Decision Support For Ecosystem Management

Keith Reynolds, Jennifer Bjork, Rachel Riemann Hershey,
Dan Schmoldt, John Payne, Susan King, Lee DeCola,
Mark Twery, and Pat Cunningham

Key questions addressed in this chapter

- ♦ *What are the systematic steps to decision-making?*
- ♦ *What is the role of decision support in ecosystem management?*
- ♦ *What are some useful analytical tools for decision-making?*
- ♦ *What decision support systems are available?*
- ♦ *Why use knowledge-based systems for decision support?*

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1 SUMMARY

This chapter presents a management perspective on decision support for ecosystem management.

The **Introduction** provides a brief historical overview of decision support technology as it has been used in natural resource management, discusses the role of decision support in ecosystem management as we see it, and summarizes the current state of the technology.

The Decision-making Process examines the seven-step process as described in the companion science paper (Oliver and Twery, this volume). At each step, there are issues, concerns, and pitfalls to be considered. This section is also, in effect, a key to software tools and systems discussed later in the chapter, because we discuss how specific tools, and to a lesser extent systems, can usefully contribute to the decision process.

Decision Support Tools provides a brief introduction to a wide variety of software tools that are potentially valuable as aids to a decision process. Some of these tools will be relatively familiar to readers. However, we expect that many readers will have had little or no exposure to a number of these tools, so motivating examples are liberally used to suggest how and why specific tools may be useful. Discussion in this section has been kept as nontechnical as possible.

Knowledge Based Systems provides an overview of an important, and relatively new, decision support technology that is particularly valuable for handling problems that do not readily lend themselves to neat algorithmic solutions. Frequently, for example, we do not understand a problem precisely enough to develop a numerical solution. Nevertheless, enough of the problem may be understood that professionals with years of experience in the problem domain can reason about it intelligently and offer useful solutions.

Promising Possibilities picks up on the theme of where decision support technology is today from the Introduction, and speculates about what we might expect to see in the near future.

2 INTRODUCTION

Decision support technology and practice as it now exists is an amalgamation of many different approaches and technologies. Classical decision science, systems science, and statistical theory are essential ingredients of modern decision support technology, but each was a thriving branch of management science long before the advent of computers. Indeed, serious development in these lines of research goes back at least to the turn of the century.

2.1 Historical Background

The advent of commercial mainframe computer systems in the 1960s coincided with massive growth in natural resource management and management science by public agencies. Also during this period, public interest in land management activities grew rapidly. In such an environment, simulation modeling and linear programming quickly rose to prominence in the 1970s as basic tools for understanding and managing natural resources, respectively. The resulting information explosion, which appears almost quaint now in retrospect, in turn spurred advances in database management and geographic information systems from the mid-1970s to the mid-1980s. The pace of development in these relatively new fields was only accelerated by the advent of personal computers in the mid-1980s.

By the mid-1980s management science had matured to the point where the complexity of systems in general, and natural systems in particular, was now becoming painfully obvious to most managers, scientists, and the public. Many types of natural resource management problems were not readily reducible to simple mathematical relationships that could be conveniently handled by technologies such as simulation and goal programming. Expert system (more generally, knowledge-based system) technology grew quickly as an alternative problem-solving method for messy real-world problems (Davis and Clark 1989).

At each step in the evolution of decision support technology, new emerging technologies have been embraced and used to enhance the power of existing technologies to assist with solving problems. Most recently, we have seen the integration of decision theory with GIS applications to produce powerful new groupware technologies that can assist with evaluating complex spatial information in a decision process. In addition, the emergence of the Internet's World Wide Web has revolutionized the ability to share information among natural resource managers, the scientific community, and the public. All these technologies, however, are only useful to the extent that they serve the ultimate purpose of decision support, to improve the decision-making process by helping integrate better information into the planning and evaluation of decision alternatives (Fedra 1995).

2.2 Role of Decision Support in Ecosystem Management

Decisions in ecosystem stewardship involve complex interrelationships. In many cases, even the experts do not understand and cannot explain all the relationships that may be affected. The success of management depends on the success of the decisions that are made. Decision-making is a logical thought process that identifies and clarifies the problem, current knowledge, and possible solutions, resulting in the best decision at the time. As problems and solutions become more complex, assistance in evaluating them becomes helpful or even necessary. New understanding of public interests and desires has led to changes in approaches to public land management. With the new management approach embodied in the concept of ecosystem stewardship, decisions now involve larger, more diverse topics, multiple spatial and temporal scales, cross many different organizational hierarchies, and involve diverse groups of stakeholders. Decision-making in natural resource management has become more complex by several orders of magnitude as a result.

Multiple goals are becoming common as part of agencies' mandates and usually involve compromises and numerous interest groups or stakeholders. Organizational mandates, economic needs, social desires, and the decision-makers' knowledge and background determine the inputs upon which decisions are based and what information is used to make them. Solving such complex problems now typically entails the use of several to many different types of resources, tools, and systems in the various phases of a decision process.

Decision support techniques cover an array of methods to acquire, organize, and analyze large amounts of diverse information. Decision-makers need to understand the perceived problem, the perceived goal, and the impacts of different courses of actions on local communities, user groups, and other interested parties. The problem may only be a perception or the result of conflicting objectives. Social values usually are incorporated into decision-making through social surveys and public meetings. A variety of analytical tools are available to evaluate such sources of information.

2.3 Scope of the Chapter

Tools and systems to help us make better decisions are essential to good stewardship. The decision-making process itself is critical, so we begin with a discussion of the process in the next section.

The fourth section focuses on an array of specific software tools, and is organized somewhat along the lines of the third section. We have kept the discussion in this section relatively nontechnical. We make no claim for a comprehensive treatment of decision support tools in the fourth section. There are far too many to include them all. On the other hand, we hope we have made a useful beginning, and that reader suggestions will lead to inclusion of new topics in subsequent editions.

The fifth section treats the relatively new, important class of systems known as knowledge-based systems. There are many flavors of knowledge-based systems, but they all share the characteristic of symbolic reasoning. That is, rather than manipulating data as more familiar simulation models do, knowledge-based systems operate on more abstract types of information. For many real-world problems, the scope and complexity of the problem makes use of such systems a practical necessity. This is certainly true for ecosystem management.

3 KEY TO TOOLS FOR DECISION-MAKING

A decision usually is considered successful when actual consequences meet expectations, or when a different but equally satisfying result fortuitously occurs. According to Oliver and Twery (this volume), several things are helpful:

- an understanding of what is being decided, both what is known and what is not known;
- the understanding is accessible in a manner that can be understood by the decision-maker;
- the problem, issues, and tradeoffs are understood;
- alternative actions can be developed and compared so that consequences of each action can be understood.

The basic role of decision support is to provide information to decision-makers in an effective, efficient manner that expedites the decision process. Numerous *software tools* can facilitate specific parts of the decision process. Programs exist, for example, to help a decision-maker determine goals, objectives, and priorities, formulate alternative options, analyze options, and evaluate potential consequences (Oliver and Twery, this volume). The fourth section of this chapter focuses on tools. In our usage, a *decision support system*, in contrast, is a software application that provides an integrated environment in which a collection of tools can efficiently be used together to manage a larger portion of the overall decision process. Section 6, Examples of Decision Support Systems, briefly summarizes attributes of some major systems that have been developed in the past 20 years. None of these systems, however, address more than a portion of the complete decision process.

3.1 Need for Decision Support Tools and Systems

Land and wildlife management and related social issues are complex. The issues have many facets, and ecosystem processes are complex and interrelated. Not all issues are well defined and not all ecosystem processes are understood. Mathematical concepts, knowledge of wildlife, habitats, geography, and other fields are based on many decades of accumulated experience. The current trend is for interdisciplinary teams to examine the issues and ecosystems using all available data to recommend a series of actions and alternatives to resolve the issues. For this type of effort, decision support tools and systems can be very useful.

3.1.1 The NEPA Process

Federal agency decisions must go through a process outlined in the National Environmental Policy Act. Section 102 of the Act contains action-forcing provisions. Each federal agency has expanded the general procedures of the Act in departmental policies describing specific steps that agency decision-makers must take in a specific order. The Act outlines a format that federal governmental agencies must follow to evaluate the impacts of a particular project on a variety of themes. Themes include both natural (air quality, water quality, endangered species, wetlands, ...), cultural (archeological, historic structure, cultural landscape) and social (values and economics). The process involves identifying an issue, developing alternatives to resolve the issue, evaluating these alternatives based on impact, and selecting a preferred alternative. The alternatives and impact assessments are developed by interdisciplinary teams. The assessments may include a scoping phase, assessment phase, and plan development phase. Each phase may include a different type of public and technical expert involvement.

3.1.2 An Idealized Process

The steps described here reflect the progression of logical, scientific thought processes described by Oliver and Twery (this volume). This systematic and objective scheme is highly optimistic, assuming a relative lack of conflict, a high level of honesty, and a process relatively free of the confusing complexity typically found in situations involving land management. The process outlined in the paper therefore is presented as an ideal to be sought, providing ways to approach the objectives for decision-making in most federal agencies.

Use of a process that considers all essential elements of the problem is key to effective decision-making. Objective, systematic procedures have emerged in many management and engineering fields to ensure that various values are identified and treated fairly in the decision-making process. The process is useful if its limitations are known and appreciated, and if it is used appropriately. These procedures are generally incorporated into the planning procedures outlined by NEPA and generally follow the steps listed below, although at times steps may be combined or subdivided.

