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"Regional ecological management and assessment and computational ecology"

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Regional ecological management and assessment and computational ecology

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One of the most important functions of the environmental sciences today is to analyze the impacts of human actions on ecosystems and to provide management recommendations to ameliorate these impacts. In all parts of the world ecosystems are affected by the shrinkage and dissection of natural areas, disruptions of natural cycles, and the input of pollutants. The scales of the effects of these anthropogenic impacts range from very local to regional and therefore require assessments that can span these scales as well.

Environmental scientists are increasingly using mathematical or computer modeling approaches for impact assessment. Some of these modeling approaches are tailored to deal with small scale concerns such as effects of toxicants on local biological populations. Other approaches, such as analyses of potential land use changes, aim at the county-level spatial scale, whereas a few address questions on much larger, regional scales; for example, the problems of northwestern forest management as it impacts the spotted owl.

Because most cases of anthropogenic impact include specific problems on a number of different scales, it is appropriate to develop general methods for across-scale coupling of models to provide input to the assessment of these impacts on natural systems.

Ecological Assessment

Ecological assessment refers to the determination of the impacts of various anthropogenic influences on a natural system. Common components of such an assessment would be:

Changes in population densities of "important" species, either culturally or economically
Biodiversity effects
Non-native species introductions
Changes in community structure (which may not necessarily be associated with biodiversity changes)
Effects of pollutant inputs
Direct effects of human actions on the system (e.g. hunting, deforestation, sewage/waste disposal)
Indirect effects of human actions (e.g. habitat fragmentation, soil erosion, salinity changes)

Coupled with the above for regional assessment would be taking account of the human actions impacts on human systems as well, including:
Human population density changes
Economic impacts
Land use changes and effects on urban/rural/commercial/residential percentages and the long term impact of these on future human needs
Agricultural productivity
Social/cultural changes
Cultural attitudes towards conservation

Regional Environmental Issues

At regional scales (e.g. on order of 100-1000's of square km), environmental modeling requires taking account of smaller scale heterogeneity in underlying habitats, trophic structures, and human impacts. Typical aggregated models, in which a few compartments represent major components of the system (e.g. primary production, nutrients, biomass density) and the model tracks changes in these components through time, require either large scale-data sets to parameterize at regional scales, or else make many assumptions about how basic physical and biotic processes scale from smaller, more accurately understood systems. Large scale data-sets are few, except for those available from remote-sensing information, making both the construction of defensible aggregated models (as well as the validation of any regional scale model) truly challenging.

The most important recent technological advance associated with regional scale modeling and assessment is the use and availability of Geographic Information Systems (GIS), allowing for the rapid visualization and analysis of two-dimensional images, such as those obtained from satellite or airplane remote sensors. GIS data are readily available for a variety of habitat characteristics, including basic vegetation maps, land-use maps, soil maps, road maps, population density, etc. In utilizing these data however, one must be aware of inaccuracies (e.g. ground-truthing is expensive and difficult to do correctly without long-term support mechanisms), and be aware that to date there are relatively few dynamic data sets available for characteristics which would be needed for ecological assessment (e.g. dynamics of vegetative succession).

GIS data, in addition to generally being static and thus providing only a "snapshot" of the system, do not readily allow one to track the animal components of a system, without using some proxy models, such as habitat suitability indices. Such indices have their own inaccuracies, as they assume that localized population estimates may be based totally upon habitat measures, ignoring biotic interactions. Although the technology is available to radio tag and track individual animals, except for a few large mammals and commercial species, this has been too expensive to apply in general (and probably will be for the forseeable future).

The above limitations of GIS has led to a call for linking spatially explicit ecological models to GIS data, allowing one to produce dynamic models at local scales within a GIS framework, and allowing at least for the potential to produce models that can analyze the effects of management systems on a variety of components of the natural system, not just those which can be observed remotely.

The easiest method to produce a spatially-explicit ecological model is to take a standard ecosystem-type model (e.g. for biomass in different trophic compartments), link it's parameters to local habitat variables available in a GIS framework, run the model independently in each pixel (or some combination of pixels, depending upon the scale for which the model is appropriate), and then link the spatial components by having some movement of state variables between pixels. This is the approach of some commercial packages (e.g. RAMAS/GIS). There are numerous computational and modeling issues associated with this approach, and there are alternatives.

