ARTIFICIAL INTELLIGENCE AND DECISION SUPPORT IN NATURAL RESOURCE MANAGEMENT

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ABSTRACT

Making good decisions for natural resource management has become increasingly difficult. Forest managers have too much information, too many decisions to make, and too little time to do any of it. In addition, the objectives are changing and the diversity of needs that must be met is growing. Computer decision aids can help sort and process information and expand our ability to make good decisions in the face of these constraints. Artificial intelligence (AI) technology allows inclusion of knowledge processing in the decision support environment. Management of forest ecosystems involves a mixture of quantitative and qualitative elements that can be captured effectively with multi-component decision support systems (DSS) including expert systems, databases, models, geographic information systems, and user interface components such as hypertext and graphics. AI technology and expert systems are less visible as separate entities and more often occur as part of broader decision support environments. Decision support systems have been developed for a diversity of resource management applications, including management of wetlands, grazing lands, landscapes, community forests, and biodiversity, to name just a few. Two areas of current research are development of more effective integrating paradigms and transfer of the products of AI/DSS technology to the end user.

Keywords: decision support; expert systems; artificial intelligence; software; computers.

INTRODUCTION

Making good decisions and solving problems effectively is the basis for the work we do. Individual, organizational, national, and global success and survival depend upon making good decisions over the long term. The goal of this paper is to briefly review the current status of decision support systems in natural resource management. This review specifically excludes decision support systems in forest products manufacturing and mill operation. We will review the nature of decisions and the evolution of computer decision support systems, and survey a number of current efforts to illustrate where we are and where we might be going with this technology.

DECISIONS

To make good decisions, decision makers need to
(1) understand the problem,
(2) have access to the relevant information (sorted out from the irrelevant),
(3) know how to use this information (the best knowledge), and
(4) have time to apply that knowledge.
In addition, they must be aware of the most effective strategies to use in making decisions of various types (Rauscher 1996).

This task, however, has become increasingly difficult. The people making decisions have too much information and need to make too many decisions in too short a time. The amount and complexity of information available to resource managers is increasing at a faster and faster rate. With advanced technologies such as remote sensing, we are collecting and storing data that were not even collected a decade ago. The amount of written information, both qualitative and quantitative, is also proliferating to the point where the sheer volume of pertinent literature available to the decision maker is virtually unmanageable. At the same time, there is a persistent scarcity of human experts as people shift jobs and retire, and as agencies and institutions restructure.

Decision-making capabilities in forestry and demands on managers are also challenged by the need to meet more objectives and to satisfy a greater diversity of needs. As natural resource management moves from a difficult multiple-resource management paradigm to an even more difficult ecosystem management paradigm, the need for better and more powerful decision-making aids becomes urgent.

Natural resource systems are typically highly complex and dynamic. Decision support for their management must take into account significant variation in type, scale, and depth of information and knowledge, as well as variation in space and time (Lowes & Bellamy 1994). Resource management problems usually involve a mixture of natural science and engineering aspects, as well as socio-political and economic elements (Fedra 1995). While measurable phenomena and causal relationships characterise the former domain, our knowledge about these phenomena is far from complete and, even in the best of circumstances, resource managers often have to make judgments based on imperfect knowledge. The socio-political and economic domain of resource management is characterised by subjective or collective values and judgments, preferences, perceptions, expectations, and plural rationalities rather than a universal, agreed-upon yardstick. In the scientific and engineering domain, assessment also involves forecasting, designing, and analysing "What if?" scenarios, which is an inherently difficult problem and usually fraught with large uncertainties.

The Role of Computers

Computers can help. They can sort and process the information in different ways; they provide the tools to capture and use both quantitative and qualitative knowledge; and they can do it faster than humans can do it. Thus, with the new computer tools that are available to us, we can enhance our ability to make good decisions. With appropriate decision support tools, resource managers can make good decisions with a wider range of information available, even when the decision must be made very often or very rarely. However, creating truly useful programs for decision support has been anything but easy.

