A WORKSHOP ON MODELING IN NEON

Proceedings of a workshop held July18-20, 2005
Woods Hole, MA

Sponsored by
The National Science Foundation

Organizing Committee
John Hobbie (chair), Barbara Bond, Jerry Melillo, Bill Parton, Debra Peters, Gil Pontius, Ed Rastetter, Dean Urban

Hosted by
The Ecosystems Center, Marine Biological Laboratory

EXECUTIVE SUMMARY

Models are ubiquitous tools for advancing science; they allow scientists to deal with the complexity of the natural-human environment, with the interdisciplinarity of national environmental problems, and with the novelty and sheer quantity of data from observatories such as NEON. Models will play a central and essential role in NEON from the first steps of planning to the final stages of synthesis and forecasting. Models are essential for selecting sensors and designing optimal plans for sensor array deployment, data assimilation, error analysis, quality assurance, interpolation to fill the inevitable gaps in data, and for forecasting trends. Models will be required by NEON for spatial projections within regions and across the nation as a whole, and for high-level synthesis within and across the major questions that organize NEON research. Finally, models will facilitate outreach by NEON to stakeholders including decision makers at the local, regional and national scale.

Making modeling an explicit part of NEON will require:

- *A NEON Forecast Center to make systematic predictions at the continent-scale, integrate forecasting capability across the Observatories, and interact closely with agency partners.*
- *An explicit modeling component integral to its design and ongoing operations at each NEON Observatory.*
- *Cyber-infrastructure support for modeling tools for synthesis and forecasting.*
- *A flexible design for the modeling component that can facilitate evolution as network needs change.*
- *An ongoing process of user-engagement to ensure relevancy for NEON model and forecast outputs.*
- *A high-level component of NEON governance for planning and oversight of models.*

INTRODUCTION

Predictive models are a familiar part of life in the 21st century. Weather models interpolate pressure gradients from spatially distributed radiosonde atmospheric sensors, identify storms, and predict their trajectories. Economic models summarize patterns of productivity and spending at local (micro) scales to predict national and global (macro scale) changes in GNP. Epidemiological models are the basis on which global plans are being constructed to predict annual flu outbreaks, eliminate polio, control malaria, and slow the spread of HIV. In all instances, the usefulness of these models depends on the scientific rigor of model formation and testing as well as on the availability of the primary data upon which conclusions are based.

NEON (National Ecological Observatory Network) is being planned with funding from NSF's Major Equipment and Research Facility Construction program (MREFC). It will be a network of nationally deployed facilities and infrastructure including sensors and the cyber-infrastructure necessary for data collection and sample analysis, education, training, and outreach. NEON will collect environmental/ecological data at a wide range of sites covering the entire nation. Its goals are to document and forecast changes in ecology at regional and continental scales caused by climate and land-use change, alterations of biological and hydrological systems by humans, and movements of genes, invasive species, and disease-causing organisms.

It is clear that models must play a central role in every aspect of NEON: to inform the deployment of sensor arrays; to be used in data assimilation, error analysis/quality assurance and data "gap filling"; and to forecast changes at local, regional and national scales. Furthermore, the high-level synthesis required to address NEON's major questions, to inform resource managers and decision makers, and to communicate with and educate the general public, must be based on models fully integrated with the data collection and synthesis activities upon which NEON is based. In addition to the infrastructure provided by the MREFC program, NSF must fund modeling projects targeted at optimally employing NEON observatory data and forwarding the NEON goals of synthesis and forecasting. An NSF-funded workshop held at the Marine Biological Laboratory 18-20 July 2005, began the process of describing the modeling needed to carry out the NEON goals.

MAJOR RECOMMENDATIONS

- **NEON should implement a NEON Forecast Center to make systematic predictions at the continent-scale, integrate forecasting capability across the Observatories, and interact closely with agency partners.**
- **Each NEON Observatory should include an explicit modeling component integral to its design and ongoing operations.**
- **NEON should dedicate resources to support modeling within the categories of cyber-infrastructure tools and equipment, of forecast capabilities, and of outreach.**
- **NEON should institute an ongoing process of user-engagement to ensure scientific and community relevance for model development and application.**
- **The modeling component of NEON should have a flexible design that can facilitate the evolution corresponding to network needs.**
- **NEON governance should include a separate high-level component for planning and oversight of models.**

