MEMORANDUM
July 9, 2004

TO: Participants in NEON Ecological Aspects of Biogeochemical Cycles Workshop

FROM: Russ Monson, Jeff Goldman, Rina Aviram, Turner Odell, and Brad Spangler

SUBJECT: Pre-meeting materials

This document contains pre-meeting materials for the NEON workshop on ecological aspects of biogeochemical cycles. They have been compiled by the American Institute of Biological Sciences (AIBS) and RESOLVE, in consultation with Russ Monson. The materials include the current draft meeting agenda and a set of background reading materials. The reading materials provide a current explanation of the rationale behind this summer's NEON workshops, a series of excerpts from reports on previous NEON planning meetings, and a piece from a project called EarthScope that has taken a similar approach to NEON in developing its orientation and key research questions. Please be aware that NEON has been evolving throughout its planning process and continues to do so. These materials therefore reflect that evolution and are not definitive statements on the ultimate design and future of NEON. However, they should provide all workshop participants with a common knowledge base regarding how NEON has been conceptualized to date.

We understand that all of the workshop participants are busy people and therefore have done our best to keep the background materials to a reasonable length so as to not overwhelm anyone with an extreme reading load. If you are able to take a look at these materials in advance, it will help us all make the most of the time we will spend together in Boulder.

As you read through the materials, please keep in mind the two key objectives for the workshop: 1) *to identify the key scientific questions, hypotheses, or issues around which NEON should be organized in order to support research in the biogeochemistry arena*; and 2) *to suggest infrastructure design needs associated with those key research questions*. In addition, prepare yourself to think big and to think in terms of what may be possible in the future, not just what is possible today.

Below is an outline of the pieces incorporated in the NEON Biogeochemistry Pre-Meeting Materials file. The outline includes the citations for the full documents from which the reading materials were drawn as well as information about accessing them on the web.

The NEON Biogeochemistry Pre-Meeting Materials should include:

1) **Ecological Aspects of Biogeochemical Cycles Workshop Agenda**

2) **"Rationale for NEON Summer Workshop Series," American Institute of Biological Sciences, July 2004.** This piece offers AIBS's explanation of the path leading to the 2004 summer workshop series.

3) ***IBRCS White Paper: Rationale, Blueprint, and Expectations for the National Ecological Observatory Network*, Infrastructure for Biology at Regional to Continental Scales (IBRCS) Working Group and American Institute of Biological Sciences, March 2003.** This excerpt consists of the executive summary of the paper. It outlines NEON's general mission, the scientific rationale behind the need for NEON, how NEON may operate to meet that need, and the results NEON is intended to produce. As noted, this paper represents one stage in the evolution of the NEON concept. Full report available at: http://ibrcs.aibs.org/reports/pdf/IBRCSWhitePaper_NEON.pdf

4) ***NEON: Addressing the Nation's Environmental Challenges*. National Research Council, 2003. Washington, DC: The National Academies Press.**

   - Executive Summary: This piece summarizes a National Research Council report that examines NEON's potential to fulfill the NSF charge of addressing the most pressing environmental challenges of the day at continental and regional scales. Full report available at: http://www.nap.edu/books/0309090784/html/

   - Biogeochemistry Excerpt: This excerpt from "Chapter 2: Environmental Issues of National Importance and the Role of the National Ecological Observatory Network" of the 2003 NRC report, outlines the nature of the ecological challenge of [WORKSHOP TOPIC] and how a national network of biological infrastructure like NEON would contribute to addressing it.

   - Examples of Observatories & Integration Excerpt: This excerpt from "Chapter 3: Concept and Implementation of the National Ecological Observatory Network" of the 2003 NRC report provides examples of potential NEON infrastructure designs.

5) ***Report to the National Science Foundation: Fourth Workshop on the Development of National Ecological Observatory Network (NEON): Standard Measurements and Infrastructure Needs*. June 2002.** This excerpt discusses the potential measurement approaches and potential NEON infrastructure needs associated with the biogeochemistry challenge.
   Full report available at: http://ibrcs.aibs.org/reports/pdf/NEON4_June2002.pdf

6) ***EarthScope: Scientific Targets for the World's Largest Observatory Pointed at the Solid Earth*. October 2001.** This is an excerpt from a report on a project similar to NEON. The piece provides examples of research questions from the EarthScope project that are of similar breadth to the research questions that this workshop is designed to elicit.
Full report available at: http://www.earthscope.org/assets/es_wksp_mar2002.pdf

Action Item: Finally, to help participants become familiar with one another, we ask that you please provide us with a brief, one-paragraph description of your background and research interests (including citations for 2-3 recent publications if available) as soon as possible. Please send them to Rina Aviram at raviram@aibs.org. The short bios will be compiled and made available to all participants.

NEON Workshop on Ecological Aspects of Biogeochemical Cycles

July 20-21, 2004
Boulder, Colorado

Convened by
Russell Monson, University of Colorado, Boulder
In Conjunction with The American Institute of Biological Sciences
With Support from The National Science Foundation

Agenda

Meeting Objectives:

- *Identify the key scientific questions, hypotheses, or issues around which NEON should be organized in order to support research in biogeochemistry; and*
- *Suggest infrastructure design needs associated with these questions.*

Tuesday, July 20

	Topic	Lead
8:30 AM	**Light Breakfast Available** Served Continental style; optional attendance.	
9:00	**Opening Remarks/Setting the Stage**	
	• Welcome	Monson
	• Group introductions	
	• Context for meeting; desired outcomes	Monson
	• How we are going to get at those issues: review of agenda and ground rules	Facilitator
9:30	**NEON: Where We Are Today**	
	• Ground covered to date	Goldman
	• Questions & answers	
10:30	**Break**	
10:45	**Criteria That Will Be Used to Prioritize Among Suggested Questions, Hypotheses, and Issues** *(to be determined by participants)*	Facilitated
11:15	**Small Group Work to Generate Candidate Questions, Hypotheses, and Issues** *(4 groups of 5; questions suggested during pre-meeting consultations will be used to stimulate small groups' thinking.)*	Facilitated (2 facilitators rove between the 4 groups)

	Topic	Lead
12:45 PM	**Lunch**	
1:45	**Small Group Reports to Plenary: Suggested Questions, Hypotheses, and/or Issues** *(10-minute report out from each of 4 small groups, followed by reflective plenary discussion of themes that emerged.)*	Facilitated
3:15	**Break**	
3:30	**Selecting Key Questions, Hypotheses, and/or Issues** *(Using "n/3" technique, apply previously agreed-upon selection criteria to brainstormed list of possible questions, hypotheses, and/or issues to select items to be recommended as focal points.)*	Facilitated
5:15	**Closing Comments/Plan for Next Day**	Monson
5:30	**Adjourn for the Day**	

Wednesday, July 21

8:30 AM	**Light Breakfast Available** Served Continental style; attendance optional.	
9:00	**Opening Remarks.** • Review Agenda for the Day • Reflections from Day 1	 Monson
9:15	**Small Group Work to Generate Suggestions Re: Infrastructure Associated With Suggested Questions, Hypotheses, and Issues** *(4 groups of 5; each group focuses on infra-structure needs associated with just one of the priority questions / hypotheses / issues identified on Day 1.)*	Facilitated (2 facilitators rove between the 4 groups)
10:45	**Break**	
11:00	**Small Group Reports to Plenary:** *(15-minute report out from 1st 2 of the 4 small groups, followed by questions and answers)*	Facilitated

	Topic	**Lead**
12:00	**Group Photo**	
12:15	**Lunch**	
1:15	**Small Group Reports to Plenary (cont'd)** *(15-minute report out from remaining 2 of the 4 small groups, followed by questions and answers)*	Facilitated
2:15	**Plenary Discussion: Infrastructure Needs.** *Reflective discussion of themes and insights that emerged from small group presentations on infrastructure needs)*	Facilitated
3:15	**Break**	
3:30	**Plenary Advice to Report-Writers.** *Full group will have an opportunity to offer suggestions to the subgroup that will produce the workshop report. Focus will be on identifying key points and themes to highlight in the report.*	Facilitated
4:15	**Closing Comments**	Monson/ AIBS
4:30	**Adjourn**	

Rationale for 2004 NEON Summer Workshop Series

American Institute of Biological Sciences
Infrastructure for Biology at Regional to Continental Scales Project

The Infrastructure for Biology at Regional to Continental Scales (IBRCS) project of the American Institute of Biological Sciences (AIBS) engages the scientific community in exploring the infrastructure needed to make advances in ecological and other biological disciplines that span regional and continental scales. The primary focus of the project has been the proposed National Ecological Observatory Network (NEON), an initiative to establish a national platform for integrated studies and observation of natural processes at all spatial scales, time scales, and levels of biological organization. Through meetings, publications, and other outreach activities, AIBS has tried to educate the prospective NEON community about the program, provide venues for communication about NEON and related opportunities, serve as a central source of information, and help the community navigate the often shifting scientific, social, and political landscape on which NEON is developing.

Identifying and Addressing Needs

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. To physically create NEON, Congress must first appropriate funds in the MREFC account for its construction. A critical prerequisite to that milestone is the delivery of a detailed Project Execution Plan (PEP) or implementation plan. A prerequisite to the PEP is a detailed description of the physical design of the network [i.e., a description of the infrastructure to comprise NEON, where it will be located (or how it will travel), and how it will be connected and incorporated into a functioning network]. Furthermore, a prerequisite to that physical design is a definition of the scientific objectives and targets of NEON. In summary, the following three sequential activities are critical to the goal of creating NEON: **Define** the science; **design** the network; **plan** the implementation.

A National Research Council Committee on NEON recently recommended six grand challenge areas that require a national platform for research and education, and AIBS is now helping the community further define NEON science objectives and network design in the context of those challenge areas through a series of workshops. By conducting workshops in partnership with experts from the prospective NEON community, these workshops will provide venues for discussing, developing and prioritizing NEON's science objectives. The goal of the workshops is to (1) identify the key scientific questions and hypotheses related to the challenge area that can be best addressed by a distributed and integrated ecological research facility, such as NEON and (2) suggest infrastructure design needs for NEON, based on the technological and scientific requirements associated with those questions and hypotheses.

