Ecological Impacts of Climate Change

Report from a NEON Science Workshop

August 24–25, 2004
Tucson, Arizona

National Ecological Observatory Network

American Institute of Biological Sciences

IBRCS
Infrastructure for Biology at Regional to Continental Scales
A community resource by AIBS

The IBRCS Program

The Infrastructure for Biology at Regional to Continental Scales (IBRCS) Program, an effort by the American Institute of Biological Sciences (AIBS), launched in August 2002 with support from the National Science Foundation. The following are the program's goals:

- Help the biological and the larger scientific community—within and beyond the AIBS membership—to determine the needs and means for increased physical infrastructure and connectivity in observational platforms, data collection and analysis, and database networking in both field biology and other more general areas of biology and science.
- Provide for communications within this community and with NSF regarding the development and focus of relevant infrastructure and data-networking projects.
- Facilitate the synergistic connection of diverse researchers and research organizations that can exploit the power of a large-scale biological observatory program.
- Disseminate information about biological observatory programs and other relevant infrastructure and data-networking projects to the scientific community, the public policy community, the media, and the general public.

The program is led by a working group comprising biologists elected from the AIBS membership of scientific societies and organizations and appointed from the scientific community at-large. It is assisted by a variety of technical advisors. The program has a special focus on the National Ecological Observatory Network (NEON), which is a major NSF initiative to establish a national platform for integrated studies and monitoring of natural processes at all spatial scales, time scales, and levels of biological organization. Jeffrey Goldman, PhD, is the Director of the IBRCS program. He and Richard O'Grady, PhD, AIBS Executive Director, are co-principal investigators under the grant. Additional information is available at *http://ibrcs.aibs.org*.

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Convened by the American Institute of Biological Sciences in conjunction with Julio Betancourt, USGS, Dave Breshears, University of Arizona, and Pat Mulholland, Oak Ridge National Laboratory, with support from the National Science Foundation NEON workshop series

About the American Institute of Biological Sciences

The American Institute of Biological Sciences is a non-profit(c)(3) scientific organization of more than 6,000 individuals and 86 professional societies. AIBS performs a variety of public and membership services, which include publishing the science magazine, BioScience, convening meetings, and conducing scientific peer review and advisory services for government agencies and other clients.

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Cover:

Photograph by Julio Betancourt. The photograph on the cover was taken from the University of Arizona's Desert Laboratory, an ecological preserve on Tucson's westside with a 100-year tradition in long-term ecological research (*http://wwwpaztcn.wr.usgs.gov/*). Tucson and its surroundings embody many of the contemporary and intertwined environmental issues to be addressed by NEON. The photograph shows a flare-up on the third day (6/19/03) of the Aspen Fire, which lasted a month and burned 85,000 acres of montane forests and woodlands in the Santa Catalina Mountains. The Aspen Fire is one of many large-scale disturbances linked to ongoing Western U.S. drought since 1999. The extent and intensity of such drought-related disturbances are being magnified by unnatural accumulations of woody biomass and increasingly longer and hotter summers. The Santa Catalinas, and other "sky islands" in the region, support small, isolated populations of plants and animals that could be pinched off the summits by stand-replacing fires and global warming. In the effort to control erosion, seeding after the Aspen Fire inadvertently introduced non-native cheatgrass (*Bromus tectorum*). In the desert below, exotic and flammable grasses that flower in winter (*Bromus rubens*) and summer (*Pennisetum ciliare*) take decadal-scale turns invading Sonoran Desert plant communities that evolved in the absence of fire; these invasions have profound implications, including wholesale changes in nutrient distribution and dynamics. In addition, Tucson has myriad hydrological problems, and has shifted supplies from a climatically buffered, ground-water aquifer to climatically variable riverflow. Ground-water overdraft since World War II eliminated perennial flow and malaria from local floodplains. Like other metropolitan areas like Phoenix, Las Vegas, and Los Angeles, Tucson now imports a good bit of its water from the Colorado River. The flow of the Colorado River was allocated across western states based on unusually wet conditions and could now be drying up. In Tucson, well-intentioned efforts to restore local wetlands now have to contend with short supplies and uncertainties about standing water, West Nile virus and other infectious diseases. Meanwhile, Tucson continues to grow and grow, paving its way to Phoenix and beyond.

NEON Workshop Series

The National Ecological Observatory Network (NEON) is a major initiative proposed by the National Science Foundation (NSF) to establish a continental-scale platform for integrated studies on natural processes at all spatial scales, time scales, and levels of biological organization. NEON is anticipated to provide the resources and infrastructure for fundamental biological research that will enhance our understanding of the natural world, improve our ability to predict the consequences of natural and anthropogenic events, and inform our environmental decision-makers.

The previous two years of NEON-related activity have revealed several steps that the scientific community must take along the path to the creation of NEON. Prior work showed that in order to develop a detailed description of NEON's physical design, an important milestone for NEON, the scientific objectives and targets of NEON must first be defined. With this in mind, as part of the NSF-funded Infrastructure for Biology at Regional to Continental Scales (IBRCS) project, AIBS, in partnership with experts from the prospective NEON community, convened a series of workshops between March and September, 2004, focused on the following ecological themes, which have been proposed as guideposts for the design of NEON:

- Ecological implications of climate change
- Land use and habitat alteration
- Invasive species
- Biodiversity, species composition, and ecosystem functioning
- Ecological aspects of biogeochemical cycles
- Ecology and evolution of infectious disease

The goal of the workshops was to highlight urgent scientific questions that NEON can address, define science requirements associated with those questions, assess the state of currently available infrastructure, and discuss needs for future infrastructure development. The recommendations that grew from these meetings, as captured in this report and others in the series, will guide subsequent NEON planning.

This workshop series opened up the NEON planning process to a diverse group of scientists from academia, government, and the NGO community. In total more than 120 scientists participated in these meetings—some were previously involved in NEON activities, while others took part in a NEON effort for the first time.

Executive Summary

The Grand Challenge

If ecologists are to be successful in distinguishing competing and interacting causes of large-scale ecological changes and associated feedbacks to the atmosphere and hydrosphere, they will need to match the spatial and temporal scales of analysis employed routinely by climatologists. This report identifies and discusses 10 fundamental questions for evaluating ecological implications of climate change at regional-to-continental scales and makes recommendations for the necessary infrastructure to address those questions.

Ten Fundamental Questions

1. What are the time-space domains of ecological variance, and how are they influenced by the spatial and temporal scales at which climate varies and changes?
2. How does (will) climate change affect the genetic interactions within and among species and, ultimately, the evolution of communities and ecosystems?
3. At a regional to continental scale, how will key characteristics of soils in U.S. ecosystems vary in responsiveness to climate change and other anthropogenic influences?
4. What are the ecological consequences of changes in these soil characteristics in response to climate change and other anthropogenic influences?
5. How does climate variation impact the dynamics of biologically available water in terrestrial systems, and how do those dynamics in turn affect ecological patterns and processes at regional-to-continental scales?
6. How do changes in climatic means and variances alter ecosystem-facilitated biogeochemical cycles, associated greenhouse gases, and energy feedbacks to the climate system, including the impacts on net ecosystem exchange, evapotranspiration, groundwater recharge, and surface- vs. groundwater use?
7. How does the nature of hydrologic variation (timing, magnitude, duration and frequency) influence aquatic systems with respect to (a) extent and distribution, (b) biotic structure and productivity, and (c) nutrient inputs and subsequent eutrophication?
8. How do climatic changes interact with anthropogenic modifications of hydrology to influence exchanges of materials between aquatic ecosystems, terrestrial systems, and the atmosphere, as well as the behavior of aquatic

systems as conduits or barriers to species exchanges and migrations?

9. How do changes in temperature regimes (interannual, seasonal, diurnal) influence inputs to and processing of materials in aquatic ecosystems?
10. Synthesis question: How will changes in climate influence regional ecosystem structure and function, and how will these ecosystem changes feed back to climate, hydrology, and biogeochemical cycles?

Major Infrastructure Recommendations

- Develop a six-layer infrastructure that includes (1) comprehensive coverage (e.g., satellite imagery), (2) public observation/measurement sites (approximately 100,000), (3) strategically located gradient transects within each major ecoregion and intensively instrumented sites along each gradient, (4) intensively studied manipulation experiments at sites along the gradients, (5) statistical and simulation modeling tools, and (6) information management for quality control and accessibility.
- Establish networks that take advantage of available historical, paleoecological, and paleoclimatological data with baseline value. Expand the spatial coverage and time-depth of these records where needed, and use observational networks and modeling to improve interpretation of these baseline data.
- Establish a U.S. Phenological Network that relies largely on public observers and is designed to integrate ground-based and remotely sensed observations; evaluate opportunities to integrate the network with the National Oceanic and Atmospheric Administration's (NOAA's) ongoing effort to modernize its National Cooperative Mesonet; deploy fixed and mobile platforms for optical measurement of ground vegetation; make aircraft platforms available to the ecological community to measure landscape-level patterns of vegetation structure and composition, disturbance events, and phenology.
- Collaborate with existing programs to develop and improve clearinghouses for georeferenced distributional data for plants and animals; incorporate and compare bioclimatic models that can be used to explore potential range shifts.
- Develop climate change genetics and genomics facilities that can address how climate change is affecting the genetic structure and interactions of species and whole communities of organisms. Such facilities should be readily accessible to scientists from diverse disciplines, promote integration of research specialties from genes to ecosystems, and include both physical and life sciences.
- Develop a national-scale analysis of baseline soil characteristics (abiotic and biotic) and their responsiveness and resistance to climate change and other anthropogenic influences; include experimental manipulation of temperature and precipitation.