The traditional use of computers has been for information processing and the development and manipulation of models of various types. Decision support systems evolved in response to the need to make traditional management information systems and models more user-friendly and interactive—to integrate the data-processing capabilities of the computer with the managerial judgment of the human. Early decision support systems were aimed at resource management at a local or regional level (FORPLAN, for example). Increasingly, applications have been integrated to provide a range of functions for solving more complex problems. Systems linked in this fashion include databases, geographic information systems, data exchange systems for importing and exporting data, simulation or optimisation packages, and user presentation modules.

Important limitations to these systems were—from the users' point of view—their difficulty to learn and to use, and, once answers were obtained, the difficulty of interpreting the output. From the developers' point of view, it was impractical (in terms of both cost and effort) to incorporate into them the features—the "intelligence"—that would make them easier to learn and to use.

ARTIFICIAL INTELLIGENCE

The goal of the general field of artificial intelligence (AI) is to add humanlike features of behaviour to computers. This goal includes making computers easier to use, creating more effective communication between user and computer, and making them able to deal with words and ideas, incomplete or uncertain information, and more complex or ambiguous problems. In its early days as a formal discipline—in the late 1950s and the 1960s—AI researchers sought ways to build a "general problem solver", a program based on the idea that there exists a basic human ability to solve problems, independent of subject matter. Debate continues today as to whether such an ability really does or does not exist but, in any case, efforts to create programs with this ability did not meet with much success. By the 1970s, it became apparent that intelligent problem solving, in humans and computers, is based on large amounts of domain-specific knowledge, and the AI field of expert systems, or knowledge-based systems (KBS), was born. Progress in this field over the past 15 years or so, along with improvements in hardware and software for building such systems (e.g., greater speed and memory, lower cost), has created a rapid movement of AI/expert system technology into the hands of people building decision support systems for natural resource managers (Schmoldt & Rauscher 1996).

Expert systems allow us to encode knowledge to act upon information—including output from models—in intelligent ways. Where quantitative models are lacking, qualitative aspects of the problem may be treated using this approach. The main strength of expert systems is the application of a large amount of specific, context-dependent, inferential knowledge. Using some of the newer computer tools and approaches, we can capture the best knowledge of our best people about what to do with information, and make this component of decision making more consistently accessible to those who need it. Until recently, this level of activity was the sole domain of humans who—as we have seen—are often overloaded, have little time, and too much information.

DECISION SUPPORT SYSTEMS

For a time, when expert systems first captured the imagination of resource managers, emphasis was on development of stand-alone systems that made decisions and presented the manager with specific recommendations for action. These early expert systems, and virtually all of the successful systems in regular use today, usefully encapsulate knowledge from various sources, such as experts and user-supplied data, to give advice in narrowly defined domains such as disease diagnosis, timber management, and mill operations (e.g., Davis & Clark 1989; Rauscher & Hacker 1989; Durkin 1993).

As expert system software and associated technology have evolved, however, expert systems are more and more often found as part of large decision support systems that can help solve problems in broader, less narrowly defined domains (Janssen 1992; Turban 1993). Contemporary decision support systems combine human judgment with computer processing to produce a diversity of meaningful information for decision making. Rather than replacing the need for human decision makers, these systems, like their predecessors and their domain-specific contemporaries, become extensions of decision makers' reasoning processes and capabilities (Sage 1991; Silver 1991). They help managers make decisions in situations where human judgment is an important contributor to the problem-solving process, but where human information-processing limitations impede decision making.

The purpose of a decision support system is to help a manager make decisions in semi-structured and unstructured problems. They can help with four steps in decision making:
(1) Analysing the situation
(2) Designing the alternatives
(3) Choosing the course of action (i.e., making the decision)
(4) Evaluating the "goodness" of the choice and its implications.

While some decision support systems may support only the first two steps, most useful systems attempt to provide help in all four of these steps. Expert systems have important and specific roles in this process. They form part of the user interface to provide intelligent-seeming responses to the questions asked of the user and the displays with which the user interacts. They are one of the tools available for analysis and advice for particular domain-specific issues. Finally, expert systems can be used to implement components of the decision-making process, in particular the automation of the intuitive method of choosing among alternatives.

