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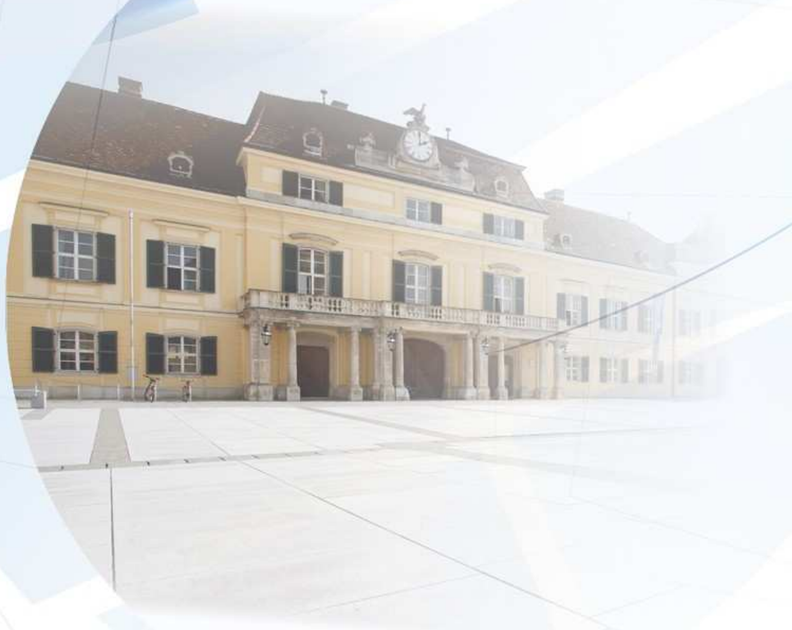

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DEVELOPMENT AND USE OF ECOLOGICAL MODULES IN RESOURCE DEVELOPMENT SIMULATION

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Abstract

This paper reviews the approaches we have developed for modelling biological interrelations within ecological systems and describes how these are incorporated within simulation models of resource and environmental problems which have economic, social, and physical dimensions in addition to ecological ones.

I. Development of Ecological Modules

There is a pressing need for validated submodels of key ecological processes (e.g. predation, competition, reproduction, etc.) which are general, precise, and realistic. One of our aims is to develop a library of modules which can be used within any model involving ecological relationships. The aim is to develop equations which, with the minimum number of parameters, contain the variety of behaviors occurring in nature. The approach used to develop these process submodels involves four stages, each of which is demonstrated in this paper by specific examples involving predation and competition.

A. Systems Conceptualization and Identification

1) The process is decomposed in a series of steps into its constituent components. The components are formally

defined as those monotonic relations whose differentials are also monotonic, i.e. simple fragments in which the function consistently rises or falls in a linear, convex, or concave manner. The advantage of this definition is that each relationship is then so simple it is possible to erect alternate hypotheses of causation and design the critical experiments necessary to test the hypotheses.

2) The components are then identified as basic or subsidiary ones. The former are universal components which underlie all examples of the process, and typically concern fundamental attributes of space and time. The latter are behavioral or physiological components which can be present in some situations and absent in others (e.g. learning). It is these subsidiary components which generate the great variety of forms found in ecological processes. As an example, the predation process has nine subsidiary components which can be present or absent, so that potentially there can be 2^9 or 512 structurally different variants of this response. The great advantage of this technique of decomposition and organization of components is that this high variety can be traced to the operation of a manageable number of components since the variety increases geometrically as the components increase arithmetically.

B. Experimental Analysis and Model Development

The above conceptual framework defines the set of relationships that must be specified for the whole process.

Where few data are available, experimental analysis is necessary and the framework provides the organization needed to develop a sequence of experimental steps from which the model evolves. The first step is to devise or discover a situation which is reduced to a set of the basic components and no others. Because it is so reduced, it is simple enough to unravel, experimentally, the actions of and interactions between the small number of components. When adequate hypotheses have withstood experimental testing, they are each expressed as a fragmental equation of a specific action or interaction. These can then be combined into a basic equation representing the combined action of the basic components. This provides the base to proceed to the next step where one additional subsidiary component is added. Again, a situation is devised which is more complex only by the addition of that component and is sufficiently amenable to minimize the practical problems of experimental analysis. In this manner, therefore, more and more of the process is analyzed and incorporated within a deterministic simulation model which contains the detailed causal relations.

C. Process (Systems) Analysis

The conceptual framework can be used to deduce the qualitative types of response that are possible. Many of the components, although different in causation, have very similar effects. Thus, although the nine subsidiary components of predation generate 512 structurally different cases, these collapse into eight qualitative types of response, each with a unique form of behavior. Each represents a biologically limiting condition defined by the absence of specific subsidiary components and each has subsequently been shown to exist in nature. At the same time, the full simulation model can be used to generate these same cases either explicitly or as the consequence of a sensitivity analysis. As this is done, it becomes possible to define precisely the biological and physical conditions which define each response type.

D. Development of an Analytically Tractable Module

The simulation model's main value is as a base for deduction and experimentation. Because of their complexity and large number of parameters, they generally are not practical modules to use in the analysis of a specific resource or environmental problem. In such cases it is essential to have simple, analytically tractable modules which are reduced to the minimum number of parameters and yet still generate each of the qualitatively distinct types of response. In the predation example, we were able to design such a module which collapses the 50+ parameters of the simulation model into a tractable five parameter variant. It generates each of the eight qualitative types and faithfully describes all the real life examples of predation, competition by predators, and grazing in the literature. It represents a very general and tested resource acquisition module.

