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Biodiversity, Species Composition, and Ecosystem Functioning

Report from a NEON Science Workshop

July 26–28, 2004
Carmel Valley, CA

National Ecological Observatory Network

American Institute of Biological Sciences

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

The IBRCS Program

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

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

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

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Convened by the American Institute of Biological Sciences in conjunction with Michael F. Allen, University of California–Riverside; and Brent Mishler and Craig Moritz, University of California–Berkeley, with support from the National Science Foundation

About the American Institute of Biological Sciences

The American Institute of Biological Sciences is a nonprofit 501(c)(3) scientific association headquartered in Washington DC, with a staff of approximately 30. It was founded in 1947 as a part of the National Academy of Sciences and has been an independent organization since the mid-1950s, governed by a Board of Directors elected by its membership. The AIBS membership consists of approximately 6,000 biologists and 80 professional societies and other organizations; the combined individual membership of the latter exceeds 240,000 biologists. AIBS is an umbrella organization for the biological sciences dedicated to promoting an understanding of the natural living world, including the human species and its welfare, by engaging in coalition activities with its members in research, education, and public policy; publishing the peer-reviewed journal, *BioScience*, and the education website, *www.actionbioscience.org*; managing the project office for the National Ecological Observatory Network, *www.neoninc.org*, providing scientific peer review and advisory services to government agencies and other clients; convening scientific meetings; and performing administrative services for its member organizations. Website: *www.aibs.org*.

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Key Words: National Ecological Observatory Network; biological infrastructure; biodiversity; species composition; scientific facilities; science workshops

This document is available from:

American Institute of Biological Sciences
1444 I Street, NW, Suite 200
Washington, DC 20005
tel. 202-628-1500
fax 202-628-1509
mbrown@aibs.org

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Cover:
Yellowstone, our first national park, with a bison—one of the first conservation issues—and also the hot springs from which organisms with the enzymes necessary for PCR were studied. Photo by Edith Allen.

NEON Workshop Series

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

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

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

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

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

Executive Summary

Six fundamental questions

Using surveys and discussion, we narrowed our focus on NEON down to six key questions organized in two parts.

Part one: Initial conditions

1. What is the current biological diversity of the United States?
2. What are the spatiotemporal patterns regulating evolution?
3. How are key ecological and evolutionary processes regulating biodiversity distributed in space and time?

Part two: Predicting the direction and rate of change

4. How does ecosystem functioning change as biodiversity changes, and how does biodiversity change as ecosystem management changes?
5. How does changing biodiversity and ecosystem functioning affect human services (e.g., clean water, soil for agriculture) provided by ecosystems?
6. What elements are needed to generate modeling capacity for predicting changes in biodiversity and ecosystem functioning and the implications of change to human needs?

Infrastructure recommendations

Addressing the first set of questions (1–3) requires a mobile sampling and analysis system and wide array of sites to integrate a broad range of environments and human needs. These sites should comprise hundreds of individual locations, including natural reserves from all different biomes, agricultural and marine stations, and suburban and urban study sites. NEON should provide the geographic infrastructure to integrate the numerous layers of relevant data that tie together NEON-specific as well as historical samplings using a wide range of taxon information, down to the population level in some instances, and in other instances only to various clades. NEON can capitalize on existing natural reserve systems; marine, forest, and agricultural experiment stations; urban parks; museums, biocollections, and databases; and genomic institutes already established at universities and federal research sites across the country.

The second set of questions (4-6) revolves around organizing experimental **regional observatories** designed to assess both the impacts of changing environments on biodiversity and the reverse question of the impacts of changing biodiversity on ecosystem functioning. We anticipate organizing 30 to 40 such observatories based on infrastructure capabilities coupled with analyses of sampling design prior to placement. These need to be stratified across the major ecoregions of the country. One focus could be along local to regional environmental gradients, implemented using a regional approach across continental-scale gradients.

Answering these questions requires a highly developed and networked infrastructure. Observatories should include new biological assay techniques including image sensing, microarray chips, and behavioral sensing systems. These must be coupled with high-resolution sensing capacity (from microbes to weather), cutting edge geographic information systems, modeling capacity, and data management and exchange capability. All sites also need mobile capacity to respond to events both anthropogenic and natural.

Introduction

NEON is the latest step by scientists to establish an ecological baseline at a continental scale and develop a suite of tools with which the environmental health of the nation can be determined. Historically, our nation has completed many surveys and produced data sets going back to the initial charge to the Lewis and Clark Expedition (1803) to observe "the soil and face of the country…its growth and vegetable productions…the animals of the country…times of appearance of particular birds, reptiles or insects." These efforts include the establishment of the US Geological Survey (USGS); the US Entomological Commission (1876), which later became the National Biological Survey, then the US Fish and Wildlife Service; and the Biological Resource Division of the USGS (1995). In 1995, the National Science and Technology Council of the Executive Office of the President introduced a set of strategic planning documents, including the Committee on Environment and Natural Resources, to articulate goals, objectives, milestones, and metrics for the Federal Research and Development system. One topic identified as in need of research in that report was Biodiversity and Ecosystem Dynamics.

By the late 1990s, scientists recognized the need to develop an observatory, a tool available to ecological researchers across the nation, that would assess the biological resources and the rates of change in those resources, culminating in first the Biodiversity Observatory Network (BON) and finally NEON, a research platform available to ecological researchers across the nation. Underlying these efforts was the realization that ecologists could provide helpful information for society, in part because new information infrastructures were finally becoming available allowing scientists to integrate large masses of data from wide-ranging disciplines. New sensing technologies for both biotic and abiotic properties from the micro- to the macroscale are rapidly becoming available to assess dynamic processes never before studied *in situ*.

Two specific undertakings led to the identification of "Biodiversity, Species Composition, and Ecosystem Functioning" as a key topic area within NEON. The first was the effort under the umbrella of the American Institute of Biological Sciences, forming the Infrastructure for Biology at Regional to Continental Scales (IBRCS) Working Group. In the IBRCS White Paper (2003), the goals articulated for the NEON Mission included these:

- Develop a detailed understanding of how organismal physiology and species dynamics influence ecosystem processes.
- Provide conceptual, mathematical, and statistical tools to project how disturbance of communities and ecosystems affects their composition, structure, and functioning.

- Lead to the development of new instruments, information technologies, and modes of data sharing that allow measurement and analysis of processes beyond the research of small groups of investigators.

Subsequently, the National Research Council identified six critical environmental challenges of national concern for which our current knowledge is inadequate to address, including "biodiversity, species composition, and ecosystem functioning." In designating this area, the NRC report noted the following:

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.