With its partners from the ecological community, AIBS will convene workshops to explore how NEON can be designed to address the following environmental challenges:

(1) **Biodiversity, species composition, and ecosystem functioning**
Dates: July 27-28, 2004
Location: UC Hastings Reserve, Carmel Valley, CA

(2) **Ecological aspects of biogeochemical cycles**
Dates: July 20-21, 2004
Location: Millennium Harvest House, Boulder, CO

(3) **Ecological implications of climate change**
Dates: August 24-25, 2004
Location: Westward Look Resort, Tucson, AZ

(4) **Ecology and evolution of infectious disease**
Dates: August 31-September 2, 2004
Location: Belmont Conference Center-Baltimore, MD

(5) **Invasive Species**
Dates: March 18, 2004
Location: Westin Grand Hotel, Washington, DC

(6) **Land use and habitat alteration**
Dates: August 25-26, 2004
Location: Belmont Conference Center-Baltimore, MD

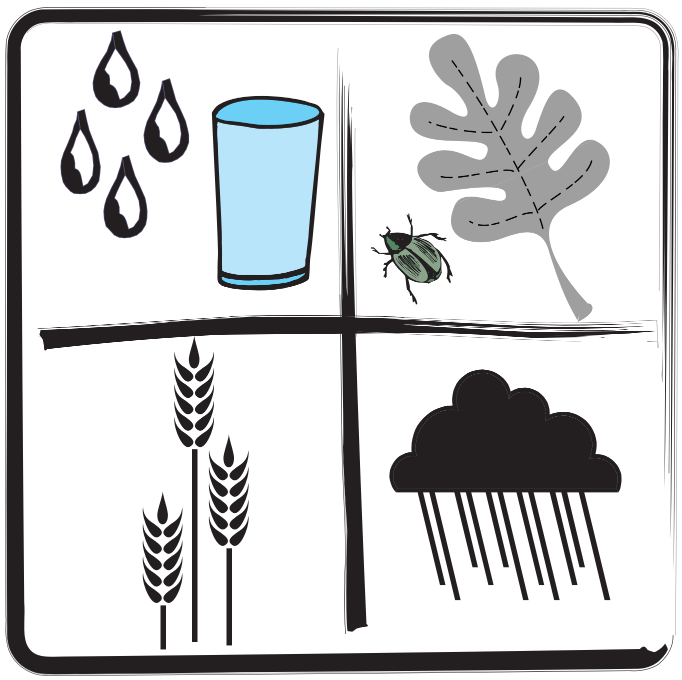
To ensure that all the workshops result in compatible and consistent types of recommendations and that the recommendations are promptly disseminated, the workshops will be developed in partnership with and facilitated by a professional meeting facilitation firm, Resolve, Inc. Resolve is an independent, neutral, not-for-profit organization that provides facilitation and mediation support in environmental and health matters and has successfully worked with AIBS on prior NEON meetings.

How Will Workshop Results Be Used?

Recently, NSF responded to favorable language from Congress, a National Academy of Sciences study on NEON, and an AIBS-organized NEON coordination conference by soliciting proposals for a NEON Coordinating Consortium (NCC) and Project Office. These entities will be responsible for developing the ultimate design and implementation plan for NEON. Proposals are currently under review and the formation of the NCC and project office is scheduled to begin during fall 2004, with the actual design work to begin at some point thereafter. With NEON again in the Administration’s budget request to Congress for FY05, the need to make progress on the NEON science plan and infrastructure requirements is immediate. These workshops are designed to meet the need for continued progress on the NEON design. The results will be made available publicly but will also be specifically forwarded to the NCC and project office, once established. Thus, the recommendations arising from this workshop series will constitute a head start on activities requested by NSF and the results of the workshops will feed into subsequent NEON planning activities when they begin.

IBRCS White Paper

Rationale, Blueprint, and Expectations for the National Ecological Observatory Network



Infrastructure for Biology at Regional to Continental Scales (IBRCS) Working Group

American Institute of Biological Sciences

neon
National Ecological Observatory Network

American Institute of Biological Sciences

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

Executive Summary

This white paper was developed by the Infrastructure for Biology at Regional to Continental Scales (IBRCS) Working Group as part of an American Institute of Biological Science's IBRCS project. The aim was to further advance the National Ecological Observatory Network (NEON) initiative by explaining the scientific rationale behind the need for NEON, how NEON will operate to meet that need, and the results that NEON is expected to produce. The IBRCS Working Group was aided by input from other scientists and organizations. As a result, this white paper represents the views of a broad segment of the scientific community.

NEON Mission

In the past century we learned an enormous amount about individual species and about ecological processes at the scale of watersheds and landscapes, but there is much we do not understand. In this century we must further our understanding of ecological processes and learn how local processes can be scaled up to biomes or continents if we are to accurately predict changes in the composition, structure, and dynamics of the nation's ecosystems and understand how those changes are likely to affect us. To develop that understanding, a new type of scientific infrastructure is needed—an infrastructure that enables the simultaneous collection of compatible data on fundamental ecological and evolutionary processes over broad geographical and temporal scales. NEON is a National Science Foundation (NSF) research platform that will apply experimental, observational, analytical, communication, and information technologies to investigate the structure, dynamics, and evolution of ecosystems in the United States, to measure the pace of biological change resulting from natural and human influences at local to continental scales, and to forecast the consequences of that change. The mission of NEON is to establish and sustain the scientific infrastructure and develop the intellectual capital needed to address critical questions about changes in ecological systems and to evaluate the impacts of those changes.

Scientific Rationale

Studies of the processes that affect our nation's ecosystems have been limited mostly to small geographic areas because they were conducted by small teams at single sites. While such studies have generated critical insights into ecological and evolutionary processes, many of the most challenging questions in the ecological, evolutionary, and biodiversity sciences require us to understand processes that operate over larger spatial and temporal scales and at all scales of biological organization, from molecules to biomes. Recent advances in analytical instrumentation, computer networking, information management, experimental methods, and computational analysis have set the stage for national, coordinated observations of our biological, physical, and chemical world. NEON will provide the infrastructure that allows scientists to investigate the suite of challenging and significant scientific problems requiring coordinated observations over large spatial and temporal scales. In addition to enabling groundbreaking research in the ecological, evolutionary, and biodiversity sciences, NEON will foster research in engineering and technology, information technology, and statistics and mathematics. From the ecological perspective, NEON will help us to understand the present composition and functioning of contemporary ecosystems, to elucidate how contemporary ecosystems have been shaped by historical natural and anthropogenic processes, and to forecast how contemporary ecosystems may respond to changes in key drivers.

NEON Design

NEON will be a common science facility open to all qualified users. Each regional observatory in the network will itself be a network of facilities, such as biological field stations; LTER sites; national parks; college or university campuses; marine laboratories; federal, state, and local agency field stations; or nature preserves. To ensure that NEON encompasses a broad range of ecosystem types, a minimum of 17 observatories is needed, 16 in the United States and 1 in Antarctica. Each observatory will include both a core site that is extensively instrumented and a number of satellite observatories that are less extensively instrumented. Highly specialized research infrastructure, including field-based sensor arrays, flux towers, stable isotope analyzers, microarray analyzers, and automated DNA sequencers, will be part of the NEON infrastructure.

The process of creating NEON involves building observatories sequentially through a process involving competitive peer review of observatory proposals, which allows the final structure of NEON to capitalize on the most creative ideas from a broad spectrum of the environmental science community.

A NEON Coordinating Organization (NCO) is envisioned to handle the national-level organization and administration. The NCO should be an open membership-based organization, broader than the institutions that operate and manage the regional observatories. A representative governing body with appropriate officers will formulate procedures, and a professional staff will see to administrative matters and work with the regional observatories to implement procedures.

A standard suite of instruments will be deployed and standardized measurements taken at NEON observatories to provide compatible data sets and analytical capability. These comprehensive measurements of (1) climate and hydrology, (2) biodiversity dynamics, (3) biogeochemistry, (4) biosphere–atmosphere coupling, and (5) spatial analysis and remote sensing, combined with manipulative experiments, provide the foundation for addressing questions about biodiversity and ecosystem function, carbon dynamics, invasive species, coupling of human and natural systems, ecology of infectious diseases, and biogeochemical imbalances.

Information technology (IT) is a key infrastructural component of NEON. It must bind together the core and satellite sites of an observatory with those of other observatories across the nation and integrate these distributed sites into a single, functional research tool. An important IT challenge lies in seamlessly integrating massive volumes of data into useful products. Such integration requires the adoption or, when necessary, development of standard protocols for data specification, data storage and dissemination, metadata specification, and data accessibility. Strong and continuous collaborations among individual observatories, the NCO, and other relevant experts and organizations will generate the cyber-infrastructure that overcomes this challenge. An important goal for NEON is to provide timely and broad access to all data; thus, NEON data policies will promulgate a cultural change that values data sharing.

In addition to observational data, and syntheses from these data, NEON activities will result in acquisition of objects within the physical, chemical, and biological domains. Curation of objects for current and future use requires a variety of appropriate repositories. In turn, efficient use of the collected objects requires comprehensive tracking and inventory information.

NEON will promote scientific cooperation and partnerships as a way to leverage resources, expertise, and information among research universities; federal, state, and tribal agencies; and for-profit and nonprofit organizations. NEON proposals for individual observatories and the NCO must clearly indicate that significant partnerships have been developed and that others will be sought.

Scientific Results and Products

A well-executed NEON program will result in many difficult-to-anticipate advances in ecological science. One general advance from NEON will doubtless be the explosive development of regional ecology, involving integrated understanding of flows of material, energy, nutrients, biological entities, and information through regional landscapes and watersheds. In addition to such general theoretical advances, we can identify the specific types of data and other products that NEON will provide.

NEON will produce data on climate and hydrology, biodiversity and population assessment, biogeochemistry, and spatial analysis and remote sensing, in addition to the data generated by manipulative experiments. Other products include new instruments and technologies; ecological models; data processing, summarization, and communication technology; and specimens and samples.

Education and Public Outreach

To be effective over its life span, NEON must engage and involve students, scientific and nonscientific groups, and the general public at all levels. NEON's dynamic and user-ready knowledge base, comprising real-time and continuous network data, will be a considerable asset for the teaching community and other public and private organizations. NEON will serve as a model of true integration of research and education.

Education and public outreach committees created by the NCO will guide the NEON education and public outreach missions and formulate strategic plans. Professional staff in the NCO education and public outreach offices will implement these strategic plans and coordinate programs with regional observatories. The education committee will explore all areas of formal and informal education, specifically focusing on the K–12 and undergraduate levels, but also including continuing education and special programs targeting underrepresented groups.

The public outreach office will coordinate closely with the education office and enact relevant recommendations from the public outreach committee. Public participation at NEON observatories will be fostered, and special efforts will be made to reach sectors of society traditionally underrepresented in science and environmental programs. The public outreach office will actively promote NEON resources and opportunities to the public, interface with print and broadcast media, publish newsletters, and disseminate press releases about items of popular, scientific, or agency interest.

Benefits and Applications

This synergy of new tools and approaches will benefit scientists by advancing the frontiers of knowledge and research capacity in ecology and will produce new perspectives in ecosystem science. NEON will provide critical infrastructure to support NSF research programs, such as

Biocomplexity in the Environment. In addition, NEON will provide the platform for performing research in coupled human and natural systems research, coupled biological and physical systems, and people and technology, three priority areas designated by the NSF Advisory Committee for Environmental Research and Education. The NEON program can also fill a significant gap in infrastructure for researchers from smaller institutions who want to conduct large-scale ecosystem research.

The NEON infrastructure will encourage collaboration between the research community, environmental monitoring programs, and the natural resource management community. Data emerging from NEON research sites will help inform decisions regarding management of the nation's natural resources. For example, the location and design of the NEON sites will help establish regional reference points for biological and ecological indicators of ecosystem function, something that will help state and federal agencies in setting goals for environmental management and protection. NEON observatories will also support extensive research on molecular phylogenetics and phylogeography, tools that federal and state agencies are increasingly using to establish conservation priorities.

