COMPUTATIONAL ECOLOGY

Mathematics, computational technology, and ecology merge to meet environmental challenges

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In the hazy, humid mountains of Tennessee's Smoky Mountains, a tradition as 'old as the hills' continues to this day. Each year the locals collect wild leeks that grow in clumps near mountain streams. But in places throughout this mountain region, these culinary delights are diminishing. That's where mathematics comes in. By applying mathematics to an ecological question, mathematician Louis Gross has developed projections to help resource managers determine recovery strategies. That way the people of this region can enjoy the experience of collecting wild leeks for a long time to come.

Louis Gross, an Ecological Society of America member, is an applied mathematician and Director of the University of Tennessee's Institute for Environmental Modeling. For years he has used mathematics to address ecological, social, and other questions.

"Mathematics, as the language of science, is used not only in basic theoretical ecology," says Gross, "but to address very practical questions arising from environmental problems."

He points to the field of ecotoxicology, in which mathematical models predict the effects of environmental pollutants on populations. The field of natural resource management uses models to set harvest quotas for fish and game, and conservation ecology uses mathematical models to determine the likely effects of various recovery plans for imperiled species and to help design nature preserves.

"Computational ecology allows you to project--under certain assumptions--what you might expect to happen," explains Gross. "It's an interdisciplinary field that quantitatively describes and analyzes ecological systems by using empirical data, mathematical models, and computational technology."

Gross notes that as a field, computational ecology is quite young, though its components are not new. Many factors gave birth to the field, including new computational technology and mathematical approaches, as well as heightened social awareness of ecological and environmental issues. Technological advances, such as high resolution images captured by satellites can be processed and interpreted by new types of software using increasingly fast computers. This combination can produce maps that visually depict ecological variables across huge areas. In addition, the technology now exists to remotely follow the movements of many individual organisms using telemetry, a method applied routinely for certain endangered and threatened species. Finally, the general public's concern about the environment is driving the need for better information about how to sustain and restore natural resources in the face of increasing pressures.

Computers allow one to delve more deeply and represent more closely ecological systems, systems that are managed by people, such as fisheries, says James Anderson, a fisheries scientist with the University of Washington's School of Fisheries.

"We're using a lot of different tools as we try to interpret ecological systems in terms of mathematics," says Anderson.

Computational ecology relies on computers, but it depends upon analytical or symbolic mathematics to provide the insight, he explains. The best way to operate is to use computational and mathematical ecology in concert when exploring a particular question.

Anderson and his staff at Columbia Basin Research, a group in the School of Fisheries, use mathematics to study fisheries and ecological systems and are currently involved in research that seeks to find out to what degree removing four dams from the lower Snake River will improve fish survival. Since deconstructing dams is a multi-billion dollar "experiment," finding out as much as possible beforehand is highly desirable. Anderson outlines the analytical approach and computational approaches used to supplement each other in addressing this question:

Analytical: Look at the mortality rate of the fish, which depends upon how much time it takes the fish to migrate through a river system, plus the distance it must swim. Two possible scenarios that drive the mortality rate are exposure time and the gauntlet effect. The gauntlet effect is used to measure mortality when smolts (juvenile salmon) face a certain number of "pockets of predators" through which they must pass. Exposure time is relevant when the predators do not gather in defined "pockets" but instead swim freely over a broad area. Two coefficients (distance and time) are used in this analysis. Anderson, calls it a very simple, but elegant (the highest form of praise in mathematics) analytical approach.

Computational: The computational approach uses computer software, called Swarm, to build an individual based predator-prey model. The model follows individual fish, both predator (in this case, Small-mouth Bass, Wall-eye, and Northern Pike) and prey (salmon smolt) and makes rules for each about their behavior as well as for various scenarios involving flow and dam removal.

Variables include:

- the speed (velocity) of water the fish prefers
- the size of the fish
- whether the fish likes rocky or grassy habitat
- the water temperature preferred by the fish
- how it eats
- how fast the fish swims

Using the Swarm software, a researcher can investigate what affects the fish's movement.

In addition, says Anderson, "This computational method allows you to integrate into a mathematical model, many different measurements people are making so that you can figure out what pieces are controlling the big questions," explains Anderson. "We can't do that with a simple, analytical method, though we need it to understand the underlying, basic patterns of what's taking place. Computational ecology allows you to represent details at the level required for people to actually manage the system."

