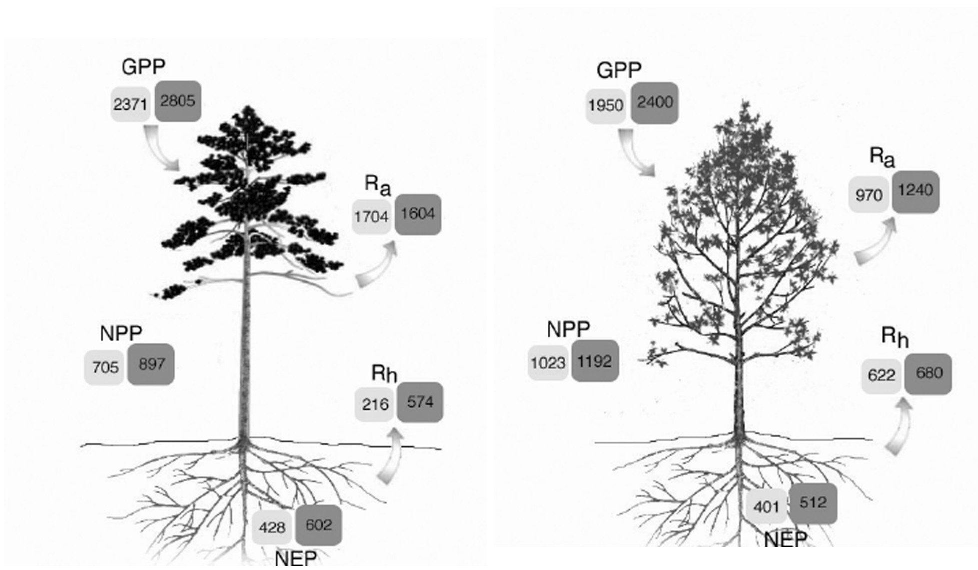
Ecological Aspects of Biogeochemical Cycles

Report from a NEON Science Workshop



July 20–21, 2004
Boulder, CO

National Ecological Observatory Network

American Institute of Biological Sciences

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

The IBRCS Program

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

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

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

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About the American Institute of Biological Sciences

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

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Cover:
Data were provided by E.H. DeLucia and R.J Norby and the illustration was prepared by A. Singsaas. Carbon budget (gC m^{-2} y^{-1}) for a pine forest (left) and sweetgum forest (right) exposed to ambient (~370 ml l^{-1}; light bubbles) and elevated (~570 ml l^{-1}; dark bubbles) atmospheric CO_2. Gross primary production (GPP) represents annual net photosynthesis; respiration from plants (Ra) and soil microbes (Rh) return large quantities of C to the atmosphere; net primary production (NPP) represents the annual increment of C in the ecosystem and net ecosystem production (NEP) represents the accumulation of C following losses by Rh.

NEON Workshop Series

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

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

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

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

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

Introduction

Humanity has entered a century of environmental uncertainty. Changes to the biogeochemical cycling of carbon, nitrogen, phosphorus, and other key elements on Earth, and the maintenance of key biogeochemical resources such as air, water, and soil, will lie at the center of scientific, societal, and political agendas for decades to come. The principal challenges of the proposed NEON will be to define the past, present, and future states of these elements and resources within the United States and assess the potential impact of biogeochemical changes to the vitality of the American public. Existing biogeochemical networks in the United States are insufficient to provide the synthetic perspective required for addressing these critical national needs. Many of the networks are operated with regional interests in mind, and often databases for the networks are not easily combined across regions or disciplines. A clear need exists for integrating ecological data at the national level. Recognizing these important priorities, we set out to accomplish two goals during a workshop to develop biogeochemistry initiatives for NEON. First, we defined the most relevant scientific questions in biogeochemical cycling as related to NEON. Second, we used those questions to develop a specific implementation plan for developing and deploying NEON infrastructure in the area of biogeochemistry. As background for our discussions, we relied heavily on past workshops and efforts, including the NRC NEON Report (September 2003) and the NSF-sponsored workshop on NEON infrastructure (NEON Planning Workshop IV) held in Boulder, Colorado, in June 2002.