In general, artificial intelligence techniques, such as those used in expert systems, can allow decision support systems to (Rauscher 1995):

- Simulate current decision-making practices by focusing on the managerial decision-making process, rather than on functional components of ecosystems;
- Incorporate experience and rules of thumb with the latest in scientific research;
- Provide intelligent explanation of what is happening in the program;
- Provide intelligent front and back ends to the decision support database and modelbase management systems and to the functioning of the user interface;
- Simulate the expertise-based components of the decision-making methods;
- Help users to intelligently modify various parts of the decision support system while they are running it;
- Help decision makers to understand and structure their own goal criteria and then help them determine a utility function to be used to evaluate alternatives; and

- Develop expert systems that can help formulate the problem and design steps of the decision-making process.

DECISION SUPPORT IN NATURAL RESOURCE MANAGEMENT

Natural resource management applications require the integration of a number of specific technologies to accommodate the heterogeneous data and knowledge, and to take advantage of the respective spatial and temporal analysis capabilities of alternative technologies (Coulson *et al.* 1987). The first integrated artificial intelligence-based systems in resource management linked expert systems to simulation models (e.g., McKeon *et al.* 1982) and/or databases (e.g., Bellamy 1986), facilitating their use and helping the user interpret results. Others used artificial intelligence technology to create intelligent geographic information systems (GIS) (e.g., Robinson & Frank 1987). More and more, however, decision support systems incorporate several components—knowledge bases with geographic information systems, models, databases, and a diversity of user interface components such as hypertext and graphics that help the user understand and interpret what the system is doing.

A brief description of some decision support systems that are the focus of current efforts in natural resource management and related areas of agriculture will illustrate the types of applications and the potential for the future of this technology in resource management. These cover a range of applications and combinations of technologies.

Spatial Modelling of Succession in a Savanna Landscape

This decision support system links a rule base with conventional models and GIS to model secondary succession on a savanna woodland site in southern Texas (Loh & Hsieh 1995). The rule base contains factors believed to have regulated landscape development and is linked to a growth model. Landscape patterns are then generated, analysed, and displayed through manipulation of a geographic information system. In the test cases, the system verified the roles of annual rainfall and soil characteristics, and suggested that, with proper control, the landscape could be maintained at its current state.

ELDAR: Predicting Ecosystems from Land Resource Data

The Alberta Research Council's forest information technologies program is concerned with the design and implementation of ecologically oriented spatial and knowledge-based systems to support forest and land resource management (Mulder & Corns 1995). As part of this program, a decision support system was designed to represent the knowledge used by a forest ecologist to classify a forest ecosystem from a variety of data sources. The Ecological Land Data Acquisition Resource (ELDAR) predicts ecosystems from topography, forest cover, and soil maps. It works in conjunction with a geographic information system. A prototype has been developed in collaboration with the Canadian Forest Service and the Foothills Model Forest in Hinton, Alberta. Extensive field testing has shown that ELDAR is a practical tool that can assist with the creation of an ecosystem-based land inventory with prediction accuracies of up to 94%. It has the potential of providing major cost savings in inventory management, most notably reforestation. Prototypes of the ELDAR have been installed at the Foothills Model Forest and at the McGregor Model Forest in Prince George, British Columbia. A commercial version of the system is expected to become available in late 1996.

Decision Support for Agricultural Landscape Analysis

Agronomic experts in France frequently use satellite imagery (land-use maps) to map and make diagnoses of the region's agriculture (Le Ber 1995). Artificial intelligence techniques are used because the experts have knowledge about regional soils, climate, agricultural systems, cropping techniques, and the relationship between landscape and agriculture. Reasoning methods include analysis, comparison, and classification of landscape situations. The Aréopage system was developed to help the agronomic experts analyse satellite images. It recognises objects and villages on the map, calculates the various properties of the objects, and then analyses village farming situations. The system uses several knowledge levels (both geographic and abstraction levels) and various ways of reasoning to characterise and compare the farming situations observed in the images.