- Develop infrastructure for an ecologically meaningful evaluation of the water budget that provides estimates of "biologically available water"; develop a strategy for collaboration with the Consortium of Universities for the Advancement of Hydrologic Science, Inc., (CUAHSI) and its hydrological observatories that distinguishes NEON by its focus on biologically available water; develop and deploy mobile systems to manipulate the water budget.
- Develop hierarchical monitoring networks within river basins that enable assessment of land–water chemical exchanges and physical and biological processes in streams, rivers, and their associated riparian systems; develop an associated network of wetland flux towers.
- Develop central laboratories for standardization and calibration of equipment and for sample archiving.
- Develop a new generation of simulation models that are tightly linked with conceptual models, ground-based data, spatial databases in geographic information systems, and remotely sensed images. The objective of integrated modeling will be to (1) synthesize information from observational layers, (2) generate testable hypotheses, (3) identify gaps in knowledge, and (4) forecast future ecosystem properties and dynamics. These new models should be easily accessible and usable and should explicitly include nonlinear dynamics, threshold behavior, time lags, and hysteresis.
- Develop new technologies and techniques for forecasting at regional-to-continental scales that allow evaluation of connectivity within and among regions, provide guidance on what key parameters need to be observed, and develop new scaling relations that account for nonlinearities, threshold behavior, and time lags.

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Introduction

The last few decades have seen impressive advances in our understanding of the Earth's climate system, comparable in scope to the revolution launched by the theory of continental drift and plate tectonics. This climatic revolution, encompassing the ability to reconstruct the past, understand the present, and predict the future, has stimulated a reevaluation of process and scale in related disciplines such as hydrology and ecology. This reassessment revolves around two overarching principles. First, climate is the result of a linked ocean–land–atmosphere system. Ecosystem dynamics on land have strong feedbacks on the surface water and energy balance, and on the exchange of certain greenhouse gases. Second, the transient behavior of atmospheric planetary-scale waves drive temporally and spatially averaged exchanges of heat, momentum, and water vapor that ultimately determine and synchronize large-scale patterns in growth, demography, disturbance, and biogeochemical cycling. These synchronous patterns should be especially conspicuous in the United States, which encompasses the sensitive middle latitudes and borders two large oceans with well-defined variability and teleconnections at interannual to multidecadal time scales.

Despite notable progress, there is a current mismatch in scales of investigation by climatologists vs. ecologists. This mismatch compromises our ability to detect regional- and continental-scale biotic responses to global climate change and associated feedbacks. Traditional ecological approaches have been inadequate not only for understanding biotic responses to climate, but also for determining how changes in the biosphere will in turn affect the climate and at what scales. The present challenge is for ecologists to deploy instrument platforms and implement regional- to continental-scale observations and experiments that are designed purposefully to help monitor, detect, predict, and possibly mitigate the ecological implications of climate change.

It is only logical that an NRC panel would identify forecasting and detecting ecological responses to climate change and variability as one of six principal challenges envisioned for NEON. An obvious and efficient way to construct such a network is to leverage existing infrastructure. Several ecological networks with national coverage have emerged over the past couple of decades, for example the Long-Term Ecological Research (LTER) and AmeriFlux networks. Although they have provided important studies, insights, and syntheses, it is important to note that these networks developed opportunistically among individual sites and were not specifically designed to capture regional-to-continental scale patterns and responses. Thus, connectivity among sites and associated nonlinear dynamics cannot be addressed with the current set of sites. While it is crucial that NEON connect with existing networks, it is equally important that NEON infrastructure be designed to explicitly address regional-to-continental scale issues and to invest strategically in the suite of sites that will do so most effectively.

This report provides insights from the NEON workshop on the ecological implications of climate change. There is substantial overlap between this topic and each of the five other topic areas (biodiversity, invasive species, biogeochemistry, land-use change, infectious diseases) proposed for NEON by the National Research Council.

We recognized several competing philosophies in the workshop, notably the tradeoffs between (a) experimental approaches and purely observational and synoptic approaches, and (b) investing in a few, highly instrumented sites and investing in a more distributed network. In part, this tension underlies regional differences in ecological sensitivity to climate and the history and intensity of land use. In the drier and less settled West, much of the interest lies in the availability of water to drive ecological processes and the sustainability of "natural" ecosystems. Understandably, there is keen interest in hydroclimatic variability, truly synoptic approaches, terrestrial ecosystems, and the individualistic responses of native species. In the more humid and developed East, there is more emphasis on water as a conduit for energy and matter. Consequently, there is a clear bias toward ecosystem processes, traditional plot-to-basin scale approaches, wetlands, and goods and services sustained from altered communities. These regional differences are fundamental and argue against a one-size-fits-all, hub-and-spoke design for NEON. First, there may be many circumstances that call for the same measurements to be made at prescribed temporal and/or spatial intervals nation-wide. Other circumstances, however, may require different protocols in different regions. Second, many of the workshop participants were skeptical about the efficiency of the hub-and-spoke design of early NEON discussions, with the activities focused at a few central observatories that control the distributed networks. From the onset, the emphasis should be on wall-to-wall coverage and the distributed networks.

The differences in approach also derive from the necessity to study mechanism and process by means of reductionist methods (e.g., experiments) at fine scales, while also detecting and observing patterns and responses at the broadest scales. Ecologists are most familiar with working at relatively fine scales of individual plants (or animals) and plots where experiments are most practical. But, clearly, to encompass climate variation and its impacts on ecosystems, we must also expand to the broader scales of landscapes, regions, and continents, where observational and inductive approaches using networks are essential.

In our workshop discussions, there were evident tradeoffs in the need for lower-risk, short-term successes vs. high-risk, longer-term investments such as complex studies of ecological processes and the development of cutting-edge technology. Workshop participants unanimously recognized the need to leverage existing research facilities, networks, and programs and ensure continuation of support by the various mission-oriented government agencies under which they operate. NEON will need the full cooperation of all existing research sites and networks, and to fill in other areas (spatially, temporally, and knowledge-based) that have not been studied in the past, in order to address the 10 questions identified in this report.

Workshop participants were selected to encompass multiple disciplines and regions. We were unable to cover all bases, however. In some cases, we asked workshop participants to consider areas outside of their own immediate expertise. A notable omission was expertise about coastal and marine systems (and the impacts from rising sea level); further modifications or additions related to this and other areas may be necessary.

Based on a review of pre-workshop interviews with a subset of participants, we categorized the high priority questions related to the ecological impacts of climate change into five general areas:

I. Large-scale phenology and population dynamics in terrestrial ecosystems
II. Soil ecosystem dynamics
III. Ecohydrology and atmospheric couplings in terrestrial systems
IV. Hydroecology and terrestrial–aquatic linkages
V. Synthesis of ecological responses and feedbacks

This report identifies 10 fundamental questions on the 5 topical categories presented above and recommendations for associated infrastructure. The topical areas follow a logical progression. We use question 10 and the final section (V) to synthesize the report.

I. Large-scale Phenology and Population Dynamics in Terrestrial Ecosystems

A. Questions and Discussion

1. How do the spatial and temporal scales of climate variability interact with phenology, plant and animal growth, disturbance regimes, and population dynamics? What are the time–space domains of ecological variance, and how are they influenced by the spatial and temporal scales at which climate varies and changes?

2. How does (will) climate change affect the genetic interactions within and among species and, ultimately, the evolution of communities and ecosystems?

Traditionally, bio- or ecoclimatic regions have been defined on the basis of climatological means rather than on climatic variability and its organizing effect on ecosystems. Regionalization (e.g., principal components analysis) of U.S. climate histories is now possible with more than 100 years of instrumental data and more than 500 years of tree-ring reconstructions. This will allow definition of hydroclimatic areas (regions with spatially autocorrelated or synchronous climatic histories) at different interannual to multidecadal time scales and regional to continental scales. Variability in both soil and air temperature is strongly modulated by precipitation (e.g., cloud cover, soil moisture, and sensible heat effects), and hence precipitation regionalizations also should apply indirectly to temperature variability. Based on progressive temporal smoothing of these annually resolved records, we can define hydroclimatic areas that should increase in size with increasing time scale of variability (i.e., climatic synchrony occurs over increasingly larger areas from interannual to multidecadal time scales). What is the imprint of this spatiotemporal structure in climate variability on ecological processes from regional to continental scales? The answer to this question is critical for determining how ecosystems that are shaped by a particular timescale of climate variability will react to longer-term climatic change. It is also critical for forecasting the extent to which responses of ecosystems particularly sensitive to climate change may propagate through adjacent regions.

There is a critical need in ecology to understand processes that give rise to spatiotemporal variations in ecosystem dynamics, and to be able to distinguish inherent system variability from signal due to land-use effects, invasion, or climate variability and change. We should treat synchrony as part of the ecological process, rather than treat it simply as the error term (spatial autocorrelation). Extrinsic (climate and land use) and intrinsic forces interact to determine large-scale patterns of plant growth, population abundance, and ecological disturbance. Knowledge about the spatiotemporal scales of this interaction is needed to inform predictive models, as well as monitoring strategies to anticipate and detect ecological responses to climate variability and change.