3.2 Systematic Steps in Decision-making

Oliver and Twery (this volume) describe many ways to make a decision; this section concentrates on the systematic steps and the decision support tools that are available and helpful. As outlined here, there are seven steps. Many decisions do not need such an elaborate process. Most decisions related to maintaining existing conditions fall into this category. Actions on a small scale also may not need an elaborate decision-making processes. Yet even when there may be an implicit consensus to maintain a situation, this too should be regarded as a decision (to do nothing) that should be subjected to review according to the steps outlined. And when a change in action is considered or new issue is dealt with, Step 1 becomes an important consideration.

3.2.1 Step 1. Identify the problem, decision-makers, their authorities, the stakeholders, and the decision-making process

Anyone who has participated in a truly inclusive decision-making process knows that the process can get very messy. Relatively new tools can facilitate communication and the sharing of information. *Groupware* can help in providing an equal footing and building consensus. The *Internet* can be helpful in exchanging and updating information, thus keeping all interested parties informed. And there are many tools for presenting information and visualizing data. Much experience demonstrates that no matter how good a specific decision is, if local people are not involved in a decision that impacts them directly or their lifestyle indirectly, they can force a change in the decision or, at a minimum, thwart progress by opting out of the process.

3.2.2 Step 2. Define the problem and refine the objectives

Although a great deal of attention is given to solutions, it is usually the *definition* of the problem that is the most important part of the decision process. Improper problem definition has resulted in many bad decisions. Recognizing the arena of the problem is important: is it political, economic, environmental, social—or all of these and more? To understand the full ramifications of a problem, *demographic analysis* and *groupware* may be helpful.

Exploring the needs of participants does not mean that complete consensus on goals for land management will be achieved or that everyone will agree on all objectives, but a full discussion of goals through a participatory, consensus-building process should help secure agreement among stakeholders and decision-makers that the targets are explicit and valid. This process, which can be aided by groupware, is likely to make the later steps in the process easier to complete. Other tools for refining problems and objectives include scoping, influence diagrams, decision trees such as that used in the analytic hierarchy process, and value models.

3.2.3 Step 3. Develop alternative actions to achieve the objectives

A creative step in decision-making is the generation of alternatives designed to address the problem by focusing on the objectives. If the decision has implications that may affect multiple stakeholders, broad participation from different interest groups is vital. An open process that encourages ideas from as many sources as possible is therefore crucial. In addition to groupware, tools that aid in this step are: *GIS map visualizations,* and *simulation modeling.* The benefit of these aids is often significantly improved by facilitation, perhaps by a professional who has no stake in the outcome.

3.2.4 Step 4. Compare each alternative with the objective

Predicted outcomes of implementing alternatives can be developed, and tradeoffs and consequences of each alternative can also be developed and compared. Predictions are commonly generated by *simulation models* (e.g., stand growth, habitat suitability, economic consequences, oil spill trajectories and others). Most such models were not specifically developed for policy analysis, so their use should be tempered with awareness of their limitations. Sensitivity, risk, and certainty analysis (Haynes and Cleaves, Cleaves et al., this volume) can help analyze outputs of these models and their reliability.

It is almost always a useful exercise to develop a table that compares alternatives according to their ranks or scores on each objective, even if is not possible to assign quantitative scores to each cell. Multi-objective analysis tools such as *goal programming* or the *analytic hierarchy process* can be used to further refine this basic analysis.

It is helpful to determine the likelihood that a given alternative will realize a given objective, and although group discussion may provide judgments, more sophisticated models based on research may be needed, especially if the group needs to examine consequences for particular communities. In developing these probabilities and weighted values, *groupware* techniques using *spatial analysis* models can be valuable in helping an interdisciplinary team of decision-makers and stakeholders to analyze differences and rank priorities. Value judgments and measures of uncertainty may need to be introduced when alternatives are evaluated against objectives. To build trust in decisions, presentation of comparative case studies can be helpful. For example, it may be possible to compare alternatives with the range of variation of actual management actions in the same type of ecosystem.

3.2.5 Step 5. Choose a preferred alternative

There are many ways to evaluate alternatives. Some objectives may be more important (or be held by more powerful participants) than others, and options that address such goals will probably rank high. Selection of a preferred alternative will probably not satisfy all objectives, values, stakeholders, and decision-makers. Nevertheless, if the attempt to select the alternative that most completely satisfies the most objectives is done in an open, creative process, it is generally more acceptable to the largest number of people. But it is ultimately the decision-maker that is responsible for choosing the alternative to be implemented. This needs to be understood at the beginning of the process.

It is important that decision-makers understand the tradeoffs and consequences of each alternative, as well as interrelations between alternatives and objectives. A matrix that shows these relations is convenient and helpful. Various *optimization* and *priority setting* tools are available to decompose more complex problems into simpler components. Analysis tools such as the *analytical hierarchy process, linear programs,* and *knowledge-based systems* may help.

3.2.6 Step 6. Implement the chosen alternative

It might be assumed that implementation of the selected alternative or alternatives follows the decision-making process, but such a perspective ignores the adaptive management philosophy that is fundamental to ecological stewardship (Everett et al. 1994, Holling 1978). Because every decision is itself an experiment, with unforeseen consequences as well as hoped-for results, new decisions will be required in the future. Indeed, a decision implementation process is itself part of the alternative scheme, and as such is subject to analysis.

In fact, there is no clear line between alternative selection and implementation. For some decision problems, the alternatives may be specified so precisely that selection of *what* action to take also clearly implies *how* the action should be implemented. In general, however, a decision about what action to implement does not necessarily resolve how it should be implemented. Moreover, while scientific understanding of natural and social systems has advanced tremendously in this century, we are still a long way from having neat algorithmic solutions to most real-world problems. As a result, professional judgment and experience are still highly valued commodities. Unfortunately, expertise is often in short supply. *Knowledge-based systems* have emerged as a powerful technology to deal with these realities.

3.2.7 Step 7. Monitor and evaluate

Stewardship is an iterative process. Each decision and its consequences provide the framework for future decisions, which themselves inevitably create, or fail to solve, problems that drive new decisions, and so forth. Monitoring resource conditions before and after a management action helps in evaluating the effectiveness of the decision and is an essential ingredient of the adaptive management paradigm (Bormann et al., this volume). Careful documentation of the decision-making process and evaluation of outcomes on a more or less continuous basis greatly improves our ability to manage natural resources and to communicate with concerned publics. A variety of systems (Section 6) provide some degree of integrated support for significant portions of the decision process.

3.3 Hypothetical Case Study: Habitat Fragmentation in Westcoe

A primary goal of ecological stewardship, particularly in park lands, wilderness areas, and refuges, is the maintenance and restoration of ecological diversity. At the same time, there are always strong pressures to increase resource utilization (visits, timber yield, animals grazed, ounces of gold mined). The greatest challenge facing managers of these lands is degradation from increased use and development. The goals of ecosystem sustainability and resource utilization conflict, and therefore require an approach that recognizes that tradeoffs are necessary between the economic and social forces of development and accessibility, and the biophysical forces of complexity and diversity.

This section presents a hypothetical case study in which a group of land managers and stakeholders, using the seven-step scheme presented here, designed a decision process for restoring habitats within a large region.

Step 1. Identification of the setting

Problem identification

Westcoe is a large, roughly rectangular region about 100,000 km^2 in size and wholly or partially containing the habitats of many small animals and several large species. Equally important, Westcoe also spans the jurisdictions of numerous governments and several federal land management organizations (national parks and forests, etc.).

Although a formal process of problem identification was undertaken in step 2, the study team (a loose association of managers, scientists, and citizens) explored the problem of habitat fragmentation early on by sharing ideas, reading a few key articles and book chapters, and communicating with their wide network of contacts in government, industry, and academia.

This open-ended group of participants determined that habitat fragmentation was a problem that existed in space and time, and that it could be measured by monitoring species diversity. There was much anecdotal as well as documented evidence that some species in the region had disappeared and that others were on the decline due primarily to the absence of sufficiently large, contiguous areas of undisturbed land. The most recent concern was over the welfare of the spotted rat, whose main source of food was the nut of the purple pine, which was most abundant in large undisturbed patches of relatively old forest.

The first decision was to examine environmental conditions within a large rectangular region sufficiently large to encompass key ecosystems within which the largest animals were found. This preliminary data-gathering activity was open-ended and also helped to suggest human organizations that would need to participate in the decision process.

Decision-maker identification

In the process of studying the problem, the team compiled a list of all of the people (officials, executives, landowners, land-users) who probably had some capacity to influence the state of animal habitats in the region. This list was structured according to a rough scale dimension, with some decision-makers having more control (over a wider area or for a longer time period or over more resources) than others. These decision-makers were invited to participate in a series of workshops covering the decision process steps. The workshops were open-ended and meant to define the problems and identify people who might have ideas to contribute.

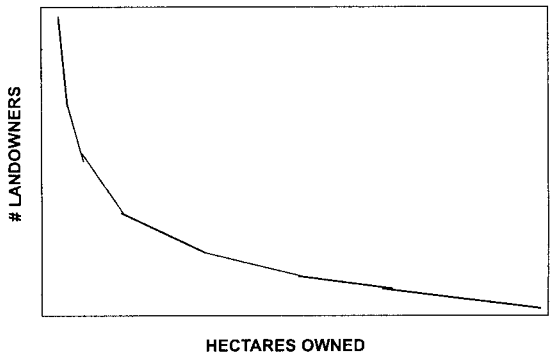

Fig. 1. Number of landowners versus size of ownership.