Wetland Management on National Wildlife Refuges

This decision support system, still under development by the USDI National Biological Service and Colorado State University, will help staff of national wildlife refuges with integrated management of wetlands (Sojda *et al.* 1994). As the project evolves, emphasis is being placed on trumpeter swan management as a test focus. Several computer-assisted strategies, including artificial intelligence and geographic information systems, are integrated in this system to help set local objectives and programs within multiple geographic and temporal scales.

Decision Support for Grazing Land Management

Recent introduction of new pastoral legislation in the Northern Territory of Australia, and growing public concern for the sustainable use of rangelands in this region, led to a need for more objective advice to land managers and management agencies on the risks to the land resource base from grazing. Landassess DSS is an integrated knowledge-based spatial decision support system being developed to help with the sustainable management of Australia's northern grazing lands (Lowes & Bellamy 1994). The system incorporates a knowledge base of management and ecological information, a natural resource database, a geographic information system, and scientific and economic models. The system produces advice on environmental and economic risks to the rangeland.

Community Forest Geographic Decision Support

This knowledge-based geographic information system is being developed in response to the United Kingdom's recent surge of interest in the creation of community forests (Burkmar *et al.* 1994). Its aim is to help meet the challenges of developing these forests in ecologically sound ways while respecting landowners' wishes and coping with high visitor pressure. In this system, there is strong emphasis on modular development, because each of the ecological program domains is large enough to warrant an application of its own. However, all of them have common requirements and can make use, for example, of the geographic information system display capabilities or access a database/knowledge base for soil. Thus the geographic information system and database components are created as separate modules, each of which can be used by any of the other modules.

Land Information Management (KBLIMS)

The Knowledge-Based Land Information Manager and Simulator (KBLIMS) is a system being developed by the University of Toronto to manage spatio-temporal simulations of ecological processes (Mackay *et al.* 1994; Robinson & Mackay 1995). The system is organised around a watershed-based model of terrain. KBLIMS includes modules for extracting a watershed representation directly from grid digital elevation models and an information system allowing the selection, browsing, navigation among, and query of watershed objects using a graphical user interface. KBLIMS provides a unique decision support system for integrated resource management in forested watersheds.

Managing Biodiversity

Like many other countries, Australia has international obligations to maintain its biological diversity since ratifying the International Convention on Biological Diversity. Ecologically sustainable development (ESD) is the development of environmental resources to develop industry and generate wealth and employment, while conserving ecosystems for the benefit of future generations. Biodiversity is integral to assessment of ESD. This project provides an overall strategy for applying information technology to the management of biodiversity, using forests as a case study (Davey *et al.* 1995). The system will integrate intelligent tools for conferencing, text-retrieval, and debate-handling, automated modelling tools, and intelligent processing of remotely sensed and field-collected data. It incorporates models of succession and population viability, graphics, rule-based systems, geographic information systems, text facilities, and databases.

Forest Management Advisory System (FMAS)

FMAS is a decision support system for the management of even-aged stands of aspen and red pine (Nute *et al.* 1995). It integrates a knowledge-based system for treatment prescriptions, previously published growth and yield models for aspen and red pine, a hypertext encyclopædia of aspen forest management, and a variety of help and explanation facilities. The functional focus is timber management of single stands over multiple, even-aged rotations. The general design methodology is applicable to timber management applications of any even-aged management system worldwide, given appropriate changes in the knowledge bases and growth and yield projection systems. A toolkit for the development of decision support systems in PROLOG (DSSTOOLS) was used for FMAS. DSSTOOLS is documented by Zhu (1996) and the latest version is available by anonymous FTP at "ai.uga.edu" under the directory "pub/forest/DSSTOOLS".

Integrated Forest Resource Management (INFORMS)

INFORMS (the Integrated Forest Resource Management System), being developed by Texas A&M and Region 8 of the USDA Forest Service, is a decision support system to help project-level planning and development of environmental assessment on lands managed by the USDA Forest Service (Williams *et al.* 1995). Components include a geographic information system, a relational database management system, a user interface system, rule bases, and various simulation models. The system is designed to be flexible and thus accommodate existing ranger district databases and resource analysis tools. The ultimate goal is to build a tool that is configurable across all Forest Service districts.

