Multi-scale Modeling of Ecological Systems: Systems Biology in Application to Natural Resource Management

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System Biology: Some History

Themes of this 1979 collection of papers included:
Models: defining appropriate equations and linking these to data for parameterization
Hypothesis formulation: viewed as generated from complex models rather than from observations
Scales: combining processes operating on different spatial and temporal scales
Validation: determining appropriate methods to evaluate models to assert when they may be applicable
Computation: while only early computers were available, simulation methods were paramount
We are still grappling with many of these same issues

Models: we have moved well beyond the simple differential equations used in the early systems ecology, and now have a plethora of model structures to choose from (cellular automata, individual-based models, network methods, discrete dynamical systems, partial differential equations), but model detail is still constrained by data

Hypothesis formulation: these are now arising from viewing systems in an evolutionary perspective with broader considerations of processes from the genome to the community
We are still grappling with many of these same issues

Scales: development of genetic methods has fostered a much wider set of possible system connections, and there are many alternative approaches for spatial heterogeneity but multimodeling to combine processes operating on different spatial and temporal scales is still limited.

Validation: developing a general methodology to say when a model is “good” has not been successful - complexity arising from stochastic and chaotic components limits our ability to completely analyze potential model behaviors.

Computation: we can now simulate systems with many thousands of interacting processes in space and time, but obtaining insight from these complex models is still difficult (leading to data mining methods for models).
System Biology: a recent view

1. Are there still new life forms to be discovered?
2. What role does life play in the metabolism of planet Earth?
3. How do cells really work?
4. What are the engineering principles of life?
5. What is the information that defines and sustains life?
6. What determines how organisms behave in their worlds?
7. How much can we tell about the past and predict about the future by studying life on earth today?

The Role of Theory in Advancing 21st-Century Biology: Catalyzing Transformative Research (NRC, 2008)
Moving Forward in Systems Biology:

One approach is to start with particular challenges in biology and use these to motivate new mathematical models and develop appropriate new techniques as necessary.

One very general challenge is:
How representative are observations and methods we develop for one biological system for applicable to other systems, at different locations, in different organisms, or at different levels of organization in the hierarchy of biology?
Overview

• Background on natural resource management
• Everglades restoration and ATLSS (Across Trophic Level System Simulation)
• Invasive species management
  – Optimal control for generic focus/satellite spread
  – Spatially-explicit management of Old World Climbing Fern
• Wildlife management -the black bear case
  – Optimal control in a simple metapopulation case
  – Individual-based models and preserve placement
• Some lessons from our experience
Problems in Natural Resource Management

- Harvest management
- Wildlife management including hunting regulations and preserve design
- Water regulation
- Invasive species management
- Disease control
- Wildfire management
- Biodiversity and conservation planning

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Computational Science for Natural Resource Management

Recent advances in miniaturization, computing power, remote sensing, and modeling are revolutionizing the science of natural resource management. But these advances also bring many challenges. This article highlights some key problems in resource management that represent opportunities for computer scientists and engineers in search of challenging practical problems.

Natural resource managers must balance the needs of complex, dynamic ecological systems with the competing demands of social, political, and commercial stakeholders. Natural resources include wildlife and habitats that provide significant recreational (such as hiking, fishing, and hunting), economic (such as timber harvesting and gene mining), aesthetic (such as scenic landscapes), or functional (such as nutrient retention and flood control) value. The ecological and environmental processes governing functioning ecosystems are difficult to manage because they involve multiple components that operate over broadly disparate temporal and spatial scales. To manage the components of natural reserves, biologists have traditionally relied on rule-of-thumb strategies based largely on what worked in the past.

Model-driven strategies have largely replaced the data-driven approach. Model-driven strategies attempt to project system behavior under alternative management scenarios. Such models are frequently wedded to emerging technologies for data collection and monitoring, such as real-time remote sensing and GPS. But while these advances greatly improve ecological information’s temporal and spatial resolution, they also generate large volumes of data. This flood of information increases the demand for efficient data analysis, storage, and communication. At the same time, the evolution of approaches based on disparate technologies and computing platforms complicates the sharing and integration of data from different sources.

As resource managers struggle to cope with these challenges, they’ve turned to computational science for solutions. The rapid advance of software and architectures designed to exploit improvements in networking, interoperability, and data management has revolutionized natural resource management. The recent changes to natural resource management in many ways mirror those of molecular biology, whose dependence on high-performance computing is well-known. For example, researchers have expressed biochemical network models as stochastic Petri nets, a mathematical formalism developed in computer science. Another example is the use of high-performance algorithms to improve the computationally intense sequence comparisons used in molecular phylogenetics.