Biodiversity and the relationship between diversity and ecosystem functioning is a crucial central element in NEON. The biotic component of ecosystems processes all elements, provides our food and fiber, leads to new medicines, cleans our air and water, and, indeed, even regulates our climate. Yet, the diversity and traits of organisms have generally been overlooked in many scientific and in economic analyses. If NEON is to succeed in any of the six grand challenges, development of a national infrastructure for characterizing and quantifying biodiversity must become a central topic (Figure 1).

This workshop was convened to identify key challenges and to begin to develop an infrastructure that can be organized into an integrated NEON design.

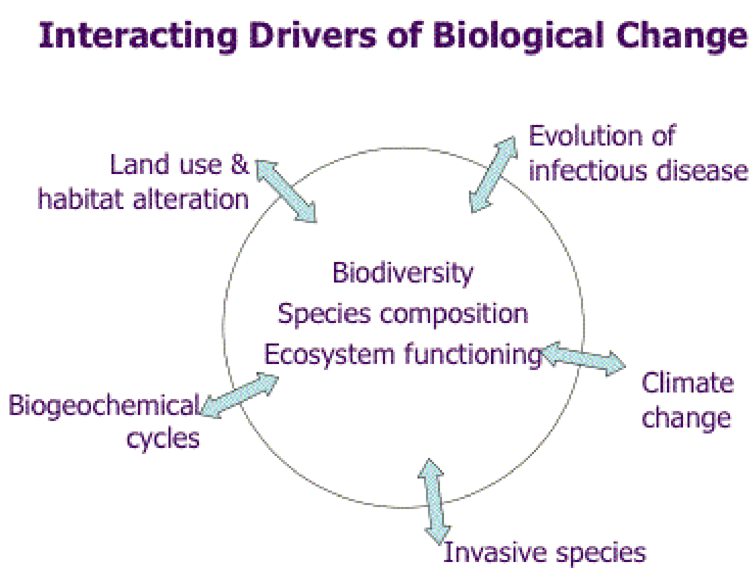

Figure 1. Relationship of biodiversity, species composition, and ecosystem functioning to the key priority topic areas of NEON.

Definition and Scope

We recognize that there are almost as many definitions of biodiversity as there are groupings of scientists. A SCOPE workshop (Solbrig et al., 1991) concluded, "The diversity found within species is the ultimate source of biodiversity at higher levels. Genetic variation, life-history traits, population dynamics and genetic population structure all shape and influence the way a species interacts with its environment and with other species." The Rio de Janeiro Convention on Biological Diversity noted that "'Biological diversity' means the variability among living organisms from all sources, including inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems." The NRC report stated that "Biodiversity (or biological diversity) refers to the number of species and extent of genetic variability in those species in a given site."

Based on input from the workshop group, and realizing that the above definitions are perhaps too limited in their primary emphasis on the species level, we used the following working definition: Biodiversity is the entire tree of life from the smallest gene lineage through its many nested branches of organisms and all their ecological interactions.

The study of biodiversity evaluates information on genes that define structural, physiological, and biochemical traits that, in turn, determine organism growth, and whose differential survival is determined by evolution. Populations of organisms interact across temporal and spatial scales with other populations (communities) and the abiotic environment (ecosystems) to regulate the life-supporting physical and chemical properties of Earth (Figure 2).

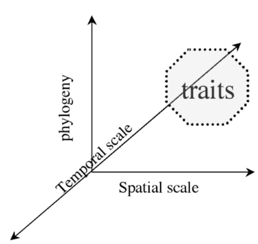

Figure 2. Traits of organisms are restricted by their phylogeny but exist at distinctive temporal and spatial scales. These limitations determine their ecosystem services.

Goals

The twin goals of the workshop were (1) to identify key questions that are needed to understand the key roles of biodiversity and ecosystem functioning, and (2) to develop a framework for the infrastructure needed to address these questions.

In addition to these goals, we appreciate the need for this infrastructure to be flexible enough to facilitate the development of the next generation of research questions.

Fundamental questions

Using surveys and discussion, we narrowed our focus on biodiversity and NEON down to six key questions embedded in two categories:

Initial conditions

1. What is the current biological diversity of the United States?
2. What are the spatiotemporal patterns regulating evolution?
3. How are key ecological and evolutionary processes regulating biodiversity distributed in space and time?

Predicting the direction and rate of change

4. How does ecosystem functioning change as biodiversity changes, and how does biodiversity change as ecosystem management changes?
5. How does changing biodiversity and ecosystem functioning affect human services (e.g., clean water, soil for agriculture) provided by ecosystems?
6. What elements are needed to generate modeling capacity for predicting changes in biodiversity and ecosystem functioning and the implications of change to human needs?

Recommendations

We then focused on the infrastructure needed to undertake such monumental efforts. In particular, we noted that these two categories have different structural needs. In the first category (questions 1–3), mobile sampling and analysis systems and a wide array of sites are needed to integrate the broad range of environments and human needs. These sites should consist of hundreds of individual locations, including natural reserves from all different biomes, agricultural and marine stations, suburban and urban study sites, and they should be well integrated with natural history museums and their databases. NEON should provide the geographic infrastructure to integrate the numerous layerings of relevant data that tie together NEON-specific as well as historical samplings using a wide range of taxon information, some down to the population level, some attributable only to clades at various levels. A critical source of baseline biodiversity information are the nation's museums and herbaria and the biocollections communities information networks, such as FishNet, HerpNet, Ornithological Information System (ORNIS), and Mammal Networked Information System (MANIS), all NSF funded. At the very least, these data can indicate major gaps in taxonomic and geographic knowledge of the nation's biodiversity. NEON can also capitalize on existing natural reserve systems, for example the University of California Natural Reserve System; Archbold Biological Station; forest, agricultural, and marine experiment stations; and Long-Term Ecological Research (LTER) sites, from wildlands (e.g., Palmer Station in Antarctica to Toolik Lake in Alaska) to coastal marine (e.g., Gump Station, Everglades, and Plum Creek) to urban (e.g., Baltimore, Phoenix). These surveys represent a scalable information base ranging from Archaea and bacteria to plants and animals.