Habitat Suitability Models:

Habitat evaluation procedures (HEP) are a formalized methodology for impact assessment to evaluate and predict effects of resource projects on wildlife habitat. This typically relies on species-habitat evaluations, integrated through a Habitat Suitability Index (HSI) model for each species of concern. This yields Habitat Units (HUs) for each region using

$$HU = \sum_{i} HSI_i \; A_i$$

where HSI_i is the HSI for species i and A_i is the area of habitat surveyed for species i. HSIs are always in [0,1] and are assumed to be proportional to carrying capacity. Thus HUs give a means to combine habitat requirements for several species in a single measure.

Habitat suitability index (HSI) models have been constructed for over two hundred species . These models are an attempt to summarize in a way useful to managers the site characteristics which affect the utilization of particular habitats by a variety of wildlife species.

Example: White-tailed deer

$$HSI = \sum_{i=1}^{n} QF_i \; DF_i \; EV_i$$

where i gives the classes of suitable forage (e.g. acorn mast, twigs, mushrooms, etc.), QF_i is the quantity of suitable forage available per unit area, DF_i is the digestibility of the forage, and EV_i is the energy value of each forage class. The above is calculated over a "standard habitat unit" which would provide a fixed amount of energy for deer, and the above HSI is then normalized by this amount (so it is in [0,1]).

In practice, the HSI above is calculated for each cover type present (e.g. oak-hickory forest, pine, shrub, etc.), then the HSI values are averaged over the region of evaluation by multiplying by the area of each cover class and normalizing by the total area.

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Note: a good background reference on HSI-type approaches is *Wildlife 2000: Modeling Habitat Relationships of Terrestrial Vertebrates,* (J. Verner, M. L. Morrison, and C. J. Ralph eds.) Univ. of Wisc. Press, 1986.

Problems with HSI Models:

1. Models are based only on local habitat variables, completely ignoring any effects due to species interactions, except those due to indirect effects on related habitat variables.

2. Models ignore the spatial interactions of habitat types across a landscape. There is no simple means to factor in spatial constraints on habitat use without adding a host of new variables. This leads to difficulty in situations for which the size, shapes, edge effects, and neighborhood relationships have a greater effect on habitat preference than small-scale forest composition and structure variables.

3. Models generally assume a piecewise linear relationship between the habitat variables and the components of suitability, an assumption for which there is very little evidence.

4. Models do not take account of the issue of presence/absence of a species, and thus ignore any historical influence on potential local abundance. In fact, there has been very little evidence produced that the models are at all good proxies for local abundance. Evidence for this is difficult to obtain since the models are often modified slightly for particular local conditions, and not applied uniformly across a large enough region that one could test their aability to predict abundance.

5. HSI's are inherently static entities, so any dynamics they produce are driven completely by changes in habitat variables, ignoring the inherent dynamics and demography in the species being considered.

Computational Ecology

Computational Ecology is "an interdisciplinary field devoted to the quantitative description and analysis of ecological systems using empirical data, mathematical models (including statistical models), and computational technology".
Computational methods are essential to deal with many ecological issues, particularly those involving several organismal, temporal, or spatial scales. A Workshop on this subject dealt with 3 general areas of: Data Management, Modeling, and Visualization
- report available at
http://www.sdsc.edu/Events/compeco_workshop/report/tex/version3/report/node1.html

Thus computational ecology links together observational data from the field and remote sensing, with mathematical models and computer simulations, and offers the potential to address issues at regional scales for which standard models in mathematical ecology are inappropriate. The tradition in mathematical ecology is to focus on biotic interactions and ignore the dynamics of underlying environmental factors which may be more critical to understanding of natural system response that just the biotic interactions. This is done for very pragmatic reasons - dealing with non-autonomous systems is difficult analytically without strong assumptions on the nature of the driving factors (e.g. assuming periodicity).

Data Management: Ecological data are relatively sparse, irregular in character, contains a mixture of data types, and scales of measurement vary widely over time and space. The metadat, used to describe the data, are as diverse as the data itself. Problems then arise in how to maintain such data so as to be usable for diverse researchers with varying hardware and software. Thus standardization is a major concern.

Mathematical modeling: To date this has focused on ascertaining general properties of natural systems from basic assumptions. Taking into account stochastic factors, the range of organismal scales from individual through ecosystem, and external forcing functions such as weather and human-controlled impacts represent a very small fraction of the modeling work done to date. Although sufficient computational power now exists to handle such models taking these into account, it is not part of the culture of the field, which appreciates generality over precision and realism.

Visualization: A wide variety of statistical techniques have been developed and/or applied to ecological data sets historically to aid in elucidating patterns in these data. Visualization methods have developed to the point where we can emphasize information with particular features in complex data sets. Not only are such methods important for observational data, but they are critical to analysis of model output and comparison of such output to observations.