The key decision-makers in the Westcoe region were forest and park superintendents as well as the largest landowners (those owning more than 1,000 hectares apiece). As usual, this distribution of land-ownership/control was highly skewed, with a few decision-makers controlling a lot of resources and many individually controlling little (Fig. 1).

Stakeholder identification

Beyond the decision-makers are stakeholders: those people who might have some stake in the problem of habitat fragmentation (people concerned about the welfare of the animals) as well as any people whose welfare might be affected by efforts to address the habitat problems. Although typical decision-makers were to be found at the right end of Fig. 1, typical stakeholders were at the left. An initial list of decision-makers and stakeholders was drawn up with the idea that the list would be expanded as participants identified others and as word of the workshop spread.

- At the very beginning of the process, the facilitators obtained consensus about and broadcast several key rules of the process:
- Participants would be open-minded and respect one another's differences.
- A win–win atmosphere would be more productive than one in which competition was used to gain advantage.
- Effort would be made to work out disagreements and not railroad decisions.

Exploration of the decision-making process.

It was not enough simply to list and contact people relevant to the problem; information was also needed about how the ecosystem worked and how land use was planned. In effect, the list of decision-makers and stakeholders was structured into a process that explained who controlled what and whose welfare was at stake. This preliminary study of the existing decision process helped to distinguish among such roles as responsibility, policymaking, implementation, authority, etc. Understanding the network of power relationships was not easy, but was regarded as vital to changing the way decisions were made.

One of the most difficult challenges faced in the Westcoe region was securing agreement that habitats were indeed being fragmented by land use practices. At the early stages of the process it was sufficient for participants to agree what fragmentation was, and that it might be influenced by local developments (clear-cutting, mining, subdivisions, road building, etc.). It was also important not to let people engage in blaming at this (or any other) stage, but simply to begin to understand the nature of the problem. Everyone needed to know that their ideas and concerns would be heard and that all would share in the available information.

Perhaps the most useful tool at this stage was the Internet and electronic mail. All communication was posted on a Westcoe home page and mailed to a freely available list of addressees, who were encouraged to share ideas, information, opinions, and facts. This electronic data was maintained by a neutral facilitator hired to work at a local community college. Those without electronic communication access were sent a monthly newsletter that summarized the digital traffic.

Throughout this process the emphasis was on openness and inclusion, so that no one would feel left out and everyone would feel that they had a stake in the outcome of the process. This stage took over a year, and helped to clarify positions but also establish a degree of trust and understanding.

Step 2. Problem and Objective Refinement

Problem definition

A second workshop was convened to discuss the nature of the habitat fragmentation problem. The participants heard presentations from ecologists on the structure and dynamics of habitats and from wildlife biologists on the history of key species in the Westcoe region. One hundred years of climate data and available maps and studies had been examined to determine that the most significant changes in the region were due to:

- logging of old-growth forest,
- road-building,
- agricultural development on about half of the land in the region, and
- the flooding of a major valley for an irrigation and power dam.

While there was no disputing these changes or the economic benefits prosperity they had brought to the region, there was considerable debate about what the impact of these changes was on wildlife. The group decided that a high-priority task was the development of a geographic information system (GIS) database for the region so that the area could be studied. A regional university was selected as the site for this database, which was to be accessible through the Internet. Although the system did not have the full functionality of a state-of-the-art GIS, the university staff was committed to providing information (maps, time series, summaries of research) in response to requests from the participants.

A critical component of the analysis done for the Westcoe region was a study of habitat fragmentation, which was shown to be a complex problem that involved a wide range of theoretical and technical issues [Santa Fe paper]. A small team of university geographers and park biologists studied the ecological diversity of the area and focused on where spotted rat nests had been found over the past six years. The nests appeared to be located within groves of purple pine trees at least 30 years old, below altitudes of 4,000 meters, and at least 2 km away from paved roads. A number of paper and computer maps of the area, as well as site studies, were used to produce a GIS habitat suitability map. This map demonstrated that habitat "patches" where such conditions existed had become smaller, less numerous, and more isolated since 1950, and that these changes threatened the survival of the animals. This team developed an interactive visualization tool that showed:

- where the animals were ranging now,
- where the conditions existed,
- how those conditions had changed during the past 100 years, and
- how future decisions might influence the welfare of the animals.

This analysis identified two key patches the rat depended upon, but indicated that the smaller patch was barely large enough to support the local population.

A side benefit of this process was that some of the more vocal and assertive participants realized that they would need to learn more not only about their region but also about the technology that was being used if they were to legitimately express their ideas and opinions. This common task faced by all helped to foster a sense of collegiality.

Exploration of objectives

Although several participant groups wanted to focus right away on "solutions" to the "problem," the facilitators were successful in getting people to discuss their vision for the region in terms of various objectives. At this point the discussion dealt with groups and objectives. Although the discussions were wide ranging, the overall structure was suggested by Table 1. that summarized the objectives of each group:

Table 1. Summary of Stakeholder Objectives

	Objectives			
Stakeholders	Jobs	Wilderness	Access	Spotted Rat Survival
Ranchers				
Farmers				
Backpackers				
Townsfolk				
Etc.				

The table was merely a framework for discussions that took place over 6 months and culminated in a 2-day workshop. One benefit of this table was that people saw themselves as being in more than one group, and sharing the objectives of other groups. Another benefit of this process was the realization that habitat fragmentation was just one issue facing the region and that the spotted rat was just one Westcoe species "group" that had been affected by the changes of the past 100 years. The various groups were coming to see themselves as part of a complex, interconnected whole; all of them—old-timers and newcomers alike—were in the same boat, along with the plants and animals of the ecosystems.

Step 3. Alternative generation.

A consensus arose that at least the spotted rat was endangered and perhaps facing imminent extinction in the region if it was not provided a sufficiently large and contiguous habitat within which to breed and find its favorite foods, particularly purple pine nuts. The rat, the pine tree, the larva of the wandering moth (a parasite of the pines), as well as numerous other plants and animals — including humans — were linked in a complex system including the physical environment, climate, soils, etc.

One year was spent collecting spatial and temporal data at multiple scales about the Westcoe region so that the participants could better understand the key factors influencing the welfare of the spotted rat. The data were organized into the GIS so that participants could view various interacting "layers" of the physical, natural, and human environment. Although the GIS could not be viewed interactively by all participants at

Table 2. Alternative approaches to the problem of rat survival

Alternative	Objective				
	Spotted Rat Survival	Wilder-ness	Access	Jobs	Cost
Cease Management					
Continue Current Practices					
Empty Dam					
Land Exchange					
Rat Zoo					
Wilderness Refuge					
Etc.					

distributed sites, electronic requests for information were filled by the university, and graphic output to them was put on the Internet.

Toward the end of this fact-finding process, a call went out over the communication network for alternative approaches to the problem of rat survival. At the beginning, a brainstorming process solicited dozens of ideas that could be expected to have some impact on the rat population, and a public meeting narrowed the discussion down to six, of which a few are shown in Table 2.

Step 4. Alternative Comparison

Each of the alternatives was first examined nominally: what would be the impact (positive, negative, neutral) on each of the values? A (usually public) cost was also added. After much discussion, the alternatives were then given scores from –2 to +2 to help rank the alternatives. The table was used for four things:

1. A comparison down the columns showed which alternatives best addressed each of the objectives.
2. A comparison across rows showed which objective was favored (or hurt) by each alternative.
3. Manipulating the scores helped the group see how sensitive the scheme was to the scoring system.
4. Comparisons with the stakeholder/objective table helped the group link alternatives to other groups and explicitly discuss which alternatives might be favored by whom.

These meetings were also supplied with carefully designed maps, images, tables, and graphs that had been produced by the geographers and biologists. The various groups were particularly excited by the interactive graphics that enabled them to visualize the consequences of the options. The three kinds of people involved in the Westcoe issue — scientists and technicians, decision-makers, and stakeholders — were formed into teams. Each team was essential to the study and policy process, and the decision tools could not function without technical, policy, and community inputs.

The table comparing each alternative with each objective was mainly a framework for discussion and a challenge to the participants to fill in the information that would enable them to recommend choices to decision-makers. This framework provided scientists and technicians with a challenge to develop models that could help forecast the results of choices, and to do this they needed to present information on the latest research about the way ecosystems work.

Two problems that particularly concerned the participants were time and chance:

- When would the effects of a given decision be visible?
- What were the chances that a given choice would have the intended effect?

Although there were no definitive answers to these questions, a tabular framework, coupled with intensive group discussions and exchange of ideas, helped the participants gain a sense of the costs, likelihood of success, and possible unforeseen consequences of a given alternative. Throughout the process, a constant stream of maps, time series graphs, and statements from the researchers circulated among the group for discussion and comment. Everyone was encouraged to contribute to the process and, because the above ground rules were observed, almost everyone did add something to the debates.

Step 5. Alternative Selection

Obviously it was too much to expect that a single alternative would be found to be preferred by all participants. Some people had more at stake than others, some had more authority or control over more resources, and some groups were better organized. The links among groups, objectives, and the alternatives generally made it clear who would prefer which option, but the open debate about values, preferences, and stakes helped participants understand the mutual needs of the people involved and appreciate the concerns of neighbors, officials, those with a long history in the Westcoe region, and so forth.