On the other side of the United States, Gross and colleagues are also striving to generate more detailed information. The large research team is working on a project funded by the Biological Resources Division of the U.S. Geological Survey in the Florida Everglades. The team is using computational ecology to project the relative impact of future management options in the

Everglades region. The area has suffered from drastic changes to its water flow patterns resulting in major declines in species, high levels of toxicants, such as mercury, and a host of other problems. Plans to restore the area are complicated by agricultural demands and urban pressures.

Using a so-called multi-model, ATLSS (Across Trophic Level System Simulation), Gross and his colleagues are analyzing the ecological impacts of various restoration plans for the region. A multi-model, explains Gross, is an essential tool in gauging ecological impacts at a level needed to develop management plans.

The ATLSS model uses mathematical approaches such as spatially-explicit species index models, and differential equations for structured population models and individual-based models (Swarm is one software for this).

"ATLSS is one of the most complex and sophisticated ecological modeling approaches ever attempted," says Gross. "It attempts to simulate the interactions of the various elements of wetlands within the framework of a single, encompassing computational scheme."

Because interactions occur at various organismal, temporal, and spatial levels, a single modeling approach is not appropriate, Gross explains. The ATLSS team is developing a set of models designed to integrate three approaches for different trophic (feeding) levels of the system:

- process models for lower trophic levels (periphyton, insects, zooplankton)
- structured population models (amphibians, reptiles, groups of fish and large invertebrates, such as crayfish)
- individual-based models (wood storks, blue herons, alligators, deer, panther)

These models are integrated across the freshwater landscape of the Everglades and coupled to Geographic Information System (GIS) data. GIS data generates maps of vegetation, land use, soil type, roads, and population density. In the final step, all this information is coupled to a hydrology model and used to assess the effects of proposed restoration scenarios on various components that constitute the Florida Everglades.

Says Gross "There are lots of regional-level problems--similar to the Everglades--involving spatial control, where this sort of approach is applicable. Examples include human activities such as fertilizer applications in crop systems, questions about where and when to harvest forests, and whether or not to keep dams."

"Computational ecology will play an increasingly important role in managing the competing demands on our natural resources," agrees Anderson. "Take water resources," he says. "In Washington State, the struggle to alleviate the risk to endangered fish while accommodating the needs of a burgeoning number of people in the state is severe. Computational ecology can help us determine, on a case-by-case basis, what the likely implications will be for various steps the state might take."

By integrating Geographic Information System tools with software such as SWARM, one can project likely outcomes to the ecology and economy of the area under different regulations and policies, he explains.

Anderson acknowledges that models, by their very pioneering nature, will always be viewed with some skepticism. But, he argues the best way to increase their validity is through better, longterm data. One largely untapped way to do that is to get the public involved, says Anderson. A project called Salmonweb (http://www.cqs.washington.edu/salmonweb) is an on-line effort to train the public to learn how to collect scientific data; monitor their surroundings and feed this information into the database for use by scientists.

Anderson is excited about the potential power of Salmonweb.

"We need the public to monitor the environment to address these questions. The public's contribution is going to be of real value to computational ecology."

Gross agrees that the potential for Salmonweb, and for the field of computational ecology itself is tremendous. Four years ago, Gross, along with other scientists with a variety of backgrounds, held a workshop that took a look at the state of computational ecology and assessed its strengths, weaknesses and potential. Each workshop participant provided a list of key issues they felt were important to the future of the field. The overarching conclusion of the resulting report, The State of Computational Ecology, is that "A wide gap currently exists between the information that managers and decision-makers require and the data that can be supplied by ecologists to address global change, biodiversity, and sustainability issues."

Ecologists have historically grappled with conceptual questions about how nature works. Mounting environmental challenges are now spurring the need for more detailed ecological information that can be applied to the practical areas of conservation and natural resource management. In particular, the need to understand the effect of human activities--to be able to project likely scenarios--is becoming more urgent.

This is an enormous challenge given that the phenomena that ecologists study operate over spatial and temporal extents larger and longer than any one scientist can effectively study. This means that ecological data differ from other scientific data in that they are comparatively irregular in character and often sparse.

Among the specific challenges identified by the group is the need to develop standards so that more data can be readily shared, and results compared among researchers, improving software for ecologists with limited modeling background, and integrating multi-models (such as ATLSS in the Everglades) across scientific disciplines.

No formal follow-up has since occurred since the 1995 Workshop, but individuals in the field are striving to address the challenges it described.

Gross and Anderson believe computational ecology will play a pivotal role in solving environmental challenges in the coming century.