Northeast Decision Model (NED)

NED is a decision support system for ecosystem management (Kollasch & Twery 1995; Rauscher *et al.* 1995) being developed by the Northeastern Forest Experiment Station in co-operation with the Southern and North Central Forest Experiment Stations, the Eastern and Southern regions of the National Forests, and numerous others. NED provides site-specific expert recommendations on silvicultural prescriptions to optimise management of multiple resources on forests of the north-eastern United States. The vision driving NED is that demands for a variety of resource values can be evaluated and met best by first determining the priorities of all management objectives, next resolving trade-offs among them, and only then selecting activities compatible with all goals and most likely to produce specified desired future conditions. This is being accomplished by starting from the best of the present state of decision support methodology for silviculture and expanding it to incorporate prescriptions for wildlife, water resources, recreation, ecological, and esthetic values. Version 1.0 of NED, which focuses on the analysis step of the decision-making process, is due for release in early 1997.

Analysis and Communication of Ecosystem Management (KLEMS)

A partnership of two universities and elements of the USDA Forest Service has been developing the analysis and communication tools necessary to support ecosystem management decisions (Laacke 1995). So far, several elements of the decision support system have been developed, including a temporal analysis data model for a geographic information system, linking a large wildlife habitat database to two geographic information system programs for analysis of ecosystem status and change, evolution of a wildlife-centred concept of landscape analysis, and application of fuzzy set theory to resolve data incompatibility questions. Resource specialists ensure that landscape data used are correct and applicable to the analysis by creation of rule sets that translate data and guide analyses.

Grazing Lands Applications (GLA)

This decision support system integrates a number of different sources of information to develop ecologically and economically viable alternatives for production and development of grazing lands (Sheehy *et al.* 1993). The system is currently being used by Natural Resource Conservation Service personnel in Texas, Utah, and Oregon.

At present, multi-functional decision support systems for natural resource management are in transition from development to field testing. We know of no instance where a field-tested ecosystem management decision support system of this type enjoys widespread daily use, although a large number of more narrowly focused decision support systems are being used successfully, especially in forest industry and related areas of agriculture. In the USDA

Forest Service national forest system, about a dozen ranger districts, out of approximately 500 nationwide, are currently evaluating the use of one or another of the large-scale systems listed here. We anticipate that it will take approximately 10 years of further development, with active user feedback and healthy competition among numerous development teams, before decision support systems for natural resource management will be in common use.

DISCUSSION

Computers have a number of important roles in contemporary natural resource management. With them, we can magnify human productivity and effectiveness, and meet the increasingly diverse challenges that confront us. Human capabilities can be enhanced with intelligent computing systems, and national concerns addressed more effectively, with greater communication and collaboration as changes are made along the way. Nevertheless, we are still just beginning to apply intelligent computer programs effectively in forest management and much remains to be done. Two key challenges (among many) are integration of program components and technology transfer.

Improving Decision Support Paradigms

It is clear that many current, large-scale decision support systems of the type described here have bits and pieces of very useful functions incorporated in their design, but very few have been fully accepted and frequently used by resource managers. The inescapable conclusion is that decision support systems are at the beginning of their evolutionary cycle. The size and complexity of the task is an obstacle to their development. The difficulty of integrating proprietary software, and the lack of generally accepted standards for presentation of data and graphics and the management of models are also problems in large-scale systems, as are the cost and time needed to develop a significant product.

