Biological Invasions: A Challenge in Ecological Forecasting

J. L. Schnase
NASA Goddard Space Flight Center, Code 930
Greenbelt, MD 22701 USA

J. A. Smith
NASA Goddard Space Flight Center, Code 920
Greenbelt, MD 22701 USA

T. J. Stohlgren
USGS Midcontinent Ecological Science Center
Fort Collins, CO 80523 USA

S. Graves
University of Alabama
Huntsville, AL 35899 USA

C. Trees
NASA Headquarters, Code YS
Washington, DC 20546 USA

Abstract – The spread of invasive species is one of the most daunting environmental, economic, and human-health problems facing the United States and the World today. It is one of several grand challenge environmental problems being considered by NASA's Earth Science Vision for 2025. The invasive species problem is complex and presents many challenges. Developing an invasive species predictive capability could significantly advance the science and technology of ecological forecasting.

I. Introduction

Non-indigenous invasive species may pose the single most formidable threat of natural disaster of the 21st century. The direct cost to the US economy alone is estimated at $100-200 billion per year, greater than all other natural disasters combined [1]. The spread of invasive species is growing as globalization increases the movements of pest and disease organisms. The issue has developed diverse stakeholder support, ranging from land management agencies, states, the agricultural industry, conservation organizations, and private landowner groups. The National Research Council's Committee on Grand Challenges in Environmental Sciences has identified increased understanding of biodiversity and ecosystem functioning as one of eight "Grand Challenges in Environmental Science" and has emphasized the need for developing improved management techniques for non-indigenous invasive species [2].

NASA's Earth Science Vision for 2025 calls for significant advances in our ecological forecasting capabilities [3]. Last year, we focused on the broad area of ecological forecasting [4]. We now are looking at specific forecasting challenges beyond 2010 to 2025, including sustainability of terrestrial biomass, fisheries sustainability, carbon cycles in marine and coastal systems, and the ecological consequences of climate change and land use change. The first challenge we are addressing is the problem of biological invasions.

The invasive species problem provides an unusual opportunity to advance the science and technology of ecological forecasting [5]. Environmental grand challenges, such as this, require problem-oriented science that can integrate physical, biological, chemical, and human systems well enough to predict the response of critical regions or phenomena to multiple causal, stressor variables. Understanding the interactions of these systems is imperative, because the many environmental factors now undergoing change make it difficult to assess the impact of any single change in the Earth system or the outcomes of mitigation strategies. This problem also is interesting in that much of the science and technology required to predict biological invasions also is required to map "hotspots" of biological diversity.

II. Invasive Species

During the past century, non-indigenous plants, animals, and pathogens have been introduced at increasing rates into all US ecosystems. A growing number of these species are becoming invasive, and contribute to declines in native species diversity, changes in ecosystem function, and cumulative direct economic impacts currently estimated at more than $137 billion annually.

An "invasive species" is defined as a non-native species whose introduction causes or is likely to cause harm to the economy, environment, or human health. The cost of infestations of leafy spurge alone to agricultural producers and taxpayers is $144 million/year in the Dakotas, Montana, and Wyoming. Aggressive invasive fishes in the Great Lakes threaten a commercial fishery valued at $4.5 billion which supports 81,000 jobs. Invasive Norway rats cause up to $19 billion/year in environmental and economic damage. Non-native livestock diseases cost $9 billion/year. In the coming decades, increasing human travel and trade and changing types and patterns of environmental disturbance are expected to exacerbate these impacts. Because of its high diversity of environmental conditions and habitats, the US is particularly vulnerable to invasions.

The US has begun to mount an organized effort to address the invasive species threat, coalescing around Executive Order 13112 (1999). There is now a National Invasive Species Council, which has issued a draft Management Plan, and has assembled several technical working groups. The National Biological Information Infrastructure has several regional programs developing invasive species information systems as their highest priority initiative, and plans to establish a national node for invasive species in the 2002. These efforts are coordinated with international initiatives under the United Nations (the Global Invasives Species Programme, GISP), NAFTA (the North American Biodiversity Information Network, NABIN), the Summit of the Americas (the Inter-American Biodiversity Information Network, IABIN), and a number of bilateral agreements, to develop international exchange on invasive species information. Globalization has greatly increased the international movements of harmful species through travel and agricultural, horticultural, and pet industries, and has become a principal impediment to international trade agreements.

All of these efforts recognize the central role of space-based sensors and advanced computational, modeling, and information technologies. Both the potential for movements of invasive species, and the susceptibility of sensitive habitats to new invaders are known to be strongly influenced by climate warming, changes in rainfall, soil moisture, and runoff, and are increasingly driven by extreme events. Many invasive species also greatly alter the water relations, carbon storage, fire cycle, and reflectance properties of landscapes, and may be an important feedback link to climate.

III. Technology Challenges

High resolution mapping of biological resources is central to confronting the invasive species threat. For terrestrial ecosystems, to meet the needs of the invasive species science and policy communities, we must be able to identify dominant plants and vegetation structures with a reasonable ability to distinguish between species. This is becoming possible with hyperspectral instruments at meter-scale resolutions, particularly when combined with LIDAR and other active or passive microwave sensors that can detect meter-scale vegetation structure, landforms, soil moisture, and soil surface properties. Researchers now use a variety of geostatistical, biogeographical, and remote sensing methods to map biological resources. These methods integrate multiple types and scales of data, including satellite images, aerial photography, and ground data of various resolutions, but only on a limited bases. Most work focuses on terrestrial ecosystems, but the problems extended to aquatic and marine environments as well. A robust, comprehensive, regional-scale invasive species forecasting capability of the future will require significant technology advances.