Criteria for Prioritizing Key NEON Biogeochemistry Questions

The scientific foundation of the NEON biogeochemistry effort requires key questions that are broad enough to capture the multiple physical and biological dimensions that frame this discipline, relevant enough to provide insight toward solving the most important environmental issues facing society, and prescient enough to forecast future changes in Earth system processes. Additionally, we recognized the need to integrate issues of biogeochemical impact with those of the other grand challenges in the emerging NEON effort, i.e., land-use change, loss of biodiversity, spread of invasive species, impact of emerging diseases, and climate change. In order to identify and prioritize key science questions, we adopted the following criteria for appropriate NEON biogeochemistry questions, which should:

- Highlight the unique potential of ecology for solving problems related to Earth system change
- Be simple organizing/integrating questions

- Be answerable only through the use of NEON infrastructure
- Be relevant to society at large

Within these broad, primary criteria, we recognized that a NEON biogeochemistry question should also more specifically:

- Enable the discovery of general biogeochemical principles
- Enable the development of quantitative predictions and models
- Complement existing biogeochemistry research programs
- Complement other NEON research themes or "grand challenges"
- Relate to biogeochemical cycles that affect environmental sustainability

The Key NEON Biogeochemistry Questions

Using the criteria stated above, we recommended three general sets of questions to frame the biogeochemistry component of NEON. In developing these questions we recognized that NEON should be designed to (a) enable researchers to examine biogeochemical cycles and their couplings, (b) determine the role of humans as agents of biogeochemical change, and (c) discover key indicators that can be used to assess biogeochemical change and susceptibility to perturbations. This will permit scientists to make conclusions about the resilience of ecosystems to future perturbations and identify those ecosystems that might be particularly vulnerable.

1. Regulation and connection among biogeochemical cycles (Box 1)

Fundamental connections among biological state variables, such as the level of biodiversity in an ecosystem, the state and dynamics of food web and other community-level interactions, and biogeochemical cycling, are still not well defined in both terrestrial and aquatic ecosystems. Also, scientists recognize the need to expand their perspective beyond isolated biogeochemical cycles and consider the connections, constraints, and feedbacks among multiple cycles. Thus, we know there are tendencies for changes in the hydrologic cycle because of climate variability or in the nitrogen cycle because of human activities to influence the carbon cycle, but they are poorly understood. Basic ecosystem research in all of these facets of biogeochemistry is critical to advancing a comprehensive perspective of the Earth system. A large-scale NEON facility will be crucial for integrating data sets and models that pertain to different biogeochemical cycles and cross broad geographic boundaries but have traditionally been sequestered within regions or national research agencies.

Box 1. What are the physical, biological, and social processes that regulate the cycling of and interactions between C, N, P, H_2O, and other materials at multiple (spatial, temporal, biological) scales?

A. What are the mathematical relationships that define biogeochemical processes, and how do we use these relationships to design new computer models of biogeochemical cycles?

B. What are the relationships among biodiversity, ecological webs, and biogeochemical cycling in both terrestrial and aquatic ecosystems?

C. What are the major processes of biogeochemical material transport (e.g., dust, N, C, pollutants) defined at multiple scales and between disparate ecosystems (e.g., aquatic and terrestrial)?

D. What are the mechanisms that connect one biogeochemical cycle to another? Are there general principles that define these connections, or are the principles novel depending on the type of biogeochemical material and ecosystem considered?

2. Anthropogenic influences on biogeochemical cycles (Box 2)

Human influences have reached virtually all regions of the global biosphere, and ecosystems will likely become even more managed in the future. Human activities continue to alter natural biogeochemical balances, including the direct infusion of biogeochemically relevant materials into the environment (e.g., CO_2 and NO_x) and the indirect influences of altered land-use patterns and climate change. Use of fossil fuels has increased preindustrial atmospheric carbon dioxide concentrations by 36% over the past century, and the application of agricultural fertilizers, along with the release of nitrogen oxides to the atmosphere during fossil fuel combustion and biomass burning, have nearly doubled the global rate of terrestrial nitrogen fixation. Invasions of ecosystems by pernicious species such as western cheatgrass have increased as the result of global commerce and, through effects on natural processes (such as the fire cycle), have perturbed the natural rates of carbon and nitrogen cycling. Given the high degree of mobility of humans and the long-distance reach of their impacts on the global environment, large-scale measurement networks, such as NEON, are key to the integration needed for comprehensive biogeochemical evaluation.