The USDA Forest Service's Interregional Ecosystem Management Coordinating Group Ad Hoc Task Team for Decision Support Tools recently completed a survey of 26 Federal Government decision support systems for ecosystem management across the United States (H.T.Mowrer, Rocky Mountain Forest and Range Experiment Station, pers. comm.). Developers were asked to evaluate their systems based on their potential to support ecologically based natural resource management activities. Through this process, the task team aims to elucidate the types of ecosystem management questions requiring formal decision support and to develop a format for comparing decision support systems based on their ability to address these needs. The evaluations consisted of 48 questions covering scope and capabilities, spatial issues, basic development status, input and output data requirements, user support, performance, and computational methods. Although a full analysis of the survey results is still in preparation, certain preliminary generalisations can be made. Few, if any, of the decision support systems reviewed do a good job of aggregating multiple decisions within a single spatial scale (i.e., watershed/management unit, forest, or ecoregion) to support development of integrated, interdependent, and coherent alternatives. Effectively translating these alternatives to higher or lower spatial scales still remains largely an unsolved problem. Software support for group decision analysis and consensus building within the framework of an ecosystem management decision support system is also a weak point of most of the systems surveyed. Finally, all the decision support systems surveyed concentrate primarily on the biophysical domain. Few of them explicitly address and integrate social and economic criteria and issues. In conclusion, among the 26 systems surveyed, almost all of the pieces that are needed for effective ecosystem management decision support can be identified and have been addressed in some fashion. However, no single one of the 26 systems addresses a significant portion of the relevant activities that must be integrated to truly support ecosystem management decision making.

Nevertheless, resource management decision support systems will inevitably improve both in functionality and in operating efficiency. The development of software methods and standards is critical. Rauscher *et al.* (1995) and Kollasch & Twery's (1995) scheme for integrating models, databases, hypertext, and knowledge bases, and Chandrasekaran's (1987) idea of generic tasks, are steps in the right direction.

Technology Transfer

A problem with decision support systems in general, and large-scale systems in particular, is that few are actually used (Silver 1991; Sequeira *et al.* 1996). Emphasis in their development has been on *verification* (Does it work?) and *validation* (Does it do what it's supposed to do?), because these modes of evaluation are comparable to similar procedures in traditional software engineering. For a number of reasons, questions about *utilisation* (Is the program being used by the people it was designed for?) have not been asked very often. There has been discussion of implementation (usually defined as distribution and maintenance of the system), but even here, it is generally assumed that the system will be used by the people for whom it was designed. Although most of the expert systems and decision support systems that have been developed work well, very few of them (some say no more than 10%) have been actually used in the way that was envisioned by their designers.

A part of the problem has been and continues to be the focus on the software itself—on evaluating the performance of the system in isolation. Yet we know there are many factors, other than whether the software works, that influence whether a person uses a computer. Before a person will try to use a program to do a task, much less use it regularly, the program must be compatible with a diversity of its user's needs. Questions that can be asked address both the difficulty *and the meaning* of the task to the user (Does he/she *want* help doing the task?), the user's social and professional environment (Is use of the program convenient? Accessible? Rewarded?), and the user's psychological makeup (Is the interface design specific enough for the type of user?). There are many complex interactions of environment, task, and individual psychology that influence whether the system will be just tried and then abandoned, or actually adopted for long-term use, and whether the user will put the effort necessary into learning how to use the system.

In a recent study, 33 public land managers and consultants from the United States Inland North-west were interviewed about their use of decision support systems (A.K.Gardner, University of Idaho, pers. comm.). Interviewees represented the USDA Forest Service, the Bureau of Land Management, and the Natural Resource Conservation Service. Although analysis of the collected data is not yet complete, several factors have emerged as inhibitors of decision support system adoption by these users. These include (1) unfriendly user interfaces, (2) users not included in the design process, (3) lack of needed specificity of application, (4) lack of portability of the decision support system from one geographic region to another, (5) lack of graphical output and spatial representation, and (6) lack of integration of knowledge across agency/academic boundaries.

The problem of interface design occurs across a wide variety of applications. Despite the fact that many developers consider the process of designing interfaces obvious, few could identify the major *principles* of interface design (including user involvement and interactive development cycles) (Gould & Lewis 1983). Sequeira *et al.* (1996) and Gardner (pers. comm.) note that this situation exists in the area of natural resource management. Interfaces are given cursory treatment and not considered an important part of the research effort. As a result, systems emerge that are loosely integrated and hard to use and understand.