E. Testing the Module

In the final stage the descriptive power of the module is tested in two ways--first against all the cases generated by the full simulation model and second against data in the literature relating to the response.

II. Development of Regional Models

A library of generalized and tested modules is the first important ingredient in developing a new generation of models which focus on specific resource or environmental problems. Such examples owe their specific character to the specific actors in the system and to the specific type of sequencing of events in space and time. But in all cases the generalized modules can provide the universal functions for linking these events. Only a few well developed modules of this quality are available but temporary and tentative functions exist or can be quickly developed for use in regional simulation of the environmental consequences of development.

The second important ingredient in developing regional models is an environment for inclusion of the economic and social dimensions as well as the ecological ones. In our examples we develop the models with a small group of economists, ecologists, mathematicians, and resource specialists, concentrating initially on designing a rough model as quickly as possible. As the properties of this model are explored in simulation, the sensitive points are identified so that priorities for research and data can be identified to permit the next cycle of model revision and policy analysis. Through trial and error we have developed a number of devices to facilitate communication across disciplinary lines. These include types of flow charts, cross-impact variable matrices, degree of precision tables and interactive computer graphic displays. Examples will be presented.

The third essential ingredient is to assure that the models have policy relevance, i.e. respond to the appropriate questions. We attempt to achieve this by involving policy people from agencies as an integral part of the model building effort. Their primary role is to define goals and disaggregate the system into relevant impact variables of importance in policy decision. This process is distinct from the model builders' disaggregation into submodels and state variables, but each process interacts with the other. In addition, they become an integral part of the model building effort and for that reason develop a more effective understanding of the weaknesses and limits of the model.

The final ingredient relates to use of the models. To date, we have largely confined ourselves to interactive man-machine gaming simulations using graphic displays. In this way, some sense of the effect of specific interventions is obtained, sets of policies are defined and alternate futures explored. We need now to add more formal techniques of policy analysis. Most important, we need to develop more effective ways of presenting information in forms which are understandable to and controllable by the various role players in the decision process.

III. Behavior of Models

The above techniques will be illuminated by reference to the behavior of three models--a recreational land use model of a portion of British Columbia, a land use model of a large hydroelectric power development in Northern Canada, and an ecological model of predator-prey interaction.

In our explorations of the behavior of these models a number of different characteristics have emerged. One of the more interesting concerns a general tendency of the modelled systems to exhibit more than one domain of "stability" or attraction around equilibrium points, trajectories or limit cycles, with at least one domain bounded by an unstable limit cycle. The feature of these boundaries is that they, rather than the area immediately surrounding the various equilibrium states, are critical to the overall behavior of the system. Points on either side of the boundary will ultimately track to their respective predictable equilibrium states; points near the boundary are liable to be flipped across it from one domain of stability to another in the face of small perturbations. The size of the domain and the strength of the damping forces near its bounding edge thus in large part characterize the ability of the system to maintain a structural integrity in the face of unexpected perturbations. If the domain is relatively small, then a small perturbation can flip the system into another domain, thus altering its subsequent behavior out of all proportion to the size and duration of the perturbation applied. Moreover, the weaker the damping forces in the vicinity of the boundary, the greater the likelihood that a small perturbation will cause that boundary to be crossed, regardless of the size of the respective domains. Finally, we note that in our ecological examples the parameter values occurring in nature seem generally to produce domains that are large, with rather weak damping around the equilibrium and strong damping at the boundaries.

From an equilibrium-oriented viewpoint, then, these systems can appear rather weakly damped and quite sensitive to disturbance. But from the viewpoint of the boundary, they are immensely stable with a high degree of persistence. In a sense this is what ecologists have always been saying--that what is important is not the efficiency of such systems but the probability of their persistence. This orientation switches attention away from events near the equilibria to the events near the boundary of stability, and it is this switch that for us is placing so much of our understanding in a very new light.

We see some interesting consequences which could emerge by applying the resilience concept to policy analysis and the planning process. The analyses described above lead to the realization that natural systems have experienced traumas and shocks over the period of their existence and the ones that have survived have explicitly been those that have been able to absorb these changes. They have, therefore, an internal resilience related to both the size of their domain of stability and the nature of the damping forces near the boundaries of the domain. So long as the resilience is great, unexpected consequences of an intervention of man can be absorbed without profound effects. But with each intervention it seems that the price often paid is a contraction in the domain of stability until an additional incremental change can flip the system into another state. In a development scheme this would generate certain kinds of "unexpected" consequences in response to deceptively "minor" perturbations--a freeway which changes the morphology of a city so that the urban core erodes; an insecticide which destroys an ecosystem structure and produces new pest species. We seem now to be faced with problems which have emerged simply because we have used up so much of the resilience of social and ecological systems. Up to now the resilience of these systems has allowed us to operate on the presumption of knowledge with the consequences of our ignorance being absorbed by the resilience. Now that the resilience has contracted, traditional approaches to planning might well generate unexpected consequences which are more frequent, more profound, and more global. The resilience concept provides a way to develop a planning framework which explicitly recognizes the area of our ignorance rather than the area of our knowledge.