IMPLEMENTING MODELING THROUGHOUT NEON

1. **Planning and design stage** – NEON should use models to help select variables that must be measured to address NEON goals, to locate sensors along important gradients, and to identify the appropriate spatial and temporal scales for sensor deployment. Experiments, if conducted as a part of NEON, should be designed to both augment ecological knowledge and allow testing of predictive models. Modeling experience and capabilities should be a part of the criteria in the NSF competition for operation of NEON Observatories (as announced at the June 2005 NEON meeting at Estes Park, Colorado).
2. **Ongoing Operations –** NEON should adopt operational methods to ensure that emerging issues are quickly addressed with the latest developments in modeling and data synthesis. NEON should also set standards to ensure consistent model-based methods of data assimilation and "gap filling", within- and across-region interpolation, error analysis, and quality assurance. Without these methods, cross-site synthesis will not be possible. Models will also assist, and should be employed, to provide quantitatively reliable transitions from one sensor technology to another. This aspect of NEON modeling should be funded as a part of the infrastructure.
3. **Synthesis** – Synthesis of observations for characterizing system dynamics, spatial effects, and changes in the flux of material or organisms requires an integration of models and data. Therefore, NEON should support the design of models to ensure data synthesis to address NEON questions at local, regional and national scales. Inter-site and inter-model comparisons should be employed to assure the sufficiency of data-model linkages and accuracy of predictions. In addition, models and data must be in place to tie disparate sensor types for early-warning and real-time assessment of ecosystem dynamics. The interdisciplinary nature of the environmental phenomena being studied argues for a close coordination with synthesis efforts under other initiatives, such as CUAHSI and CLEANER.
4. **Spatial projections –** NEON should develop methods and protocols for the consistent extrapolation of spatial data (e.g., topography, climate, soils, etc.) derived from diverse sources that vary in format, quality and scale. Partnerships among diverse governmental agencies, universities and NGO's must be instituted by NEON to assure timely data acquisition and synthesis. NEON must promote methods of map analysis to assess the accuracy and reliability of spatial projections.
5. **Forecasting –** NEON goals of forecasting depend on models to project or predict changes in the system based on Observatory and other prior observations. These models are essential tools for near-term warning (e.g., fire likelihood, aquatic hypoxia) as well as real-time assessments (e.g., insect outbreaks, drought stress). In addition, the development of linkages among ecological, hydrological, climatological, and sociological models will be necessary for forecasting ecological changes at all scales and for assessing uncertainties and the response to stochastic events. In view of the importance of forecasting, NEON should incorporate into its governance a high-level component devoted solely to planning and integrating of modeling. A dialogue with experts from the numerical weather forecasting community is advised.
6. **Model design** – The modeling component of NEON should have a flexible design that facilitates the evolution of the network. We view NEON as a dynamic network that will change with time as new environmental challenges are identified, new sensors are developed,

and new types of forecasting are demanded to guide environmental management and policy. As in all scientific endeavors that link data collection and modeling, we expect constant iteration between these two components of NEON. Through the process of data-model fusion we will define new data needs as well as the types of model refinements that better synthesize the data. This iterative approach is essential to meeting an ongoing goal of NEON -- to improve our forecasting ability so as to better serve society with science.

7. **Outreach** – NEON should make full use of models to help the general public and decision makers visualize and integrate the broad range of NEON and related data sets. This role of models is particularly important to communicate uncertainties, to explore "what-if" scenarios, to assess management strategies, and to develop ecological indicators (e.g., critical loads) for decision makers. Education programs should be initiated to develop model proficiency in the next generation of scientists and models should be developed as teaching aids for K-12, undergraduate, and graduate students.

ROLE OF MODELING IN LINKING NEON DATA TO NEON QUESTIONS

The major goals of NEON have been distilled down to three key overarching questions:
1) How are ecological systems affected by changes in land use and climate across a range of spatiotemporal scales?
2) How do changes in availability and distribution of the Nation's water affect ecological systems?
3) How do the patterns and movement of genes and organisms across the continent affect biodiversity, ecosystem function and the spread of infectious diseases and invasive species?

The answers to these three questions encapsulate the knowledge needed to preserve the Nation's natural heritage and to sustain the land's ability to provide ecological services like fiber and food production, maintenance of reliable sources of clean water, maintenance of natural features like floodplains that mitigate extreme events, the control of invasive pest species, and the inhibition of the spread of disease. Through NEON we can envision new opportunities to transform our understanding of ecology on large scales based on experimentation, environmental surveillance, and forecasts at regional to continental scales: opportunities that we could not conceive of 10 years ago. To capitalize on these opportunities, NEON should institute an ongoing process of user-engagement to ensure relevancy for model and forecast outputs. Model development and application should be guided by the needs of NEON, not simply by the idiosyncratic goals of individual modelers.