We believe that climate variability synchronizes phenology, plant and animal growth, population abundance, and disturbances to various degrees (depending on organism, biome, and region), but the spatiotemporal domains of that synchrony are still largely undetermined. We note that European ecologists have long focused on climatically driven ecological synchrony—the so-called Moran effect—reaping the benefits of several national networks with long-term annual animal abundance data. In the United States, ecological synchrony remains intractable because there are few networks designed to reconstruct or monitor ecological variability at the required intervals in time and space. Identification of scales over which ecological patterns and processes are synchronous is required to minimize investigative effort in the field, maximize the generality of research results, and enhance the predictability of ecological responses to climate.

The signal of climate influence on ecosystems is evident as patterns of synchrony and asynchrony across multiple locations. Indeed, the absence of any regional synchrony in ecological pattern would suggest the absence of any influence of varying climate. In contrast, highly synchronized pattern or process—such as regionally synchronized disturbances, natality, mortality, or growth rates—would point to climate as a dominant, external driving variable in ecosystem dynamics. This concept of climatic and ecological synchrony suggests an efficient strategy for detecting and evaluating climatic influence and regional-to-continental-scale entrainment of ecosystems: Regional-scale networks of observational, experimental, and modeling efforts should be designed to study synchronous and asynchronous ecological patterns and processes and to detect their coherence with climate variations at similar spatial and temporal scales.

A crucial challenge for NEON is to develop methods for integrating traditional, plot-to-basin studies (which developed at those scales for very practical reasons) so they scale up to regional and continental levels. Additionally, methods are needed to integrate traditional plot-to-basin studies with the large-scale networks, observation platforms, and models that will ultimately be the monitors of climate-scale change. Coupling biological responses to land-use and biophysical changes at scales meaningful to atmospheric responses will require fast response sensors of heat and moisture exchange. Climate- and human-induced changes in phenological patterns over landscapes meaningful to the mesoscale climate can be observed and modeled over 10-km^2 regional studies.

Thirty years of NEON observations will not be enough time to capture many of the large-scale ecological responses to climate change. NEON will have to rely to some extent on baselines provided by historical ecology, though we recognize the potential for unprecedented changes due to interactions of unusually rapid changes in climate, exponential growth in human activities, and a growing list of naturalized, nonnative species poised to become invasive. We may be on the verge of biotic reorganizations of communities and landscapes that lack analogs in the modern world or even in the Quaternary Period.

Phenology

Phenology is the most sensitive and easily observed indicator of the biotic response to climatic change at local to continental scales. Defined as the study of the timing of recurring or cyclic biological phases (e.g., date of first flowering, budbreak, unfolding of first leaf, first spring migration, molting events), phenology indicates climate-related factors such as the length of the growing season, frost damage, timing and duration of pests and diseases, water fluxes, nutrient budgets, carbon sequestration, and food availability. Long-term phenological changes can cascade to other trophic levels in both linear and nonlinear ways.

Large-scale shifts in phenology will be one of the first-order effects of global warming, but the brevity and limited scope of existing phenological records will make it hard to distinguish the effects of directional anthropogenically forced climatic change from natural, multidecadal climate variability. The Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO), for example, statistically explain more than half of the variance in decadal to multidecadal (D2M) precipitation variability across the United States, as well as a significant amount of the temperature variability. Synoptic phenological data for the United States are currently limited to a few horticultural species (e.g., lilac and honeysuckle) over the last 40 to 50 years, barely enough time for one or two realizations of these low frequency, sea surface temperature (SST) variations.

The link between satellite-detected green-up and surface phenology is still poorly understood, so there remains a key role for ground-based phenological networks focused on both natural and agricultural systems. Phenological networks exist in Europe, in Canada, and globally, but the United States does not have a single, regional-scale phenological observation network, let alone a national one. A comprehensive, wall-to-wall U.S. Phenological Network is not only necessary but is also an obvious way to involve the general public as routine observers, thus increasing awareness of ecological responses to climate change. Recent work in both the western United States and New England provides a notable example of how phenological data can be used in tandem with hydrologic trends to sort out competing causes for continental-scale environmental changes with far-reaching societal consequences.

Disturbances

Forest fires, insect outbreaks, and hurricanes are three kinds of broad-scale disturbances that are directly linked to climate variability and change. The key distinguishing feature of these climate-driven disturbances is the temporal synchrony of their occurrence over broad spatial scales. For example, East Coast and Gulf Coast hurricanes, with their preferred pathways and profound ecological influences, are not temporally random (stationary) phenomena. These hurricanes are modulated in part by the Atlantic Multidecadal Oscillation, with more frequent and intense hurricanes in decades of North Atlantic warming (1930–1960, 1995–present). AMO variability has been reconstructed for the past 500 years and could be used to model and test historical ecological consequences of hurricane activity at a subcontinental scale. It is likely that disturbances such as windstorms (including downbursts, microbursts, extratropical cyclones, and tornadoes), hard freezes, and snowstorms are clustered in time and space and thus have similar synchronizing effects.

In the West, paleoecological reconstructions show that El Niño/Southern Oscillation (ENSO) variability produces regionally synchronized fire years, which tend to punctuate the more variable, localized record of fire occurrences at the stand and watershed levels. Regional- to continental-scale synchrony of fire and climate was dramatically illustrated during recent drought years (e.g., 1988, 1989, 1996, 2000, 2002) when massive forest fires erupted in forests throughout western North America, from Mexico to British Columbia. Similarly, drought-weakened trees and warmer temperatures in the past 5 to 10 years have led to broadscale bark beetle outbreaks throughout the Southwest and extending into the northern Rockies of western Canada and Alaska. Both fire and insect outbreak regimes track large-scale climate variability associated with ENSO, PDO, and AMO; warming will lengthen and intensify the fire season and amplify the scale and duration of insect outbreaks.

There is a need to understand the interaction between landscape alteration, climatic change, and changing probabilities for disturbance. Recent increases in the frequency and extent of all disturbances suggest that ecologists should also focus on monitoring and forecasting the outcomes of succession on regional to continental scales. After all, it is in the wake of such large-scale disturbances and an increasingly warmer climate that the distribution and abundance of dominant species will change. Disturbance will play an important role for hysteresis and threshold effects capable of moving ecosystems to new states. We should focus not just on nonnative species but also on complexes of native species capable of becoming invasive ones in a warmer world where succession will be more frequent and less predictable.

NEON should assist in coordinating, refining, and utilizing existing disturbance databases and networks, such as wildfire occurrence and forest insect and disease records kept by federal agencies (e.g., U.S. Forest Service, Bureau of Land Management, National Park Service, state agencies). Although some of these records are multiple decades in length, they have not been coordinated and assembled into readily accessible and reliable national-scale databases. An effort comparable to the Historical Climatology Network (http://cdiac.esd.ornl.gov/epubs/ndp019/ndp019.html) is needed (e.g., an Historical Disturbance Network), whereby the existing numerous observational datasets are compiled and sorted, tested for accuracy and homogeneity, adjusted as necessary, and filled in where possible, and then the database is made available and continuously updated.

Population abundance

There are few regional efforts in the United States that track natality and mortality of individual species on annual to decadal time scales. Surprisingly, there are few regionally integrated demographic histories or monitoring efforts that could be used to understand the linkage between climate and demographic processes such as episodic surges in recruitment and mortality (a notable exception being the U.S. Fish and Wildlife Service's Breeding Bird Survey). Such demographic histories, if they existed, would be essential to both detect and forecast ecological responses to climate. Seedling surveys for dominant species are seldom undertaken with the right design or at the appropriate spatial or temporal scales required to separate climatic from local effects. Relevant biological phenomena such as widespread masting for dominant trees are not monitored. For example, there are 20 million hectares of pinyon–juniper woodlands in the West, the third most widespread vegetation type in the entire United States. Ecologists assume that regional surges in pinyon pine recruitment are associated with irregular mast years when seed predators become satiated. This theory, although widely accepted, has never been tested because we lack long-term observations of pinyon masting and survivorship at local to regional scales.

Many ecosystems suffered broadscale plant mortality across western states in the ongoing drought of 1999–2004. Such broadscale mortality affects both the age structure and genetic makeup of regional populations and preconditions the responses of the surviving populations to subsequent climatic variability. Other megadroughts (the 1950s) have reset demographic clocks, but questions remain about the added influence of longer, hotter summers on the scale and intensity of plant mortality. Drought-induced changes in vegetation can produce secondary ecological effects, such as increases in soil erosion and in the incoming, near-ground energy. A quick-response team (DireNet) was organized to study this unusual resetting of regional demographic and genetic clocks, but it has been stymied by insufficient resources. The research community currently lacks the direction and infrastructure required to sort out the role of multiple stresses (drought, longer and hotter summers, bark beetle outbreaks) or to properly gauge the ecological and evolutionary consequences of such extreme events as they happen.

NEON should provide the critical infrastructure to study broadscale and episodic patterns of births and deaths in plants and animals. NEON infrastructure should be flexible and portable enough to accommodate study of extreme, resetting events with large-scale consequences.

Species distributions

Ecological responses to climate change will involve distributional changes, but there are many obstacles to detecting and modeling range shifts. For example, comprehensive and digitized data for plant and animal distributions are mostly lacking except for a few guilds (e.g., birds and mammals). The distributional data that do exist are generally biased by spatial and temporal patterns in the intensity of sampling effort, they are georeferenced at uneven quality and resolution, and they are commonly subject to gross errors of omission and commission.