After a long period of discussion, the group decided on a combination of three options:

1. Family A was given 25 years of grazing privileges on forest land in return for a contribution to the local conservancy.
2. Two land holdings of roughly 1,000 hectares owned by one family were bought by a local conservancy and added to the smaller habitat patch.
3. Plans for an additional dam upstream of the existing dam were to be reviewed because the reservoir was adjacent to a small, spotted rat habitat patch.

The GIS was a central tool in this decision-making process. Participants became quite adept at using some of its capabilities, not only panning and zooming around the region, but also examining buffers, techniques for weighting data layers, and querying statistics about habitat patches. A side benefit of this process was the significant increase in computer literacy, especially among several young people from small towns where job prospects were limited. Also, a few farmers intended to adopt some form of spatial database systems in their business management, as well as. Indeed, everyone seemed to agree that the ecosystem consisted of many animals — including humans!

Step 6. Alternative Implementation

The alternatives chosen consisted of a strategic package of options:
- further studies
- negotiations
- land exchanges
- improved communication systems
- education, etc.

Such a complex scheme obviously could not be implemented at once, so a plan was developed to oversee the process with each participant reporting on progress made. As participants became involved in the decision process they came to appreciate that any choice was an experiment and not a simple cause and effect sequence. In fact, their choices came to be viewed as part of an endless succession of experiments whose consequences were borne by the environment and its individual organisms. Every choice, no matter how small, was to some extent a leap into the unknown, except that in the Westcoe "laboratory" the unknown was at least being studied through the sharing of the best information available.

Step 7. Monitoring and Evaluation

The decision-making process broadened and deepened the sense of stewardship among the participants, who came to realize not only that choices were experiments but also that such manipulation of the natural and human environment required continual monitoring of the environment and evaluation of the costs and benefits of options selected. Even before any decisions were made, the groups were asked to consider at least three kinds of situations:

1. How to measure the direct benefits (e.g., for the spotted rat) of alternatives chosen.
2. How to foresee future indirect effects (e.g., for ranchers) from individual alternatives acting upon the environment.
3. How to envision synergistic effects of multiple alternatives (e.g., from irrigation and climate) working together within systems.

Participants in this process ultimately came to share a vision of ecological stewardship not as a single decision-making problem or even as a repetitive cycle of decisions, but as a process of choosing and monitoring at multiple scales with a shared sensitivity to the welfare of the landscape, plants, animals, and fellow humans.

Conclusions

The geographic information systems used in the Westcoe situation were valuable in all steps of the decision process. At the beginning, GIS was used as a management information system to simply keep track of the spatial, temporal, and textual data useful to groups and teams. And from the beginning of the process, GIS provided maps at suitable scales of many aspects of the environment, from demographics and roads, to satellite images and animations of habitat change. The GIS was also used to demonstrate simple "what-if" scenarios that showed, for example, how projected timber practices might impact future habitats. Finally — and here is where Westcoe made a significant scientific contribution — GIS was used to model habitat fragmentation as an intricate geometric and environmental process that could not have been understood without modern hardware and software.

The Westcoe issue was dominated by two kinds of complexity. First, the problem of habitat fragmentation was shown to be a highly technical issue requiring inputs from scientists, managers, and those who knew the region. It simply was beyond the resources and competencies of any one group. Second, the GIS technology was itself complicated to use and understand. Although the technical experts could "run" the models and make the maps, they needed inputs from non-technicians for their work to be of any value. This complexity required intense collaboration if the tools were to be useful.

Everyone was surprised at how long the Westcoe process took. Although some optimists forecast that the steps would require 18 months to follow, the actual time was over five years:

- Problem identification: 12 months
- Alternative generation: 9 months
- Alternative study and selection: 12 months
- Implementation: 18 months
- Evaluation: 12 months

4 DECISION SUPPORT TOOLS

This section provides an overview of several tools that are, or could be, used for decision support. Because this work is intended for a broad, diverse audience, discussion has been kept as nontechnical as possible. Our primary goal is to introduce managers to a variety of tools potentially valuable for ecosystem management. References at the end of the chapter should be consulted for detailed treatments of theory and application.

4.1 Introduction

To put the subsequent discussion of specific tools into context, consider the basic elements of the adaptive management process (Fig. 2). In a very real sense, public participation is central to the adaptive management process (Bormann et al., this volume). Public involvement may be somewhat limited in the implementation and monitoring phases, but it is generally critical to the assessment phase in terms of generating the key questions that drive an assessment. Similarly, public involvement also is critical to the planning phase in terms of developing socially acceptable desired future conditions for ecosystems. Section 4.2 focuses on enhancing public participation. In Section 4.2.1, we discuss use of the World Wide Web and related technologies both as a means to disseminate information to the public and as a means to get public comment. Section 4.2.2 discusses the use of groupware technology as a means to foster team collaboration in problem solving and as a collaboration tool in public meetings. Somewhat more broadly, section 4.3 considers a sampling of analytical tools that, while not specifically promoting public participation, can support the adaptive management process by helping management teams better understand public values and their basis.

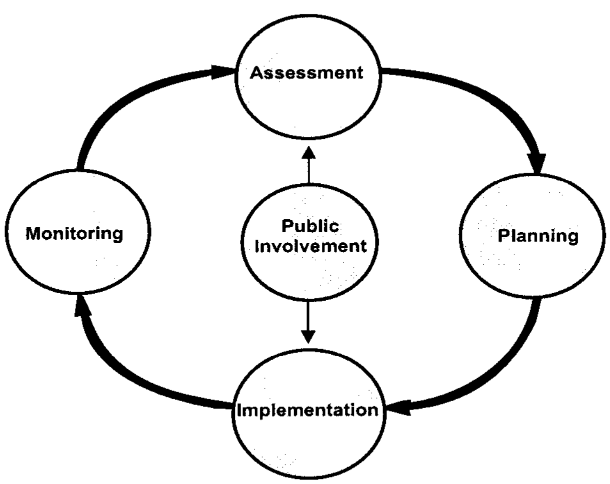

Fig. 2. The adaptive management process of ecosystem management.

Section 4.4 discusses two basic approaches to setting priorities, allocating resources, and selecting alternatives. Section 4.4.1 discusses linear programming and related technologies that have a relatively long history in the planning domain. In the vernacular of management agencies, it is not uncommon for managers to think in terms "making a decision." One has only to look at the regulatory language of agencies to see how this concept has been institutionalized. In reality, a process as complex as adaptive management contains hundreds or even thousands of decision points. In Section 4.4.2, we discuss the analytic hierarchy process (AHP) which can be used at many places throughout the complete adaptive management process (Fig. 2). In particular, the AHP might be used to select the key questions as input to an assessment, to select among desired future conditions as input to a planning process, to select among alternative methods for implementing features of an accepted plan, and to select among alternative monitoring programs.

Simulation and spatial analysis have come to be standard tools both in planning and implementation, and are discussed in sections 4.5 and 4.6, respectively. Sections 4.7 and 4.8 deal with a few less commonly used tools that may also be relevant to planning and implementation.

4.2 Enhancing Public Participation

A number of new technologies have greatly enhanced public access and exchange of information. Hypermedia, including the Internet and the World Wide Web, is perhaps the best known and fastest growing information access technology. Groupware technology facilitates more efficient group decisions by providing a new medium for the exchange of ideas and information.

4.2.1 Hypermedia, the Internet and the World Wide Web

The term hypermedia is used to describe an information system that has active cross-references that allow the user to jump to other parts of the system as desired. Access to information in a hypermedia database is therefore nonsequential. The requirement for active cross-referencing makes a computer necessary to implement hypermedia.

The Internet is a global network of computers that originated in the late 1960s as ARPANET, a system developed by government agencies to decentralize information resources and communications needed for managing defense contracts. The Internet now includes well over 10,000 commercial and research networks linked by a common set of communication protocols that allow users of any one network to communicate with or use the services located on any other interconnected network. Members of the Internet include universities, other research institutions, government facilities, and many corporations.

The Internet was not a particularly user friendly environment until the introduction of the World Wide Web (WWW) in the early 1990s. The WWW provides a relatively simple graphical interface to the Internet for browsing information on distributed sites. The WWW project, started by CERN (the European Laboratory for Particle Physics), has effectively built a globally distributed hypermedia system. The web is accessed with browser software such as Netscape, Lynx, Internet Explorer, and Web Surfer, that reads hypermedia documents using HTTP (hypertext transfer protocol) protocol, and can fetch and display other hypermedia documents from any other source connected to the WWW.

Accessibility

One of the most important features of the coevolution of hypermedia and the World Wide Web is their ability to greatly enhance access to information. Often, the problem is not finding information, or even building a place to store it, but rather filtering out useful from irrelevant or redundant information (Devlin and Berk 1991). Hypermedia currently comprise our most powerful tool for organizing and synthesizing the complex human knowledge base. Hypermedia systems have many advantages that make them well suited for creating and publishing almost any type of document (McKnight et al. 1991). Easy access, defined as providing information in a way that meets users' needs and allows them to move between chunks of information quickly and easily, may be one of the biggest advantages to placing information into a hyperbase (Schlumlienzer 1989). Hypermedia improve access by:

- Providing a single access system for material that, in print, is scattered in physical as well as logical space.
- Allowing lengthy text to be easily searched, edited, and pasted into other hypermedia documents (Martin 1990).
- Allowing writers to offer different outlines, called facets, of the same text material so that readers can choose among them for more flexible access (Bolter 1990).
- Allowing low-cost publishing and widespread distribution on CD-ROM optical disks (McKnight et al. 1991).