NEON will benefit society by improving our understanding of the implications of ecosystem change for human welfare. Healthy ecosystems provide many goods and services that are essential underpinnings of our nation's economy. Ecosystem services include drought and flood control, pollination of crops, purification of air and water, pest and weed control, carbon storage, and decomposition of wastes, while goods include food, fiber, and pharmaceuticals. Furthermore, data from NEON can be used to predict the ecosystem responses to major meteorological and geological events such as hurricanes and volcanic eruptions. In addition to forecasting the ecological and environmental effects of extreme natural events, the NEON program will allow us to assess ecosystem response to human-induced stresses such as acid rain and global warming. NEON is a powerful research tool for discovering and identifying new introductions of non-native species, whose cost to the economy can total $137 billion annually, and investigating their ecological impacts.

Conclusion

The forefront of ecological research is headed evermore toward a focus on questions and concepts that are relevant over large geographical regions, and this highlights the need for coordinated scientific infrastructure that is itself spread over large regions. Ongoing advances in our technical capability permit the development of networks of people and tools that can meet that need.

NEON has been designed by the scientific community to capitalize on such capabilities and to enable discoveries about our nation's ecosystems that until now have been impossible to address. By fostering collaboration, the development of new tools and technologies, and the study of regional- and continental-scale questions, NEON will produce new perspectives in ecosystem science and thus public benefits, both anticipated and unforeseeable.

NEON

Addressing the Nation's Environmental Challenges

COMMITTEE ON THE NATIONAL ECOLOGICAL OBSERVATORY NETWORK

BOARD ON LIFE SCIENCES

DIVISION ON EARTH AND LIFE STUDIES

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

Executive Summary

Human technology, land use, and resource acquisition have accelerated the pace of regional and global environmental change to the extent that human actions are now a major force in the stability and functioning of most terrestrial, aquatic, and marine ecosystems. Those human-induced changes in our environment are expected to increase greatly over the coming decades, causing environmental issues to be one of the greatest challenges of the 21st century. The nation needs and deserves a scientific understanding of its natural and managed ecosystems that is sufficient to assess how alternative human actions might impact the functioning of ecosystems and the services that they provide the nation and to identify science-based solutions to ecological problems. Achieving the necessary mechanistic understanding of the environment, developing predictive ability and identifying solutions would require fundamental advances in basic scientific knowledge that can only be derived from a regional- or continental-scale program of experimental and observational research focused on the major environmental challenges that the nation faces.

The study of direct effects and feedbacks between environmental change and biological processes is inherently interdisciplinary and national in scope. Existing large-scale research programs, such as the National Atmospheric Deposition Program/National Trends Network, Global Energy and Water Cycle Experiments, and Moderate Resolution Imaging Spectroradiometer, have focused mostly on the physical and geochemical aspects of environmental change. To complement those programs, research should focus on the fundamental biological processes that underlie climate change and biogeochemical cycles and other important human-driven environmental change, such as introduction of invasive species, emerging diseases, and the loss of biodiversity. Research should synthesize population and ecosystem processes across regions with different environmental characteristics that influence ecological communities and across the continent. Biological research of such regional and continental scale has not been undertaken to any substantial extent, because of the inability of traditional small-scale ecological approaches to be scaled up to regional or continental scales. Indeed, neither the infrastructure required for such large-scale efforts nor the research efforts exist.

The National Ecological Observatory Network (NEON) proposed by the National Science Foundation (NSF) would be a network of infrastructure that would support continental-scale research on pressing environmental challenges. Major Research Equipment and Facilities Construction (MREFC) funding was requested to build a network for a coordinated, nationwide multisite network for experimental and observational environmental research. NEON would enable the study of common themes and the sharing of data and information across sites. It would facilitate a more integrated approach than merely linking existing research sites, such as the Long Term Ecological Research (LTER) sites, by allowing research on drivers of environmental changes to be pursued across the complete spectrum of ecosystems. It would be dedicated to producing the key results and fundamental scientific principles that are needed to project how human actions would likely affect natural and managed ecosystems across the nation in the coming decades.

PROCESS AND PURPOSE OF THIS STUDY

To evaluate the suitability of NEON to fulfill that role, NSF asked the National Research Council to convene an ad hoc committee to evaluate which major ecological and environmental issues and national concerns could be addressed only on a regional or continental scale, whether the current concept of NEON was optimal to address them, and what effects NEON would have on science and society (see Box ES-1).

The committee hosted a Web forum and a Web-casted workshop at which representatives of the Directorate for Biological Sciences, various relevant government agencies, and professional organizations spoke on NEON's potential. The broader scientific community was invited to post comments and views on the NEON Web forum. The committee also reviewed the reports of six NSF-supported workshops on NEON

Box ES-1
Statement of Task to the Committee on the National Ecological Observatory Network

1. What are the important issues in ecology and environmental biology that can only be addressed on a regional or continental scale? Are any of these issues of national concern?
2. Is a national network of field and laboratory research infrastructure (e.g., environmental sensor arrays, remotely operated gas and ion analyzers, biodiversity monitoring instrumentation) needed to address these questions?
3. Will NEON, as conceptualized in the series of six community workshops, be able to provide infrastructure and logistical support to address ecological and environmental questions of national concern?
4. What impact will NEON have on the scientific community and the next generation of scientists?

(NSF 2000 a,b,c, 2002 a,b,c), an American Institute for Biological Sciences report on NEON, and a variety of documents on NEON prepared by NSF, including its 2004 budget request to Congress. Information from all those sources was the basis of the committee's deliberations, which resulted in the conclusions summarized below.

CONCEPT AND POTENTIAL CONTRIBUTION OF THE NATIONAL ECOLOGICAL OBSERVATORY NETWORK

The committee felt that the vision of NEON, as developed by the scientific community in six workshops, was best articulated in two NSF statements: "collectively, the network of observatories will allow comprehensive, continental-scale experiments on ecological systems and will represent a virtual laboratory for research to obtain a predictive understanding of the environment" and "NEON will be focused around a very broadly based, general research question—what is the pace and nature of biological change. Individual observatories would have a broadly defined observatory-specific theme that would be consistent with this overarching NEON question."

The committee strongly endorses that vision as the central focus of NEON. In addition, the committee found strong support for NEON in other federal agencies, ecological scientific societies and organizations, and members of the scientific community. The committee did not address many of the minor differences and ambiguities that unavoidably arose when seven separate groups considered the diverse issues related to a potential NEON network

If NEON is implemented to fulfill that vision, the committee believes that it would be pivotal in addressing regional and continental questions of great scientific and social importance. NEON would facilitate coordinated research efforts by providing nationwide facilities for environmental biology that transcend the budget of a single university or consortium. The central goal of NEON should be to perform comprehensive, regional- to continental-scale experimental and observational research on the nation's natural and managed ecosystems to obtain an in-depth understanding of the environment in order to assess vulnerability and resilience of ecosystems to environmental changes. The resulting knowledge would allow the identification of how various alternative societal actions and policies would affect species and ecosystems, and would suggest remedies and solutions to environmental problems.

The major environmental challenges facing the nation that must be addressed by NEON result mostly from human actions that have regional, national, or global causes or effects. In the committee's view, the major ecological and environmental challenges that need to be addressed on a substantially expanded scale include the following:

- *Biodiversity, species composition, and ecosystem functioning*. Decreases in biodiversity and changes in species composition accompany most human uses of the biosphere. The loss of biodiversity can affect ecosystem functioning and ecosystem services of value to society. The loss of biodiversity and shifts in ecosystem composition range from local to continental scales, and thus must be studied on their natural scale if their national implications are to be understood.
- *Ecological aspects of biogeochemical cycle.* Humans are dominating natural processes as the major suppliers of the basic elements of life (carbon, nitrogen, phosphorus, and sulfur). The redistribution of those chemical elements, and human-produced toxins, on regional and continental scales may have profound effects on human health and on ecosystem function and stoichiometry, which may result in shifts in biodiversity, toxin accumulation, and concentration through the food chain.
- *Ecological implications of climate change.* Human-induced climate warming and variability strongly affect individual species, community structure and ecosystem functioning. Changes in vegetation in turn affect climate through their role in partitioning radiation and precipitation at the land surface. Climate-driven biological impacts are often only discernable at a regional-continental scale. Regional changes in ecosystem processes affect global water and carbon cycles. Therefore, a national approach to understanding biological response to climate variability and change is required.

- *Ecology and evolution of infectious diseases.* Exposure to and the dynamics, spread and control of emerging diseases and their effects on humans, crops, livestock, and wildlife require a new level of understanding. The majority of emerging infectious diseases in humans either utilize vectors such as mosquitoes or ticks, or are zoonotic diseases that are transmitted from wildlife. That will require knowledge of spatial variations in exposure, of the population dynamics of disease reservoirs, of the effects of pathogens on individual behavior, of the molecular basis of host-parasite interactions, and of the interactions with other pathogens and environmental threats.
- *Invasive species.* Invasive species affect virtually every ecosystem in the United States, and can cause substantial economic and biological damage. The identification of potentially harmful invasive species, the early detection of new species as invasion begins, and the knowledge base needed to prevent their spread require a comprehensive monitoring and experimental network and a mechanistic understanding of the interplay of invader, ecosystem traits and other factors including climate and land use that determine invasiveness.
- *Land use and habitat alteration.* Deforestation, suburbanization, road construction, agriculture, and other human land-use activities cause changes in ecosystems. Those changes modify water, energy and material balances and the ability of the biotic community to respond to and recover from stress and disturbance. Actions in one location, such as farming practices in the upper Midwest, can affect areas 1,000 or more miles away because areas are joined by water and nutrient flow in rivers and by atmospheric transport of agrochemicals.

The committee listed the six issues in alphabetical order and did not attempt to prioritize them in any way. These ecological and environmental issues have been studied on a local scale, but results from those studies are confined by their spatial scale and cannot be extrapolated to address national concerns. The committee concluded that a comprehensive understanding of those environmental issues can only be achieved through regional to continental scale research using a national network of experimental and observational research infrastructure. Although the committee acknowledges that there are other ecological and environmental issues that can be addressed only on an expanded spatial scale, it suggests those six issues because of their immediate importance. Because the six issues presented above are interrelated at many levels, they present many opportunities for research integration and for sharing resources.

The 20th century saw many threats to the environmental health of the nation, such as decreasing water availability and deteriorating water quality, spread of invasive species and emerging infectious diseases (for example, West Nile virus), and extinction of valued species, some of which are new and emerging while others have been persisting for a long time. Current responses to environmental problems are mostly attempts to reverse the adverse trends because we lack a comprehensive understanding of the source of problems. Such an understanding can only be achieved though multiscale research that combines experimentation and observation replicated at numerous sites across the nation. A network of nationwide infrastructure, such as NEON, would enable local to regional to continental scale environmental research that would otherwise be impractical or impossible due to logistical constraints. Thus, studies at NEON would allow environmental scientists and biologists to be active in mitigating large-scale adverse impacts before they become severe threats to society. The scientific advances made possible by NEON would allow forecasting of the effects of alternative environmental policies and actions. Environmental forecasting is crucial for determining the net costs and benefits of alternative policies and thereby helping society to choose policies that provide the greatest long-term net benefits.