Most bioclimatic models entail statistical calculations of climatic envelopes for the species' distribution. There are a plethora of these biogeographic models, but intermodel comparisons are seldom attempted to explore differences and achieve consensus. Moreover, there are surprisingly few deterministic models for species distribution that are based on expert knowledge of life history. This explains our poor understanding of genetic, physiological, demographic, and dispersal constraints on species ranges.

To date, predictions for range shifts have mostly entailed application of projected climatic changes from general circulation models to climatic envelopes for species distributions. These exercises ignore most of the biology and dynamics involved in range contraction and expansion. For example, we know little about the range of genotypic variability available for range responses: How fast can gene flow occur to allow adaptive responses within a species range? We have limited understanding of how changing probabilities of long-distance dispersal, which cannot be measured empirically, can affect rates and patterns of spread. Until very recently, oversimplified spread models generally ignored the influence of heterogeneity in landscape structure and climate variability on different time scales. Such variability may contribute to the so-called “environmental stochasticity” that explains why invasions fail multiple times before they eventually succeed. We also have a limited understanding of extinction and colonization processes in increasingly fragmented landscapes. Fragmentation isolates populations and increases the risk of local extinction. For those organisms that can hitch a ride, however, a pervasive transportation network increases the chances for rescue by immigration from afar. This applies to both native and nonnative, ruderal species, and we should only have to look roadside for the initial stages of invasions driven by climatic change.

These are all serious shortfalls in our understanding of species distributions that NEON could help overcome. A three-pronged approach would be to (1) identify key players (species), rates, and processes from paleoecological and historical records of migration and ongoing invasion; (2) improve empirical observations and modeling of species ranges and limits; and (3) design experimental studies to identify the mechanisms and sensitivities of individual species and genotypes to potential range shifts with climate change.

Climate change genetics

Global change biology relies heavily on the morphological species as the basic unit of analysis. Ecological responses clearly vary with genotypic differences among populations, however, and global change itself may affect microevolutionary processes. There is increasing need for the application of ecological and quantitative genetics in the prediction of ecological responses to global change. Because genomics and genetic analyses are crucial for understanding the ecological and evolutionary consequences of climate change, well-equipped research and training facilities are essential for critically addressing these challenging issues. Often, genetic analyses have been out of reach to many biologists and scientists from other diverse disciplines due to technically demanding procedures and expensive instruments. With the establishment of an environmental genetics and genomics center, we could broaden access to all interested researchers. By making such a facility readily available to researchers from a wide range of disciplines, the climate change debate could be firmly based on genetic changes in the biota. Because there is increasing evidence that climate change affects the genetic structure of populations and even communities, the integration of genetics into the debate will firmly found all arguments within a genetic/evolutionary framework. Because we also suspect that climate change events represent major evolutionary bottlenecks, modern molecular genetics facilities are essential for rigorously and unequivocally demonstrating the consequences of climate change on our communities and ecosystems.

B. Infrastructure

Historical ecology as a baseline for NEON

In the planning stages, NEON should invest considerable effort in identifying sites where there are sufficiently long time series of measurements or observations to yield meaningful baseline information. Such information could encompass high-resolution climatic reconstructions, long-term changes in community composition and structure, disturbance frequencies, process rates, trends, periodicities, and other dynamical behavior. NEON should extend and broaden the scope of observations at these sites and thus add value to these baseline sites.

NEON observations could help improve calibration of critical paleorecords. For example, there are a number of millennium-length tree-ring reconstructions of temperature throughout the United States, principally from upper treeline. Many of these records show unprecedented tree growth in the last few decades, presumably in response to a longer growing season, but possibly to other factors such as carbon dioxide (CO_2) or nitrogen fertilization. Few of these sites are fully instrumented, however, to measure individual tree-growth or stand-level responses to weather. Moreover the temperature reconstructions are based on linear regressions using far-away stations rather than mechanistic tree-growth models that can be validated with local data.

High-resolution and gridded drought and precipitation reconstructions for the United States span 1000 years or more and are now available for most of the entire United States (www.ngdc.noaa.gov/paleo/pdsi.html). There is an unprecedented opportunity to use these climatic reconstructions to explore sensitivities of ecological models. Stand or gap models could be forced with real climate histories to make predictions about predominant age structures in regional forests as affected by climate. In turn, these predictions can be tested with modern age structure data collected at the appropriate spatial scales and temporal resolution to test hypotheses about regional synchrony. Such an approach could also be extended to combine repeated forest inventories (e.g., U.S. Department of Agriculture's Forest Inventory and Analysis, or FIA), tree-growth chronologies, and remotely sensed growth indices for evaluating forest growth at multiannual and regional scales.

Plant migrational histories, which are now available for a host of dominant species in the United States, offer another interesting opportunity for NEON. Recent work shows that the ratio of specialist-to-generalist bees in stands of creosote bush in the Southwest is a function of time (measured in centuries to millennia) since the arrival of creosote bush. This raises the intriguing possibility that many population, community, and ecosystem properties vary as a function of time since colonization by the dominant plant species (or the time since the last major disturbance). NEON could take advantage of the wealth of plant migrational data to resurrect the chronosequence approach to investigate these temporal effects on ecosystems, and it could use them in predicting future ecological changes associated with the movement of dominant plant species.

A national phenological network

NEON should establish and support a U.S. Phenological Network that includes public observers and is designed to ultimately integrate ground-based with remote sensing (e.g., Normalized Difference Vegetation Index, or NDVI) observations. We recommend that, as soon as possible, AIBS and NEON, Inc., develop a working group that includes remote sensing and phenology experts from across the country.

An obvious model, if not a direct link, for a U.S. Phenological Network would be the National Weather Service's 100-year-old Cooperative Observer Program (COOP), which relies on more than 11,000 volunteer stations to provide observational meteorological data, usually consisting of daily maximum and minimum temperatures, snowfall, and 24-hour precipitation totals. COOP stations and about 1,000 Automated Surface Observing System (ASOS) airport stations make up the federal government surface weather and climate-observing network. U.S. participants are provided with a set of simple weather instruments and observing instructions by the National Weather Service, which manages the network.

NOAA is now planning to modernize COOP and integrate all surface-weather observing systems into an expandable and adaptable National Cooperative Mesonet (NCM) (www.nws.noaa.gov/om/coop/coopmod.htm). Some objectives of modernization include a 20 x 20 mile^2 grid (target: 8,000 stations), with increased density in the West and Alaska; hourly temperature and precipitation data (resolution of 0.01 inch) available near real-time; 24-hour snowfall and snow depth available daily; electronic data communications, storage (backup), dissemination, and archiving; and measurements of soil temperature, moisture, relative humidity, and evaporation in agriculturally sensitive areas supporting USDA's requirements. Additionally, COOP observations will have centralized near real-time Internet data access. This revamping of the COOP network will presumably happen by 2008.

NEON should instigate discussions with NOAA on the possibility of integrating a U.S. Phenological Network with a new and improved National Cooperative Mesonet. In an ideal world, a subset of phenological observations would be made in cooperation with existing NCM stations, and in return NEON would help support new NCM stations at phenological observation sites of special interest to the ecological and hydrological communities. The main objectives would be a thorough understanding of vegetation phenological cycles and their relationship to temperature and precipitation; comprehensive ground-truthing of green-up and other remotely sensed phenological measurements; and eventual detection and discrimination of long-term phenological trends in response to long-term climate variability and global warming.

An integrated system for ground, aircraft-based, and satellite measurements of vegetation

We need fixed and mobile platforms for optical measurement of ground vegetation. Low-cost, commercially available digital cameras are also needed for qualitative and quantitative assessment of ground-cover vegetation, including seedlings at the field scale. Other microscale (on the ground) measurements of phenology, density, frequency, cover, structure, biomass, litter, and gaps are needed for local-scale experiments to study detailed processes and to validate ecosystem models and coarser-scale imagery.

Within the domain of remote sensing, aircraft-based instruments hold a central and irreplaceable role to achieve the goals of the NEON program. Remote sensing data provide the detailed spatial context within which other ecosystem measurements can be extended and interpreted. Remote sensing instruments today can discriminate major species, cover types, tree density, crown closure, and leaf area, but other elements still have to be observed on the ground, particularly understory and midstory seedlings, shrubs, perennial and annual forbs. NEON could make aircraft platforms available to the ecological community to measure landscape-level patterns of vegetation structure and composition, disturbance events, and phenology. An essential role of the NEON aircraft measurement program is to support scaling between point data collected at intensively studied sites and larger-scale data derived from satellites and land surface modeling, and to fill in temporal sampling. Another role of the aircraft program is to aid in development of optimal sampling strategies for field campaigns.

Aircraft instruments offer far greater flexibility than satellites in the timing and spatial resolution of data acquisitions and provide the only available means of obtaining certain forms of data. The platform could be aircraft or unmanned aerial vehicles (UAV) or geosynchronous satellites. If the second or third platforms were available, one could make diurnal measurements; with the first and second platforms, one could control the altitude of flight for multiscale studies related to nonlinear ecological responses.

A range of instrument capabilities is available for airborne platforms that are needed to meet the broad scope of NEON objectives. The airborne instruments of high priority include high spatial resolution data that provide (1) hyperspectral imagers that permit characterization of the landscape based on principles of spectroscopy, (2) LIDAR (light detection and ranging) imagers and profilers to provide key measurements that quantify land surface properties (e.g., biomass and three-dimensional structure), and (3) thermal imagers to provide information on the distribution of surface temperature.