The second category (questions 4–6) revolves around organized experimental systems designed to assess both the impacts of changing environments on biodiversity [e.g., Center for Embedded Networked Sensing (CENS) James Reserve testbed, and the Kellogg Biological Station agroecosystem LTER site] to the inverse question of the effects of changing biodiversity on ecosystem functioning (e.g., the Cedar Creek LTER site). Answering these questions requires highly developed and networked infrastructure with high-resolution sensing capacity of the biotic and physical environment (from microbes to weather), and cutting-edge geographic information systems (GIS) and modeling capacity. Current discussions anticipate the need for 20 to 40 such sites, organizationally based on infrastructure capabilities coupled with analyses of sampling design prior to placement. These would need to be stratified along compelling ecological, environmental, and biological gradients and/or across the major ecoregions of the country.

In order to maximize our ability to detect and interpret patterns in biodiversity, the proposed observatories must be embedded within a defined series of compelling ecological, environmental, and biological gradients; these gradients themselves should in turn be nested within several of the major ecoregions of the United States (stratified sampling). In this way we should be able to assess how geographically distinct flora and fauna respond to similar ecological forcing functions, and to develop new predictive models for biodiversity and ecosystem function. The sites chosen for NEON observatories should be placed along gradients in primary productivity and in food web structure; these two factors are by consensus considered to be among the two most important local ecological controls of species richness. Intensity of human disturbance would be the third axis of variation. Our general suggestion for observatory siting should be structured as in Figure 3. Such a design would then be repeated for multiple additional ecoregions and habitat types (aquatic, terrestrial) within each ecoregion. Even a brief reading of the recent ecological

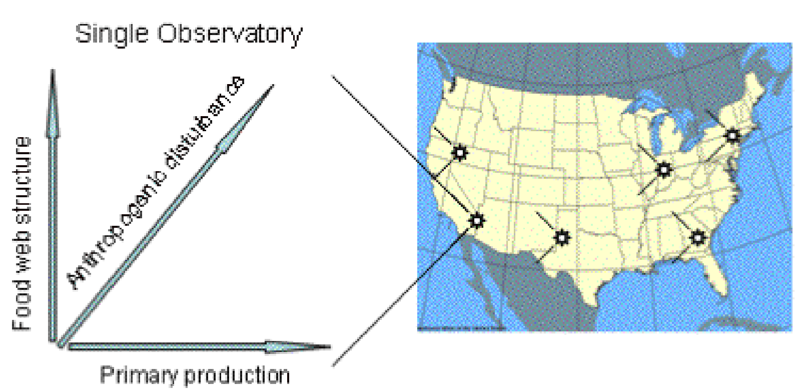

Figure 3. Gradients integrated into the localizing of an observatory within gradients across the United States.

literature suggests that relatively simple questions—such as What is the shape of productivity–diversity curves?—still remain poorly answered, and relatively few efforts have been made to collect parallel data for multiple taxa, using consistent sampling methods and analytical tools. Such methodological consistency is a *sine qua non* for NEON. Efforts should be made to ensure that this biodiversity network produces a broad, scalable information base that ranges from the Archaea and bacteria to plants and animals. There should be an extremely careful attempt to include representative examples of both aquatic and terrestrial habitats.

Finally, each of these sites must include a mobile capacity to respond to events that are both natural and anthropogenic. These can be widespread and growing issues, such as sudden oak death syndrome and West Nile virus, or regional issues such as wildfire or land-use shifts.

Together this requires a structure that integrates both centralized and distributed resources along cyberinfrastructure and biodiversity gradients, using newly developing sensing and analytical technologies that lead to modeling and predictability (Figure 4).

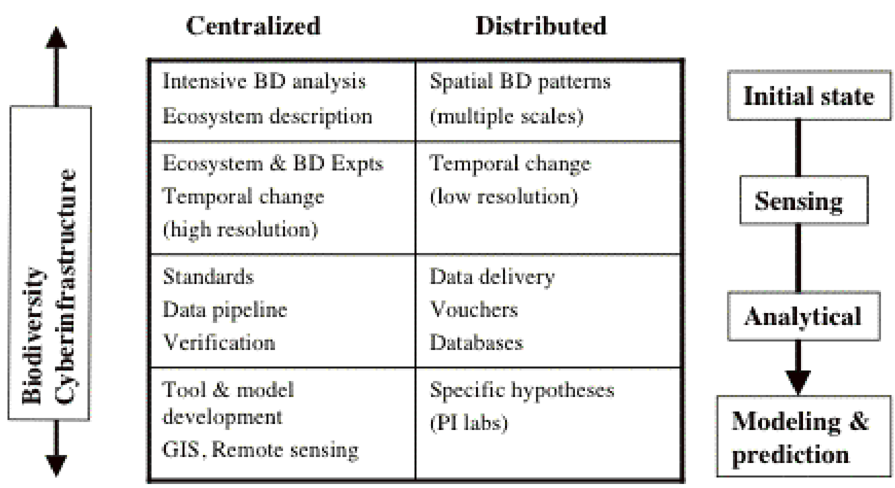

Figure 4. The relationship between the centralized and distributed components along infrastructural and conceptual methodological gradients organized for each regional observatory.

Linkages between Questions, Infrastructure, and NEON

Part one: Initial conditions

1. What is the current biological diversity of the United States?

In this initial question, we focus on one of the most challenging topics in NEON. The goal of NEON is to look across the United States and characterize the actual phylogenetic structure of biodiversity. It is not to continue current approaches, simply making species lists and surveying for endangered or potentially endangered species. One goal is to facilitate integration of the existing information (e.g., in museums, herbaria and biocommunity networks) with targeted surveys of the diversity of species in existing study areas ranging from parks and reserves to agricultural stations and urban parks. Many of these activities are already underway, such as the California Natural Diversity Database (CNDDB) and National Biological Information Infrastructure (NBII). However, a simple listing of species is not achievable for the many varied prokaryotic organisms or for the vast majority of eukaryotes such as fungi, nematodes, mites, and protozoa. Furthermore, such a species list, even if achievable, does not capture most information about biodiversity. But we can build on the Tree of Life concept to characterize biodiversity phylogenetically, at a range of different scales, for many sites across the country.

This exciting new approach will allow scientists to focus on *lineages* exhibiting *traits* that are essential to the functioning of ecosystems, including their natural growth requirements and adaptability under different conditions. Using this approach, scientists can also systematically work through lineages in different areas to identify useful organisms (for example, those that break down pollutants) or are known to produce products or antibiotics under different conditions (for example, penicillin, polymerase chain reaction enzymes). By developing such a rich, phylogenetically and spatially structured database, linked to physical specimens curated in museums, scientists gain a baseline for many different groups of organisms against which change (temporal and spatial, natural or human caused) can be measured quantitatively.