As a consequence of computerization, management programs have grown rapidly in size, com-
What is challenging about natural resource management?

• Involves complex interactions between humans and natural systems
• Often includes multiple scales of space and time
• Multiple stakeholders with differing objectives
• Monetary consequences can be considerable
How can mathematics and modeling assist in solving problems in resource management?

- Provide tools to project dynamic response of systems to alternative management
- Estimate the “best” way to manage systems - optimal control
- Provide means to account for spatial changes in systems and link models with geographic information systems (GIS) and decision support tools that natural system managers and policy makers need.
- Consider methods to account for multiple criteria and differing opinions of the variety of stakeholders
Optimal Control of Disease

Rabies in Ohio

Model
- Spatially explicit dynamics.
- Search for optimal strategy.
- Parameters
  * Cost of control efforts
  * Control Success Rate
  * Disease Dynamics

Data
- Demographics.
- Locality records.
- Movement patterns.
- Infection rate.
- Disease virulence.
- Effectiveness of vaccination baits.

Computational Support
Use of parallelization and optimization techniques improve speed, allowing greater freedom in modeling and more accurate forecasts of disease incidence and spread.

Control Strategy
Aerial release of vaccination baits creates geographic “fire-break” to slow the encroaching wave of infected animals.

Monitoring
- Trap and test individual animals.
- Remote sensing of radio-collared individuals.
- Molecular analysis of disease demographics and viral strain diversity.

vaccine zone

Fox rabies in Czech Republic

Geographical location of rabies cases

About 28 million vaccine baits were distributed in the Czech Republic from 1989-2006. There were 5 children treated for bat rabies in 2005.
Optimal Control Applied to Biological Models

Suzanne Lenhart
John T. Workman
Wildfire Control

Optimal Control Schemes
- Fire Management Scenarios
- Disease Control Scenarios
- Invasive Species Control

Computational Steering Console
- Real-Time Fire Suppression
- Shared Equipment Coordination
- Fire Crew Scheduling
- Remote Sensing

Integrate System Modeling

Multi-Component System

Fire Simulation
- Herbivore Density
- Soil Nutrients
- Vegetation Growth

Simulation Driver
- Ground Water
- Surface Hydrology
- Rainfall

Job Scheduler
Spatial Control Framework

1. Input fire start location
2. Search proximate fire start location samples
3. Look up table
4. Estimate optimal fire break area
5. Set population size
6. Is this the optimal solution?
7. Output of fire spread
8. Visualization of output for the optimal fire break

Input fuel map
Input fire spread parameters

Parallel computing
- Genetic Algorithm
- Cellular Automata

Cellular Automata
- Fire spread simulation
- Output of fire spread
- Fitness function
- Reproduce
- Crossover
- Mutation
- New generation of fire break
- Is this the optimal solution?
- Yes
- No

Transform new generation to fire break location
Wet Season: May-October

Dry Season: November-April

Photos: South Florida Water Management District
Collaborators on ATLSS
Everglades natural system management requires decisions on short time periods about what water flows to allow where and over longer planning horizons how to modify the control structures to allow for appropriate controls to be applied.

This is very difficult!

- The control objectives are unclear and differ with different stakeholders.
- Natural system components are poorly understood.
- The scales of operation of the physical system models are coarse.
So what have we done?

Developed a multimodel (ATLSS - Across Trophic Level System Simulation) to link the physical and biotic components.

Compare the dynamic impacts of alternative hydrologic plans on various biotic components spatially.

Let different stakeholders make their own assessments of the appropriate ranking of alternatives.

http://atlss.org
Assessment of the Effects of Proposed Water Regimes

Map printed October 10, 2001

Universal Transverse Mercator (UTM)
NAD83
Zone 17

Scale: 1 : 4124008

Analysis Type: Comparison Analysis
Method: KDE
Date: Wed Oct 10 15:03:29 2001

- Baseline Scenario
  Time Interval: 1975 (1 year)
  Hydrologic Regime: F2050
  Analysis Model: Long-legged Wading Bird ROI

- Alternative Scenario
  Time Interval: 1975 (1 year)
  Hydrologic Regime: D13R
  Analysis Model: Long-legged Wading Bird ROI

Regional Subdivisions: NHD Sub-regions (p2y)
List and links to all papers I discussed are at:

http://www.tiem.utk.edu/ITR06/