Validation: Very little agreement has been reached on how we decide when a particular applied model is acceptable for predictive purposes - a very contentious area.

Prediction for natural systems

Computational methods allow us to investigate far more realistic ecological models than we might do otherwise. It is driven by the need to improve our predictive capabilities - to more accurately assess the future impact of human actions on natural systems. The phenomena that ecologists need to include to carry this out frequently operate on spatial and temporal scales larger and longer than any individual can study effectively. This naturally implies the importance of teams of researchers collaborating over long periods, rather than the single-investigator with students approach typical of much of ecology in the past.

The difficulty of manipulating and replicating experiments at landscape scales raises issues about experimental design, the regularity and longevity of sampling, and the integration and storage of data.

A central issue in computational ecology is the need to link dynamic processes that operate across differing spatial regions and at different rates. How do we link natural and anthropogenic forces that influence the demand for biological resources with the dynamics of those resources? How much averaging and smoothing of very high resolution biological data must be done to match the lower resolution of geophysical data while preserving the prediuctive capabilities of the approach for the underlying natural systems? All this is clearly tied in with both what it is we wish to predic, as well as the accuracy desired for sucha prediction to be useful.

Focus of my remarks: Computational technology and the management of resources, and the interface between the science of ecology and the politics of decision-making

Landscape-scale Management:

Much of applied resource management occurs at the landscape scale, and has the potential to make use of spatially-explicit information (often included in some form of GIS data base) to analyze current and past trends and effects (e.g. on animal population sizes, vegetation community structure, etc.) and make predictions about effects of possible management scenarios. This can involve linking models for landscape change at various scales to the economic impacts of such changes. As of yet, we have experience with very few such approaches (for one example involving a Markov-transition approach to landscape change see the LUCAS Home Page at http://www.cs.utk.edu/~lucas/index.html), and yet regional assessment programs aimed towards comparing various management plans require the type of fairly detailed analysis provided by extensions of such approaches.

Multimodeling:

Historically, much of modeling in both theoretical and applied ecology has dealt with models that aggregate across a variety of scales (temporal, spatial, and organismal). Thus classical models have been dynamical systems with state variables being the densities of species, and these have served as the basis for much of ecosystem modeling. Taking account of spatially-heterogeneous systems, with different trophic levels having different inherent spatial and temporal scales, requires a mixture of modeling approaches rather than a single one-model-fits-all view. Thus, we have been developing (in the ATLSS project) the methodology for a multimodel (for non-biological examples see the site http://www.cis.ufl.edu/~fishwick/research/node2.html) which combines process-oriented compartment models for the lower trophic levels, structured population models for intermediate trophic levels, and individual-based models for higher-level consumers. Procedures for developing and analyzing such ecosytem-scale multimodels in combination with economic and social impact models remains an area of great future importance.

Spatially-explicit Control:

Management that occurs at landscape scale (e.g. forest harvesting, water flow management, conservation preserve design, etc.) is not an all-or-nothing affair that occurs uniformly in space. Rather, realistic management scenarios must take account of spatial heterogeneity in underlying resources, as well as how such heterogeneity interacts with management through time (local ecological succession for example). Given that there are a variety of potential criteria which affect the system management, so that the underlying non-spatial issue may be viewed as a multiple criteria optimization problem, how should the "control" of the system be applied spatially in order to carry out the optimization? This is a little-developed area of applied mathematics, particularly in systems in which there are stochastic factors which interact with the management scheme. Yet it lies at the heart of much of applied ecology today.

Take Home Messages for Doing Regional Assessments

1. Collaborate - with mathematicians/computer scientists if you are a biologist, with biologists if you are mathematically trained, as well as with economists, sociologists, and regional planners.
2. To have a real impact, choose a specific local/regional problem and become an expert on as many aspects of the problem as you can master.
3. You are responsible for teaching the next generation - regional assessment is an excellent teaching tool to aid those you mentor in developing their own modeling skills.
4. Appreciate both the diversity of underlying problems associated with any regional assessment as well as the diversity of possible approaches necessary to address them. Do not limit yourself to one approach - be open to approaches suggested from other disciplines. At the same time, realize that the abstraction provided by mathematical approaches may allow us to find commonalities across problems arising from many different natural systems.
5. There's lots of open problems - we all need to learn from each other.

Above all, do not get discouraged by the complexity of the problems facing us - *keep trying*!