Box 2. How are human modifications of biogeochemical cycles affecting ecosystem services?

A. How do humans affect forms, rates, and spatial patterns of nitrogen, carbon, and phosphorus inputs (e.g., deposition and fixation) and outputs (e.g., harvest), and what are the consequences of human perturbations to these material inputs to biodiversity and ecosystem services?

B. How does land-use change affect the major controls over the U.S. carbon and nitrogen cycles?

C. How do biogeochemical cycles vary along management intensity gradients?

D. What anthropogenic contaminants will have important biogeochemical impacts, and how do we predict them?

3. Keystone biogeochemical processes (Box 3)

Understanding the resiliency of ecosystems and biogeochemical cycles to human perturbation is a key priority in future management strategies. The concept of resiliency is connected to those key points that control biogeochemical budgets and are thus most susceptible to perturbation from external forces. The NEON reference design should include ecosystem resiliency as a core priority during the development and planning process. In particular, the design of network strategies that bring into focus comparative insight among ecosystems along gradients of human influence will enable researchers to identify those key processes that, when compromised, subject an ecosystem to degradation and loss of biogeochemical integrity. There are fundamental pieces of information that are still missing from current conceptual models of ecosystem resiliency—information that could be added from intensive, wide-spread measurement networks such as NEON.

In addressing these proposed sets of questions, we advocate design strategies that provide the broadest possible coverage of regional ecosystems. In addition to observational networks in natural ecosystems, we also recommend that NEON provide the foundation for conducting manipulative experiments that allow for the testing of hypotheses, and that the networks should extend across the boundaries of natural ecosystems and intrude fully into bordering urban and suburban areas.

Box 3. What keystone biogeochemical processes govern the resilience of ecosystems to perturbations, and what are the key biogeochemical indicators that reflect a weakening of resilience in the face of perturbation?

A. How do species invasions of ecosystems and the emergence of novel diseases influence biogeochemical cycles in terrestrial and aquatic ecosystems?

B. What are the critical feedbacks between ecosystems and climate change, and how do we quantify these feedbacks in computer models of biogeochemical cycles?

C. How can historic biogeochemical changes inform us about the critical processes involved in future biogeochemical change?

D. Do connections among fundamental ecosystem properties, such as biodiversity and biogeochemical cycling, influence the tolerance and resilience of ecosystems to perturbation?

High Priority Areas for the Development of NEON Infrastructure in Biogeochemistry

Based on the questions that were developed and described above, NEON infrastructure should support biogeochemical research in three key areas: biogeochemical pools and fluxes, the influence of land-use change on biogeochemical cycling, and changes in biogeochemical cycling through time.

1. Biogeochemical pools and fluxes

Of primary importance to the NEON biogeochemistry effort is a focus on closing biogeochemical budgets, defining the mechanisms that drive biogeochemical fluxes, and measuring the flux and transport of key biogeochemical elements and compounds. To some degree these three needs are similar in the way that they hamper progress in the biogeochemical sciences. Gaps in the budgets of most biogeochemical cycles, inadequate insight into the mechanistic drivers that control fluxes, and inadequate measurements of flux rates resist our ability to produce meaningful and accurate models. It is ultimately process-based models that will allow the biogeochemical community to extrapolate beyond the current state, into the realm of future biogeochemical trajectories and to spatial domains not readily amenable to long-term measurements. The needs in this area are equally demanding for both terrestrial and aquatic ecosystems.