A hyperspectral imager can provide quantitative data (e.g., plant species, pigments, C_{lignin}) measured at the complexity of the landscape, including measurements that characterize both atmospheric composition and surface conditions that are used in ecosystem and climate models. The LIDAR measurements provide detailed information on topography, canopy height, plant density, and understory presence. Thermal imagery provides distributed calibrated surface temperatures for energy budget and flux studies. Collectively, the instrument pod would be able to measure soil and plant canopy temperatures that, in combination with meteorologic data (vapor pressure deficit, air temperature, wind speed), allows for the retrieval of latent energy terms of the energy balance equation. Furthermore, in the shortwave spectral region, thermal imagery can estimate canopy water content and surface moisture content.

Species distribution data and modeling

NEON should collaborate with existing informatics programs to develop clearinghouses for georeferenced biological and environmental data necessary to evaluate climatic effects on biota, and it should have the full compliment of ecological models available to assimilate those data. Despite ongoing efforts such as the National Biological Information Infrastructure (NBII), the United States currently lacks an environmental portal comparable to Australia's Environmental Resource Information Network (ERIN).

Regional genomics laboratories for climate change biology

To meet the needs of a diverse constituency, we need instrumentation and technical support for multiple, regional resource facilities that will support the complete processing stream associated with genetic and genomic analysis. This includes sample preparation, polymerase chain reaction (PCR) amplification, data generation, and data analysis. The example system outlined below could be scaled up to meet increasing demands:

- *Capillary electrophoresis (CE) automated DNA sequencer (ABI 3730xl).* This is a 96-capillary instrument that separates DNA fragments with single base resolution. This separation capability enables efficient DNA sequencing and DNA genotyping. The genotyping capabilities include microsatellite, amplified fragment-length polymorphism (AFLP), and single nucleotide polymorphism (SNP; SNaPshot) analysis. At maximum capacity, this instrument is capable of 2,304 genotyping or sequencing runs per 24-hour period (1 hour runs by 96 capillaries). Through multiplexed PCR reactions and short run time, the genotypic analysis capacity is even greater if small fragments are used.

- *High-capacity thermocyclers (MJR Tetrads)*. In order to fully utilize the DNA analyzer (ABI 3730xl), each system would need two 384-well MJF Tetrads, each with four thermocycling blocks. The total capacity of a four-head, 384-well thermocycler is about 1,500 PCR/sequencing reactions every three hours, or about 12,000 reactions per day.
- *Robotics for fluid handling (Perkin Elmer MultiPROBE II HT/EX)*. An eight-probe robotic liquid handling system is also needed for assembling PCR reactions, pooling reactions, and preparing samples both before and after thermocycling, but prior to capillary electrophoresis. This system is easily linked to the thermocyclers.
- *Sample preparation lab*. Among the basic capabilities should be high capacity tissue extractions, DNA isolation, PCR, agarose gel electrophoresis, organic extractions in fume hoods, sample storage in ultracold freezers, refrigerated cabinets, and so on.
- *Information technologies for data acquisition, processing, and analysis*. We suggest that the above facilities also include a high-speed local area network, central data storage, and data transfer and backup that is coupled to work stations for individual data analysis. This is a crucial support piece for the data flow from the DNA analyzer to analysis stations.

II. Soil Ecosystem Dynamics

A. Questions and Discussion

Soils are unique ecosystem components for assessing responses to climate change and land use because their structure and biogeochemistry are integrated products of past climates and environmental changes (with evidence of these recorded in paleosols and with depth), while key soil ecological processes today reflect the interaction of this structural and chemical legacy with the extant climate, land use, and vegetation. Overlaying a spatially variable climatic future on a soil template built by an equally variable history will yield spatial and temporal complexities in responses and consequences that can only be understood at regional to continental scales.

Soil biota and critical soil processes associated with carbon (C) and nitrogen (N) cycling are particularly responsive to temperature and moisture. Air temperatures are projected to rise, atmospheric deposition is altering N deposition and other nutrient inputs, and precipitation regimes (amount, seasonality, and variability) are expected to be altered to different degrees across the United States. Our understanding of small-scale soil heterogeneity and microbial processes is advancing rapidly. This improving, process-based understanding must be integrated with a larger-scale perspective. If the key ecosystem services soils provide are to be maintained, an integrated, large-scale assessment of climate and soil ecosystem relationships and a sensitivity analysis of potential future responses are needed.

3. At a regional to continental scale, how will key characteristics of soils in U.S. ecosystems vary in responsiveness to climate change and other anthropogenic influences?

Ecologists have long recognized the importance of soil biotic and abiotic properties on spatiotemporal variation in primary productivity and trophic interactions among plants and animals. Therefore, a comprehensive understanding of the factors contributing to continental-scale patterns of spatiotemporal variation in soil biotic and abiotic properties is critical to predicting and mitigating a suite of ecological consequences of climate change, including changes in primary and secondary productivity and constraints on distributional shifts of plant and animal species.

Currently, potential regional-scale responses of soil ecosystems to global climate change are poorly understood, particularly responses of the biotic component, only a fraction of which has been either functionally or taxonomically characterized in a small number of ecosystems. The available data from local studies suggest, however, that soil processes are important drivers of aboveground processes. For example, soil biodiversity can influence interactions, such as competition, among plant species, as well as plant community productivity and diversity. Soil organisms have also been shown to respond dramatically to changes in climate, although the feedbacks of these changes to plants and other trophic levels have rarely been explored. The responses of the soil biota to climate changes are thus critical to consider. A NEON network will allow us to look broadly at the impacts of climate change on soil ecosystems beyond the ecosystem-specific studies that characterize the field today. An emphasis on variation among soil ecosystems in responsiveness to climate change will provide a powerful data set that illuminates the ecosystems that are most sensitive to climate changes and in which further detailed mechanistic studies are necessary.

4. What are the ecological consequences of changes in these soil characteristics in response to climate change and other anthropogenic influences?

Soils, through their hydrological and nutrient supply functions, are strong determinants of ecosystem productivity and consequently the dynamics of species at higher trophic levels that depend on primary producers. Although soil ecosystems per se (belowground food webs, community structure) will respond in important ways to abiotic changes and productivity, any assessment of the ecosystem consequences of soil responses to climate change must also be integrated with network-level measures of aboveground ecological dynamics.

Hence, while it is important to measure changes in soil properties with climate change, it is critical to monitor the consequences of those changes as well. For example, does the loss or gain of species of soil microbes with global warming impact nutrient cycling or nutrient uptake by plants via associations with soil microbes? Only if such higher-order consequences are also measured will the strength of the comparative approach that the NEON network allows be realized in improving our understanding of the importance of the enormous amount of biodiversity and spatial complexity inherent in the soil.

We recommend the development of a national-scale analysis of baseline soil characteristics (biotic and abiotic) and an assessment of their responsiveness and resistance to climate change and other anthropogenic influences (such as land use). We envision a baseline soil characteristic map as an initial short-term product, derived from ecoregion-specific inventories of soil characteristics and assimilation of existing data. NEON resources would then be allocated to overlay the responsivity/resistance attributes of soils to projected climate change. This national comparative approach would yield information similar in form to maps of "biodiversity hotspots" of threatened and endangered species.

A national- or even continental-scale assessment of soil characteristics and responsivity/resistance to climate change and other anthropogenic influences would present unparalleled benefits spanning from more basic to highly applied research in the NEON framework. In an applied context, it would identify key areas or "hotspots" within and among ecoregions that are likely to show the greatest changes in response to, for example, altered temperature and humidity regimes, thereby helping to set research priorities. In a basic research context, both the baseline analysis and responsivity/resistance assessment would contribute fundamental knowledge of the mechanisms of large-scale spatial heterogeneity in soil characteristics and soil ecosystem dynamics, as well as an understanding of the extent to which these influence large-scale spatial and temporal dynamics of species at higher trophic levels.

Coupling the development of national-scale soil analyses with inventories and monitoring of plant and animal populations at the same scales would facilitate investigations by NEON researchers into the higher-order ecological consequences of soil responses to climate change. Monitoring and quantifying the phenomenon of large-scale ecological synchrony in space and time as a means of forecasting regional-scale similarities and dissimilarities in soil characteristics and response to climate change contributes to building a unifying theme for NEON. Such an approach would greatly enhance efforts to increase the information-gathering efficiency of large-scale research by minimizing spatial redundancy in the allocation of limited financial and human resources.

Examples of soil characteristics that merit priority for quantification and monitoring include soil biodiversity, structural characteristics, and soil processes. Soil biodiversity, including species diversity of bacteria, fungi, and invertebrate soil fauna, may be a key determinant of the functional stability of ecosystems in response to global climate change. Soil structural characteristics include bulk density, cation exchange capacity (CEC), moisture holding capacity, soil aggregates, and soil C/N. Soil processes include weathering rates, soil C and N dynamics, mineralization, and trace gas flux.

B. Infrastructure

Collection and assimilation of baseline data

The assimilation of baseline data is a crucial element of infrastructure development. These data will be critically important to identifying potential material overlap with existing networks and gaps in existing information. This will maximize efficiency in research development. We therefore recommend funds be made available in the initial period of NEON research for assimilation of existing data. We furthermore wish to explicitly encourage collaboration with existing agencies in assimilation of baseline data.