Performance support, the idea that systems must be designed to support the work of the user, changes the emphasis from design driven by technology (with the user doing all the adapting) to design driven by the needs of the user (with technology adapting to meet these needs) (Carr 1992). The challenge for decision support system developers is to identify commonly found decision-making needs and to devise computer-based tools that support them. Some of these needs are (Silver 1991):

- better exploration of alternatives
- better identification of problems and opportunities
- methods for coping with multiple or undefined objectives
- methods for coping with risk and uncertainty
- identifying and managing human biases in the decision process
- tools for the meta-choice of what methods to use and when
- better tools to help users learn faster
- better tools to help users communicate more effectively
- better tools to understand and explain the decision process

Doing this requires that we understand and use the scientific knowledge about how humans make decisions. Expertise in decision making itself is as important in resource management as understanding the biology and sociology of the organisms being managed (Cleaves 1995). Although they are intensively trained in their profession, few natural resource managers are also trained in the essential skills of decision making and the recognition and avoidance of the many human cognitive biases (Sage 1991). In building decision support systems, we learn more about the essential qualities of good decision making and, at the same time, gain tools to help us make better decisions.

As the range of problems we consider in making forest management decisions expands, the range of tools we require to solve them will also grow larger. As problem complexity increases, the power of the tools we command to help solve those problems must also increase. Current efforts in decision support system development are anticipating these needs and represent the seed from which tomorrow's powerful decision support tools will emerge.

REFERENCES

BELLAMY, J.A. (Ed.) 1986: Papua New Guinea: Inventory of natural resources: Population distribution and land use handbook. *CSIRO Division of Water and Land Resources, Canberra, Natural Resources Series No. 6.*

BURKMAR, R.; BASDEN, A.; PETCH, J.; YIP, J. 1994: The community forest geographic decision support system: A knowledge-based geographic information systems. *AI Applications 8(1)*: 40–2.

CARR, C. 1992: Performance support systems: A new horizon for expert systems. *AI Expert 7(5)*: 44–9.

CHANDRASEKARAN, B. 1987: Towards a functional architecture for intelligence based on generic information processing tasks. Pp.1183–92 *in* Proceedings, IJCAI-87; Milan, Italy.

CLEAVES, D.A. 1995: Assessing and communicating uncertainty in decision support systems: Lessons from a policy analysis on ecosystem management. *AI Applications 9(3)*: 87–102.

COULSON, R.N.; FOLSE, L.J.; LOH, D.K. 1987: Artificial intelligence and natural resource management. *Science 237*: 262–7.

DAVEY, S.M.; STOCKWELL, D.R.B.; PETERS, D.G. 1995: Managing biological diversity with intelligent systems. *AI Applications 9(2)*: 69–90.

DAVIS, J.R.; CLARK. J.L. 1989: A selective bibliography of expert systems in natural resource management. *AI Applications 3(3)*: 1–18.

DURKIN, J. 1993: "Expert Systems Catalog of Applications". Intelligent Computer Systems Inc., Akron, Ohio.

FEDRA, K. 1995: Decision support for natural resources management: Models, GIS, and expert systems. *AI Applications 9(3)*: 3–19.

GOULD, J.D.; LEWIS, C. 1983: Designing for usability: Key principles and what designers think. Pp.50–2 in Guindon, R. (Ed.) "Cognitive Science and Its Application for Human-Computer Interaction". Lawrence-Erlbaum, Hillsdale, New Jersey.

JANSSEN, R. 1992: "Multiobjective Decision Support for Environmental Management". Kluwer Academic Publishers, Dordrecht.

KOLLASCH, R.P.; TWERY, M.J. 1995: Object-oriented system design for natural resource decision support: The Northeast Decision Model. *AI Applications 9(3)*: 73–84.

LAACKE, R.J. 1995: Building a decision support system for ecosystem management: KLEMS experience. *AI Applications 9(3)*: 115–27.

LE BER, F. 1995: A prototype model-based expert system for agricultural landscape analysis. *AI Applications 9(2)*: 91–102.

LOH, D.K.; HSIEH, Y.C. 1995: Incorporating rule-based reasoning in the spatial modeling of succession in a savanna landscape. *AI Applications 9(1)*: 29–40.