Hypermedia become a still more powerful technology when implemented on the World Wide Web. Many, if not most, federal and state agencies now have "home pages" on the World Wide Web that provide gateways for the many publics that are potentially interested in their activities.

Low Cost and Rapid Dissemination

Implementation of hypermedia on the World Wide Web has the advantage of low reproduction cost and rapid dissemination of updates, and offers the opportunity to integrate the three major electronic industries of computing, publishing, and broadcasting (Nielsen 1989). Updating, publishing, and distributing information in hypermedia can be made more efficient than using print media.

Education and Training

Hypermedia can be effective learning tools to the extent that they focus on the important relations between the concepts and the subject. The hope is that because hypermedia focus on structure as well as content, a deeper understanding of the subject matter may be imparted to the student (Shneiderman and Kearsley 1989). Hypermedia are useful for "just-in-time" learning because they allow the user to find required problem-related information quickly. Hypermedia may thus be used as an immediately accessible reference source to provide timely and useful information for solving specific problems in real time (Nielsen 1989).

Reduced Document Size and Complexity

The hypermedia environment is well suited for bringing large, complex bodies of information together in small physical spaces to emphasize the interconnectedness of knowledge (Slatin 1990). The ability of hypermedia to link large quantities of information makes it possible to combine related information that otherwise might not be combined. The best hyperdocuments are those that seem much smaller than they actually are because the user can access information quickly and easily (Martin 1990). Detail is hidden from the user until and unless the user chooses to view it. Thus, it is possible to include appendices, examples, background information, original sources, bibliographic references, and other reference material (Shneiderman and Kearsley 1989) without materially increasing the complexity of the hyperdocument the user sees.

Applicability

Hypermedia introduce two fundamental changes to knowledge management. The first is the capability to interactively store and retrieve large amounts of different types of information such as text, graphics, voice, and video (Shneiderman and Kearsley 1989). Hypermedia may radically alter the way in which we read, write, and organize our knowledge (M&night et al. 1991). The second fundamental change concerns new abilities to share information (Shneiderman and Kearsley 1989). Hyperdocuments, once begun, can be expanded and improved iteratively. Each iteration, possibly worked on by different people, can be more comprehensive and useful than previous ones.

Good hyperdocuments can store large quantities of data, information, and knowledge in a small physical package and a manageable conceptual space (Martin 1990). Access by searching and browsing is fast and easy. The advent of economical CD-ROM technology and gigabyte size hard disks makes it practical to work with extremely large sets of information. Documents that are information-rich, highly cross-referenced, or have complex, well-defined structure can benefit from conversion to hypermedia (Riner 1991). Some specific types of documents that are good candidates for hypermedia conversion are manuals (maintenance, procedure, operation, and programming), textbooks, tutorials, technical references, standards and guides, and reports (Martin 1990, Riner 1991, Shneiderman and Kearsley 1989).

The World Wide Web is now recognized as a powerful medium for effectively communicating an organization's mission, goals, objectives, and activities to a broad audience. However, the World Wide Web is more than just a mechanism for conveying agency information to the public. Among the communication protocols are specific methods for letting the audience respond to the organization. The system provides two-way communication. This basic capability can be the basis for creating questionnaires and other formats to accumulate input for development of alternatives and for setting agency priorities. The technology almost certainly will not entirely replace the need for conventional public meetings. In effect, however, it will expand the meeting room to include a much larger potential audience.

4.2.2 Groupware Technology for Group Decisions

There are two general approaches to group decision support systems (GDSSs). Each approach concentrates on a different skill:

1 Information management and exchange of information. This generally takes the form of a computer-based, workbench environment to facilitate group communication. Xerox Corporation has a conference room equipped with networked microcomputers flush with the table top. Each participant has his or her own computer terminal on which to create responses and add information.

2 Interpersonal communication. The emphasis is to create a group-centered problem-solving environment. The University of Arizona has a conference room with no evident technical devices, but such devices are available to the leader or facilitator, when appropriate, at the point of a laser beam. The room is oval with a smooth table top and white screens on all walls for writing. One of the screens is for slide/overhead displays and another for computer screen images. The emphasis is on facilitation of communication.

A good GDSS provides a balance between content, process and structure. It incorporates knowledge about how people make choices individually. Input is required from three disciplines: information technology, decision theory, and group process psychology. A GDSS helps a group make better, more acceptable decisions, build commitment in a group, and generate agreed-upon actions (Phillips 1988).

Features of a good GDSS include:

- problem centered
- process oriented
- deals with group dynamics
- sound modeling approach so results are believed and trusted
- flexible so changes in perspectives, problems, and issues can be accommodated
- adaptable to group needs (fixed rules or sequences of activities inevitably fail).

Group decision support systems are one approach to resolving conflicts. GDSSs use information technology to help groups of people consider uncertainty, form preferences, make judgments, and take decisions. GDSSs use information technology, both computers and telecommunications, to increase the quality and productivity of group decisions. The computer is used to communicate ideas, access data, calculate results, display findings, and store information. The use of structured meeting procedures helps to generate ideas, rank alternatives, and make decisions. Use of this technology, in conjunction with a skilled facilitator, can improve the efficiency and quality of the decision process, and improve the likelihood that all participants will walk away from the experience satisfied with the process and its outcome.

The structure has explicit steps to define the issue and then to create, organize and rank the alternatives. IBM found that a GDSS approach in 30 meetings saved more than 55 percent of the projected person-hours in meetings. Boeing Aircraft Corporation saved an average of 90 percent time on a range of team projects using GDSSs.

GDSS technology is most appropriate for small- to medium-size groups. It is best used in an environment in which the players are willing participants who have come together with a reasonably well-defined sense of purpose.

There are four classes of meetings appropriate for GDSS:

1. same time/same place (face to face)
2. same time/different place (teleconference)
3. different time/different place (computer conference)
4. different time/same place (shift work)

One assumption is that human interaction is the prime component of a good meeting and that introducing too much structure into the process can inhibit the interaction. Standard meeting processes such as brainstorming, organizing the results, and voting on the outcomes can be developed before the meeting.

4.3 Understanding Public Values: Demographic Analyses

The chapters in this volume on "Public Expectations and Shifting Values" (Bliss; Cordell et al.) and "Cultural and Social Diversity and Resource Use" (de Buys et al., Raish et al.) emphasize the need of land managers to understand the attitudes, needs, and aspirations of their publics if they are to provide effective service. Results of well-designed and well-implemented surveys provide valuable raw material for obtaining that understanding. In this section, we describe a few statistical methods relevant to analysis of demographic data and data on public values. Much of the motivation for development of these methods actually originated in the social sciences because potentially complex relations among numerous groups and factors tends to be the norm rather than the exception in demographic analyses.

4.3.1 Cluster Analysis

The goal of cluster analysis (Cooley and Lohnes 1971) is to identify clusters or groups of observations that share similar characteristics. In a later section, we discuss discriminant analysis as a means of classifying cases into groups. In discriminant analysis, group membership is known beforehand and the focus of analysis is on identifying variables that can predict group membership. In cluster analysis, on the other hand, groups are not known beforehand, and the focus of analysis at least initially is simply identifying logical groups on the basis of the variables used to characterize an observation from the population being sampled. Cluster analysis has been used in a wide variety of contexts (Romesburg 1984). For example, cluster analysis has been used for identifying symptom groups in medical diagnosis, and target groups in marketing. It has frequently been used in biology to classify plants and animals (Gauch and Whittaker 1981).

4.3.2 Canonical Correlation Analysis

Suppose we have survey data that includes demographic information about some segment or segments of a population, as well as metrics that express their values, interests, attitudes, etc. There are thus two domains of information: demographic and value (or attitude). Canonical correlation analysis can be applied to describe the degree of interrelatedness of information in the two domains (Cooley and Lohnes 1971, Stewart and Love 1968, Miller 1969). Aside from being an analytical tool in its own right, canonical correlation also provides a basis for a number of other analyses. For example, canonical correlation is used in multivariate analysis of variance (discussed below).

4.3.3 Factor Analysis

Factor analysis is a statistical method used to identify a small number of underlying factors that effectively summarize inter-relations among a potentially large group of variables (SPSS 1993). For example, a combination of survey and census data might contain 50 to 100 variables associated with such concepts as community involvement in resource management planning, urbanization, industrialization, prosperity, education, environmental awareness, etc. None of the latter concepts can be directly measured by a single variable. Instead, each concept can be thought of as an abstract entity (e.g., a factor) that underlies a set of related variables. Similar to multiple regression analysis, a factor analysis yields a model of the form

$$\text{comminv} = a\,(\text{urban}) + b\,(\text{industr}) + c\,(\text{prosp}) + d\,(\text{educ}) + e\,(\text{envaware})$$

in which *a–e* are coefficients used to combine factors, and names for factors have been abbreviated.

There are two basic objectives of factor analysis. The first is to reduce a large number of variables to a small number of factors. The second is to obtain factors to which we can attach some meaningful interpretation. In general, the factors are not known ahead of time; they are a product of the analysis.