The committee strongly supports the creation of a NEON-like program and commends NSF's overall vision for NEON. However, it feels that the proposed implementation plans need modification and refinement to ensure that NEON would focus on the most important scientific issues, efficiently provide the national network of infrastructure essential for each challenge, encourage creative research, and meet the requirements of MREFC funding. First, in NSF's current plan, a NEON network would be built gradually via funding of one or two regional observatories at a time. Thus, NEON would not be a truly national network of sites until all the observatories are funded and built, which could take more than a decade. Second, the formulation and implementation of each regional observatory would be driven mostly by responses to requests for proposals. Institutions or consortia would submit proposals with their ideas of design and implementation to compete for a contract to build and operate a NEON observatory with a proposed budget of $20 million for construction and $3 million for maintenance. That approach has the great advantage of encouraging creativity and investigator dedication, but it would decrease the ability of NEON to address major environmental challenges in a coordinated regional to national manner. Moreover, NSF's current approach does not provide the committee or Congress with a clear idea of what each NEON observatory would look like or do. Detailed design and implementation plan is often required to obtain MREFC funding.

To establish a coordinated, efficient, and truly nationwide network, the committee suggests that NSF structure NEON according to the environmental challenges to be addressed rather than by locating one site in each ecosystem type represented in the United States. Thus, NEON would consist of a total of six "observatories" (rather than 17), one for each of the six environmental challenges. Each observatory would consist of multiple sites chosen simultaneously and located strategically across the nation to ensure adequate regional and national coverage for addressing the challenge. The funding needed to set up and maintain each of the six observatories would depend on its specific focus and plans, and the costs for an observatory might substantially exceed the $20 million for construction and $3 million for annual maintenance that NSF estimated for its original concept of a network of 17 regional observatories. The total costs for six national rather than 17 regional observatories might, however, be comparable with or less than costs for the original concept, particularly because infrastructure for research on more than one of the six themes could be colocated at many sites. Most important, sufficient funds should be allocated to ensure that each observatory is a truly nationwide network. Specific research projects conducted at individual sites within a NEON observatory should be funded through other NSF research, rather than infrastructure, programs.

Second, the committee believes that NEON observatories could contribute to and potentially unify relevant environmental data that are being gathered by other federal, state and local agencies. Moreover, particular NEON observatories could build on existing NSF research sites (LTER sites), the Department of Energy's programs (Free-Air Carbon Dioxide Enrichment experiments and AmeriFlux eddy flux towers), and other projects. The committee supports NSF's effort to have NEON observatories form partnerships with other federal, state, and local agencies and suggests formulation of plans to address such issues as standardization of protocols and data and coordination of research.

NEON programs would be ideal location for undergraduate and graduate interdisciplinary training and for K-12 students and teachers to study science on the basis of observation and experimental inquiry. The integration of research, education, and public outreach should be a central feature of NEON, and educational and outreach plans should be included from the inception of each observatory.

FINDINGS AND RECOMMENDATIONS

On the basis of its analyses, many of which were summarized above, the committee strongly endorses a NEON-like endeavor and the broad vision of NEON's mission that NSF articulated in the opening sentences of its 2004 congressional budget request. We offer the following findings and broad recommendations to help NEON to achieve its goals.

Finding 1

The committee identified six critical environmental challenges that are regional, continental, or global in their extent—biodiversity, species composition, and ecosystem functioning; ecological aspects of biogeochemical cycles; ecological implications of climate change; ecology and evolution of infectious diseases; invasive species; and land use and habitat alteration. Although all six issues are of national concern, at present we do not have knowledge adequate to address them. Rapid and substantial advances in basic scientific knowledge would be needed for society to deal with those major environmental issues wisely.

Recommendation 1

The committee strongly recommends that the nation and NSF give highest priority to research on the six environmental challenges the committee identified.

Finding 2

An in-depth understanding of the causes and consequences of the six challenges is needed to allow assessment of potential ecosystem responses and to formulate effective environmental policy. Meeting this need would require large-scale experimentation, long-term observation, and scientific synthesis that could be carried out only using a network of nationwide infrastructure and research sites that are optimized for the purpose.

Recommendation 2

The committee strongly endorses a NEON-like endeavor and the vision of the mission of NEON that NSF has articulated. As proposed by NSF, the central goal of NEON would be to perform comprehensive, regional- and continental-scale experimental and observational research on the nation's ecological systems to obtain an in-depth understanding of the environment. That knowledge could serve as a basis for developing predictive capability and would allow assessment of how alternative societal actions and policies will affect species and ecosystems and the services that they provide to society.

Finding 3

NEON, as currently proposed, would be built piecemeal via funding of one or two regional observatories at a time, and each observatory would be managed by a different university or consortium. Such a design and implementation might hinder the integration and the national nature of the network of sites and make it less than optimally effective in facilitating coordinated regional- and continental-scale research.

Recommendation 3

Each NEON observatory should be initiated as a nationwide network of facilities and infrastructure designed by a coalition of many multi-investigator, multi-disciplinary teams from across the nation to address optimally one of the six major environmental challenges. Each observatory should accommodate a combination of experimentation and observation and should comprise a collection of nationwide sites—whether terrestrial, freshwater, or marine—that are most relevant to its central theme. Sufficient funds must be allocated for the development of each NEON observatory as a nationwide network. Because the six research themes identified by the committee have overlapping infrastructure needs, construction of each new observatory could successively build on sites and infrastructure of existing observatories. Each later observatory could leverage investments made in the existing ones; this would increase the effectiveness and decrease the cost of the entire network.

Finding 4

The committee agrees with the fundamental concept of NEON as stated by NSF and with many of the major recommendations derived from the six workshops. It believes that NEON would provide opportunities for large-scale environmental research and enable intellectual and scientific development that is impossible with existing infrastructure. However, the effective implementation of NEON and the maximization of its contributions to science and the nation require a refined focus and a more detailed plan for its implementation.

Recommendation 4

The creation of a NEON observatory addressing one of the six major environmental challenges would probably be a multistep process involving open workshops and working groups on that challenge, peer-reviewed preproposals submitted by different teams for work on that challenge at particular sites, and discussion and coordination among the chosen teams to synthesize the diverse ideas generated and create final plans for the entire observatory. The goals of the multistep process are to optimize the ability of various scientists to contribute creativity and personal commitment to the observatory and the ability of the multiple teams and sites to pursue their shared challenge in a coordinated manner. The result would be a clear vision of what the observatories are intended to look like and achieve, which would additionally provide a better fit within the purview of Major Research Equipment and Facilities Construction funding. The committee offers some specific suggestions:

- NSF should encourage NEON observatories to form partnerships with existing informatics centers (for example, the National Center for Ecological Analysis and Synthesis, the National Biological Information Infrastructure and GenBank) or use them as models.
- Each NEON observatory should form partnerships with appropriate federal, state, and local agencies and organizations to coordinate and optimize data collection and sharing. Establishing memoranda of understanding could facilitate partnerships and collaboration.
- The committee endorses NSF's proposal of a coordinating unit to oversee the implementation and operation of NEON. It recommends that a single scientific oversight committee, preferably formed by a neutral body such as a multiuniversity consortium, provide this oversight.

Finding 5

The challenge of educating the next generation of scientists, teachers, and students and of reaching out to the public about environmental science and issues cannot be met casually by individual researchers. Nothing short of an integrated, sequenced education and outreach plan that meets national standards, targets audience needs, and is based on measurable outcomes will answer the leadership and education vision set forth to NSF by the National Science Board. The NEON observatories are ideal venues for such an integrated, robust education and outreach plan.

Recommendation 5

NEON's education programs should be targeted at undergraduate and graduate students and faculty, precollege students and teachers, and informal education, and citizen outreach. We recommend that multiple, systematic programs be integrated into the NEON proposal and developed, sequenced, and planned beginning at each observatory's inception and with attendant funding mechanisms and budgets.

If implemented in the general format outlined above, NEON could provide the fundamental scientific advances needed to understand how human-induced environmental change influences the long-term quality of life and wealth creation for the nation. Long-term outputs would include a science-based approach to environmental policy, risk analysis for environmental threats, evaluation of potential approaches to the threats, and a venue for increasing public awareness and understanding of environmental issues. NEON could revolutionize the discipline of environmental biology by transforming ecology into a more mechanistic science that generates predictions and solutions that would help society to deal actively with major environmental issues.

CHAPTER TWO

Environmental Issues of National Importance and the Role of the National Ecological Observatory Network

The committee examined and identified the main environmental challenges facing the nation. This chapter also discusses the importance of developing education programs in environmental science for the general public and the next generation of scientists.

This chapter outlines briefly the nature of the six ecological and environmental challenges and how a national network of biological infrastructure like NEON would contribute to addressing them. The six challenges are presented in alphabetical order, and the committee feels that addressing any of them would advance environmental science. The contribution of a network of biological infrastructure to education and how they complement each other are also discussed.

ECOLOGICAL ASPECTS OF BIOGEOCHEMICAL CYCLES

Alteration of biogeochemical cycles on regional, to continental, and global scales is a hallmark of human activity. We fix nitrogen from the atmosphere for agriculture or as a byproduct of combustion. We return carbon stored in fossil fuels to the atmosphere. We mine, smelt, transport, use and discard rare elements in support of an industrialized society. We create and release large quantities of pesticides, herbicides, fungicides and other persistent organic pollutants. Products and byproducts of our various actions escape to the atmosphere and hydrosphere and are transported over long distances, establishing connections between centers of human activity and "remote" regions.

Humans are inadvertently conducting a global experiment by modifying biogeochemical cycles through mining, combustion of fossil fuels, large-scale conversion and use of global landscapes, and modification and use of such critical elements as agricultural fertilizers. Many anthropogenic toxicants, such as mercury and polychlorinated biphenyls, are transported from their sources to distant and dispersed areas through the atmosphere. The basic elements of life and important toxins are being distributed at regional and continental scales, and may be deposited as 'toxic snow' in remote and seemingly pristine sites as alpine and northern lakes (Schindler 1999). Emissions of carbon, nitrogen, and sulfur have altered their availability to land and water biota and created shifts in biodiversity and ecosystem function. Heavy metals and organic compounds are transmitted to soils and waterways and are often accumulated and concentrated through food chains.

Common characteristics of such alterations from preindustrial conditions include an increase in cycling rate through the atmosphere and biosphere, increases in the atmospheric reservoir, and enhanced bioavailability. For example, it is estimated that humans have more than doubled the rate at which reactive forms of nitrogen are created from the relatively inert N_2 in the atmosphere. The production of nitrogen fertilizers with the Haber-Bosch process, high-temperature combustion of fossil fuels, and an increase in the cultivation of legumes are the primary causes of the doubling of terrestrial nitrogen inputs. Similarly, human activity now dominates global phosphorus and carbon cycling, land use, marine fisheries, and much of the hydrologic cycle (Vitousek et al. 1997, Carpenter et al. 1999, Postel 1999).

