot address all of the questions raised in this Special Issue (Peters *et al.* p 229), as a research platform, it will be the backbone of evolving efforts to observe, understand, and forecast environmental change in the Anthropocene Era.

Acknowledgements

We thank the participants in the Sioux Falls workshop and J MacMahon, P Duffy, T Hobbs, B Wee, D Johnson, K Remington, D Greenlee, H Loescher, A Marshall, B Hayden, D Urban, and J Franklin for their contributions to the NEON design. We thank S Aulenbach for his assistance with graphics.

References

Bailey RG. 1983. Delineation of ecosystem regions. *J Environ Manage* **7**: 365–73. doi:10.1007/BF01866919.

Berkner LV and Marshall LC. 1964. The history of oxygenic concentration in the Earth's atmosphere. *Discuss Faraday Soc* **37**: 122–41. doi:10.1039/DF9643700122.

Crutzen PJ and Steffen W. 2003. How long have we been in the Anthropocene Era? *Climatic Change* **61**: 251–57.

Doney SC and Schimel DS. 2007. Carbon and climate system coupling on timescales from the Precambrian to the Anthropocene. *Annu Rev Environ Resour* **32**: 31–66.

Field C, DeFries R, Foster D, *et al.* 2006. Integrated science and education plan for the National Ecological Observatory Network. www.neoninc.org/documents/ISEP_2006Oct23.pdf. Viewed 8 Mar 2008.

Hargrove WW and Hoffman FM. 1999. Using multivariate clustering to characterize ecoregion borders. *Comput Syst Sci Eng* **1**: 18–25.

Hargrove WW and Hoffman FM. 2004. The potential of multivariate quantitative methods for delineation and visualization of ecoregions. *Environ Manage* **34**: S39–S60.

Hargrove WW and Pickering J. 1992. Pseudoreplication: a sine qua non for regional ecology. *Landscape Ecol* **6**: 251–58.

Omernik JM. 1987. Ecoregions of the conterminous United States. *Ann Assoc Am Geogr* **77**: 118–125. doi:10.1111/j.1467-8306.1987.tb00149.x.

Ruddiman WF. 2003. The Anthropogenic greenhouse era began thousands of years ago. *Climatic Change* **61**: 261–93. doi: 10.1023/B:CLIM.0000004577.17928.fa.

Authors – left to right
Michael Keller
NEON Inc, Boulder, CO; USDA Forest Service, PR
David S Schimel
NEON Inc, Boulder, CO
William W Hargrove
USDA Forest Service, Asheville, NC
Forrest M Hoffman
Oak Ridge National Laboratory, Oak Ridge, TN