2. The influence of land-use change and other anthropogenic perturbations on biogeochemical cycling

The coupling of biogeochemical models to ground-based and remotely sensed data should be addressed with a high priority. "Biogeochemical mapping" will be required to define the spatial extent of pools and fluxes and thus allow for the spatial continuity of biogeochemical models across the entire NEON network of sites. A spatially explicit perspective on biogeochemical cycling will permit the biogeochemical outputs of one NEON site to become the biogeochemical inputs of adjoining sites. The coupling of biogeochemical cycles to spatially defined databases will also provide the foundation for informed use of the models in the face of continually changing landscapes. To the extent that land-use change also underlies perturbations such as biological invasions and emerging diseases, it will allow the coupling of biogeochemical models to models associated with the other grand challenges in ecology.

3. Changes in biogeochemical cycling through time

Knowledge of time-continuous biogeochemical cycling will allow us to accurately validate biogeochemical models using past, known climate and landscape scenarios and subsequently project model outputs into future unknown scenarios with confidence. Accordingly, a high priority should be placed on examining paleobiogeochemical cycles and coupling this insight to paleoclimate and paleovegetation databases. Once again, it will be crucial to couple time-dependent biogeochemical modeling with time-dependent predictions in the other grand challenges in ecology.

Details of Infrastructure

In order to support these three areas of high priority, the following specific items of infrastructure will be required for the NEON biogeochemistry effort.

1. Flux and pool-size measurement networks

Flux towers can provide insight into the fluxes of carbon, water, ozone, and novel elements and compounds that are emerging on the biogeochemical scene (e.g., nitrogen oxides, ammonia, mercury vapor, methane). NEON should integrate with the AmeriFlux network and the emerging plans for broader flux networks as part of the North American Carbon Program (NACP). In addition to these more traditional biogeochemical fluxes, an emphasis should be placed on measurements of dust/particulate transport using dust traps and/or mobile wind tunnel studies that, combined with models, can predict dust movement from landscape surfaces. Tower flux measurements using the eddy covariance approach require validation with complementary measurements. Net ecosystem carbon and water exchange must be validated by independent measurements of aboveground and belowground growth, leaf area index, litterfall, dynamics of coarse woody debris, decomposition, soil respiration rate, water runoff, precipitation, soil water storage, and evaporation. The strategies used in this validation should be integrated with the Tier 3 strategy intended for the NACP.

2. Deposition networks

Dry and wet deposition need to be measured across a broadly distributed network, which may include the NEON tower flux sites. Deposition measurements should include amount, intensity, chemical species, and particle sizes. The National Atmospheric Deposition Program (NADP) is a network that already assesses wet deposition. Dry deposition is measured by the Clean Air Status and Trends Network (CASTNET), which is operated in connection with the NADP. Additional sites for deposition measurement, beyond those at tower sites, may need to be added to fill in the gaps of the NADP and CASTNET networks. As a strategic component, NEON needs to develop a plan to improve our understanding and provide a network that can quantify erosion from various landscape surfaces. This will need to be done by means of a distributed network of erosion studies combined with modeling.

3. Stable isotope networks

The measurement of the stable isotopes of carbon, hydrogen, nitrogen, oxygen, and sulfur in organic and inorganic materials is required to provide crucial insight into physical changes in the environment and the biogeochemical response of organisms to those changes. The NEON reference design needs to develop both local and national strategies for stable isotope analysis. This will require regular sampling of the atmosphere, soil, vegetation, animals, and water within each NEON region and synthetic coordination at the national level to ensure consistency in analysis and interpretation. A more definitive statement of isotopic analytical needs and strategies for NEON has been prepared by a subgroup of interested scientists ("Stable Isotopes: A Critical Component of NEON," by D. Williams, R.D. Evans, B. Hungate, R. Doucett, J. Ehleringer).