4.3.4 Multivariate analysis of variance

In canonical correlation analysis, the focus of the analytical method was on understanding the interrelatedness of two sets of variables (e.g., demographic and attitude variables). In multivariate analysis of variance (also referred to as MANOVA), we are likewise interested in these relations, but with the additional consideration of groups (SPSS 1993). Suppose, for example, that we have survey data that contain demographic and attitude data as before, but now we also have an additional variable for each observation that identifies the survey respondent as belonging to one of several groups. The groups, for example, might indicate particular categories of forest resource users. In the canonical correlation analysis, neither variate domain was explicitly considered to be either the dependent set or independent set.

For the MANOVA analysis, we need to recast the problem slightly. Here, we will treat variables in the attitude domain as the dependent variables. The primary class variable (independent variable) of interest in the MANOVA is the group. However, other variables in the demographic domain might be of interest as either additional class variables or covariates. A variable such as income might be included as a continuous covariate or transformed into categories such as low, medium, and high for use as a class variable. With these modifications to the problem, we can pose such questions as:

- "Is attitude in general related to group or other class variables?"
- "Are all groups different with respect to attitude, or do some share similar attitudes?"
- "Are attitudes consistently different by group, or are some independent of group?"
- "Are there significant demographic covariates?" and
- "If there are differences in attitude among groups, what are they?"

These are just some of the basic questions that might be posed. An important point here is that the types of questions addressed by MANOVA are virtually identical to questions typically addressed with the more familiar analysis of variance (ANOVA). In fact, MANOVA is simply a generalization of ANOVA for problems in which there are not one, but multiple response variables that need to be considered simultaneously. Alternatively, ANOVA can be thought of as a special case of MANOVA.

4.3.5 What Are These Analyses Good For?

While simple statistical summaries of survey data can certainly yield useful information for management, more sophisticated analytical methods will often provide a much more complete understanding of the information. Pairwise correlations between individual demographic and value measures are certainly of interest, but if there are, say, 10 measures in each of two domains, the manager has to evaluate 100 separate correlations when considering how a variable in one domain is related to a variable in the other. Moreover, within each domain there are 45 more correlations that describe the inter-relatedness of measures within the domain. Developing useful generalizations from all this information would be a challenge, and if the manager also wanted to draw useful inferences from the information, there is a basic statistical problem of correlated responses.

To understand the value of statistical tools that reduce the dimensionality of data, suppose we have two observations *i*, each with a value *x* and *y* associated with it. The two *x–y* pairs can be plotted in two-dimensional space in the good old Cartesian coordinate system and we can easily visualize the spatial relation of the two plotted points. It is a bit more work, but plotting and visualizing the spatial relations of *x–y–z* triples is also not that difficult. On the other hand, if we have survey data with 10 values for demographic information and 10 values for value/attitude information associated with each survey observation, our problem now has 20 dimensions. It is virtually impossible to visualize relations among values in such a high-dimensional space. Each of the methods we have been discussing in this section reduces the dimensionality of the problem to few manageable dimensions whose meaning can be understood in terms of the original variables.

4.3.6 When Is Demographic Analysis Appropriate?

Virtually all managers need to deal with diverse groups of publics. Often there are easily recognizable interest groups to which we can attach a name such as environmentalist, timber company, etc. Among a large collection of groups, the boundaries may not always be so clear. Moreover, the individuals that compose a group might be characterized by a wide array of demographic descriptors such as urban/rural, education level, income level, etc., as well as a wide array of values and attitudes related to such things as protecting resource values, using resources, recreation, and spiritual concerns. We have only scratched the surface. For any given situation in which demographic analysis might be useful, there are typically numerous groups, demographic characteristics, values, and attitudes that potentially need to be considered. How does a manager begin to sort out all these relations?

The general prototype situation we have just described is complex, but also quite common. Simple univariate statistics may shed some light on relations among groups, demographics, and attitudes, but these statistics will generally provide an incomplete, or even incorrect, picture of these inter-relations. The problem is that demographic and attitude measures tend to be inter-related both *within and among* sets. A statistically valid approach to sorting out these dependencies generally requires multivariate analytical methods. The term multivariate may sound formidable, but it's really a simple enough concept. Univariate analysis is concerned with a single response (dependent) variable. For example, univariate regression analysis can be used to develop a model that predicts the weight of an individual as a function of height. If, instead, however, we wanted to predict both weight *and* chest measurement as a function of height, the situation is no longer so simple. We could obtain a univariate regression model for each of the two response variables, and people often do this. However, the two models are not independent of one another. The parameter estimates will be correct, but the statistical tests of significance will be incorrect because the two separate univariate regressions do not take account of the very probable correlation among the two responses. For this case, we need to use multivariate regression.

4.4 Setting Priorities and Selecting Alternatives

Decision-makers are faced with the dilemma of how to allocate scarce resources to achieve goals such as maximizing profit from timber harvesting, maximizing wildlife habitat, minimizing travel distance, and maximizing recreational opportunities. Often these goals are conflicting. Usually there are a large number if not an infinite number of possible solutions. Sometimes there is more than one solution that can provide either the same or a close objective function value.

4.4.1 Linear Programming and Related Methods

A decision-maker's first step is to define the problem and then translate this definition into mathematics. The goals are expressed as functions of the decision variables, or activities. The goals are called objective, criterion, or cost functions. Usually, but not always, there are additional constraints that must be satisfied. The decision variables in the cost and constraint functions have a coefficient that indicates the value of the decision variable in the function. The constraints have a bound which they must either meet exactly, not exceed, or exceed. An example of an optimization problem might be to maximize the habitat for a wildlife species. This is the goal. The decision variables might be individual stands of trees. There might be a constraint on the amount of harvesting and another constraint limiting the habitat for predators of the protected species.

The linearity and nonlinearity of the objective and constraint functions as well as the nature of the coefficients determine the applicable optimization procedure. The most commonly used of all optimization procedures is linear programming. A linear program has a single objective function, which is a linear function. The constraints are also linear functions. The coefficients are assumed to be known precisely. Very large problems can be solved using linear programming. A medium-size problem has 5,000 constraints and 20,000 decision variables. An advantage of linear programming over other optimization techniques is that it allows the decision-maker to perform sensitivity analysis. Questions concerning the impact of a change in the cost coefficients, in the bounds, in the constraint coefficients, or the addition of a new constraint or decision variable can readily be answered. A solution to a linear program will terminate with a single optimal solution, an alternative optimal solution, or no solution. For these reasons, many nonlinear problems are put into a linear programming format.

A nonlinear programming problem is characterized by a nonlinear function either in the objective function, the constraints, or both. The coefficients are known precisely. Integer and mixed-integer problems require either all or some of the decision variables to have an integer solution. The coefficients are known precisely.

If there is more than one objective function, then the problem is a multiple objective program. A problem in which the coefficients are not known precisely may be solved either by stochastic programming or fuzzy programming.

Many problems in ecosystem management may be formulated as network or a graph. A network consists of points connected by lines. For example, the vertices could represent forest stands and the lines could represent wildlife corridors between the stands. Many network problems can be formulated as linear programs. However, there are more efficient techniques available to solve network problems. Large network problems can easily be solved on the computer.

Dynamic programming is not a technique or an algorithm. Rather it is an approach to formulating a problem and structuring its solution. Each problem is unique. Problems are broken into a series of consecutive stages. Decisions are made at each stage based on the principle of optimality. Dynamic programming can find optimal solutions to problems under conditions which another procedure would fail. However, the size of the problems can easily become intractable. This is called the “curse of dimensionality.”

More and Wright (1993) provide a listing of software packages for many of the procedures described above.

4.4.2 What Is the Value of Linear Programming and When Is It Appropriate?

Solving large-scale, complex problems is a major issue in land management planning. For each forest management unit, the decision to harvest, thin, or do nothing, affects wildlife dispersion and migration. A harvest plan that is as little as one percent from the optimal can equate to millions of dollars of lost revenue. With the current emphasis on biological diversity and spatial habitat modeling, optimization software will play a major role in land management decisions. Computers can evaluate large numbers of decision variables and constraints that could not be evaluated otherwise. This gives managers information on how to prioritize and allocate their scarce resources.

The Ecosystem Management staff of the USDA Forest Service developed SPECTRUM to model alternative resource management scenarios across landscapes and through time. Its primary application is scheduling vegetation activities. SPECTRUM may be used for management of other resources. It uses the linear programming solver C-Whiz from Ketron Management Science. With the purchase of additional software, problems requiring more complex mathematical formulations such as multi-objective and mixed-integer programming may be solved.

SARA is a set of programs and templates for matrix generation and report writing to build and evaluate solutions using linear programming models of forest ecosystem planning. Alternative solutions are built from the bottom up within a commercial spreadsheet such as EXCEL. SARA can be connected to a GIS and related databases. It is widely used to determine economic-ecological tradeoffs.

Hof and Raphael (1992) used nonlinear programming to investigate three approaches for finding the optimal allocation of forest age classes to meet multispecies conservation objectives for 92 species of amphibians, reptiles, birds, and mammals. Each species has a viability function, which is nonlinear. The constraints were linear.

Sessions (1992) modeled the habitat connection problem using graph theory. Some stands are identified as critical wildlife habitat. These stands are surrounded by other stands that are eligible for cutting, but there must be corridors left for wildlife. The solution to this problem is part of the SNAP II software package.

