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Editorial

ARTIFICIAL INTELLIGENCE AND EXPERT SYSTEMS IN ECOLOGY AND NATURAL RESOURCE MANAGEMENT

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ABSTRACT

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Ecologists have a variety of tools for collecting and analyzing data, but relatively few tools that facilitate ecological reasoning. Up to this time, simulation models have been the basic means of organizing ecological knowledge in a way that can be rapidly processed by computer. Technologies for computer-based manipulation of knowledge have been developed in artificial intelligence. The areas of ecological science in which this technology is likely to prove important include: modelling and simulation, integration of qualitative and quantitative knowledge, theoretical development, and, natural resource management. Researchers and managers in both basic and applied ecology will be affected by these developments as AI-derived technologies are added to the ecological toolkit.

INTRODUCTION

As it is currently taught and practiced, ecology reflects in large measure the collection of ever more data. Ecologists delight in pointing out the complexity of ecological systems, the difficulty of performing controlled, replicated experiments, the impossibility of experimenting on large-scale systems, the immense number of variables to be considered, the bewildering array of ecological behaviors that are possible, the exasperating ability of living organisms to acclimate, adapt, evolve. Yet, with the exception of computer simulation modelling, ecologists have developed, or adapted from other disciplines, virtually no computer-based tools that might help them think about this mass of information.

The ecological knowledge base, spanning as it does the range from physiology to the biosphere, is already enormous and growing continually. This huge knowledge base challenges us to develop new and more efficient ways of organizing, processing, and analyzing ecological knowledge to

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emphasize and facilitate the process of *ecological reasoning*, rather than data reduction. Moreover, it is essential to take up this challenge if ecological science is to have any impact on the social, political, and management decisions influencing the course of the biosphere.

Can artificial intelligence, with its emphasis on understanding how the human mind organizes and processes massive amounts of information, help? The technologies emerging from AI research may provide the high speed, computerized tools and techniques that aid ecologists in thinking and reasoning about ecological complexity, unifying theory, and mechanisms for applying ecological knowledge to real problems. Although a period of exploration and testing is necessary to delimit the scientific role that AI can play in ecology, it is certain that some of the techniques will become an accepted part of the ecologist's toolkit. The articles in this special issue represent some of the first steps being taken to adapt AI techniques to ecological research. In addition, these papers illustrate the major research areas briefly sketched below.

Artificial intelligence

Artificial intelligence (AI) is a branch of computer science that is principally concerned with using computational models to understand how humans think (Tanimoto, 1987). Major research areas include expert systems (ES), search methods, knowledge representation, logical and probabilistic reasoning, learning, natural language understanding, vision, and robotics (Cohen and Feigenbaum, 1982). The catch phrase, 'AI (or expert systems) techniques', generally refers to computer methods developed in one or more of those areas. Expert systems technology (Jackson, 1986), for example, represents an integration of methods from several AI research areas such as search methods, knowledge representation, and logical reasoning (production systems). For a long time, relatively little AI research found a pragmatic use outside of academia. However, the development of expert systems led many researchers from numerous other fields to explore the potential applications of AI to their particular disciplines. Expert systems technology thus became the major development that led to the explosion of interest in artificial intelligence that we are currently experiencing. However, it is by no means the only AI technique applicable to ecological research.

Expert systems

An expert system is a computer program that can solve problems in a specific area of knowledge (the problem domain) as well as a human expert (O'Keefe et al., 1987), or, that automates tasks that are normally performed by specially trained or talented people (Shannon et al., 1985). Expert systems research led to a methodology for separating knowledge in the form of rules, principally IF/THEN statements, from the procedures used to invoke these rules to solve a problem (Buchanan and Shortliffe, 1985). A collection of IF/THEN statements is only one of various methods used for knowledge representation. At its simplest, an expert system therefore consists of a knowledge base containing the rules and a procedure (inference engine) for processing the rules. This separation of knowledge from procedure has also given rise to the terminology 'knowledge-based systems'.

The principal method of developing an expert system is to interview the expert intensively to develop rules by which he or she solves problems or produces a diagnosis/evaluation. The process of extracting, formatting, and encoding an expert's knowledge in a computer program is referred to as knowledge engineering. Because the inference engine can be constructed independently of the knowledge base, it is possible to build an expert system 'shell'; that is, a program that requires the user to provide only the knowledge base. The user can therefore become both the expert and the knowledge engineer. There are now a number of implementations of expert system shells available (e.g., Epp et al., 1988).

The image of computer programs serving as experts has diverted attention away from the use of AI/ES technology for ecological research (in contrast to applications) (e.g., Loehle, 1987; Noble 1987). The exercise of building an expert system often reveals weaknesses in existing knowledge that point to needed research. These systems also serve to indicate the quality of decisionmaking that is possible with existing knowledge (e.g., Starfield and Bleloch, 1983, 1986). Expert systems techniques can be used to produce both stand-alone applications and components for other types of systems (i.e., embedded expert systems). These techniques can be used to add so-called 'intelligent' components to standard programs and models (Coulson et al., 1987). But most importantly, AI/ES techniques can be used to investigate ecological problems, particularly those associated with the development of coherent theory and ecological reasoning processes. Artifical intelligence methodologies, including but not limited to expert systems, may ultimately prove useful as tools for exploring ecological issues and developing ecological theory (Rykiel and Mayer, 1988).