Identification of the extent of, and gaps in, existing baseline data must be followed up with collection of additional baseline data of sufficient spatial coverage to facilitate a complete national assessment. Of key importance is determining the number of observatories and associated field sites needed to represent variation within and among the ecoregions represented in the United States. At a minimum, we recommend one observatory per ecoregion, functioning perhaps as a data management/analysis center, with multiple associated field/sampling sites per ecoregion. Analyses of baseline data should be used to determine the appropriate sampling resolution within and among ecoregions.

Sampling, monitoring and experimental approaches

We recommend a uniform and hierarchical sampling and monitoring approach at each observatory. Each region will have its own region-specific protocols dictated by the characteristics of the system being studied, but common national goals must still be met. For example, we anticipate the need for a denser sampling network in highly heterogeneous regions (mountainous) than in more homogeneous regions (e.g., Great Plains). Even though the questions require a national-level effort, the recommendations for infrastructure need to be region specific. An analysis of variance for each soil attribute will be very useful in determining the minimum and optimal number of sampling points.

We recommend that observatories within NEON should be centers for analysis of samples and depositing data, but not necessarily responsible for data collection (though permanent observations could be recorded at them). Surrounding these observatories would be multiple sampling/field sites, which may or may not require stations (i.e., buildings and facilities), but where data would be collected.

After obtaining baseline data at a site, we recommend resampling permanent plots every few years to assess changes in response to climate change. Additionally, we recommend an experimental component, manipulating temperature and precipitation to quantify response. Superimposed on this, we recommend a comparative approach to quantify differences along temperature and precipitation gradients (or other pertinent, natural gradients). The gradients would be defined according to the variables of interest, and the location of the sites would be dictated by the existence of spatial variability in the variables of interest. We emphasize that the experimental sampling and observational monitoring should be very closely coupled. The protocols for experimental and observational sampling should not be rigid but should feed back on each other and evolve together.

Archiving of soil samples for future analyses

Archiving of soil samples should be an important component of NEON. New technologies will continue to emerge and can enable analyses that were not feasible before. For example, two new methods for measuring soil carbon are showing promise. One of the methods is based on neutron attenuation and allows in situ measurement of a small square (e.g., 1 m x 1 m) of soil. The other method is based on laser-induced breakdown spectroscopy (LIBS), in which a small point on the surface of a soil sample is turned into plasma and the emitted spectra are captured and quantified. The LIBS approach shows promise for ultrahigh spatial resolution of soil sampling and can be expanded for many other elements of biogeochemical interest. A major investment in soil sampling will ensure that new time series data sets can be developed as measurement techniques further evolve.

III. Ecohydrology and Atmopheric Couplings in Terrestrial Ecosystems

A. Questions and Discussion

Researchers in ecohydrology and atmospheric science are recognizing the need for increased interdisciplinary work to address complex environmental dynamics. By ecohydrology we mean the study of terrestrial plant responses and effects on the land-phase of the hydrologic cycle. This encompasses the role of vegetation in water balance, energy partitioning, and surface fluxes. An improved coupling between ecohydrology and atmospheric science is needed to evaluate the responses of ecological systems to climate change and variation, and the associated feedbacks of ecological systems to climate.

5. How does climate variation impact the dynamics of biologically available water in terrestrial systems, and how do those dynamics, in turn, affect ecological patterns and processes at regional-to-continental scales?

Ecological responses to climate change will be tightly coupled to changes in the amount of water that is available to biota, which we will refer to as "biologically available water." Often precipitation alone is used to forecast ecological change, yet precipitation alone may be a poor predictor of ecological response. Precipitation is only the first step in the water budget that leads to biologically available water; other processes such as interception, infiltration, redistribution including runoff and run on, and soil evaporation may need to be considered to accurately assess the amount of water available to biota. This issue has arisen repeatedly in recent workshops bringing ecologists and hydrologists together.

Soil water is a closer proxy of biologically available water than precipitation alone. Soil water dynamics reflect not only precipitation but also a variety of other factors in the water and energy budget. Despite the central role of water limitation in driving many ecosystem dynamics, ecologists have attained astonishingly few long-term data sets on soil water dynamics, and there are few long-term data sets of soil water at high temporal resolution (e.g., hourly to daily; for a notable exception see Oklahoma Mesonet at http://okmesonet.ocs.ou.edu/). Similarly, hydrologists have often focused on water quantity and quality issues and bypassed collection of soil water data.

Another important aspect of determining biologically available water is to partition the various components that are lumped under the term of "evapotranspiration." Evapotranspiration is usually the dominant part of the water budget, in more arid systems accounting for more than 95% of incoming precipitation losses. Yet few studies have partitioned the major components of interception, soil evaporation, and plant uptake and transpiration. The separation of these categories is required to evaluate biologically available water. Hence, although ecologists have long recognized the fundamental importance of water in driving ecosystem dynamics, and hydrologists have focused on water quantity and quality issues, we are currently a long way from having a sufficient quantification of the dynamics of biologically available water and understanding the associated ecosystem responses.

An improved understanding of many ecosystem dynamics requires improved estimates of biologically available water. For example, thresholds for extensive tree mortality in response to regional drought, such as the current pinyon mortality event described above, should be more closely tied to patterns of soil water and plant water potential than precipitation alone. Water budgets are rarely quantified over periods long enough to capture interannual variation, in enough detail to capture soil water content from a plant-centric perspective, or over large enough areas to determine the degree of synchrony between climate, soil water, and vegetation response.

Some of the most rapid changes in vegetation are likely to be associated with regional-scale, drought-induced mortality. Hence, understanding, quantifying, and forecasting biologically available water and how it will change in response to climate change is particularly important with respect to threshold values for ecosystem responses. These ecologically important responses include processes such as triggering of transpiration, production, reproduction, dispersal, cavitation, germination, establishment, and mortality. A focus on biologically available water may enable us to detect stronger synchrony between climate drivers and ecological responses. Hence, an important goal is to determine if we can we forecast biologically available water and associated ecological responses.

6. How do changes in climatic means and variances alter ecosystem-facilitated biogeochemical cycles and associated greenhouse gas and energy feedbacks to the climate system, including the impacts on net ecosystem exchange, evapotranspiration, ground water recharge, and surface- vs. groundwater use?

Only recently are scientists beginning to appreciate and quantify the extent to which changes in land surface vegetation can provide feedbacks to climate. This issue requires a more direct integration of ecology, hydrology, and atmospheric science. A major issue of concern is how ecological changes at regional-to-continental scales, driven by both climate variation/change and changes in land use, will facilitate feedbacks that link ecological, hydrological, and atmospheric processes.

Building on the example discussed above on regional-scale, drought-induced dieback in dominant tree species, we need to determine if the expected changes in near surface energy and water budgets are of sufficient magnitude to feed back to precipitation patterns. Even a reduction of tree cover from about 40% to about 25% can produce a large, nonlinear change in the distribution of near-ground energy input; more extensive tree mortality would be even more dramatic. Related alterations of the water budget would also be expected.

Atmospheric scientists are providing ever-growing evidence that changes in land surface properties can and do indeed feed back to alter precipitation and temperature patterns. Although much of this research has focused on land surface changes associated with anthropogenic land-use change, feedbacks of similar magnitudes are certainly plausible in conjunction with regional-scale mortality of dominant tree species and need to be evaluated more fully. A major investment is needed to determine if we can forecast ecologically facilitated feedbacks on carbon, water, and nutrient cycles.

B. Infrastructure

The infrastructure needed to address the questions about ecological–hydrological–climate linkages in terrestrial ecosystems requires a combination of intensively studied sites and a much more extensive distribution of some related measurements. The infrastructure envisioned is a regional-to-continental network of nodes, some of which are more intensively instrumented and studied. Existing and anticipated infrastructure associated with programs other than NEON is insufficient to address the questions above, particularly because the measurements are too sparse and hydrologically biased for regional-scale ecosystem evaluation. Further, lack of consistent use of methods for measuring soil water potential and soil water content has diminished the applicability of existing data for evaluating regional-scale hydrological responses.

The proposed infrastructure is designed to allow development of a mechanistic link between abiotic drivers and biotic responses at regional-to-continental scales. The envisioned infrastructure would allow detection of regional-to-continental scale temporal variation for sites that include important gradients. The infrastructure would capture the interplay between near-continuous abiotic variable assessment and biotic variables assessed at different temporal scales across the gradient. Further, the infrastructure would include both intensive and distributed sites, plus use of existing networks. A full suite of standard meteorological measurements is assumed for each major node within the network and is not detailed below. New technology should be evaluated as to where embedded sensor arrays might be employed.

Focus on an ecologically meaningful water budget

We propose infrastructure that allows a full evaluation of the water budget at intensively measured nodes of the network. Measurements would be needed for precipitation, interception and canopy wetness, runoff, subsurface flow, deep drainage, water table, streamflow, litter water content, soil water content and soil water potential, plant water potential, and plant transpiration. Additionally, measurements would be needed of ecosystem-scale water and CO_2 fluxes, supplemental soil flux measurements, and perhaps flux measurements of other biogenic compounds. Using emerging technology, we would also envision continuous, automated measurements of stable isotopes of C, H, and O using field-deployable, tunable diode lasers to evaluate not only the scalars but also their associated pools. Sapflow systems would be applied to estimate transpiration rates of dominant species.