One immediate issue is to develop common currencies for measures of biodiversity. Species lists and population estimates are the initial step but ultimately are not likely to serve as the optimum currency, given that species concepts vary greatly among groups and among specialists. However, by producing local phylogenies, identifying lineages at all nested scales, modern comparative methods will allow for valid contrasts, even with a partial census between sites or through time.

A second issue is to construct surveys that integrate updated conservation needs. Many conservation reserves are based on old, often out-dated surveys. Newer technologies (genetic tests) are being developed that allow for the identification of individual animals (such as bird songs) and their lineages (at more and more inclusive scales) and can be coupled with their individual behaviors to determine if a population can remain viable within the existing study network.

This issue is also crucial in that we possess no national-scale baseline against which changes in biodiversity caused by natural and human activities can be measured. There exist many descriptions that are local (e.g., individual research stations, some going back over a century) or regional single-sample expeditions (such as the Lewis and Clark expeditions, and the George Bird Grinnell survey reports). Although these allow individual peeks into history, they provide no comprehensive evaluation of change. Local current phylogenies can be compiled into organized, scalable regional to national phylogenies, which can then be directly compared to historical phylogenies. Thus, a picture of our changing continent can become apparent.

A third issue is to simultaneously explore lesser-known groups of organisms upon which the functioning of ecosystems depends and that likely hold keys to new pharmaceuticals and other biologically based natural resources. This area of biodiversity research is becoming increasingly important. In recent years, there has been an unfortunate concentration of antibiotic and agricultural gene pools into narrower sets from which minor modifications are constructed. This has resulted in more rapid evolution of resistant pathogens. However, a broad range of untapped genetic resources exists in wild plants (many of which served our ancestors) and microbes about which we know little or nothing.

Finally, the very large, integrated scale of this rational, phylogenetically based survey work will finally allow us to identify the scope of uncertainty in the current biological information available to decision makers. For example, NBII consists of a national database of species made for conservation purposes. However, this effort depends upon data with a dramatic range in quality, from surveys provided by amateurs or biased surveys without sampling rigor to high-quality data collected by government and university scientists, and is rather one-dimensionally focused on species taxa rather than the multidimensional phylogenetic approach described above. Through the approach advanced here, sampling protocols and metadata standards will be upheld, and the data from spatially and temporally effective sampling delineated.

2. What are the spatiotemporal patterns regulating evolution?

Evolutionary processes govern the composition and ultimately the functioning of biodiversity, but we know very little about how these processes work at present and even less about how they might change in the future in response to human activities. Currently, scientists can describe sequences of events that have led up to a particular suite of organisms and their activities, but it is very difficult to predict how, when, and where problems will arise, in part because biologists have focused on particular organisms or particular locations. A large-scale effort to study these patterns has not been undertaken, and there are no comprehensive, specific models that can predict which species are likely to become threatened. This is readily apparent in our understanding of extinction. Who would have predicted the extinction of the Rocky Mountain locust or the passenger pigeon? Such comprehensive models would have more than just conservation value. For example, the large-scale use of antibiotics in herding animals contributed to the development and spread of antibiotic-resistant bacteria. Understanding how bacteria and fungi exchange and preserve plasmids, and detecting how these plasmids persist and are dispersed across ecosystem boundaries, is a cornerstone evolutionary question for human health.

Following from the phylogenetic approach to biodiversity assessment described in the previous section, we could begin to develop baseline studies of current evolutionary and ecological processes. Before we can approach studies of *process*, however, we need to establish the basic *patterns* that are relevant. These would include phylogenies at several scales and, equally importantly, the mapping of functionally important traits onto these phylogenies, placing them on the map in geographic space. We will go over each of these in turn.

- **Phylogenies**. Higher-level phylogenies are routinely produced in modern biology and are indeed the focus of several NSF-funded programs, most notably the Assembling the Tree of Life program. So nothing fundamentally new needs to be added at these higher levels for NEON to work. The novel approach to be added in NEON would be the production of extensive site-based, local phylogenies, and the linkage of these informatically with existing higher-level phylogenies. By *site-based phylogeny* we envision a whole new approach to biodiversity inventory—a site would be inventoried by taking DNA samples from as many individual organisms as possible, with voucher information recorded for each sample as appropriate, possibly including precise global positioning system (GPS) coordinates, photographs, sound recordings, physical specimens for deposition in a museum, and so on. These samples will be sequenced for appropriate marker molecules (depending on the group of organisms), and phylogenies will be built (these can be linked through databases to studies from other areas). In this way, one could generate a richly structured inventory, a great improvement over the typical species list.
- **Traits.** Any trait of an organism can be mapped onto a phylogeny. The vision of NEON proposed here would include the gathering of standard ecological data for lineages and the storing of these data in databases linked to the appropriate phylogenetic level. The emphasis in developing this set of standard ecological data would be on functionally important traits. Relevant structural and behavioral traits obviously vary from group to group (from flowering plants to birds, fungi, and bacteria), yet many ecological traits are common, including substrate, light levels, water availability, reproductive status, age, phenology, associated organisms, and so on.
- **Geography.** One very important trait shared by all biological samples (and the lineages they come from) is geographic position. Using modern geographic information science, lineages and traits can be visualized at many different scales, aiding studies of ecology and evolution as well applied conservation and restoration projects.

Once these *patterns* of phylogenetically and spatially structured trait data are available in easily accessible databases, it will be possible to move to a whole new level of understanding of evolutionary and ecological *process*, which is the domain of the next major question.

3. How are key ecological and evolutionary processes regulating biodiversity distributed in space and time?

The study of biological diversity is organized around three major themes: (1) evolution and phylogeny, (2) form and function (ecology), and (3) distribution in space and time (geography). While each of these is a significant area of research, many exciting questions in ecology and evolution emerge at the intersections between these major areas. In particular, the flowering of phylogenetics in recent decades has led to innovations in the historical study of adaptation ("evolutionary comparative methods" Pagel, 1999), and the analysis of biogeographic patterns at a range of spatial and temporal scales (e.g., Morrone and Crisci, 1995; Sanmartín et al., 2001). In recent years, phylogenetics has also been brought to bear on problems in community ecology (Webb, Ackerly, McPeek, and Donoghue, 2002) (Figure 5).