To address these questions, a variety of combinations of ecological, hydrological, climatological, sociological and epidemiological models will need to be developed and integrated with one another. Some of the models will address questions at the plot and regional scale. Others will be used to forecast centuries into a future with conditions that are unprecedented in earth's history; therefore, an empirical extrapolation of responses based on current or past conditions is impossible and a mechanistic modeling approach will therefore be required. In addition, these forecasting models will need to be both spatially explicit and spatially interactive if the NEON results are to be projected from plot to regional to continental scales. To meet these goals, a major commitment to cyber-infrastructure and modeling will be needed.

To support this modeling effort, the NEON Forecasting Center, in partnership with other agencies and programs, should build a standardized data archive and retrieval system with complete coverage for the United States at as fine a spatial and temporal resolution as practicable. The types of data that will need to be archived include physical (e.g., elevation, aspect, soils), climatological (e.g., temperature, rainfall, CO_2), hydrological (e.g., channel networks, hydrographs), sociological (e.g., ownership, legal constraints on land use, demographics), and ecological (e.g., production, biomass, diversity) data. The archive should be remotely accessible, provide automated means to upscale or downscale gridded datasets in both space and time, and support processing capability for data assimilation (e.g., inverse analysis, global optimization algorithms, Bayesian analysis) and spatial and time-series analysis. The data in this archive should not only include the relevant empirical data derived from NEON and other sources (e.g., satellite data, GIS data on land use and population density, spatial surveys of soils and biomass, etc.), but also it should include "value-added" data derived from spatial interpolation and temporal forecasting based on NEON-supported models (e.g., carbon density maps derived for satellite data on spectral reflectance). This data archive should include or have network links to all the data likely to be needed to drive and test models to forecast ecological, hydrological, and epidemiological responses to land-use and climate change. In addition, the archive should compile the output from these forecasting models, facilitate additional model-data analysis, communicate forecast uncertainties, explore "what-if" scenarios, assess management strategies, and evaluate ecological indicators.

Modeling at NEON Observatories should develop and maintain the facilities and expertise for placing observations into the spatio-temporal context of the NEON data archive. In addition, Observatory modeling centers should implement model-based methods for data "gap filling", error analysis, and quality assurance as well as ecological models for synthesis of process and biotic community data. A bricks-and-mortar center would serve as a facilitation center for modeling (data storage, data analysis, meeting place for modeling discussions and workshops) rather than a place where modelers would permanently work. The staff of the center would be G.I.S. experts, modeling expeditors, programmers, and computer experts.

The NEON Forecasting Center would be responsible for maintaining consistent modeling approaches across sites, for generating and disseminating the "value-added" data derived from the integration of NEON data with models, and for national-scale syntheses and assessments. The Forecast Center should operate as a distributed modeling effort. Coordination and cooperation needs would be met by a minimum of one large meeting per year.

A key challenge for NEON is how biodiversity will be represented within models capable of forecasting across spatial and temporal scales. A new generation of models is needed in which biological diversity is represented at the resolution appropriate for specific research questions. This may involve representing an invasive species explicitly while representing the community it is invading in terms of broad functional groups.

EDUCATION AND OUTREACH IN NEON

Educational partners and stakeholders should be engaged early in NEON development. The benefits are reciprocal. NEON will benefit from identifying a key user community to help ensure relevancy and civic involvement. Students and outreach partners will be linked closely to the development of a new science of the environment, new technologies, and new ways of viewing the Earth.

As part of the educational goals outlined under the agenda of the NEON educational headquarters, NEON should support training in modeling at the undergraduate, graduate and professional level. The NEON Forecasting Center should have the responsibility for offering training opportunities include Graduate Training Fellowships, hands-on summer programs that integrate models and measurements, postdoctoral and sabbatical fellowships that support researchers during model development and innovation, and workshops focused on developing new modeling techniques and on integrating field and modeling approaches.

To be successful, NEON will require a major investment in training the next generation of quantitatively competent ecologists. Training must focus on closing the gap between field ecologists and modelers. Engineering and economics curricula typically include quantitative coursework that includes applications based on real-world data. Similarly, the integration of NEON data as examples in curricula for mathematics, systems analysis, and statistics will facilitate interest in and understanding of quantitative tools by natural science students. New coursework should be developed to promulgate new techniques (such as inverse analysis) as they emerge within ecology and related sciences.