Although increased cycling of carbon, nitrogen, sulfur, and phosphorus increases primary productivity, it also causes loss of biodiversity, changes in dominant species in ecosystems; production of byproducts, such as aluminum, other heavy metals, and tropospheric ozone, and other harmful conditions. For example, algal biomass decomposition that results from increased primary production in aquatic systems can overwhelm oxygen supplies, leading to eutrophic and anoxic conditions.

All those adverse effects are caused by the transport of locally produced compounds, wastes, and byproducts through the regional atmosphere and waterways to adjacent or distant areas of deposition and response. Therefore, understanding biogeochemistry on regional, continental, and global scales is at the heart of addressing the social and environmental problems resulting from changes in the distribution and concentration of elements. For example, carbon dynamics and sequestration in landscapes are the subjects of one of the most socially relevant biogeochemical studies that need to be addressed on a continental scale. Current estimates of carbon storage in the ecosystems of North America depend on the method used to derive.

The development of the eddy covariance method for measuring net carbon balances over short periods has revolutionized ecosystem biogeochemical studies. Eddy covariance provides a new window into ecosystem function that increases our understanding of the processes and controls that determine element balances. Over the last decade, tremendous advances have been made in the reliability and standardization of the basic measurement system and in the understanding of the physical and mathematical constraints on the interpretation of the signal received. Those developments make the technology well poised for much wider application. Currently, the United States sponsors, through the activity of a number of different agencies, a network of eddy covariance towers designed to measure net carbon balances over different ecosystems. The current system lacks both adequate replication and spatial coherence because of the mixed sources of funding and the lack of a national vision.

The congruence of national need, developing technology, and a nascent scientific network means that large gains in our measurement and understanding of carbon fluxes over native and modified ecosystems can be realized immediately through a national network of net carbon balance observatories. Such a network would benefit from the ability to plan, a priori, the optimal number, placement, and operation of a large number of replicate measurement systems. The existing AmeriFlux network (see Plate 1) provides the best current basis for making such estimates, but the network is inadequate with respect to spatial coverage, stratification by vegetation type and land use and management practices, and consistency of the sensors. For example, existing eddy covariance systems tend to be in secondary forests or other relatively stable systems that are undergoing relatively rapid carbon accumulation. Placements are beginning to expand into experimentally-modified or more recently disturbed areas, but such systems are still underrepresented.

A set of eddy covariance towers could be deployed to compare directly the effects of different land-use patterns, water-availability regimes, or pollution-deposition rates on gross and net carbon exchange. Continuous collection of flux data from such sites provides the basic information needed to test fundamental physiological hypotheses on land-use, water, and pollutant effects and would lead to the development of better models.

CHAPTER THREE

Concept and Implementation of the National Ecological Observatory Network

After identifying the major environmental challenges facing the nation, the committee proposed that the first NEON observatory should focus on one challenge and that the network should grow by addressing additional challenges. Each theme-based NEON observatory would comprise sites that span the continent and infrastructure for integrated suites of experimental manipulations, monitoring, and synthesis directed at its theme.

EXAMPLES OF NEON OBSERVATORIES AND THEIR INTEGRATION

On the basis of the six research themes, the committee outlines here some of the major infrastructure necessary to conduct large-scale research. The brief lists given below are by no means exhaustive or all-inclusive. Rather, they illustrate some of the possible infrastructure and research needs of the NEON observatory that focuses on each theme. More appropriate and complete designs would be generated through open workshops and discussions, the ideas generated in preproposals, and the synthesis of the preproposals chosen for further consideration. Although the construction, implementation, and maintenance costs of NEON observatories could be determined only after comprehensive plans have been drawn for the observatories, they are likely to vary between observatories depending on their focus and plans. Costs may substantially exceed the $20 and $3 million that NSF proposed for the construction and maintenance of each observatory. But the costs of six theme-driven observatories might be comparable to, if not less, than 17 regional observatories proposed by NSF. Program funds, in addition to MREFC and R&RA funds, should be made available for the conduct of research so that NEON facilities could be fully exploited.

Biodiversity and Composition

All the lands of the nation are deliberately or inadvertently managed by their owners. Such management has led to dramatic shifts in the abundances of species in the nation's ecosystems and equally dramatic decreases in biodiversity. The shifts in composition and diversity could strongly influence many processes, including disease dynamics, ecosystem productivity and stability, nutrient dynamics, and water quality. They may also influence human welfare by affecting the services that ecosystems provide to society. To understand better the effects of shifts in biodiversity and ecosystem services, improved monitoring programs must be established to document how various management practices influence composition and biodiversity in the varied terrestrial, aquatic, and marine ecosystems of the nation and how shifts in composition and diversity influence their dynamics, stability, and functioning. The major infrastructure and investments needed to achieve those goals could include

- A network of sites with environmental chambers and field experiments in perhaps 20 ecosystem types representing the diversity of the nation's ecosystems. The sites and chambers could be used to perform experiments designed to determine how and why various aspects of human-driven environmental change affect biodiversity and species composition. Other experiments could focus on the functional ecology of the species to determine how changes in biodiversity and composition affect major aspects of ecosystem stability and functioning.
- Facilities, and equipment for detailed monitoring of species abundances and biodiversity in relation to various perturbations and management practices in sites representing the nation's whole array of terrestrial, freshwater, and marine communities and ecosystem types from across the nation. Although biodiversity and composition monitoring may seem to be a daunting task that requires data collection at 1,000 sites or more, the Environmental Protection Agency, the Forest Service, the US Department of Agriculture, the National Park Service, NSF, and various other national, state, and regional agencies already have programs in place. Detailed monitoring could be achieved once those efforts were coordinated and expanded.
- A national program for archiving type specimens and samples of each species in soils, of water and so on, for future analysis.
- A national data and synthesis center to collate, store, and allow analysis of biodiversity and composition data and related data on site and management practices.

• Sequencing facilities and microscopes for taxonomic and phylogenetic studies.

A biodiversity observatory could collaborate or integrate with existing biodiversity programs to expand the scope and depth of biodiversity research. Examples include

• *BioMERGE*. An NSF-funded research coordinating network dedicated to fostering integration of the study of biodiversity with the study of ecosystem processes (<http://depts.washington.edu/biomerge/about.html>).

• *The National Biological Information Infrastructure (NBII)*. A broad, collaborative program to provide increased access to data on the nation's biological resources.

• *Biodiversity and Ecosystem Processes in Terrestrial Herbaceous Ecosystems (BIODEPTH)*. A pan-European study of the importance of biodiversity for the functioning of grassland ecosystems. It features the same field-manipulation experiment replicated across a continental network of sites.

• *DIVERSITAS*. An international global environmental-change research program. It is pursuing three core projects: in discovering biodiversity and predicting its changes, in assessing effects of biodiversity change, and in developing the science of the conservation and sustainable users.

Biogeochemistry

Anthropogenic activities have been altering the cycling and distribution of such major elements as carbon, nitrogen, and phosphorus. However, ecosystem structure and function also play an important role in biogeochemical cycling. The primary goal of a biogeochemistry observatory is to provide experimental and observational infrastructure for studying the biotic and biogeochemical responses of ecosystems to spatial and temporal environmental changes. The infrastructure required for large-scale biotic and biogeochemical studies could include

- A nationwide network of experimental nitrogen-deposition accelerators and controlled-environmental soil-warming chambers for studying the effects of major environmental stressors on ecosystems.
- Nested arrays of eddy covariance towers across important environmental and stressor gradients for studying atmosphere-biosphere interactions and net carbon storage with increased spatial intensity.
- Advance remote sensing and geographic information systems to support investigations into previous patterns of land use, to extrapolate site and gradient studies across the region, and to measure spatial and temporal changes in the concentrations and ratios of nutrients in the foliage of forest canopies.
- Instruments designed for monitoring chemical composition in soil and water.
- A mass spectrometer and sequencing center to study the effect of altered biogeochemical cycles on isotopic signatures of nationwide soil and water samples and on the diversity of plants and animals, respectively.
- Nested arrays of eddy covariance towers across important environmental and stressor gradients to study atmosphere-biosphere interactions and net carbon storage with increased spatial intensity and to monitor and assess physiological capacity of plants.
- Automated chambers or CO_2 soil probes for respiration measurements.
- A central facility for standardized equipment calibration.

A biogeochemistry observatory would benefit from partnerships with agencies and programs such as the following:

- *Fluxnet*. A global network of micrometeorological tower sites that use eddy covariance methods to measure the exchanges of carbon dioxide, water vapor, and energy between terrestrial ecosystem and atmosphere. Over 200 sites are used for continual long-term monitoring.

- *The National Aeronautics and Space Administration*. It has an extensive remote sensing network.
- *National Atmospheric Deposition Program/National Trends Network (NADP/NTN)*. A nationwide network of precipitation monitoring sites. NADP data products include weekly and daily precipitation-chemistry data, annual and seasonal wet-deposition data, and mercury-deposition data.

Climate Change

The central missions of a climate change observatory would be to facilitate research on the effects of different scenarios of climate change on the nation's natural and managed ecosystems and research on how functioning and status of the nation's ecosystems might affect regional and global climate change by influencing greenhouse gases, albedo, evapotranspiration, and so on. To achieve those missions, assessment and experimentation need to be conducted simultaneously and replicated across species' functional groups and ecosystem types. The climate-change observatory might require

- Facilities and equipment for detailed, long-term observations of species dynamics of locally important or interesting species and their relations to climate variability.
- Instruments for the automated collection of detailed physical information, including climate data, dynamics of soil moisture and soil nutrient chemistry, groundwater chemistry, soil and plant respiration, photosynthesis, and release of greenhouse gases.
- Experimental climate accelerators to determine the effects of possible future scenarios of climate change on the composition, dynamics, stability, and productivity of the major ecosystems of the nation. Each accelerator could comprise a set of large experimental units.
- A nationwide network of eddy flux towers to locate and understand the "missing carbon sink" of terrestrial North America and to determine how and why land and habitat use and management practices

in different ecosystems influence carbon storage and release. The eddy flux towers should be at sites in each region that have varied land and habitat uses, and should be calibrated and validated with detailed site data.

- A nationwide network of experimental climate accelerators to determine the effects of likely scenarios of climate change on the composition, dynamics, stability, and productivity of major ecosystems. The climate accelerators could be at a number of different sites, each site having large experimental units.

A climate-change observatory could partner with agencies and integrate with programs and existing monitoring schemes, such as

- *National Oceanographic and Atmospheric Administration (NOAA).* It has the Climate Prediction Center, the Climate Monitoring Diagnostics Laboratory, and the National Climatic Data Center.
- *US Global Change Research Program (USGCRP*). It supports research and observational activities on the interactions of natural and human-induced changes in the global environment and their implications for society.
- *Global Climate Observing System (GCOS).* This was established to ensure that the observations and information needed to address climate-related issues are obtained and made available to all potential users.

Infectious Diseases

An observatory for the ecology and evolution of infectious diseases could focus on some of the important and pressing disease issues in plants, wildlife and zoonotic diseases (infectious diseases shared between wildlife and humans). An observatory on infectious diseases could seek to predict the conditions that would increase risk and spread of those diseases, identifying hot spots and the nodes of infection where diseases must pass through for an epidemic to become important. An infectious-disease observatory would aim to facilitate interdisciplinary research to identify the ecological causes of emergence and the changes in evolutionary pressures that can lead to the emergence of virulent strains.