4. Atmospheric transport measurement network for regional and continental extrapolation

The atmospheric movement of particulates and gases at the regional and continental scales needs to be determined. This is probably best done within the context of a national NEON facility dedicated to regional-to-global modeling and measurement. Regional transport will likely require information about the structure and dynamics of the lower troposphere and may require the regional deployment of Lidar, Sodar, and radiosondes. Integration among regions will likely require use of a national NEON aircraft sampling strategy. Aircraft sampling should be designed to cover large geographical transects in the mixed layer and free troposphere to determine primary atmospheric transport pathways. Once again, large-scale transport sampling should be coordinated with, (a) the aircraft intensives and tall tower studies already planned for the NACP, (b) regional sampling networks associated with the North American Nitrogen Plan, and (c) regional-to-continental studies of atmospheric chemistry and ozone transport associated with the North American Research Strategy for Tropospheric Ozone (NARSTO). Representatives from all of these efforts should be included in planning discussions aimed at defining the NEON reference design.

5. Aquatic transport networks

The NEON reference design should include explicit plans for observing material transport within watersheds and aquatic ecosystems. This effort should utilize traditional, geographically distributed watershed instrumentation (e.g., gauges); where existing networks are inadequate, new gauges need to be added. Coordination with long-term US Geological Survey (USGS) monitoring of water flow and water quality is particularly important for the success of NEON. Water samples should be analyzed based on USGS established protocols; dissolved organic carbon, dissolved organic nitrogen, nutrients, cations, particulates, and so on, as well as specific compounds of interest (trace organics, heavy metals, and isotopes). Strategies should be developed to invent new sensor technologies for in situ, continuous measurement of dissolved organic substances and nitrogen. A network of lysimeters and observational wells also needs to be established on targeted watersheds in each region to examine movement through soils and along groundwater paths, respectively. Water samples from these watersheds need to be archived in quantities that will support at least three decades of research (probably on the order of five liters for each archived sample).

6. Biogeochemical analytical laboratories

NEON should provide for the establishment of analytical laboratories to facilitate the needs of each region. All laboratories in the NEON network, in turn, will need standard calibration and analysis techniques. The mission of these laboratories should be viewed not only in scientific terms but also in educational terms, providing training and career opportunities in biogeochemical analysis. The laboratories should be equipped with capabilities for gas chromatography/mass spectrometry, inductively coupled plasma-mass spectrometry, wet-chemistry analysis, plant tissue chemistry analysis (e.g., CHN analysis), soil and water analysis, and rhizotron image analysis systems. The analytical facilities should be co-located with a technology development center where scientists and engineers can work together to develop new fast-response sensors for both aqueous and gas-phase biogeochemical fluxes. The laboratory facilities could also loan instruments to various NEON field sites, greatly increasing biogeochemical research capability at minimal cost.

7. Paleobiogeochemical laboratories

Techniques for extracting information about past environments are well developed in some ways, but the paleo community has largely focused on reconstructing climate and past vegetation, not biogeochemistry per se. In developing the historical context for biogeochemistry within NEON, we recommend the following:

- Develop a strategy to incorporate a historical perspective including paleobiogeochemistry.
- Place historical emphasis on recent high-resolution records (e.g., ranging from last 50 to 10,000 years).
- Include facilities to collect and archive proxy records of multiple forms, as well as bioinformatic support of data analysis and availability (where possible, this initiative should build upon existing programs archiving paleo materials (e.g., pack-rat middens at University of Arizona and Nevada's Desert Research Institute, tree cores at the tree ring lab, sediment cores at Institute of Arctic and Alpine Research, etc.).
- Establish at least one central NEON dating facility to support network-wide paleo analyses.
- Include significant investment in both contemporary and emerging technologies relevant to paleobiogeochemistry, including compound-specific mass spectrometry and genomic analysis.

Archival facilities, including cold and ultracold rooms for some proxy archives, should be available at all observatories or at a national facility. Molecular facilities should be available to each observatory for cases in which the identification of paleobiogeochemical samples to the species level is needed. Field components of paleobiogeochemistry will be region specific; for example, in some regions the main focus may be on collection of lake or near-shore ocean cores, requiring boats and coring instrumentation, while in others the best available records may be tree rings, animal middens, and/or caves. No site will require arrays of field instrumentation; instead, the support will be for campaigns that collect the needed proxies. This research approach allows sharing of equipment among sites as needed.