The linkage between biodiversity and ecosystem functioning cannot be addressed except in the spatial and temporal context of evolutionary change. Species composition has previously formed the cornerstone of studies of ecosystem functioning. Removal studies, going back to the 1950s, have repeatedly demonstrated that individual species matter to structuring communities, and more recent studies have shown changes in overall productivity and nutrient cycling. But lineages can

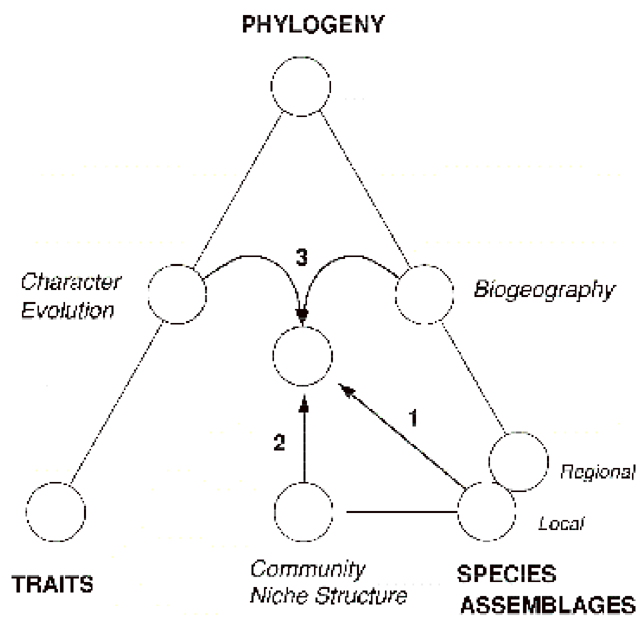

Figure 5. Schematic summary of various approaches to the integration of phylogeny traits, and communities. (1) Examining the phylogenetic structure of community assemblages; (2) exploring the phylogenetic basis of community niche structure; (3) adding community context to studies of trait evolution and biogeography (from Webb, Ackerly, McPeek, and Donoghue, 2002).

change their functional characteristics, such as size and trophic activity, within only a few generations. This sets up an important feedback loop essential to ecological processes. As individual trophic levels are eliminated in lakes, streams, parks, reserves, and rangelands, either evolutionary change could fill the gap or the entire functioning of an ecosystem could change.

As discussed above, the species concept as it is applied in plant and animal taxonomy is fuzzy, resulting in shifting species descriptions and names as molecular evidence is brought into the delineations. Moreover, fungi and microbes are very difficult to put into a species concept at all. Until recently, species removal studies ignored the critical contributions of microbes, yet their rate of evolutionary change can be rapid and have major implications for ecosystem functioning, including the development of pesticide and antibiotic resistance. Also, microbes are capable of exchanging or picking up genes present in the environment. Only NEON has the capability to study microbial evolution and feedbacks to ecosystem function at the continent-wide scale at which these changes can be magnified

The major issue facing predictability in ecological and evolutionary phenomena is projecting key processes in time and space. Current studies are limited to individual field stations, occasionally extending to a few stations within a region. It is currently impossible to understand which species respond to global change (either anthropogenic or natural) by moving or evolving *in situ*, because not enough sites have integrated data sets capable of addressing such questions.

The development of arrayed sensor technology that can describe physical features of the environment is improving almost daily. These include small-scale (centimeter to meter) analysis of temperature, moisture, and CO_2, such as that being developed by the CENS group, as well as the regional efforts such as the high-performance wireless research and education network (HPWREN) integrating research stations across southern California.

But the development of biotic sensors currently lags behind those assessing the physical and chemical characteristics of the environment. Intensive efforts are currently underway using new approaches such as antisera, microarray technology, and even newer concepts that will be described later. These have not yet been deployed in arrayed networks in the field, but testbeds should be underway within the next year.

Coupling arrayed assessments of biodiversity and physical/chemical environmental change at the continental scale will, for the first time, generate the kinds of data that can enable prediction of the spatial scaling of ecological and evolutionary processes and their interactions. NEON will help scientists determine whether or not, or to what degree, anthropogenic change is actually affecting the national ecological resources. We will be able to measure initial conditions, hypothesize change, determine whether that change occurred, and establish the scale (regional or national) at which management action should occur. Finally, this approach will give policymakers the information needed to make informed decisions about the response of the environment to local, regional, or national phenomena.

Infrastructure needs

The infrastructure needed to establish initial conditions is the equivalent of a telescope that can peer into every field station and national park, any location where survey data have been or are currently collected, and provide a framework for collecting critical missing data. It needs to be capable of extracting and organizing the existing data from field stations, agricultural experiment stations, urban parks, and museum records. Furthermore, NEON should support the capacity for automatically collecting information from a variety of sources, including sound, DNA and RNA of water and soils for total extraction, and multispectral images (from microscopic to satellite). A suite of mobile labs would be attached to each of the experimental observatories and initially used to fill in gaps in baseline data, especially for suburban and urban areas where there is a dearth of biodiversity and ecosystem functioning information. These mobile units, which are described further in part two, contain biodiversity-collecting instruments, environmental-sampling sensors, and curation capacity. In all cases, samples will be analyzed according to defined protocols and further analyzed and curated using the many genomic centers and museums already associated with federal labs and universities.

This "bioscope" also needs to be capable of collating, organizing, and making available all biodiversity data from all of these resources. We envision two components for the streams of incoming data and samples: (1) supercomputer centers, such as the San Diego Supercomputer Center (SDSC), will serve as electronic "Libraries of Congress" housing the acquired data, plus the computer resources, GIS programs, and other infrastructural needs to access and analyze data; (2) natural history museums will serve as the repositories of physical specimens, including preserved voucher specimens, living culture collections, frozen DNA and tissues, and so on.

Surveying the initial conditions of continental-scale biodiversity *per se* is probably not the direct function of NEON. Compiling the existing information in databases and museums with new data gathered from strategically chosen points, however, is an appropriate function of NEON. This effort will require increasing the cyberinfrastructure for organizing and curating literally hundreds of individual projects that have been completed, are ongoing, or will be undertaken as part of thousands of research projects. However, providing the infrastructure is an appropriate NEON undertaking. This includes sites, mobile labs, standardized analysis tools, curation facilities, and data management infrastructure. The sampling infrastructure should be concentrated at the focal experimental sites based around regional observatories. Curation facilities need to be appropriately housed at existing museums. It will be necessary to provide resources for key museums to make sure that samples are properly archived. These may be organized through the regional units in association with the experimental sites. It should be noted that data for all groups of organisms, prokaryotes and eukaryotes, must be included.

Importantly, while undertaking this large-scale collecting and analysis will be a large task, the incoming data streams should be manageable. These data inputs are likely to be a fraction of the spectral data collected by satellites, telescopes such as the Hubble telescope, interplanetary probes, or climatological data that currently are parts of coordinated research programs. Analyses of trends will become the tasks of individual scientists or groups, such as National Center for Ecological Analysis and Synthesis (NCEAS), and developed through independent grants in a manner used by oceanographers for ship or buoy data.