Specific infrastructure needs could include

- Detailed field sites recording seasonal and inert annual variations in disease prevalence and experimental sites coupled with containment facilities. Sites should be distributed in different regions to allow comparisons and replicated within regions.
- Disease-monitoring centers with sequencers, immunology and virology laboratories, and biosecure handling facilities for small-scale experiments (for example, experiments on host dynamics). Sites would require large computational power for running simulation models of the spatial spread of diseases and integrating phylogenetic studies of hosts, parasites, and environmental pressures.
- Vector screening sites related to emergence of disease, such as West Nile virus, with central identification and molecular screening laboratories.
- Epidemiological warehouses for monitoring transmission patterns and routes at the mesoscale where ecosystems level factors could be manipulated. Similar holding systems would be needed to identify selective pressures leading to evolution of new strains.
- PCR-sequencing laboratory for diagnosis of infectious agents.

Potential collaborators of an emerging-disease observatory include

- *The National Wildlife Health Center (NWHC).* A science center of the Biological Resources Discipline of the United States Geological Survey. NWHC is a biomedical laboratory dedicated to assessing the effects of disease on wildlife and to identifying the role of various pathogens in contributing to wildlife losses.
- *Forest Service Forest Health Protection Program.* A program of the US Department of Agriculture Forest Service that conducts annual aerial and ground surveys to monitor the status of destructive insect and disease pests on Forest Service lands.

• *National Institute of Allergy and Infectious Diseases.* This supports basic research on West Nile and related viruses to understand factors associated with the animal or human hosts, the microorganisms, and the environment that influence disease emergence.

• *Centers for Disease Control and Prevention.* This maintains human epidemiological data on vector-borne infectious diseases.

Invasive Species

Research at an observatory for invasive species would have a primary mission of predicting and monitoring the occurrences, spread, and environmental consequences of invasive species. Those species would include microorganisms, insects and other animals, plants, and genetically altered organisms. Achieving the mission would require a mechanistic knowledge of the invasion process and information about species traits and ecosystem states that influence invasions. The observatory's major infrastructure might be expected to include

• Major physical sites, each with containment facilities appropriate for experimental introduction of invasive species into contained communities. Experiments would be designed to determine the mechanisms of interaction among native and invasive species and to enhance our capabilities to assess an ecosystem's vulnerability to species invasion.

• Control hardware and software to monitor environmental alterations and to adjust local conditions.

• A major site serving as a central sequencing center, which could include an existing sequencing center and be equipped with molecular genetic instrumentation and such equipment as sequencers, cloning facilities, chip printers, and microarray readers.

• Facilities at each site to house local synoptic collections. Microscopes, digital photographic tools, microarray readers and gene specific probes would likely be needed.

• Experimental plots at some or all major sites outfitted with equipment needed to alter local environments, such as carbon dioxide addition rings or soil warmers, so as to determine the possible selective advantages that climate change or environmental change may confer on invasive species.

- PCR-sequencing facilities to determine origin and genetic structure of invasive populations.

The invasive species observatory could establish linkages to such agencies and programs as

- *The National Invasive Species Council.* An interdepartmental council that helps to coordinate and ensure complementary, cost-efficient, and effective federal activities regarding invasive species.
- *NBII invasive species information node (ISIN).* With its partners, this is involved in research projects to understand, document, monitor, predict, and control invasive species.
- *USDA's Animal and Plant Health Inspection Service (APHIS).* This has an invasive species program. USDA also has an invasive-species Web site with links to a number of databases (<http://www.invasivespecies.gov>).

Land and Habitat Use and Management

A NEON observatory dedicated to land and habitat use would have to be structured to allow determination of the local, regional, and continental effects of alternative land and habitat use patterns. Its central focus would be on scaling local effects up to regional or national by linking atmospheric effects and effects of aquatic transport of organisms and materials. Such an observatory could be structured in several ways and would have numerous potential facility needs. At a minimum, it would need a set of nested sites spanning a large geographic range—from midwest croplands, to suburban and urban lands, to the Gulf of Mexico—and a large range of land uses—growing different agricultural crops in different ways, managing pastures and forests in different ways, urban and suburban areas with different types of sewage treatment, and so on.

A wide array of automated sensors would need to be spread across this network of sites, such as

- Instruments designed to monitor concentrations of nitrate, phosphate, and other chemicals in soils of pastures, croplands, forests, and urban and suburban areas.
- Instruments that measure rates of water and material movement into surface water and groundwater; from groundwater to ponds, lakes, streams, and rivers; and from the aforementioned aquatic ecosystems into estuaries, nearshore marine ecosystems, and the open oceans.
- Instruments that measure atmospheric transports that link sites and regions.
- A central facility for data acquisition and informatics that could also serve as a synthesis center.

Some examples of agencies and programs that could collaborate with a land use and habitat management observatory are

- *USDA.* This agency makes estimates for major land use classes across the United States.
- *NOAA's Coastal Change Analysis Program.* A national effort to foster development and distribution of regional landscape cover/change data in the coastal zone through remote sensing technology.

Report to the National Science Foundation

From the

Fourth Workshop on the Development of a National Ecological Observatory Network (NEON): Standard Measurements and Infrastructure Needs

Held at
The Millennium Hotel
Boulder, Colorado
4-5 June 2002

Introduction

From 4-5 June 2002 a group of 22 participants and 3 observers (See appendix) gathered in Boulder, Colorado to develop a plan for standardized equipment needs and measurements for all NEON observatories. As in previous workshops, the group enthusiastically endorsed the proposed development of a national network of ecological observatories. This report provides examples of how NEON will expand research capabilities beyond anything current available, which will greatly advance ecological research and our understanding of the environment. It also provides examples of how such a network can be of service to the Nation's, including the development and training of future generations of the Nation's technological workforce.

IV. Biogeochemistry Group Report

The cycles of carbon, nitrogen, phosphorus, many other major biological nutrients, as well as trace elements and pollutants are all changing due to human activity. The dynamics of major biogeochemical cycles have direct implications for human health and well-being, both directly, and indirectly via effects on ecosystem goods and services. The pace and scale of biogeochemical changes is beyond both the time and space scales of many traditional scientific studies, and therefore requires coordinated networks that can effectively document such changes for decades, with high spatial resolution at continental scales. The observational capability of a NEON network can provide such data, thereby greatly improving our capability to predict and respond to biogeochemical changes that affect human and ecosystem welfare.

Requirements for Biogeochemical Data

At a minimum, all NEON sites must address the inputs, internal dynamics and outputs of carbon, nitrogen, phosphorus and biologically important base cations across the landscape. Analyses of other elements are encouraged as appropriate for a given site. A biogeochemical strategy should also extend beyond the major element cycles, in particular to consider the characterization of fluxes and accumulation of both organic and inorganic ecologically important pollutants. As well, a regional NEON approach must take into account the full range of landscape heterogeneity, including land use strategies, across both terrestrial and aquatic systems.

Each NEON site should include a continuous documentation of biosphere-atmosphere exchanges of CO_2, H_2O, carbonaceous trace gases, and nitrogen gases using eddy flux techniques in which standards used are consistent with the current Ameriflux network. These measurements should include isotopic characterization as much as possible, and effective landscape-scale estimates of biosphere-atmosphere exchange must also include data on the vertical structure of the lower atmosphere (e.g. lidar; see climate and hydrology section).

Core site documentation of biosphere-atmosphere exchange via the use of eddy flux techniques should be coupled with a landscape-scale strategy for documenting key components of such exchange, notably net primary production, net ecosystem production, plant and heterotrophic respiration, and the soil flux of important chemically and radiatively active trace gases. In addition, significant efforts must be aimed at documenting belowground production. We recommend the formation of a rhizotron network that is coordinated at the national level, including the development of new software that can ensure a consistent and effective strategy for cross-site comparison of belowground root dynamics. Documentation of landscape-scale carbon dynamics should also include regular measurements of litter fall (where appropriate), decomposition rates and above and belowground pools of carbon.

These ground-based strategies for documenting the carbon cycle should be coupled to the use of remote sensing data that can provide annual, spatially resolved estimates of vegetation structure and dynamics. In addition, C fluxes and storage should be documented in aquatic as well as terrestrial systems; for the former, aquatic production should be analyzed using a network of datasondes. As with the eddy-flux measurements, landscape-scale data on the abundance of biogeochemical species should be complemented by isotopic characterization of such species to the maximum extent possible.

A strategy for documenting not only land cover change, but temporal and spatial variation in land use strategies (e.g. management type and intensity) is also essential to regional-scale estimates of biogeochemical dynamics. This strategy should merge remote sensing data with ground-based information. We suggest that each NEON site invest resources in becoming a core validation sites for the EOS platform, thereby providing access to imagery. This investment is relatively modest, and consistent with needs outlined in the climate and hydrology section, as it includes documentation of albedo, diffuse and direct radiation, sun photometers for atmospheric correction, and meteorological data.

We recommend a coordinated strategy where ground-based measurements of plant biomass, tissue chemistry and water content can be coupled to analyses of satellite imagery and aircraft hyperspectral data to allow large-scale, spatially resolved estimates of such variables. The NEON program should strongly consider leasing or purchasing a light aircraft on which at least an imaging spectrometer is mounted, thereby allowing the acquisition of the spectral data at ecologically important times.

Each NEON region should document atmospheric inputs of biogeochemically important species in both wet and dry forms. Where possible, it is expected that some of this information can come from existing networks, but these networks will likely need to be augmented, most notably for dry deposition where aerosol chemical and physical properties should be analyzed. Losses of biogeochemical species should also be documented by coupling to the hydrological and climate instrumentation, and should include lysimetry, watershed-scale measurements, and groundwater analyses. Use of in-situ automated sensors that can provide real-time data on water chemistry is strongly encouraged.

In general, strategies that make NEON sites compliant and consistent with other major national networks, including NASA satellite missions, USGS water quality networks (e.g. NAWQA), NADP, and EPA air quality measurements are strongly encouraged.

Each NEON site should propose a strategy for documenting key microbial functional variables, such as nutrient mineralization and microbial biomass, at the relevant spatial and temporal scales. As sites develop in the network, common techniques for such data should be agreed upon, facilitated by the coordinating committee.

In general, data should be collected using real-time, in situ techniques to the maximum extent possible. Where this is not possible, we recommend that NEON-wide laboratory facilities be developed that are responsible for major classes of analyses, such as isotopic analyses and biogeochemical analyses that cannot be done in situ. A single, central site is desirable both for economies of scale and to ensure consistent data across sites that allow robust comparisons (see below). Such central facilities should be designed to allow rapid turn-around of samples, so that data can be as close to "real-time" as possible. More generally, the ability to acquire and process information and make it available on-line rapidly is an essential component of all NEON sites. Thus, a strategy for routine, rapid automated data posting should be proposed.