"Large interdisciplinary groups of scientists must collaborate, share data, and address questions reaching across huge ranges of space and time," says Gross. "And computational technology, coupled with mathematics and ecology, will play an ever-increasing role in generating vital information society needs to make tough decisions about its surroundings."

Definitions

Individual-based models simulate consequences at population and community levels of interactions between individuals. These are called agent-based models in computer science. Examples include plants and animals in and around a lake, or automobiles in a traffic jam. The characteristics of each individual are tracked through time. This is in contrast to models where the characteristics of individuals within a population are averaged together.

Spatially explicit individual-based models simulate individual behavior on an explicit geographic landscape. Some individual-based models are not spatially explicit, meaning that they assume spatial homogeneity in the environment.

Process models mimic the dynamics of natural system components by including the basic chemical and physical properties of these components and their interactions. These are typically applied to nutrient and energy flows, and to lower trophic level organisms in cases when within-population structure is not of central concern.

Structured models break populations down into groups with the assumption of homogeneity within each group. These are typically applied to populations in which age and size structure are important. Most human demographic models are of this type.

Differential equations specify the rates of change of key components of the system. For models with discrete time intervals, difference equations give the change in key components over these time intervals.

Static spatially-explicit species index models incorporate the spatial and temporal variation of key habitat conditions across a landscape to produce localized indices of potential breeding, foraging, and survival for a particular species.

Resources

Models:

ATLSS: a regional-extent ecological simulation effort (http://atlss.org/)

CRiSP: A suite of fisheries models including passage of juvenile fish through the Columbia River (CRISP Passage), an ocean harvest model (CRiSP Harvest) and a realtime predictor of salmon smolt passage through the Columbia River (Realtime Forecaster) (http://www.cqs.washington.edu/analysis.html).

ECOTOOLS: models to study animal behavior and ecological issues (http://offis.offis.uni-oldenburg.de/projekte/ecotools/)

Gecko: a model to simulate ecosystem dynamics (http://peaplant.biology.yale.edu:8001/gecko.html)

Individual-Based Models page (http://hmt.com/cwr/ibm.html).

Models: an extensive list of texts on ecological modeling (http://homepage.ruhr-uni-bochum.de/Michael.Knorrenschild/embooks.html).

Multiscale Dynamic Simulation for Ecological Modeling by Pedro Pereira Gonçalves and Maria Paula Antunes(http://virtual.dcea.fct.unl.pt/~pedro/papers/birds/paper.html)

Swarm: a software package to simulate complex systems (www.santafe.edu/projects/swarm/)
Outmigrant survival simulator, an application using the Swarm software (http://weasel.cnrs.humboldt.edu/~simsys/migrant.html)

SORTIE: an individual-based simulation model of forest dynamics (http://www.sciencemag.org/feature/data/deutschman/index.htm)

The EPRI CompMech Program: Compensatory Mechanisms in fish populations (Electric Power Research Institute) (http://www.esd.ornl.gov/programs/COMPMECH/brief.html)

Institutions:

University of Tennessee's Institute for Environmental Modeling (http://www.tiem.utk.edu/tiem.desc.html): The Institute supports interdisciplinary research in mathematics, computational science, and ecology. As noted above, it is the headquarters for the ATLSS project to analyze potential outcomes of Everglades restoration plans. In addition, a National Science Foundation-supported project there is focused on developing curricula to give life science students quantitative training.

NCEAS: One of the key objectives of the National Science Foundation supported National Center for Ecological Analysis and Synthesis (http://www.nceas.ucsb.edu/) is to train visiting scientists to use software for data analysis and to familiarize them with network-based opportunities for collaboration. In particular, NCEAS tracks emerging technical and analytical developments, testing or implementing those especially relevant for integrative research in the ecological sciences.

The Computational Ecology and Visualization Laboratory at Michigan State University (http://www.cevl.msu.edu/docs/facilities.lab.htm): CEVL is designed to "facilitate the linkage between ecology and computational technology." CEVL's laboratory enables students and faculty to use mathematical models to develop visualization systems needed to address environmental issues. Primary focus areas include crop productivity and biological diversity in agricultural ecosystems.

Yale University's Center for Computational Ecology (http://peaplant.biology.yale.edu:8001/aboutcce.html): The Center aims to develop mathematical and computational tools. Its ultimate goal is to develop software that can be used to formulate public policy. One example is Gecko, the model mentioned above.