Anderson and Bare (1994) and Pelki (1994) both used aggregation procedures to overcome the “curse of dimensionality” in dynamic programming. The problem they examined involved tree thinning and harvesting. Tree basal area, average diameter, number of trees and volume per acre were used as stand attributes. Growth models were used to grow the stands through time.

4.4.3 The Analytic Hierarchy Process

Decision-makers are often faced with decisions that have alternatives which include both quantitative and qualitative characteristics. Saaty (1989) developed the analytic hierarchy process (AHP) in the late 1970s as a tool to aid decision-makers in structuring and prioritizing alternative choices in a decision-making environment, conflict resolution, and group decision-making (Mendoza and Sprouse 1989, Saaty 1989). The practicality of the method has lead to its widespread use for solving difficult decision problems in a wide diversity of fields such as economics, finance, budgeting, purchasing, health, medicine, manufacturing, education, sociology, transportation, planning, energy policy, resource allocation, and environmental problems (Vargas 1990, Zahedi 1986).

4.4.4 What Is Its Value?

Decision-makers have many tools for analyzing the quantitative characteristics of decision alternatives, provided some common metric of comparison can be obtained or developed. However, qualitative characteristics do not lend themselves to the same kind of analysis, nor has it been possible to compare and contrast alternatives based on the merits and foibles of qualitative and quantitative characteristics. This situation has lead many decision-makers to one of four alternative solutions to their decision problems, each of which has drawbacks:

1. confine the decision space to those characteristics which can be easily quantified,
2. devise a surrogate quantitative metric that can be applied to qualitative characteristics and inserted into the chosen quantitative decision model,
3. resort to a decision process that incorporates available information in an expert group decision process, such as the Delphi method, or
4. the decision-maker's own experience and intuition.

Solutions 1, 2, and 4 are viewed as arbitrary and unfair by interested parties who disagree with any resulting decisions and have a vested interest in the decision process, while the third is viewed as inefficient and expensive. All four solutions are viewed as exclusive and subjective by any who dislike the decisions produced by the chosen method.

The AHP was designed to assist decision-makers where not all aspects of the decision are directly quantifiable. This method has been applied extensively to many forms of decision-making problems during the past 10 years, and the literature has grown large as well. The method is relatively easy to understand and apply. The hierarchical structure of AHP helps decision-makers better understand the decision problem they are facing. Its advantages include emphasis on simple, pairwise comparisons of criteria and alternatives, its relatively straightforward solution method, and its overall simplicity. The AHP also is supported by a commercially available software product, which has greatly expanded its use and usefulness.

One of the fundamental assumptions of the AHP is that decision-makers are inconsistent in their values and judgments concerning decision criteria and alternatives (Zahedi 1986, Mendoza and Sprouse 1989). The AHP employs a measurement of this inconsistency, which can help the decision-maker learn more about the decision in question and about his or her own biases and inconsistencies (Zahedi 1986, Mendoza and Sprouse 1989, Lane and Verdini 1989).

Zahedi (1987) describes the melding of the AHP with utility theory, and concludes that in many cases the AHP will maximize the underlying utility function. Trueman (1977) defines utility as "a subjective numerical measure of the value of an act to a decision-maker when a particular event occurs." A utility function describes this value.

Zahedi (1986) describes a number of possible modifications to the AHP. Among these are the extension of the hierarchy formulation stage to time-dependent and dynamic structures, development of sensitivity analysis of the hierarchy structure, and the extension of the input data range from ((l/9) – 9) to an unbounded range. Many alternatives to the eigenvalue method have been suggested for the estimation of relative weights.

4.4.5 When Is the AHP Appropriate?

The AHP has been applied to many decision problems in many different fields of application. Vargas (1990) and Zahedi (1986) provide extensive references. Some applications of the AHP that have relevance to ecosystem management are described in the following paragraphs.

Azis (1990) describes an application of the AHP in evaluating the impact of the Trans-Sumatra Highway, after it was completed, from the perspective of local people from four provinces on the island of Sumatra. Two hierarchies were established, one for perceived positive impacts of the highway and one for perceived negative impacts. Impacts of the highway were then surveyed separately in the four provinces. The purpose was to determine how local people felt about the impacts of the highway, and what strategies should be followed for further development of the region.

Three alternative strategies (status quo development, push agricultural activities, and balanced growth) were used as the bottom levels for each of the positive and negative hierarchies. The AHP was applied to each of the hierarchies for each province. Finally, once the research team had ascertained the public's perceptions of preferred strategies, a benefit–cost (positive *vs.* negative) ratio was computed for each province by dividing the composite weight for each alternative strategy for the positive hierarchy by the composite weight for its associated alternative strategy for the negative hierarchy. The highest benefit-cost ratio was deemed the most desirable strategy for that province.

Mendoza and Sprouse (1989) describe the use of the AHP in the context of a forest planning problem. The planning process described is a twostage process in which fuzzy linear programming (an extension of linear programming employing the concepts of fuzzy set theory) is used to generate forest plan alternatives, and then the AHP is employed to evaluate and prioritize these alternative plans.

This approach differs in two ways from the current forest planning process. First, this fuzzy linear programming allows the decision-maker or modeler to establish levels of aspiration for achieving objectives, rather than requiring the absolute attainment of objectives as in standard linear programming (Mendoza and Sprouse 1989). This leads to a philosophy of satisfaction rather than the standard philosophy of optimization. Second is the use of a decision-modeling approach (AHP) to selecting the most desirable alternative plan developed by the fuzzy linear program.

Hämäläinen (1990) describes the use of the AHP in public debate over the future use of nuclear power in Finland. In this application, two prominent public personalities (one a government official opposed to nuclear power generation, the other a private corporation executive in favor of nuclear power generation) were extensively queried on their preferences towards future electrical generation options for Finland. Identical hierarchies were established for each participant, and each was asked to work through the AHP process to obtain personal priorities for electrical generation options. The entire process took place in a public forum, with the two participants failing to agree on the nature of the decision in question. This study was useful in pointing out which of the issues in the debate were important and which were not worth debating. Another important finding of this study was that specific questions about social issues (e.g., electrical energy sources) cannot be debated effectively until "the more general questions about the future of the society as a whole are resolved" (Hämäläinen 1990).

Zahedi (1990) describes the use of the AHP for evaluating and selecting expert system tools. Since many expert system tools are available with widely varying functionality and no standard means of comparison, this is an appropriate use of a formal decision analysis method. The author enumerates in detail the steps involved in formulating an AHP problem, as well as many of the differences in functionality of the many kinds of tools available.

Many other applications of the AHP can be found in the literature. One issue of the European Journal of Operational Research (Vargas and Whittaker 1990) is dedicated completely to the theory and application of the AHP, as is one issue of Mathematical Modeling (Saaty and Vargas 1987).

4.5 Simulating in Time and Space

Simulation has been used for some time to model such phenomena as forest growth, fire ecology, hydrologic impact, climate, plant growth, vegetation gaps, nutrient cycling, wildlife habitat, and almost anything else of interest to land managers. This section describes and evaluates the simulation world, concluding with a few examples.

4.5.1 How Is Simulation Used?

Simulation models are used when we need to *fabricate a situation* or estimate a value that we may be unable to measure. Typically, this situation is some time in the future, such as simulating the look of a forest after different harvesting techniques have been employed. Simulation is also employed to estimate and understand processes and phenomena in the present time period as well—for example, when there isn't the time or money to measure every tree or deer or visitor but information is needed for projection models or management decisions.

Simulation allows us to replace simple assumptions (the population of Wyoming will continue to grow at 1 percent per year) with understood relationships (immigration will slow after the year 2000). Our model of those understood relationships may be based on

- measured data,
- observations of similar situations in another location,
- the results of statistical analysis, or
- our understanding in theory of the processes at work.

Any decision support system will probably incorporate some kind of simulation model. In addition, simulation models in some form become components of other tools in this section, such as the "objective function" tools covered in the "Priority, Allocation, and Alternative Selection" section.

Simulation models may be used as *predictive* tools for estimating the value or response of an observation to different choices made, such as the response of stand characteristics to different management scenarios, or estimating the levels of future wood consumption based on population, economic indicators, and social trends.

Simulation models are also used for *extrapolating* a value of response beyond conditions within the range of measurement. The most common application is into the future. The population example above shows a simple use of regression to project U.S. demography.

Simulation models also help to fill gaps in knowledge and measurement by *interpolation* — in space, in time, or in the features associated with the particular area of interest. For example, models of evaporation require daily meteorological inputs such as air temperature, precipitation, and humidity at every location, but which are only available at fixed weather stations (Running and Thornton 1996). As another example, we can simulate detailed inventory variables for unmeasured stands based on our understanding of how similar they are to measured stands (Moeur and Stage 1995).

Finally, simulation can be a useful tool for *improving our understanding* about some phenomenon or process. For example, how do the dynamics of soil processes and the influence of environmental factors affect soil behavior and quality (DeGloria and Wagenet 1996)? Or, how might changes in climate affect the distribution of an insect pest such as spruce budworm or gypsy moth (Williams and Liebhold 1995)?

They are useful in *improving our theories* of how features and processes are related. Does a realization (i.e., the model output) coincide with our expectations or with reality? We may for example have a theory as to how a management scenario affects the visual impact of forest fragmentation on recreation areas. Simulating a future time period based on landscape design theories and comparing those results to what really happened will tell us a lot about how correct our theories about the processes at work really were.