LOWES, D.; BELLAMY, J.A. 1994: Object orientation in a spatial decision support system for grazing land management. *AI Applications 8(3)*: 55–66.

MACKAY, D.S.; ROBINSON, V.B.; BAND, L.E. 1994: On a knowledge-based approach to the management of geographic information systems for simulation of forested ecosystems. *In* Michener, J.; Brunt, J. (Ed.) "Environmental Information Management and Analysis: Ecosystem to Global Scales". Taylor and Francis, London.

McKEON, G.M.; RICKERT, K.G.; ASH, A.J.; COOKSLEY, D.G.; SCATTINI, W.J. 1982: Pasture production model. *Proceedings, Australian Society of Animal Production 14*: 202–4.

NUTE, D.E.; RAUSCHER, H.M.; PERALA, D.A.; ZHU, G.; CHANG, Y.; HOST, G.M. 1995: A toolkit approach to developing forest management advisory systems in prolog. *AI Applications 9(3)*: 37–60.

MULDER, J.A.; CORNS, I.G.W. 1995: NAIA: A decision support system for predicting ecosystems from existing land resource data. *AI Applications 9(1)*: 49–60.

RAUSCHER, H.M. 1995: Natural resource decision support: Theory and practice. *AI Applications 9(3)*: 1–2.

——— 1996: Decision making methods for ecosystem management decision support. Pp.264–72 *in* Korpilahti, E.; Mikkelae, H.; Salonen, T. (Ed.) Proceedings, IUFRO XX World Congress, Tampere, Finland, 6–12 August 1995.

RAUSCHER, H.M.; HACKER, R. 1989: Overview of artificial intelligence applications in natural resource management. *Heuristics 2(3)*: 30–42.

RAUSCHER, H.M.; TWERY, M.; PALMER, J.; HOFFMAN, R.; STOUT, S.; STEINMAN, J.; KOLLASCH, P.; BENNETT, D.; THOMASMA, L.; HORNBECK, J.; WORTH, C.V. 1995: Northeast Decision Model design document. *AI Applications 9(3)*: Insert 3,633 KB; 813 chunks; 978 links (electronic).

ROBINSON, V.B.; FRANK, A.U. 1987: Expert systems for geographic information systems. *Photogrammetric Engineering and Remote Sensing 53(10)*: 1435–41.

ROBINSON, V.B.; MACKAY, D.S. 1995: Semantic modeling for the integration of geographic information and regional hydroecological simulation management. *Computers, Environment, and Urban Systems 19(5/6)*: 321–39.

SAGE, A.P. 1991: "Decision Support Systems Engineering". John Wiley and Sons, New York.

SEQUEIRA, R.A.; OLSON, R.L.; WILLERS, J.L. 1996: An intelligent, interactive data input system for a cotton simulation model. *AI Applications 10(1)*: 41–56.

SCHMOLDT, D.L.; RAUSCHER, H.M. 1996: "Building Knowledge-Based Systems for Natural Resource Management". Chapman and Hall, New York.

SHEEHY, D.P.; CONNER, J.R.; HAMILTON, W.T.; STUTH, J.W. 1993: An ecologically and economically integrated approach to planning sustainable grazing animal production systems. *Texas A&M University, Ranching Systems Group Publication Series.*

SILVER, M.S. 1991: "Systems That Support Decision Makers: Description and Analysis". John Wiley, New York.

SOJDA, R.S.; DEAN, D.J.; HOWE, A.E. 1994: A decision support system for wetland management on national wildlife refuges. *AI Applications 8(2)*: 44–50.

TURBAN, E. 1993: "Decision Support and Expert Systems". Macmillan Publishing Company, New York.

WILLIAMS, S.B.; ROSCHKE, D.J.; HOLTFRERICH, D.R. 1995: Designing configurable decision support software: Lessons learned. *AI Applications 9(3)*: 103–14.

ZHU, G. 1996: DSSTOOLS: A toolkit for development of decision support systems in PROLOG. Master's thesis, University of Georgia, Athens.