Finally, each NEON program should devote significant resources and attention to the archival of soils, biota and water samples, stored in such a way that reconstructions of changes over time can be done in the future. A good archive strategy can allow the future production of a broad range of data that is either beyond the financial or analytical capabilities of the current program, or that is not recognized as ecologically important today.

National Analytical Centers

As the NEON effort develops, there will be a series of continuous and essential core samples, where analyses of those ecological materials are more feasibly conducted at a core national facility than at individual NEON sites. With respect to biogeochemistry, it is likely that analyses of stable isotopes and water quality chemistry are examples of such national needs. Justification for national centers with rapid analytical turnaround includes uniformity of analytical methods, consistency in standard across time for comparative consistency across data sets, and reduction in costs though large-scale sample processing. In addition, a national center serves additional critical roles, including: training for sample collection and analysis, education to train broadly in ecologically important areas, such as stable isotope analyses and water chemistry, where these sample approaches provide an integrated assessment (often at the molecular level), that can be applied to a variety of ecological questions. Having them concentrated on a single facility, rather than on multiple upgrades across individual sites also reduces the costs of future upgrades in analytical capacity. As an example of one such facility, we estimate that the cost of a central isotopic facility (light, stable isotopes only) would be approximately $1-2 million in capital equipment, with an annual O&M cost of roughly 300K.

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SCIENTIFIC TARGETS FOR THE WORLD'S LARGEST OBSERVATORY POINTED AT THE SOLID EARTH

WORKSHOP REPORT

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WORKSHOP REPORT

SNOWBIRD, UT
OCTOBER 10-12, 2001

Introduction

Many fundamental aspects of continental structure and dynamics, including those responsible for earthquakes and volcanic eruptions, are not yet well understood. This is, in part, because of the difficulty of piecing together the results of many focused, regional studies carried out by a single investigator or a small team of investigators. Most major Earth processes act, and interact, on much larger and longer time scales than can be resolved by such isolated studies. These processes drive geological events at Earth's surface that affect humankind. To understand how these large-scale systems respond to internal and external forcing requires linking detailed information about surface geology with its underlying crustal structure and extending and linking these observations to interactions between the crust and the underlying mantle.

EarthScope will provide the first detailed, integrated examination of North America's structure and will monitor plate deformation at the continental scale. The seismic and magnetotelluric component of EarthScope (USArray) will map the structure of the continent and underlying mantle at high resolution. EarthScope's geodetic components, the Plate Boundary Observatory (PBO) and Interferometric Synthetic Aperture Radar (InSAR), will measure surface motions at a variety of spatial and temporal scales. Deep drilling across the San Andreas fault by the San Andreas Fault Observatory at Depth (SAFOD) will directly determine stress conditions and rock properties in the seismogenic zone of a major fault. Combining these direct measurements with associated geological, geochronological, geochemical, experimental, and theoretical studies will provide the clearest picture yet of our continent's dynamics. EarthScope's decade-long effort thus offers the potential for unprecedented discovery and a model for a future of truly integrative, multidisciplinary research in the solid Earth sciences.

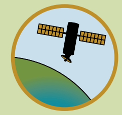
EarthScope is an interdisciplinary experiment of unprecedented resolution that will identify links between the surface geology of North America and the forces at work in Earth's interior.

To further develop ways to fully exploit the measurements provided by EarthScope's observational components, approximately 200 Earth scientists assembled in Snowbird, Utah for the first "pan-EarthScope" workshop. This report summarizes the workshop discussions, divided according to the broad scientific themes around which working groups were formed. These themes blend into a broad-ranging examination of the major issues of continent formation and the factors controlling its current dynamic behavior. This report first lists some of the key scientific questions identified at the workshop as a means of capturing our current understanding of this broad topic. With this background, we then explore the many ways in which EarthScope can contribute to answering these fundamental questions. Working groups also discussed what additional data sets, modeling efforts, and education and outreach are necessary to maximize the scientific return from EarthScope.

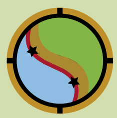
EarthScope offers the first opportunity to measure plate tectonic movements while they are happening, and at the continental

EarthScope's facilities include the following four coupled components:

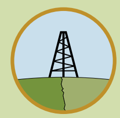
USArray (United States Seismic Array): A combination of permanent, transportable broadband, and flexible seismic arrays will map the structure of the continent and the underlying mantle at high resolution.



InSAR (Interferometric Synthetic Aperture Radar): A remote-sensing technique will provide spatially continuous strain measurements over wide geographic areas with decimeter to centimeter resolution.



PBO (Plate Boundary Observatory): A fixed array of GPS receivers and strainmeters will map ongoing deformation of the western half of the continent, from Baja California to the Bering Sea, with a resolution of one millimeter or better over regional baselines.



SAFOD (San Andreas Fault Observatory at Depth): A borehole observatory across the San Andreas fault will measure subsurface conditions that give rise to slip on faults and deformation in the crust.

spatial scale, so that the cause and effect of these movements finally can be deciphered. The combination of instrument, technique, and computational developments, the existence of a collaborative, multi-institutional, multi-agency infrastructure capable of managing an experiment of this size, and the maturity of the scientific field to which the EarthScope instrument will be directed combine to make this the perfect time to create the EarthScope facility.

The next major advance in our understanding of how the dynamic Earth works, and how humankind can best deal with both the beneficial resources and the dramatic hazards Earth provides, must come by expansion of our observational network to the scale of Earth activity. EarthScope will provide this step for the United States.

Scientific Targets for EarthScope

Fault Properties and the Earthquake Process

Key Questions

Over the last few decades, considerable research into earthquake sources and the hazards they pose have greatly improved our understanding of both. Increases in the quality and quantity of data recorded, combined with the development of new analysis techniques, have resulted in significantly better models of the earthquake rupture process. These in turn have permitted more reliable statistical seismic hazard predictions. Despite this progress, many fundamental questions concerning earthquake rupture and fault processes remain unanswered, and others have been identified as we learn more about them.

At the workshop, five outstanding, fundamental scientific questions were identified that any large-scale initiative in earthquake science needs to address:

1. How does strain accumulate and release at plate boundaries and within the North American plate? Where is slip along a fault aseismic versus seismic? What are the structure and other properties of active fault zones? How do they affect the manner in which faults slip? How can we explain the observed space-time pattern of seismicity? How do earthquakes interact with and trigger one another?

2. How do earthquakes start, rupture, and stop? Do all earthquakes start from similar beginnings, or does the nucleation process determine the final size of the earthquake? How do fault properties and rupture dynamics combine to control rupture propagation and extent? What causes the rupture to stop?

> EarthScope will help develop predictive models for earthquakes by unraveling the dynamic processes along faults, from stress build-up to catastrophic rock failure.

How are earthquake ruptures on subduction zones different from those on crustal faults? What are the causes of intermediate depth earthquakes (such as the one under Seattle in January 2001), and do they vary with depth?

3. What is the absolute strength of faults and the surrounding lithosphere? Where are plate driving forces carried? Are faults relatively low-strength features? How do faults in different tectonic settings compare?

4. What structural and geological factors give rise to intraplate regions of seismic hazard and seismicity, such as the New Madrid zone?

5. How can we accurately predict earthquake-induced ground motions over a wide frequency range? For example, what is the geometry and response of large sedimentary basins? How nonlinear is site response?

These five questions largely reflect the frustration of the Earth science community in their attempts to solve problems that 25 years ago appeared to be nearly solved. For instance, the Parkfield reach of the San Andreas fault was thought to be sufficiently well understood in terms of earthquake recurrence that a magnitude 6 event was forecast to occur there in January 1988, plus

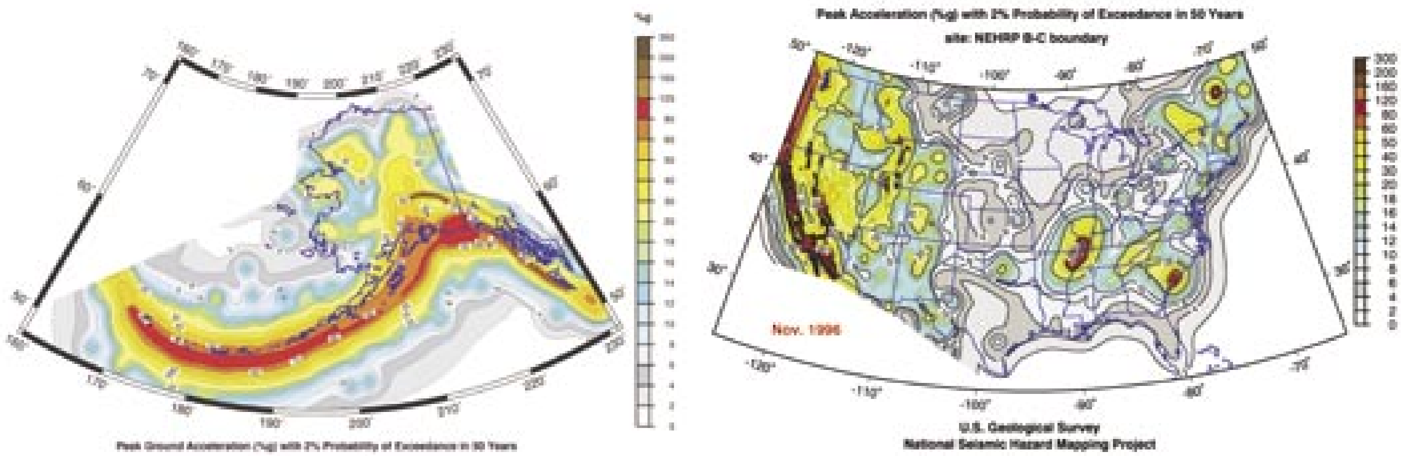


Figure 1. Current seismic hazard maps of the United States demonstrate clearly that California is not the only state to experience or expect large earthquakes. PBO and USArray will greatly improve our understanding of earthquake processes along the Cascadia and Alaskan subduction zones. USArray and InSAR will provide us with unprecedented resolution and information about the eastern half of the United States, where large damaging earthquakes can occur. Figures courtesy of the USGS.

or minus five years, at the 95% confidence level. In 2001, we are much humbler regarding our understanding of the San Andreas fault and, needless to say, are still waiting for the next Parkfield earthquake. Similarly, we do not know, within a factor of three or four, the magnitude of the stresses acting on the San Andreas fault needed to cause slip despite substantial research on this issue beginning in the 1960s. Solving these, and other, fundamental problems of earthquake occurrence and fault dynamics clearly requires a substantially augmented effort to acquire the key, but elusive, data sets that bear on these issues.

To date, most earthquake research has been focused in California, but other parts of the United States also have significant seismic hazards (Figure 1). Earthquakes have been recorded in all but one of the 50 United States, and the country includes a wide range of tectonic environments for studying earthquakes and deformation in many different conditions. EarthScope will improve our resolution of the earthquake rupture process in regions where we currently have the most detailed knowledge, such as California, but will also enable us to study regions that have received relatively little attention to date, such as the subduction zones of Cascadia and Alaska, and the more stable eastern parts of the country where seismicity is rarer, but still significant, and potentially damaging.