The data are likely to consist of several types. Sequences, microarray analyses, behavioral information (e.g., sonograms of bird songs and bat sonar inflections), real-time photographic imaging of organisms, and samples (for DNA extraction, freezing, or conventional storage) will be organized along with existing information compiled at the thousands of existing field stations.

Part two: Predicting the direction and rate of change

4. How does ecosystem functioning change as biodiversity changes, and how does biodiversity change as ecosystem management changes?

These questions require developing an experimental infrastructure designed to make predictions (and determine levels of uncertainty) about how biodiversity changes ecosystem dynamics, and the reciprocal, how changes in ecosystem management affects biodiversity. Going both directions is essential. We already know that with habitat fragmentation, biodiversity is lost. But with reducing biodiversity are we slowly losing function, or is there a threshold beyond which biodiversity can no longer sustain a functioning ecosystem and systems collapse? We do not even know if the changes in process rates are correlated linearly with loss of biodiversity, follow some feedback model, form asymptotes, follow an Arrhenius plot, or develop non-linear thresholds. Nor do we know if the reactions or thresholds (if these exist) are the same in the coral reefs and in the arctic tundra.

Just as importantly, as management strategies are undertaken to eliminate an invasive species or reduce the establishment of an emergent disease (for example, spraying for mosquitoes to control West Nile virus), biodiversity can be affected directly (e.g., by destroying soil spiders or aquatic insects that form the base of the food chain for fish) with unknown feedbacks to other ecosystem functions.

Because these questions are meant to be *predictive*, they require focused **regional observatories** with intensive infrastructure that reflect the differing conditions encountered, but they need not be answered at every site where biodiversity surveys are undertaken. The sites where these questions are studied do need to reflect the range in ecosystems across the country and should be replicated across all ecoregions or biomes.

Three conditions are needed to be able to extrapolate from one experiment to another for comparison and to make the results useful across the ecoregion. First, an experimental approach is necessary. Only through experiments can theoretical predictions be tested. Just as astronomers measure the speed of gravity as an underlying data test for attempting to formulate the unified field theory, so do experiments provide data to test models predicting the contradictory theories of diversity and ecosystem functioning. Existing examples at individual sites are well-known. What is needed is to expand these to the continental scale to determine if, as different regions and differing organisms are encountered, the processes remain the same as in the original experiment or change in some fashion. Thus, these experiments must be replicated in a range of ecosystems, aquatic, wildland, urban, suburban, and agricultural.

Second, a reference organism or clade should be identified based on the dynamics of different ecosystems. Reference organisms or groups have been demonstrated to serve a focus around which predictions can be made and experiments designed. These could be organized around phylogenic lineages related to particular keystone species, or focused around trophic levels or energy channels. These details need to be ironed out, but consistency is needed across the locales.

One of the most difficult issues is to deal with scaling, particularly in determining microbial diversity and the actual biochemical pathways that regulate ecosystem functioning. Humans respond directly to processes from 1 to 10^4 m^2. Considerable effort has been made to scale from individual satellite images (10 to 100 m^2) to continental scales (10^7 km^2), or 11 orders of magnitude. Many researchers have worked for 40 years to develop methods to integrate individual pixels into meaningful scientific information. Just as critical is the reverse. Microbes interact, release enzymes, and transform nutrients at scales of 1 to 10 mm^2! Scaling from the microbial composition or activity to the individual pixel integrates 14 orders of magnitude. To understand how biodiversity regulates critical ecosystem processes at the continental scale requires developing models that scale almost 30 orders of magnitude!

5. How does changing biodiversity and ecosystem functioning affect human services provided by ecosystems?

Ecologists and economists have studied ways to assess the value of biodiversity to human society, but these remain useful at only the global or local scale and come with high variation in estimates. Nevertheless, biodiversity alters ecosystem services in many known, and likely many unknown, ways. Identifying and quantifying these services is a proper goal of NEON at the national level. The importance of potable water cannot be underestimated, yet microorganisms both contribute to disease transmission and are the source of technologies for cleanup. Knowing what organisms are present under what conditions is essential to the health of the nation's ecosystems. A simple example, red tide, provides an illustration of what a NEON infrastructure can provide in real-time.

Numerous critical functions are differentially carried out in urban areas, agricultural fields, fisheries, and wildlands. These include carbon mineralization and sequestration, oxygen production, nitrogen deposition and utilization, noise buffers, food and fiber production, and waste disposal. Yet we lack coordinated information on how different environmental conditions, from man-made to natural, change across the country. Increasing precipitation downwind of cities because of albedo changes might have little impact in Denver, but the effect could be dramatic in Baltimore. Nitrogen deposition in agricultural fields in Ohio might not be detrimental, but it could be devastating in the deserts of southern California. Quantifying these impacts would be a priority area of concern for NEON.

A particular effort is needed to make sure that the research sites chosen reflect the interfaces between central study areas. These include the wildland–agricultural–urban interface and biome transitions. Urban–wildland edges represent a stark change in wildland functioning compared with agricultural–wildland edges. Issues such as the biota composition, trophic structure, and climate all have been demonstrated to differ between the edge types. As urban lands expand and prime agricultural and grazing lands decline, the differences in edge length will have dramatic consequences on the landscape of American wildlands. Rare and endangered species are very responsive to changing food webs that are differentially affected by the occupants of agricultural edges (snakes, rodents) versus suburban tracts (dogs, cats). Transitions between biomes represent those areas that will likely be most sensitive and a forerunner of regional change. The desert–arid woodland transitions shift dramatically with changing climate regimes and show likely water supply issues that will become apparent in the years or decades following spatial shifts in species composition.

6. What elements are needed to generate modeling capacity for predicting changes in biodiversity and ecosystem functioning and the implications of change to human needs?

Several elements become essential in organizing and utilizing the vast array of data currently existing and that will be collected by NEON. Two elements will become especially critical: predictive modeling capacity and informatics architecture systems. We need new models that are designed to organize and utilize large data sets and that predict nonlinear phenomena. Scientists often look for "simple" yet elegant formulations that yield understanding of behavior of large-scale phenomena. The equation $E = mc^2$ is such an example. However, ecologists and evolutionary biologists are generally faced with trying to predict variably scaled processes that behave chaotically.