A key development need is technology for automatically measuring plant water potential in the field, either continuously or discretely at several times during a day. We also envision tram-based measurements across portions of an intensively studied site that would allow sampling of gases, spectral data, radar, LIDAR, and meteorological data. Measures of biological response are needed at a variety of time scales, including net ecosystem exchange (30 min); leaf area index (LAI, daily); stem size changes via dendrometers (daily); harvest-based estimates of aboveground productivity (periodic, but annual at a minimum); estimates of belowground productivity (periodic, but annual at a minimum) measured or estimated from minirhizotrons, soil cores, and isotopes; seed production (annual); and establishment and mortality (annual).

A key strategic variable to measure as extensively as possible is soil water content or potential, in a standardized approach, because this is a closer proxy for biologically available water. Another technology-development need is for continuous, automated measurement of plant water potential, which would be one of the most direct determinants of biologically available water. The current methodology requires destructive sampling and manual measurements. An innovative modification of the current approach is needed to enable in situ and continuous measurement.

An evaluation of sensor locations needs to be more fully evaluated. The existing flux tower network has grown extensively over the past few years. Effective integration with this network needs to be considered both from a scientific perspective and in terms of cost-effective leveraging.

Remotely sensed measurements

Site-intensive data collection will be insufficient without integration with remote sensing technology to provide as many estimates of the above variables or their correlates as possible. It is important to develop ecologically relevant metrics to go beyond leaf area index. Spectral detection of foliar water content remains challenging, but some studies indicate that this may be quite feasible. The advantage of such metrics is that they enable a continuous metric that is a close proxy for biologically available water. NEON should be poised to take advantage of recent and developing National Aeronautics and Space Administration (NASA) platforms and to facilitate the development of better metrics for an ecologically relevant water budget. NEON should also contribute to future innovative design needed for regional-to-continental scale assessments. For example, a major technology investment that would facilitate such assessments would be a geosynchronous, ecosystem-based satellite (30-min resolution).

Mobile manipulation technology

Improved understanding and predictive capability of ecological–hydrological–atmospheric linkages in terrestrial ecosystems will require an important experimental component. The importance of integrating a major experimental component into gradient studies has recently been advocated within the ecological community. NEON should integrate the many existing relevant experimental studies, such as the free air CO_2 enrichment (FACE) sites. Several experimental systems include rainout shelters that alter precipitation input. More recently, mobile rainfall simulation systems have been developed that can extend above canopy and can be deployed in a wide variety of ecosystems. Such systems are an important addition to the set of manipulation experiments in that they facilitate evaluation of how small vs. large inputs of precipitation are partitioned ecologically. The feasibility of mobile systems for manipulating other factors such as temperature should also be evaluated. Investment in a pool of mobile instruments for manipulation would allow effective, focused experimentation for major nodes within the network.

Standardization laboratory and archival center

A central laboratory is needed as part of the infrastructure to standardize equipment, provide standard relationships such as soil water potential vs. soil water content, and to archive samples. For example, plant leaves should be archived for future analysis with molecular probes capable of detecting which genes are turned on by drought. Soil samples could be archived for future biogeochemical analyses of additional elements of concern or at higher spatial resolution than is currently feasible. Other fields of environmental science are making major investments in soil repositories. NEON should evaluate such investments and develop a system for prioritizing sample archiving.

Network linkages and cooperative agreements

The nodes for the NEON network should be selected to ensure representative coverage to address important issues related to biologically available water at regional-to-continental scales. The infrastructure should make every effort to leverage existing networks, but it should also be deployed where ecologically appropriate, recognizing that existing networks were not developed with a regional-to-continental scale ecological focus. There should be linkages to the Consortium for the Advancement of Hydrologic Sciences, Inc., (CUAHSI) and its hydrological observatories, but a NEON focus on forecasting biologically available water should be considered a key distinguishing factor between NEON and CUAHSI. Established networks that should be considered include but are not limited to AmeriFlux tier 3 sites, National Atmospheric Deposition Program (NADP) sites, U.S. Geological Survey (USGS) streamflow sites, and soil water networks under USDA-NRCS (SCAN: Soil Climate Analysis Network or SCAN) and NOAA's [GEWEX (Global Energy and Water Cycle Experiment) America Prediction Project.

Data assimilation

Real-time data assimilation is a routine exercise in numerical weather forecasting. Assimilation of historical data (with better quality control than real-time data and with additional data that may not be available real time) using the same updated model is called "reanalysis." Reanalysis has been widely used in climate studies in the past 10 years. Similarly, assimilation of real-time data from NEON needs to be developed to provide a coherent database for regional and continental studies. Models that can be used for data assimilations need to be developed as well. Whenever there is a major revision of these model(s), a reanalysis should be done. The final assimilated data set along with the models are expected to be some of NEON's most valued legacies. Collaboration with the atmospheric sciences community should be pursued in this endeavor.

IV. Hydroecology and Terrestrial–Aquatic Linkages

A. Questions and Discussion

Climate changes are expected to have large effects on the linkages between terrestrial and aquatic ecosystems that are manifested over large spatial scales. Three high-priority questions we identified deal with effects of climate change on terrestrial–aquatic linkages and the functioning of aquatic ecosystems influenced by inputs from terrestrial systems. By using the term hydroecology in this section, we mean the study of ecological and hydrological processes in rivers, lakes, and wetlands. Implicit in the term are links between hydrology and biology for understanding freshwater biota.

7. How does the nature of hydrologic variation (timing, magnitude, duration, and frequency) influence aquatic ecosystems with respect to (a) extent and distribution, (b) biotic structure and productivity, and (c) nutrient inputs and subsequent eutrophication?

Terrestrial–aquatic linkages are driven by hydrologic processes that control the spatial and temporal distribution of aquatic ecosystems, as well as the amount and timing of material inputs. Changes in the timing and amount of precipitation profoundly influence the size and distribution of aquatic ecosystems, species composition, primary and secondary productivity, the transfer of nutrients and other materials from adjoining lands to water, and the subsequent effects of these materials on wetlands, streams, rivers, lakes, reservoirs, and estuaries. For example, under wetter conditions, shallow aquatic ecosystems are expected to expand, duration and frequency of floodplain inundation to increase, and aquatic biodiversity and productivity to increase. Increased input of nutrients from terrestrial systems may also lead to increased eutrophication of rivers, lakes, and estuaries in the lower portions of watersheds. More extreme rainfall events, however, may lead to reduced biodiversity and productivity due to high rates of flushing, scour, and deposition of eroded sediments.

Effects of increased hydrologic variability may be particularly strong at high latitudes and altitudes where the seasonal distribution of snow and rain is particularly important for aquatic ecosystems, and in arid and semiarid regions where hydrologic variability is already high. Under a drier climate or one characterized by longer droughts, aquatic ecosystems are likely to contract, leading to reduced biotic diversity and productivity, as well as altered inputs to and connections among aquatic ecosystems. The effects of a drier climate may be particularly acute in humid areas, which are not adapted to long or frequent periods of drought. Increased intensity or frequency of fires in a drier climate may increase the input of nutrients, metals, and sediments and alter the quantity and chemical character of organic matter inputs to aquatic ecosystems.

8. How do climatic changes interact with anthropogenic modifications of hydrology to influence exchanges of materials between aquatic ecosystems, terrestrial systems, and the atmosphere, as well as the behavior of aquatic systems as conduits or barriers to species exchanges and migrations?

Humans are causing large-scale changes to hydrology by means of land-use changes producing higher rates of runoff, changes to channel morphology such as channelization, water removals and returns, and large-scale water diversions and interbasin transfers. Climate change may exacerbate or perhaps mitigate some of these hydrologic changes. We must evaluate the effects of climate change within the context of other direct anthropogenic changes to hydrology in order to develop a better understanding of their interacting effects in human-dominated landscapes. Important interactive effects of climate change and other anthropogenic hydrologic changes include effects on nutrient and contaminant inputs to aquatic ecosystems from urban and agricultural areas, effects on emissions of greenhouse gases such as nitrous oxide (N_2O) and methane (CH_4) from wetlands and other aquatic systems to the atmosphere, and recharge to and flow rates in regional groundwater systems. In addition, human alterations of hydrology are having large impacts on species movements and migrations among aquatic ecosystems, for both native and invasive species, and climate change is expected to alter these impacts in ways we do not understand.

9. How do changes in temperature regimes (interannual, seasonal, diurnal) influence inputs to and processing of materials in aquatic ecosystems?

Temperature regimes, including annual and interannual, seasonal, and diel patterns, have an important influence on the amount and timing of organic inputs to aquatic ecosystems from surrounding lands and on biotic processes within aquatic ecosystems. Temperature regime effects on riparian vegetation phenology, species composition, and productivity, in turn, have large effects on the biotic structure and primary and secondary productivity of streams, rivers, and small lakes. Temperature regimes also have a large impact on seasonal mixing regimes that control the productivity of lakes, as well as on the thermal habitat distribution controlling the species composition of lakes and streams. Earlier and diminished snowmelt in northern latitudes may reduce biotic habitat and productivity of streams and small lakes fed by meltwater in late spring and summer.

B. Infrastructure

Measurement of physical, chemical, and biological properties of aquatic ecosystems can provide essential information as to climate change effects on aquatic ecosystems, as well as the terrestrial systems they drain, because drainage water integrates signals from the entire catchment. Measurements related to terrestrial–aquatic linkages are essential to assessments of climate change effects on material exchanges between land and water, and on the structure and function of a majority of aquatic ecosystems that are highly dependent on inputs from terrestrial systems. NEON can be most useful in providing infrastructure in the areas of remote sensing and landscape status; nested observations within river basins; new sensors for remote, high-frequency measurements of concentrations and fluxes; new tracers for large-scale experiments; and cooperative agreements among different government agencies to coordinate ongoing observation programs and new sensor development to ensure the most efficient network of observations.