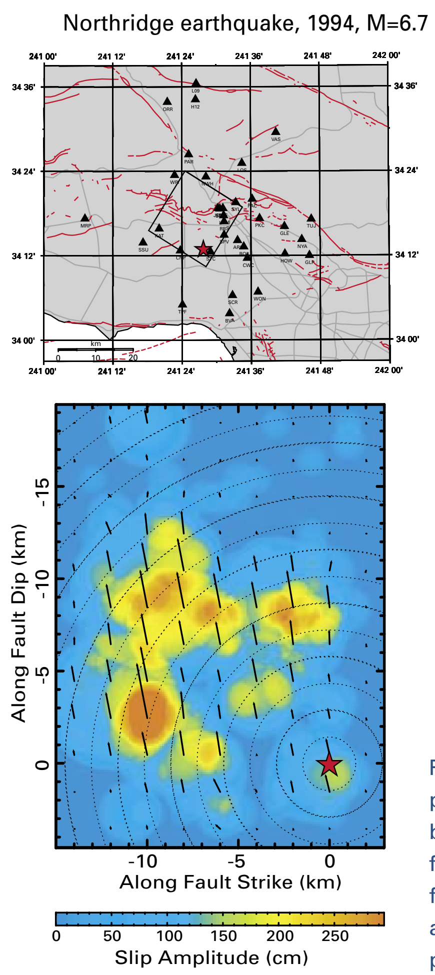
EarthScope will provide a comprehensive suite of geophysical data sets that are critically needed to advance understanding of earthquake processes and related hazards.

The EarthScope Contribution

Recent work has demonstrated that only an order of magnitude improvement in data quality and quantity will permit us to address the outstanding scientific questions about earthquake processes with any realistic hope of success. The combined EarthScope components will provide much of the data required to significantly increase our understanding of the entire earthquake rupture process. For example, previous work has demonstrated that large earthquakes nucleate as a result of processes acting at a very small scale that currently cannot be resolved. Measurements and observations from SAFOD, USArray, and PBO instrumentation will enable us to resolve earthquake nucleation processes at the smallest scale, but also capture critical information at longer temporal and larger spatial scales.

Adding a time dependence to statistical forecasts of seismic hazard is becoming possible as we begin to understand how one earthquake may affect or trigger another event. Data on earthquake interactions, detailed crustal structure, and the state of stress in the crust exist in too few parts of the country, however, for us to produce reliable forecasts. USArray will provide the needed information about crustal structure and ongoing seismicity that will greatly extend our ability to forecast hazards (Figure 2). The USGS-sponsored Advanced National Seismic System (ANSS) is also important, providing the long-term seismicity coverage needed to address seismic hazard problems. PBO and InSAR will enable us to identify where strain is building up and where it is being released on longer time scales. Detectable earthquakes may not be produced at such locations, but the crustal stress fields may be modified in ways that can accelerate or retard the likelihood of a future earthquake. The proposed paleoseismic component of PBO also is needed to provide an even longer-term perspective on crustal strain build-up and release.

More specifically, each EarthScope component will contribute to answering the five questions posed in the following ways:



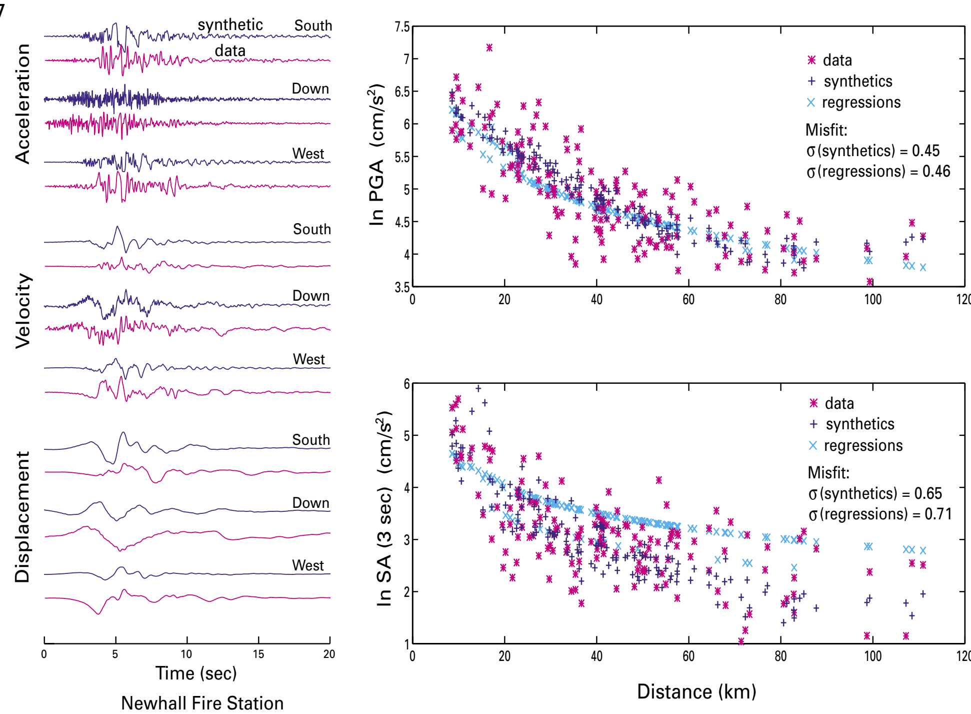


Figure 2: Predicting strong-ground motion over the wide frequency range needed for engineering purposes is becoming possible (as shown in this example from the Northridge, 1994, earthquake), but only where precise information is available on wave propagation, local structure, and site-effects. EarthScope will greatly extend and improve our knowledge of these vital parameters. The figure shows a model of the slip during the Northridge earthquake, comparison of the predicted and observed seismograms recorded at Newhall Fire Station, and the recorded and predicted peak ground acceleration (PGA) and response spectrum (SA) as a function of distance from the earthquake. Courtesy of J. Anderson and Y. Zeng, UNR.

SAFOD will provide direct observations of the structure and properties of an active fault zone at seismogenic depths. Seismic and strain observations over a number of years will provide close-in records of earthquake nucleation, rupture, and termination that are needed to address fundamental questions about the earthquake process. (Questions 1 and 2).

USArray includes the main Bigfoot transportable array, which will provide a significant improvement in our ability to locate earthquakes, and the flexible component, which can be used for higher-resolution studies of more limited areas such as detailed examination of individual faults. Crustal velocity structure and fault orientations are needed to help answer all five questions. USArray's flexible array also will be invaluable for earthquake studies by enabling dense deployment in regions where there is swarm activity or an aftershock sequence, greatly increasing the resolution of the lithosphere structure in those regions. In addition, USArray will permit detailed studies of the nature of earthquake sources in regions far from the plate boundary, and so investigate how different conditions affect the earthquake generation process.

EarthScope will enable us to observe the processes and properties of faults that drive the earthquake machine.

PBO and InSAR will provide much-needed measurements of the integrated strain field, forming the basis for resolving aseismic processes of permanent and transient deformation, as well as seismic strain recharge and release. At the detailed scale of the PBO dense clusters, observations of strain changes before and after earthquakes will be invaluable for understanding how dynamic rupture begins and ends, and what triggers it (e.g., Question 2). The larger scale PBO network and InSAR will enable us to map the distribution of aseismic strain over the continent, which is needed to understand seismicity distributions and larger-scale triggering (Question 1). InSAR and GPS also provide valuable information about the distribution of seismic slip in an earthquake (Question 2).

ANSS will play an important role in addressing these questions. The new stations will provide the long-term monitoring component essential to improve seismic-hazard modeling, as well as adding to the data available to study the earthquake source and crustal structure.

Necessary EarthScope Data Sets

At present, there is a severe lack of reliable high-resolution data on earthquake and fault properties. Thus, workshop attendees spent considerable time discussing the data sets necessary to make headway in answering the five questions mentioned above. Table 1 summarizes the discussion on: (1) which data sets are required to address the five key questions, (2) whether the data sets are currently available, (3) whether EarthScope will provide the required data, and (4) what else is needed to obtain the data.

Table 1: Data Sets Needed for a Better Understanding of the Earthquake Process

Data Set	Relevant to Questions	Available?	Will EarthScope Provide?	What Else?
Instrumental seismicity catalogues	1,2	ANSS	Not enough	Regional networks with local densifications.
Pre-instrumental catalogues	1-5	Partial	No	Additional data (especially at PBO sites). Compile existing data in usable form[1].
3D active fault map (location, strike, dip)	1-5	Partial	Partial (PBO)	Flexible array (P.I. driven).
Internal fault zone architecture in 4D: geometry (e.g., width, depth, continuity), material properties (e.g., seismic velocities, attenuation, anisotropy, viscosity), and geology (e.g., fabrics, microstructures)	1-3,5	A little	SAFOD	Flexible array (P.I. driven). Compile existing data in usable form[1].
Transitions between: (1) fault segments, (2) an entire fault system and surrounding rock, and (3) brittle and ductile depth sections	1-5	A little	SAFOD	Flexible array (P.I. driven). Compile existing data in usable form[1].
Crustal and upper mantle structure in 4D	1-5	Partial	Partial	Flexible array (P.I. driven).
Strain-rate field in 4D	1-4	Partial	PBO and INSAR	Additional geodesy.
Finite strain (geology: total fault slip, pressure solution in bulk)	1,2	Partial	No	Additional geology. Compile existing data in usable form[1].
Heat flow	1,3,4	Partial	SAFOD	At PBO and other sites. Compile existing data in usable form[1].
Electromagnetic/MT	1,2	A little	USArray	Additional measurements. Compile existing data in usable form[1].
Seismic waveforms (broadband with high dynamic range)	1-3,5	Partial	USArray, ANSS, SAFOD	Flexible array (P.I.-driven). Add broadband and strong motion to PBO sites[2].
Site response at all new and temporary sites	2,5	No	Partial	Geotechnical measurements.
Lab data of rheological and geophysical rock properties	1-4	Very little	No	New EarthScope observations will require complementary lab studies to interpret. Compile existing data in usable form[1].
Ground water and other environmental effects	1,3,5	Partial	No	Monitor ground water etc. at PBO sites.

(1) Compilation of existing data in usable form should provide best values and uncertainties for two data sets: raw measurements and interpretation. (2) The current instrumentation plan for the PBO borehole sites does not include broadband and strong ground motion seismometers. This is a major short shortcoming because the PBO sites are close to major faults, and thus are likely to experience moderate and large earthquakes. The sites may also record microearthquake data (e.g., with $M < -1$). Near-fault seismic data over broad magnitude and frequency ranges are critically needed to test different hypotheses on the physics of earthquakes and faults (e.g., existence of strong dynamic variation of normal stress during rupture propagation; scaling of earthquake properties; sources of high-frequency seismic radiation; slip histories). On-scale recording of moderate and large earthquakes over a broad frequency range will require broadband and strong ground motion seismometers at or near the borehole sites. These seismometers should be augmented at selected sites by tight 2D arrays around the fault, or at least by pairs of instruments on the different sides of the fault, to allow imaging of key rupture and fault properties (e.g., symmetry characteristics of particle motion). Detection and recording of microearthquakes may perhaps be done with the geophones currently planed at the borehole sites.