New approaches to predictive modeling are underway across the nation. Several workshops have been convened at the National Center for Ecological Analysis and Synthesis (NCEAS) on developing new models for predicting behavior ranging from primary production in oceans to microbial compositional and process change. Some of the early iterations have been integrated into habitat conservation planning. The launching of the new journal *Ecological Complexity* is another example demonstrating that the field is ready for new approaches. However, NEON will provide the integration to make sure that these models are capable of working at the continental scale, and to develop new approaches to provide visualization crucial to public education and policymaking.

Similarly, database management has taken enormous strides over the past decade. These advances have come from the recognition by the scientific community that archiving, organizing, and accessing data are crucial at regional to continental scales. The large amount of data that are being generated by newer arrayed networks of biotic, visual, and physical/chemical information is staggering. New approaches are still needed to design the means to database ecological and evolutionary information and to allow rapid access and facilitate incorporation into modeling activities. To date, these efforts are underway in local studies, but the crucial need is at the continental scale.

Because of the emphasis on automated data collection, organization, and modeling at the continental scale, NEON will transform the landscape of ecological and evolutionary science.

Infrastructure needs

Questions composing part two require the greatest infrastructure development. At these experimental sites, stationary and mobile arrayed sensors need to be deployed to provide background information to the experiments, collect the vast data streams that will serve to test newly developing theories of how our environment works, and transmit the collected data to libraries for storage, cataloging, and analysis.

At this time, research into how to construct self-organizing sensors that track organisms, environments, and events is only beginning. The LTER network has developed individual experimental systems, which are often highly labor intensive (e.g., Cedar Creek LTER), or larger-scale monitoring capacity that tracks changing vegetation production in response to changing climates (e.g., Sevilleta LTER). Other individual programs have focused on characterizing diversity of extreme systems, such as Yellowstone National Park's hot springs.

However, only recently have engineers and ecologists teamed up to interactively develop arrayed technological systems that will become capable of self-organizing environmental and organismal data. Many of these wireless arrayed sensors are being developed and the cyberinfrastructure constructed for placement in the experimental observatories. The Center for Embedded Networked Sensors (CENS) is only one example of the ongoing development of a wireless, networked array of sensors ranging from environmental to biological sensors.

Only in recent years has DNA technology become rapid enough to begin development of field sampling and assessment units. The development of microarray technology allows for the rapid assessment of particular microbes based on their sequences. Three recent technologies are unfolding that will allow this technology to move to the field. The first is the miniaturization of microarray readers. We anticipate that these will rapidly proceed and be ready by the time NEON is ready for deployment. The second is the rapid acquisition of available templates. GenBank is only one of the recent databases that can be readily searched for templates, and new sequences are added daily. Further, as groups sequence entire soil or water samples and expand the large-scale sequencing around the globe, the available templates against which a sample can be tested are increasing exponentially. Finally, slides represent only one of the approaches to organizing a reader. Newer technologies such as quantum dots, catalytic antibodies inventors, enthalpy arrays coupled with miniaturized thermocouples are becoming new, and smaller, technologies that hold promise for use in the future to sense biodiversity for literally thousands, if not more, of microbes across time and space.

Sampling issues for biodiversity are being addressed and should be part of the NEON deployment. For example, water samples can be drawn through a sample reader, then analyzed using fluorescence markers or, in the near future, DNA microarrays. In soil, plant, and animal systems, we currently have no similar delivery systems, but the collaboration of engineers and ecologists through NEON will undoubtedly generate new techniques that will be appropriate. New generations of sensors must also become available. The environment is full of clues of biological activity, from pheromones and other chemical signals to visual, radar, and sound signals. All sampling devices should be built around wireless technologies for data storage and transmission. All automated and directly sampled materials need to be georeferenced using high-resolution samplers, and these are already becoming part of metadata standards. This is essential to couple biodiversity analyses with environmental sensors, satellite imagery, GIS analyses, and other explicit spatiotemporal resolution analyses.

A final component needed for each of these regional observatories is a mobile unit for each station capable of going to any point in the field for event measurements. These should be four-wheel-drive vehicles, aircraft, and boats that can be readily equipped with microarrays, cameras, sound sensors, weather stations, and other equipment as envisioned. These systems should be capable of being deployed for biodiversity assessments in conjunction with invasive species or emergent disease monitoring. All of the instrumentation envisioned for fixed arrays can be made to be mobile. These could be readily deployable using low-pollution tractor-trailer units, such as being deployed by the Center for Environmental Research and Technology in the University of California–Riverside College of Engineering.

Ongoing advances in sensor technology provide exciting new tools that can help us to address many scale-related questions in community ecology. These technological advances have, for example, enhanced our capacity to evaluate effects of patch size on terrestrial vegetation structure, and to better characterize underlying environmental gradients that exist within the landscape.

Ground-penetrating radar ranging from hand-held units to space shuttle deployments provide distribution information from large roots and perched water tables to buried river channels. Just as important, these technologies can show the presence or absence of ground-dwelling organisms, such as hibernating desert tortoises. Multispectral imaging of terrestrial vegetation from both airborne and satellite cameras in particular is now available at a spatial resolution of 0.75 m. Parameters derived from imaging data such as Normalized Difference Vegetation Index (NDVI), and ground-level remote sensing and biophysical data, are being collected at sites across the country. These data have revealed a high degree of correlation between leaf area index and plant cover measurements and the NDVI values derived from both ground-based and aerial sensors. NDVI also has been found to be a good predictor of disturbed versus undisturbed experimental treatments within study plots. New sensor technologies have improved our understanding of aquatic communities as well. For example, changes in coral reflectance resulting from a mass die-off of the sea urchin *Diadema antillarum* in the Caribbean region have been detected using Landsat thematic mapping. These satellite images could be used not only to detect changes in coral reef cover but also to help determine connectivity between reefs in the Caribbean. Similarly, our knowledge of riverine landscapes is changing as new technical instruments, ranging from microprobes to satellites, expand to allow the examination of spatial and temporal relationships among biota, hydrology, and geomorphology across scales that vary upwards from microhabitats to channel units to valleys and catchments.

Synthesis and Conclusions

We narrowed the list of potential research directions to six fundamental questions divided into two parts.

Part one evaluates the initial conditions, with three fundamental questions:

1. What is the current biological diversity of the United States?
2. What are the spatiotemporal patterns regulating evolution?
3. How are key ecological and evolutionary processes regulating biodiversity distributed in time and space?

Part two predicts the direction and rate of change with three additional fundamental questions:

4. How does ecosystem functioning change as biodiversity changes, and how does biodiversity change as ecosystem management changes?