Remote sensing and landscape status

Remote sensing from satellite platforms offers the broadest coverage of water distribution and sediment/chlorophyll properties of water bodies. Remotely sensed data on spatial and temporal variation of surface water (saturated soils) in wetlands and riparian zones and on sediment/chlorophyll levels of rivers, lakes, reservoirs, and estuaries are needed for broad-scale assessment of climate change effects on terrestrial–aquatic linkages. In addition, new, more focused remote sensing approaches (aircraft and drones with appropriate sensors) are needed to measure water distribution, temperature, material fluxes, and biota distributions within and along drainage corridors. The specific focus on drainage corridors emphasizes measurements at the sites where land–water exchanges are concentrated. Finally, measures of landscape status, including land use, nonpoint (e.g., fertilizer applications) and point sources of nutrients and contaminants (e.g., municipal, industrial, agricultural sources), vegetation type, phenology, and biomass, as well as soil chemistry obtained from remote sensing and land-based surveys, must be coordinated and aggregated into a unified database. These data are needed to determine source terms for fluxes from land to water.

Nested observations within river basins

Drainage networks are by their nature hierarchical, and measurements related to terrestrial–aquatic linkages should incorporate this hierarchical structure. Observations of key physical (stage/discharge, temperature, turbidity) and chemical (dissolved O_2; pCO_2; pH; dissolved organic and inorganic forms of C, N, and P; chlorophyll) parameters should be made within selected river basins at sites ranging from zero-order to high-order streams and rivers. The number of sites needed to characterize land–water exchanges should decline exponentially with increasing stream order. A similar set of groundwater measurements should be included in this network, particularly in riparian zones and other land–water interfaces. This hierarchical observation network will differ from ongoing stream monitoring programs in that measurements should be made in situ, at high frequencies (minutes to hours), with automated sensors and datalogging equipment linked by telemetry to a central data repository to provide real-time data streams.

Many of the in situ sensors needed for this network (e.g., pCO_2, nutrients) are not currently available at sufficiently sensitive detection levels but could be within five years with modest instrumentation investments. In addition, new water age and chemical source tracers should be developed to provide information on the temporal, spatial, and process-based controls on material fluxes. One promising new approach is the development of "nanotracers" that could be used in field experiments to identify hydrologic flowpaths and residence times. High-frequency biological observations should also be made at this nested network of sites in conjunction with the physical/chemical measurements, but these would also require instrumentation development. Sorely needed are improvements in data telemetry that can facilitate the tagging of animals, and in microarray approaches for monitoring functional microbial parameters at high frequency.

Network of wetland flux towers

The network of flux towers that use the eddy covariance approach to determine biosphere–atmosphere exchanges of CO_2 and water vapor includes few wetland sites. Given the large potential for biosphere–atmosphere feedbacks involving greenhouse gas emissions from wetland areas, it is important to expand the flux tower network to include more and different types of wetland ecosystems (boreal, prairie, floodplain, etc.). These new flux towers should include sensors to monitor biosphere–atmosphere fluxes of N_2O and CH_4 as well as CO_2 and water vapor from plant canopies as well as the soil. New chemical or stable isotope approaches are needed to determine the source material for N and C emissions. These new approaches also should be applied to hydrologic fluxes in drainage corridors as described above.

Network linkages and cooperative agreements

There are numerous federal and state programs that conduct physical, chemical, and biological monitoring of aquatic systems. In particular, the U.S. Geological Survey has several ongoing programs at the national [e.g., National Stream Quality Accounting Network (NASQAN), National Water-Quality Assessment (NAWQA), Benchmark stations] and state level aimed at quantifying chemical concentrations and fluxes in streams and rivers that are essential to NEON. The U.S. Forest Service maintains numerous field stations that also collect these types of data, and U.S. Fish and Wildlife Service and USGS have numerous monitoring programs for aquatic biota. In addition, there are several new federal initiatives that will provide data on hydrology and chemical fluxes (CUAHSI) and initiatives to develop automated, in situ chemical sensors and other measurement systems for remote deployment (NSF's Collaborative Large-scale Engineering Analysis Network for Environmental Research (CLEANER) and Ocean Research Interactive Observatory Network (ORION) programs]. It is critical that NEON establish cooperative agreements with the appropriate agencies to ensure that these data collection programs continue and the data are available within the NEON framework.

V. Synthesis: Responses and Feedbacks

A. Questions and Discussion

10. How will changes in climate influence regional ecosystem structure and function, and how will ecosystem changes feedback to climate, hydrology, and biogeochemical cycles?

It is well documented from ecological studies conducted across a range of spatial and temporal scales that climate has both direct and indirect effects on ecological systems with significant feedbacks to the climate system. Thus, changes in climate (i.e., magnitude and direction of change, variability, and uncertainty) are also expected to have complex interactions and feedbacks with ecological systems. Forecasting future ecosystem and atmospheric dynamics under a changing climate system requires new approaches, technologies, and infrastructure that explicitly account for these interactions and feedbacks across spatial and temporal scales. These new approaches, technologies, and infrastructure are particularly relevant to addressing national scale problems that require the extrapolation of fine-scale information to broader scales or vice versa.

A changing climate is expected to have large and significant effects on structural and functional attributes of ecological systems, such as biodiversity, community composition, primary and secondary productivity, food web dynamics, and state changes, as well as biogeochemical and hydrological cycles. Disturbance regimes (e.g., fire, microbial diseases, insect pests) may be altered through interactions between ecological properties and changes in climate. Many of these responses are expected to be nonlinear and to exhibit threshold behavior with time lags and hysteresis. New approaches to extrapolating information and ecological responses across spatial and temporal scales will be required that account for these nonlinearities.

Disentangling human impacts from natural variability will remain a critical challenge. The most sensitive indicators and points of intervention leading to effective ecosystem management will need to be identified, such as those for the maintenance of threatened and endangered species, sustained biodiversity and ecosystem function, and invasive species control. Other ecosystem services may be impacted, such as minimizing erosion as well as controlling pests and diseases. Given the complexity of dynamics within the Earth system, interactions with other aspects of global change will need to be included in all analyses.

Ecological responses are expected to have strong feedbacks on the climate system, with effects on surface roughness, composition of the atmosphere (including CO_2, trace greenhouse gases, particulates, clouds), and energy exchange between the land and atmosphere (e.g., albedo, evaporation, transpiration). Feedbacks to the hydrologic cycle are expected that include effects on evaporation, transpiration, water holding capacity of the soil, erosion rates, and water quality. Feedbacks to biogeochemical cycles include effects on nutrient retention and soil development. Because these feedbacks are complex and often involve multiple interacting components of the Earth system, it is critical to consider other aspects of global change that interact with changes in climate.

B. Infrastructure

In general, infrastructure needs can be designed around six major layers (the "insect plan"). Each layer has its own strengths and weaknesses that complement the other layers. The first three layers are observational layers, while the last two are informatics layers. Observational layers decrease in spatial extent from 1 to 3 and increase in intensity of experimentation and site-based data collection.

1. The first layer is "wall-to-wall" coverage of the defined study area (continental United States or broader). A suite of new and existing aircraft and satellite images provided at appropriate spatial and temporal resolutions will be needed for the questions being addressed. These images would be combined with spectrometer and LIDAR measurements, as well as new technologies to obtain a wide range of outputs related to land-use and ecological patterns. This coverage would allow spatially continuous change detection over the entire area.

2. The second layer includes public observatories (about 100,000 sites). These observatories are low-cost, ground-based observation sites located to provide maximum coverage to detect change early. This low-intensity sampling of variables, including plant phenology and major insect outbreaks, would be provided by volunteers in a manner similar to Audubon Christmas bird counts or the National Weather Service's Cooperative Observer Program (COOP) stations.
3. The third layer includes gradient transects strategically located throughout the study area to quantify ecological variability along existing gradients. Approximately 20 sites would need to be located within each major biome or ecoregion, with a footprint of 10 to 100 km that spans important gradients, such as temperature, precipitation, disturbance, soil properties, and human population density.
4. The fourth layer includes intensive experimental sites located along gradients where a mechanistic understanding of how global and regional changes in climate affect ecosystem dynamics can be determined using experimental manipulations.
5. The fifth layer includes statistical and simulation modeling as well as other quantitative tools. These models can be used in a number of ways, including (a) to synthesize information from the observation layers, (b) to generate testable hypotheses, (c) to identify gaps in knowledge and gaps in spatial and temporal resolution of data, and (d) to forecast future ecosystem properties and dynamics under changing climate. A new generation of models will likely be needed that include nonlinear dynamics through time and space, threshold behavior, time lags, and hysteresis. These models will need to be openly available and easy to use by the ecological community.
6. The sixth layer is information management for quality control and accessibility. This layer is critically important for managing the vast amount of information available from the observational layers and models, and to ensure that the information is usable, meaningful, and easily accessible.
7. Effective implementation of this six-layer model, incorporating the more specific recommendations outlined previously, holds great potential for improving our ability to evaluate ecological implications of climate change, in terms of both responses and feedbacks. It will also provide managers and decision-makers with improved tools for addressing regional-to-continental scale issues of national and international importance.

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