Advancing our Biological and Ecological Predictive Capabilities

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Abstract – Policy makers, resource managers, and decision makers in the public and private sectors increasingly call for more and better predictions of future environmental conditions and of the impacts that environmental and societal change may have on ecosystems and the ecological goods and services that people depend upon. By 2025, a suite of powerful new remote sensing, analytical, and computational tools and capabilities will be in place. These tools will be used to assess the health and functioning of global ecosystems and to predict the effects of natural and anthropogenic change, such as extreme natural events, climate change, changes in land use, pollution, species invasions, and pest and disease outbreaks. The resulting ecological forecasts will incorporate the interactive effects of multiple biotic and abiotic stressors as well as socioeconomic factors.

I. Introduction

Today, at the beginning of the 21st Century, society is poised to understand and manage the environment in entirely new ways and at unprecedented scales. We soon will be using biotechnology to modify plants, animals, microbes, and other organisms to thrive in environmental conditions beyond what is now possible in nature and to produce new products and services for society. New monitoring and information technologies and improved scientific understanding will be used to manage the global environment for multiple uses and to achieve a variety of societal goals, such as simultaneously managing for sustainable agricultural production, minimal nutrient loss to rivers and oceans, and biospheric carbon sequestration to control atmospheric carbon dioxide concentrations. Just as we have set science and technology goals to improve weather and climate prediction, we must now address the grand challenge of developing the ability to forecast ecological and biological change. Policy makers, natural resource mangers, and the general public must have the predictive capability needed to evaluate the potential impacts of their actions on ecosystems and the sustainability of the resources and services for which they are responsible.

The U.S. Committee on the Environment and Natural Resources (CENR) is calling for a new focus on ecological forecasting. The ecological and biological sciences are entering a period in which forecasting ecological conditions, trends, risks, and opportunities are becoming both feasible and more reliable. Long-term change will be particularly important to ecological forecasting because some of the most severe and long-lasting effects on ecosystems result from chronic influences that are subtle over short periods of time. Thus, while forecasting the effects of acute stressors on ecosystems may provide analogies to short-term weather forecasts, forecasting large-scale, long-term changes to ecosystems is far more complex – akin to macroeconomic forecasts that build from expert judgment, analysis, and assessment, in addition to numerical simulation.

II. Science in 2025: Capturing Knowledge in Models

While major advances have been made over the past two decades, ecological forecasts are still constrained by critical gaps in understanding, and by an inability to deal effectively with uncertainty. To move forward, the ecological and biological modeling community must build on recent advances; couple their models with other Earth system component models, including socioeconomic models; diagnose and address current gaps in underlying scientific knowledge; deal more effectively with prediction uncertainty; and foster innovative approaches.

NASA's Earth Science Vision for 2025 calls for significant improvements in the predictive capability of evolution in the biosphere on time scales from days to months (short-term) and from years to decades (long-term). The key to success will be to effectively model *the complexities* of biological and ecological systems. Significant model improvements are needed as well as an improved understanding of fundamental processes.

Modeling priorities include understanding the effects of the physical environment on biogeochemical cycles, especially the carbon cycle; the ability of the biosphere to produce food and oxygen; and effects on agriculture and the health of marine and terrestrial ecosystems. Changes in ecological processes in response to natural variability and human activity are key issues, including predicting impacts of short-term severe events as well as responses that may take decades to unfold or involve threshold effects.

III. Monitoring Technology in 2025: Sensor Networks

Biological and ecological forecasts require reliable, accurate, and timely information about the current and historical status of ecosystems. Likewise, the success of decisions made in response to specific forecasts cannot be evaluated without ongoing monitoring of future change.

By 2025, advances in remote sensing and *in situ* observational networks will enable routine high-resolution monitoring of agriculture, forest, and fisheries productivity and health; efficiency of photosynthesis; carbon budgets; fluxes of trace gases from ecosystems (e.g., carbon dioxide, methane, and water); indicators of stress; vegetation structure; the ocean's biologically active mixed layer; species groups; disease vector habitat; rapid land cover changes; surface hydrological conditions that control biological processes (e.g., snow cover, surface inundation); biomass burning and trace gas emissions; pollution events; urban ecosystems and transportation infrastructure; and ecosystem properties affecting biodiversity.

An increase in temporal resolution beyond the average of two times per day currently available for moderate resolution (~1 km) and 2–4 weeks for high resolution (~15-30 m) environmental parameters will be needed (with frequency approaching an hourly rate for many measurements). An increase in spatial resolution also is needed in order to respond to specific requests from governments and businesses for local-scale information. There is need for "3-dimensional" monitoring, that is, measuring the vertical dimension of terrestrial and marine ecosystems (canopy height, depth of ocean mixed layer, and vertical distribution of biomass) as well as their horizontal dimensions.