A. New and Improved Measurements

Mapping the living components of our environment and making invasive species forecasts will require innovative new interfaces between bits and atoms for an "instrumented Earth." Ultimately, we will need reliable, accurate, and timely information about ecosystem biophysical structure (biomass, vertical structure, ocean particulates, pigment florescence, trace gas fluxes, near surface atmospheric carbon dynamics, stream chemistry, etc.), ecosystem functional capacity and physiological state (pigment concentrations, live biomass, biomass turnover rates, photosynthetic and respiratory capacity, etc.), and biological population mapping (species distributions, communities, functional-type mixtures, etc.) at unprecedented temporal and spatial resolutions.

Meeting these resolution requirements will involve the development of new sensors and significant changes in the architecture of space-based observing systems. Some possibilities are 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; embedded macro-/nanosensor webs with space-based coordination; adaptive spatio-temporal observations; change detection sensors with nested intensity design; and hierarchical 3D sensing for atmosphere, land, and oceans. By 2025, we hope to have made significant progress toward the goal of "anywhere, anytime, anyscale sensing on demand."

B. Modeling Requirements

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. NASA's Earth Science Vision for 2025 calls for significant advances in our ability to interactively couple ecological 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

Dealing with the invasive species problem will require a new class of hybrid predictive models — models that combine temporal, spatial, mechanistic, stochastic, and scenario-based approaches. These models also must be scalable and able to accommodate the vast range of spatio-temporal events that influence biospheric phenomena.

C. *Information Management Requirements*

Future invasive species forecasting systems will require advances in our ability to merge, analyze, interpret, and distill complex information, ranging from the molecular level to the ecosystem level to the global level. This need to synthesize large, widely distributed, and disparate data sets and to support analysis, modeling, and interpretation at varying spatial and temporal scales pushes the boundaries of what is known and what is being done in computer and information science today. 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 end users, and will foster novel interdisciplinary work. Managing complexity, in all its forms, provide development challenges equal to, if not greater than, those required for satellite engineering.

IV. WHY NASA? WHY NOW?

The National Invasive Species Council has noted, “no comprehensive national system is in place for detecting and responding to incipient invasions.” Yet the threat of invasive species is perhaps our most urgent economic and conservation challenge. There is a growing sense among land management agencies that a national assessment of native and non-indigenous plant diversity needs to be completed on all public lands. Especially high on the agenda are issues such as detecting the loss of native plant diversity caused by non-indigenous plant species, predicting where non-indigenous species are most likely to damage native diversity so that management can be targeted at the most vulnerable areas, and developing a science-based long-term monitoring plan for vegetation and soil resources.

NASA has a uniquely complementary and synergistic role to play in helping understand and manage invasive species. The Earth Science Enterprise currently provides measurements from Terra, QuickScat, Landsat 7, Jason and other missions that map key ecosystem attributes needed to predict invasive species distributions. A number of planned missions in the near- to mid-term will expand these measurements to include critical three-dimensional structure derived from SAR and LIDAR technologies. Measurements are also supported through data buys, including ocean color imagery from SeaWiFs, high resolution optical imagery from IKONOS, QuickBird, and other private sector satellites and land cover data from Landsat Data Continuity Mission (LDCM). In addition, NASA provides the computational capabilities and expertise in large-scale, coupled Earth system modeling needed to assure the successful transfer of these capabilities into operational use. Other spacefaring nations will contribute important resources to this effort as well.

V. CONCLUSION

By 2025, we hope to have refined the broad and abstract vision of ecological forecasting into a suite of practical applications for managing the environment. The invasive species problem provides a good starting point and unparalleled opportunities to advance the science and technology of ecological forecasting. And since biological invasions are a global threat, any effective solution will draw on the talents of the world community and return improvements in human well-being across the globe.

ACKNOWLEDGMENTS

We thank our colleagues on the Earth Science Vision Workgroup for the Biosphere, Ecosystems, and Human-Biosphere Interactions and others who have contributed to many useful discussions on this topic: R.J. Birk, J.S. Clark, C.F. Hutchinson, D. Peterson J.F. Quinn, E. Sheffner, W. Turner, and D.E. Wickland.

REFERENCES

[1] National Invasive Species Council. 2001. *Meeting the Invasive Species Challenge: The National Invasive Species Management Plan*, Washington, DC, 80 pp.

[2] National Research Council. 2000. *Grand Challenges in Environmental Sciences. Report of the National Research Council Committee on Grand Challenges in Environmental Sciences*, National Academy Press, Washington, DC, 88 pp.

[3] National Aeronautics and Space Administration. 2000. *Exploring Our Home Planet – The Earth Science Enterprise Strategic Plan*, NASA Headquarters, Washington, DC.

[4] Smith, J.A., Wickland, D.E., Crawford, M.K., Cihlar, J., & Schnase, J.L. 2001. Advancing our biological and ecological predictive capabilities. In: *Proceedings of the International Geoscience and Remote Sensing Symposium 2001* (IGARSS ’01, Sydney, June), IEEE 2001 International, Vol. 1, pp. 154-156.

[5] Office of Science and Technology Policy, Committee on Environment and Natural Resources, Subcommittee on Ecological Systems. 2001. *Ecological Forecasting: Agenda for the Future,* Office of Science and Technology Policy, Washington, DC, 8 pp.