A commitment to the development of the next generation of quantitative ecologists should also drive K-12 outreach programs. Modeling and quantitative tools should be used to synthesize locally collected NEON datasets so they can be used to demonstrate regional ecology and place that ecology into the local socio-economic context. Innovative visualization tools should be used to make regional ecology accessible to K-12 students.

Similar modeling efforts should be used to communicate NEON results to local community leaders, resource managers, civic groups, and other stakeholders. Communication and policy application are key goals of NEON. To achieve these goals, NEON must develop illustrative models for educating the public about ecological processes and the ecological consequences of policy decisions; models used in community education programs will be most effective if they incorporate locally collected datasets. "User-friendly" models should be developed that will allow ecologists to interact with resource managers to explore "what-if" scenarios related to management decisions. Models could also be used in training for volunteer-based data collection projects and tie the results of such projects to the broader NEON effort. Libraries and new digital knowledge systems are excellent vehicles for disseminating the NEON message to potential users and should be engaged early in outreach planning.

PARTICIPANTS

Braswell, Robbie, University of New Hampshire
Canham, Charles, Institute of Ecosystem Studies
Doney, Scott, Woods Hole Oceanographic Institution
Felzer, Ben, Marine Biological Laboratory
Gardner, Robert, Appalachian Laboratory of the University of Maryland Center for Environmental Science
*Hobbie, John, Marine Biological Laboratory
Hurtt, George, University of New Hampshire
Joyce, Linda, Rocky Mountain Research Station, Forest Service
Kicklighter, Dave, Marine Biological Laboratory
Luo, Yiqi, University of Oklahoma
*Melillo, Jerry, Marine Biological Laboratory
Moorcroft, Paul, Harvard University
Neilson, Ron, Forest Service (PNW), Oregon State University
Ojima, Dennis, Natural Resource Ecology Laboratory, Colorado State University
Pace, Michael, Institute of Ecosystem Studies

*Peters, Debra, USDA ARS, Jornada Experimental Range
*Pontius, Gil, Clark University
*Rastetter, Ed, Marine Biological Laboratory
Riha, Susan, Cornell University
Running, Steve. University of Montana.
Throop, Heather, University of Arizona
Tonitto, Christina, Cornell University
Vallino, Joe, Marine Biological Laboratory
Vörösmarty, Charles, University of New Hampshire
Wollheim, Wil, University of New Hampshire

* Organizing Committee Members who attended the workshop
Organizing Committee Members who were unable to attend
Bond, Barbara, Oregon State University
Parton, Bill, Colorado State University
Urban, Dean, Duke University

APPENDIX: IDEAS FOR A FUTURE MODELING WORKSHOP

As requested by the NSF program officer for NEON, the workshop participants conducted a "Scoping session for a much larger and open workshop on modeling and forecasting in ecology. In particular, how the research observatories and their research focus will provide the capacity for ecological forecasting." Given the tight timetable for a report, there was not enough time to discuss this topic with the thoroughness it deserves. All agreed that ecological modeling, its status and future, should be further considered in one or more workshops.

Here are some suggestions and questions:

1) The word "forecast" carries a lot of baggage and a number of people at the workshop thought it should be replaced by "prediction". Rather than debate this point, we agreed to accept "forecast" as a NEON term and to mention that modelers, at least, are not comfortable. One participant wrote "I believe that its use in the ecological context is not only inaccurate but also misleading. Even weather/climate scientists use different terms for long term estimates (e.g. scenarios), and those studies are typically linked to or used as input to ecological studies. Perhaps most significantly, the term forecast implies an inevitability, whereas long-term future conditions depend strongly on highly uncertain future human actions -- a message that should be kept clear. Using this term for political/strategic reasons I think will end up being a negative."
2) One possible theme is How would you develop a continental scale forecast? Who would use such a forecast? What would be the basis of a forecast – what format, grid, resolution, maps, etc.?
3) Various agencies are developing data sets that will be needed for synthesis and scaling of data from any observatory. What are these data sets? How would ecological observatories fit into the overall picture? What is the probable value of high-level synthesis, such as proposed by NEON, to the agencies?
4) What is the best organizational structure for NEON modeling in the future (Distributed? Consortium? Community Model?)?
5) The discussion at this workshop did not get to the level of asking What types of models are particularly in need of development?
6) There are a number of types of models used or needed for ecological analysis. These include Ecophysiology, Community, Biogeochemistry, Vegetation/biogeographic, Finite element hydrology, Catchment statistical, Cellular automata, Diffusion/reaction models of species invasion and disease spread, and Agent-based models. What is inhibiting progress with these models?