Meeting these resolution requirements will involve the development of new sensors and significant changes in the architecture of space-based observing systems. We envision smaller sensors in low earth orbit, arrayed in constellations ("sensorwebs") of very small spacecraft with "sentinel" spacecraft at much higher orbits making near-continuous observations. Moderate resolution sensors may even become unnecessary if moderate resolution data can be more effectively and efficiently derived from higher resolution data. New technology developments to increase spatial resolution, miniaturize sensors, and advance active sensor (laser and radar) capabilities are essential. Close integration of space, ground, and airborne observations and near real-time data processing, fusion, and interpretation will be necessary to take full advantage of these new observing capabilities.

IV. Information Technology in 2025: Managing Complexity

Successful forecasting and management programs will equally depend on advances in our ability to deal with merging, analyzing, interpreting, and distilling complex information, ranging from the molecular level to the ecosystem/landscape level and the global level. This need to synthesize large and widely distributed data sets in disparate forms and formats and to support analysis, modeling, and interpretation at varying spatial and temporal scales extends beyond the present boundaries of computer and information science and practice. In many cases, wholly new approaches to geospatial and temporal data management will be required, as will advances in computer-mediated collaboration, simulation and visualization, knowledge discovery, and data mining. Meeting these challenges will require increased collaboration among computer, ecological, and social scientists and the end users, and will foster novel interdisciplinary work.

A central challenge for ecological forecasting is to develop advanced tools for translating the rapidly increasing ecological knowledge base into information that is useful to decision and policy makers. The combination of complex, often non-linear interactions among a large number of components, the stochastic nature of ecosystems and their driving forces, and the practical and time-critical needs of decision and policy makers make the development of such tools imperative. Perhaps the most critical among these tools will be computer models capturing our understanding of the biosphere functioning at a range of spatial and temporal scales, developed through focused experiments, capable of ingesting data from the sensor networks described above, and providing accurate information on the current state and future evolution of the ecosystem or its components.

We need decision support systems that will integrate diverse data, computer tools, and analysis methods to generate information in formats that decision makers can easily understand and use. These systems also must integrate scenario development, modeling and simulation, geographic information system, and visualization tools.

By 2025 we will need many of the data products and interpretations from decision support systems in near-real time (~6 hours or less). Input data will come from a variety of sources: constellations of satellites, permanent ground-monitoring networks, and targeted sampling. These data must be available for ingest with minimal delay.

Collectively, these demands require dramatic improvements in data handling, transmission, storage and retrieval, automated analysis, and display. Complex systems modeling – modeling that integrates physical, biological, and socioeconomic factors – will provide guidance for the development and use of decision support and other information systems. Predictive modeling and managing of complexity, in all its forms, provide development challenges equal to, if not greater than, those required for satellite engineering.

V. Applications in 2025: Societal Uses

A. *Carbon Budget Analysis*

The Integrated Global Observing Strategy Partnership's (IGOS-P) vision for observations of the carbon cycle in the next 10 years has set the stage for future monitoring and analysis of global, regional, and local carbon budgets and the processes controlling them [1]. The vision for a carbon cycle observing system is to contribute to the integrated understanding and human management of the carbon cycle through systematic, long-term monitoring of the exchanges of greenhouse gases between the land, atmosphere and oceans, and the associated changes in carbon stocks. An observing system is called for that measures: land cover and change, the seasonal growth cycle, and fires; biomass; ecological and soils properties; surface-atmosphere fluxes, and atmospheric concentrations of carbon dioxide. These data will be used for agricultural and natural resources management and to develop effective policies to deal with climate change and adaptation.

B. *Productivity of Natural and Managed Ecosystems*

The demands of an increasing human population for food, fiber, and building materials along with economic pressures for increased efficiency will undoubtedly continue over the next 25 years, in parallel with an increasingly limiting quality and quantity of the soil and water resources that sustain food and material production. Efforts to enhance the productivity of crops, forests, and fisheries through the use of fertilizers, pesticides, crop breeding, and advanced technologies will require comprehensive monitoring and evaluation. Technologies that permit rapid monitoring of the onset of stress factors will allow mitigation actions to be taken to maintain productivity or at least reduce potential damage. Measurements of early indicators of stress will allow precise applications of water, fertilizers, and pesticides, reducing costs while maintaining yields. Such measurement capabilities at larger spatial scales (regional) over land and oceans could detect imminent productivity crashes and allow for earlier contingency planning.

C. *Improved Prediction of Land and Biosphere Changes*

Improved biological forecasts will have important implications for issues as diverse as disease mitigation, pest control, and agricultural and fisheries productivity. By 2025, the linkage between environmental factors and their consequences for human health should be understood and captured in models. Early warning systems for a range of diseases will support measures to reduce the impact and severity of epidemics. On the agricultural front, scientists in 2025 will be able to quantitatively predict the varying productivity of different strains of major crops, such as rice, soybeans, and corn in the presence of varying amounts of air pollutants and climatic conditions. Such predictions will enable new types of management decisions. For example, the forecast of a higher concentration of ozone over a cropland region will allow farmers to plant strains that are least susceptible to ozone damage.

VI. Conclusion

By 2025, ecological forecasting will have been brought to new levels through enhanced scientific understanding and technological innovations in remote sensing, computer science, telecommunications, data and information management, genomics, and nanotechnology.

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References

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