8. Scaling and modeling centers

In addition to observatory networks, the NEON reference design will require the explicit establishment of modeling consortia and platforms. The NEON effort should include modelers in all steps of planning and implementation of the observational and experimental activities at each site. NEON should include a consortium of modelers at the regional and national scales (including professionals to design interfaces between models). This consortium may be organized around a central NEON modeling facility. The aim of the modeling consortium will be to develop a broad range of models, including exploratory-frontier models (to guide network design and hypothesis-driven research), community-level, user-friendly models (for use by broad components of the NEON research community), portable models (for use by broader NEON user groups, including the general public and K–12 teachers and students), and prototype algorithms. Model development has to be closely associated with data synthesis. Thus, a centralized NEON modeling facility may be associated with existing national facilities, such as the NSF-supported National Center for Ecological Analysis and Synthesis (NCEAS).

The NEON modeling effort will have to be supported by the proposed observational networks. As a high priority, modeling efforts will require data on productivity, decomposition, species distributions, functional group diversity, nutrient and water parameters, disturbance intensity and distribution, weather and climate dynamics, soil properties, and carbon/nitrogen/phosphorus stocks and turnover rates. In order to facilitate spatial scaling, NEON modelers will also need stable isotope data, flux tower networks, and data from genomic analyses of past and present population structures and migratory dynamics. As a high priority, NEON biogeochemistry modelers will have to collaborate with the remote sensing community, including detailed spatial information on normalized difference vegetation index (NDVI), canopy lignin and nitrogen concentrations, surface biomass and vegetation structure, land-cover type, albedo, soil moisture, snowpack, and chlorophyll in freshwater and marine ecosystems (e.g., SeaWIFS-type data). Finally, the NEON modeling community will need access to belowground inventory data, data from experimental manipulations, data from paleo proxies for biogeochemical cycling rates, and continuous data across major environmental/biome gradients and across gradients from natural ecosystems through urban and suburban corridors.

9. Coupling land use change to biogeochemical cycling

Biogeochemical analysis and modeling will rely heavily on land-use data, and it is important for NEON to provide the highest resolution spatial data that is possible. This may include highly accessible connections to national archives of spatial images. In addition, instruments and personnel are needed to provide "ground-truth" information for areas covered by remote sensing. Identification of the dominant plant species in these areas is especially critical, so that information on ecosystem processes from remote sensing can be applied to other areas with similar dominant vegetation. NEON land-use efforts should also encourage linkages to long-term experiments aimed at determining the process-level connections between land-use change and biogeochemical cycling. This should include especially close connections to existing long-term experiments at LTER sites.

Within the land-use theme, we amplify the need for a national NEON modeling and synthesis center dedicated to biogeochemistry. With regard to land-use change, the center could serve as a repository for image libraries especially relevant to regional biogeochemical models, a center for the development of spatially explicit biogeochemistry models, and a training center for professionals interested in the spatial coupling of biogeochemistry models.

One of the primary challenges in coupling biogeochemical analyses to data on land-use change will be to obtain observational data from complex landscapes, including agricultural areas (with patchwork vegetation distributions), urban/suburban areas, wetlands, and steep hilly or mountain terrain. Special attention will need to be paid to these areas to ensure that they are covered by NEON observational networks, and novel modeling efforts will need to be established to enable biogeochemical analyses in complex terrain.

Concluding Statement

The principal aim of this workshop and report is to develop the intellectual framework for ecological aspects of biogeochemical cycling from which a specific reference design and implementation plan for NEON can emerge. In working toward this aim, we tried to not repeat the discussions covered by past workshops. Specifically, we recognized the very valuable suggestions produced from the NEON workshop on infrastructure (NEON Planning Workshop IV) that was convened in Boulder in 2002. The questions that we identified in the current workshop are fully compatible and complementary to the 2002 workshop recommendations. Additionally, we did not replicate the recommendations of the recent report on stable isotopes and NEON (provided in July 2004). The latter report provides the intellectual framework and specific suggestions for the development of stable isotope research within the NEON reference design. We recommend that both of these reports be included and integrated with the current report when initializing a specific implementation plan for biogeochemical research within NEON.

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