5. How does changing biodiversity and ecosystem functioning affect human services (e.g., clean water, soil for agriculture and forestry) provided by ecosystems?
6. What elements are needed to generate modeling capacity for predicting changes in biodiversity and ecosystem functioning and the implications of change to human needs?

The resources needed are twofold in character. First, establishing a baseline simply requires the development and placement of an infrastructure that integrates existing local, state, private, and national resources. The second requirement is development of a suite of regional observatories at which the fundamental experiments designed as core experiments can be coupled with state-of-the-art sensor technology to understand the fundamental relationships, at the continental scale, between biodiversity and ecosystem processes.

Answering these questions fundamentally alters the scientific approach to ecological sciences. NEON would set a baseline against which change can be predicted and those predictions measured. Further, evolutionary processes have generally been evaluated in the laboratory or assessed in the fossil record. NEON will provide the resources to study rates, directions, and ecological drivers of this fundamental process in the field. Just as importantly, ecosystem process studies have viewed species as the static, basic unit around which ecological processes would be measured. However, evolution can rapidly change within the time scales that NEON will study. Thus, ecosystem processes and evolution can, for the first time, be experimentally evaluated as the feedback processes that they fundamentally are.

NEON will also provide the resources to make realistic predictions about directions and rates of change, and determine responses to management decisions. Weather predictions require the simultaneous gathering of initial conditions and rates of change across numerous sites. The equations are predictable within known time-scales, becoming chaotic at larger scales. Biological processes are probably relatively similar. Understanding feedback dynamics nearby is probably more similar than farther away (in both time and space). NEON will allow us to test this hypothesis for the first time at the continental scale. By undertaking this effort, issues such as biodiversity loss, species replacement by invasives, and the implications of global change become predictable. From there, management decisions can be made or, when the process is beyond human control, understood and accepted.

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Workshop Organizers

Michael Allen
University of California, Riverside
Center for Conservation Biology
208 University Lab Building
Riverside, CA 92521-0334
P: (951) 827-5484
E: michael.allen@ucr.edu

Brent Mishler
University & Jepson Herbaria
Dept. of Integrative Biology
1001 Valley Life Sciences Building, # 2465
Berkeley, CA 94720-2465
P: (510) 642-6810
E: bmishler@socrates.Berkeley.edu

Craig Moritz
University of California, Berkeley
Department of Integrative Biology
3060 Valley Life Sciences Building #3140
Berkeley, CA 94720-3140
P: (510) 643-7711
E: cmoritz@socrates.berkeley.edu

Workshop Participants

James Baldwin
Boyce Hall 1455
University of California
Riverside, CA 92521
P: (951) 827-5819
E: james.baldwin@ucr.edu

Carrine Blank
Washington University
Campus Box 1169
1 Brookings Drive
Saint Louis, MO 63130-4899
P: (314) 935-4456
E: blank@levee.wustl.edu

Michael Donoghue
Department of Ecology and Evolutionary Biology
Yale University
Environmental Science Center
21 Sachem Street
P.O. Box 208105
New Haven, CT 06520-8105
P: (203) 432-3752
E: michael.donoghue@yale.edu

Alexander Glazer
Natural Reserve System
UC Office of the President
Office of Research
1111 Franklin Street
Oakland, CA 94607-5200
P: (510) 642-3126
E: alexander.glazer@ucop.edu

Amarnath Gupta
San Diego Supercomputer Center
9500 Gilman Drive, MC 0505
La Jolla, CA 92093-0505
P: (858) 822-0994
E: gupta@sdsc.edu

Mike Hamilton
University of California James San Jacinto Mountains Reserve
PO Box 1775
54445 North Circle Drive
Idyllwild CA 92549
(951) 659-3811
E: director@jamesreserve.edu

Phil Hastings
Scripps Institution of Oceanography
University of California, San Diego
9500 Gilman Drive MC 0208
La Jolla, CA, 92037
P: (858) 532-2913
E: phastings@ucsd.edu

Leonard Krishtalka
Natural History Museum and Biodiversity Research Center
The University of Kansas
602B Dyche
Lawrence, KS 66045-2454
P: (785) 864-4540
E: krishtalka@ku.edu

Bai-Lian (Larry) Li
Ecological Complexity and Modeling Lab
Department of Botany & Plant Sciences
University of California
Riverside, CA 92521-0124, USA
P: (951) 827-4776
E: bai-lian.li@ucr.edu

William J. McShea
NZP/WCS Joint Appalachian Forest Ecology Program
Conservation & Research Center
1500 Remount Rd.
Front Royal, VA 22630
P: (540) 635-6563
E: wmcshea@crc.si.edu

John R. Sauer
USGS Patuxent Wildlife Research Center
11510 American Holly Drive
Laurel, MD 20708-4017
P: (301) 497-5662
E: John_R_Sauer@usgs.gov

Val Smith
Kansas State University
Department of Ecology and Evolutionary Biology
The University of Kansas
6007 Haworth
Lawrence, KS 66045
P: (785) 864-4565
E: vsmith@kku.edu

Robert D. Stevenson
Department of Biology
University of Massachusetts–Boston
100 Morrissey Blvd.
Boston, MA 02125
P: (617) 287-6682
E: robert.stevenson@umb.edu

Karen Stocks
University of California, San Diego
San Diego Supercomputer Center
9500 Gilman Drive MC 0527
La Jolla, CA 92093-0505
P: (858) 534-5009
E: kstocks@sdsc.edu

Mark Stromberg
Hastings Natural History Reservation
University of California
38601 E. Carmel Valley Road
Carmel Valley, CA 93924
P: (831) 659-2664
E: stromber@socrates.berkeley.edu

Robert Waide
Long Term Ecological Research – Network Office
Department of Biology
University of New Mexico
Albuquerque, NM 87131-1091
P: (505) 272-7311
E: rwaide@lternet.edu

AIBS Staff

Rina Aviram
National Ecological Observatory Network (NEON)
1444 I Street NW, Suite 200
Washington, DC 20005
P: (202) 628-1500 x 231
E: raviram@aibs.org

Jeff Goldman
National Ecological Observatory Network (NEON)
1444 I Street NW, Suite 200
Washington, DC 20005
P: (202) 628-1500 x 225
E: jgoldman@aibs.org

Facilitation Team

Marci DuPraw,
RESOLVE, Inc.
RESOLVE, Inc.
1255 23rd St., NW, Suite 275
Washington, DC 20037
P: (202) 965-6201
E: mdupraw@resolv.org

Bradford R. Spangler
RESOLVE, Inc.
1255 23rd St., NW, Suite 275
Washington, DC 20037
P: (202) 965-6214
E: BSpangler@resolv.org

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