MAJOR RESEARCH AREAS

Modelling and simulation

Perhaps the most immediate impact of AI technologies will be on the way ecologists organize, develop, and implement models. Two developments are worth emphasizing. The first is the development of specialized computing environments that allow a researcher to concentrate on the problem domain rather than mechanics of manipulating the computer. Ecological modellers have used one basic knowledge representation scheme up to now, the equation. Although elegant in many respects, equations severely limit the kinds of knowledge that can be represented and how knowledge is organized. Many ecological computer models are merely procedures for producing numerical approximations to the solutions of several to many equations. These models range from difficult to impossible for a non-modeller to parameterize and operate, and especially to understand the resulting output. Thus, the majority of the research effort is devoted to producing and debugging the model with much less time spent on thinking about the problem that inspired the modelling effort to begin with. An ecological computing environment should allow an ecologist to think mostly about the ecological problem and much less about the mechanics of computing. The first halting steps toward such modelling environments are now being taken.

The second development worth mentioning is object-oriented programming systems (OOPS). In current modelling technology, ecological entities are generally represented by variables or vectors. For example, in a forest growth model, a tree might be represented by a vector of numbers that indicates its age, DBH, and height. However, there is no object in the model called a 'tree' because knowledge representation by variable (or equation) does not provide a means of defining a tree object. In addition, there is no particular data structure that associates these variables as a tree. It would seem to be much more natural to build a model using the ecological objects ecologists are familar with. Object-oriented programming is based on this idea of a set of interacting objects that are meaningfully defined in the appropriate scientific context. Examples of computer languages that incorporate the object-oriented approach are Smalltalk and C + +. Object-oriented programming may be particularly effective for hierarchical representations of ecological systems since OOPS are inherently hierarchical.

Integration of qualitative and quantitative knowledge

Much ecological knowledge is qualitative and fuzzy, expressed verbally and diagrammatically. Ecologists have no effective technology for using this vast knowledge in a meaningful way. The core of ecology does not yet exist in the form of an accepted set of mathematical expressions. There is no evident point to waiting around for ecology to become primarily quantitative, and in the mean time ignoring the predictive power of qualitative knowledge. In reality, ecologists have considerable knowledge in their heads and not many ways to make this knowledge explicit, well-organized, and computer-processable. Artificial intelligence research may provide tools in the form of symbolic computing techniques for manipulating qualitative knowledge. Many questions of interest in ecology (and especially to decisionmakers) can be answered in terms of 'better or worse, more or less, sooner or later,' etc.

The search for quantitative knowledge, must continue to discover ecological relationships that can be expressed and manipulated with the power of mathematics. The challenge is to integrate quantitative knowledge with qualitative knowledge to deal with the complexity of ecological and environmental systems. Scientifically valid qualitative predictions can be made even when quantitative predictions cannot. Often, quantitative methods are used to arrive at a qualitative prediction or decision. When quantitative methods are inadequate or lacking, estimates, predictions, and decisions must still be made in both scientific and management situations.

Theoretical development

It is perfectly valid to ask the ecologist to describe the rules by which ecological systems operate. Science is after all a search for the rules that describe the way nature behaves. We have no evidence at this point in time that there is a simple set of rules for ecological systems. Ecological systems are complex and it is not unreasonable to think that there may be hundreds or thousands of rules needed to describe, for example, the behaviour of a salt marsh. Theoretical development is hampered by the limited mental capacity we have for figuring out the consequences of even small knowledge bases. Why not take advantage of any technology that can assist us in determining the logical consequences of complicated ecological chains of reasoning.

AI technologies may eventually prove useful for theoretical development in at least three ways: organization of computer-compatible knowledge bases including both qualitative and quantitative knowledge; rapid assessment of assumptions, hypotheses, or other ideas in a theoretical context; and determining the consequences and logical consistency of long and complicated reasoning pathways.

Natural resource management and policy analysis

This is an area where expert systems are likely to play an increasingly important role. It is one of the few readily identifiable ways to introduce sound ecological knowledge into the management environment. All resource management agencies engage in planning activities that can be enhanced by AI/ES technologies. To the extent that ecological considerations can be factored into these systems, the influence of ecological science on the decisionmaking process can be increased. Resource applications can also be used to evaluate the impact of alternative management policies. While policy analysis has not been given much attention in ecological circles, it is likely to become increasingly important for translating ecological insights into management practices.

CONCLUSION

Artificial intelligence techniques are now being investigated for application to ecological science. At this very early stage of development, research is focused on how to use AI/ES technologies to further ecological research. The role that this technology can play in ecology will be decided over the course of the next decade. Many current expectations will fall by the wayside, but some will be realized and lead to useful tools for ecological research and for the application of ecological knowledge to management.

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