4.5.2 When Is Simulation Appropriate?

The usefulness of simulation depends upon several characteristics, particularly:

- How applicable is a model to the situation in which it is being applied?
- How easy is it to get the data required by the model?
- How sensitive is the model to uncertainties in that data?

Making the assumptions of a model explicit will help determine its appropriateness to a given situation. For example, if a simulation of how forest debris accumulates in ponderosa pine stands comes from detailed observations made in Oregon, an ecologist in Wyoming needs to know how applicable these conditions are to her wildlife refuge.

Simulation occurs in space, time, and scale dimensions. Some models are based on detailed studies of small patches (say of a polluted beach) and may not be appropriate for large regions (say an oceanic gulf) without significant modification. A model that does not allow the user to modify its characteristics to suit a local situation is not appropriate.

A manager should also be clear about the need for reliability. Simulation predictions may yield ‘best estimates’ of what we know about the responses of resource elements to their environment, but uncertainties may be too large for a given situation. For example, a manager might not want to use a wolf survival model that was calibrated on large numbers of animals in Russia to predict the prospects for small packs in Montana.

Sensitivity is a good guide to appropriateness. If small, seemingly subtle changes in the value of a simulation parameter yield significantly different output results, then predictions may not be reliable, especially if the parameter is difficult to measure. If both the sensitivity and the uncertainty associated with that variable are high, the model results have the potential to be misleading at best.

4.5.3 Conclusions

As modeling, simulation, and geographic information systems (GIS) develop together at an increasingly rapid pace, managers have access to sophisticated technologies for processing, analyzing, and visualizing vast amounts of digital data. The bad news, of course, is that there are ever more tools of ever increasing sophistication, and no one can know which system is appropriate in a given situation. The good news is that this enrichment is forcing scientists, technicians, and managers to work more closely together and to bring knowledge, experience, and judgment to bear on critical environmental issues. We conclude with the observation of a GIS leader (Goodchild et al. 1996, also see www.ncgia.ucsb.edu):

> Contemporary simulation modeling emphasizes cross-disciplinary approaches in which atmospheric, hydrologic, and ecological models can be linked across various space and time scales to investigate, understand, parameterize, and predict interactions between the biosphere and other Earth systems. Such modeling features the need for scaling up from plots to regions, or scaling down from the glove to river basins, ecosystems, and watersheds.... Increasingly, these advance modeling approaches are being used to support decision-making related to land and water resource management, air-quality analysis, ecosystem vulnerability assessment, and environmental risk studies.

4.6 Analyzing Spatial Information With Geographic Information Systems (GIS)

Almost all decisions in natural resource management have some spatial component. A geographic information system (GIS) is a tool that organizes data spatially (Burrough 1986, Maguire et al. 1991, Quattrochi and Goodchild 1996, Raper 1989, Rhind et al. 1992, Star and Estes 1990). A GIS can access data spatially and provide a means for its capture, storage, retrieval, transformation, manipulation, visual inspection, comparison, and analysis. A broad range of computer systems has been developed under the label of GIS. At one extreme, GISs are essentially only computer-aided mapping packages. Others contain substantial capabilities for the manipulation and analysis of spatial data. And increasingly, GIS engines are being customized to incorporate a wide variety of sophisticated capabilities such as modeling, enhanced presentation, and geo-statistical analyses, although these are still only infrequently available commercially.

Management is concerned with influencing phenomena in space and in time. Because GIS addresses the organization, management, and analysis of data in space, it can be a most useful tool in the land use planning/land management process. With it the user can collect, organize, and access data spatially, selecting an object (or class of objects) because of its location or where it is in relation to another object. GIS can help with technical spatial problems such as computing distance between points or calculating and displaying slope and aspect. It can produce tables and maps of different scenarios and analyses, providing all parties in any planning process access to the same, easily updated information. In addition, forming questions that can be answered by a GIS can force clarification of what the issues in any planning task really are.

4.6.1 Visual/Spatial Presentation

Because data are spatially indexed, they can be presented visually in the form of attractive and informative maps. The attractive and clear display of data is not a simple task, but when well done, contributes to a better understanding of a decision problem (Tufte 1983 and 1990, Monmonier 1991, Robinson et al. 1984, Wood 1992, Buttenfield 1996, Hearnshaw and Unwin 1994).

GISs vary dramatically in the amount of cartographically intelligent 'defaults' provided to the user. These can take the form of a set of effective color schemes or symbol sets/sizes to choose from, or default font sizes, or even an on-line tutorial of recommended standards, approaches, and warning signs to help the user avoid creating misleading maps. Such defaults, whether set up by the vendor or the user, can be extremely useful.

4.6.2 Spatial Analysis

It is the capacity for spatial analysis, to subject data to some analytical exploration, that separates a GIS from a computer mapping system. With computer mapping, appropriate data can be selected and maps created automatically (frequently allowing many renditions of different information to be mapped quickly), but the analysis is done entirely manually. With a full-featured GIS, the capabilities of the computer and the structure of the spatial database can be combined to generate new and useful information. Spatial and attribute models can be developed from existing knowledge and run on the layers of data. Examples include analyzing bands of satellite data to create an index of vegetation, or combining stand species composition and stand structure to create a habitat suitability index for a particular wildlife species. Such analyses frequently reveal information about the area and relationships between different variables that would not be apparent by simple visual inspection alone.

4.6.3 Spatial Data Organization and Management

A fundamental use of GIS is for the organization of spatial data, from complex topologically structured data, through huge satellite images, to simple tables of events. Almost every enterprise that operates in space needs a system to manage its spatial data. Most full-featured GISs allow basic data processing (such as getting all data layers in the same projection) and data query (such as selecting only those features that fit a certain minimum area criteria). They also allow the comparison of data that were collected, or are only available at, different spatial units or at different locations (for example, data from two sources that otherwise could not be directly compared because one is population by census tract and the other is plot locations of recreation sites). Another example would be two ground inventories, one of soils and the other of vegetation, that were taken at different times and locations.

4.6.4 When Is GIS Appropriate?

Using a GIS would be appropriate' when visualizing information spatially would support the planning process. For example:

- Where does this particular habitat of interest occur, and in relation to what ownerships?
- Where are the spruce/fir forest types in relation to the current occurrence and spread of budworm?
- Where are the abandoned mines?
- Where are the elk territories?

A GIS is also appropriate when spatial relationships between things need to be identified and/or calculated. For example:

- Where are the occurrences of a particular species habitat, how are they connected, and are there any completely isolated and farther than 100 m from another?

- Where are particular endangered habitats in relation to areas of high human traffic, and are there any occurrences within 1/2 mile of each other?

Other applications include when the spatial properties of something are of interest. For example:

- How big is the area between the roads that is proposed for purchase?
- How much area would a 100' buffer around the stream encompass?
- How many occurrences of a particular habitat are greater than 10 ha in size and greater than 500 m in their smallest dimension?
- How far is it between the current fireline and the nearest buildings?

5. KNOWLEDGE-BASED SYSTEMS

We have devoted a large portion of the chapter to knowledge-based (KB) systems on the premise that this technology is critical to providing effective decision support for adaptive ecosystem management. Although the basic concepts of the process are simple enough on the surface (see Fig. 2), actual application of the process entails many levels of tasks, each composed of numerous parallel tasks, all of which must be coordinated in some intelligent fashion. KB systems have the potential to be extremely useful in the context of ecosystem management precisely because they encapsulate knowledge of how to solve problems, largely independent of how abstract the problem may be. The basic requirement of the KB approach is that one must be able to reason about the problem. Thus, in principle, if one can explain what ecosystem management is and how one does it, then it is possible to build a system that supports it.

5.1 What Are KB Systems?

KB system theory and application have grown rapidly in the past two decades and are an outgrowth of the more general field of artificial intelligence (AI). Waterman (1986) provides a topology of AI (Fig. 3) that includes KB systems and expert systems as special cases of AI in general. AI systems make use of cognitive models (i.e., models of human thought processing, or idealized human thought processing) to emulate intelligent behavior. This approach contrasts sharply from systems that employ traditional analytical methods consisting of mathematical models to perform some task, such as problem solving, pattern recognition, etc.

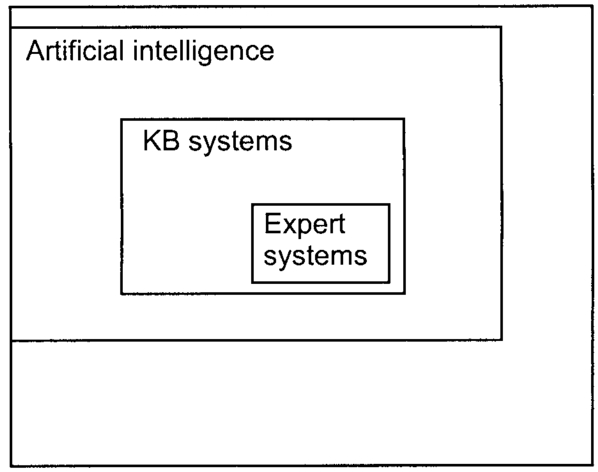

Fig. 3. Domains in artificial intelligence.

Knowledge-based systems are distinguished as a subset of AI systems by the fact that KB systems make domain knowledge explicit and separate from the remainder of the systems reasoning mechanisms (inference engine). Expert systems are distinguished from KB systems in that the knowledge base of an expert system is not derived from generally available (public) knowledge (e.g., textbooks, etc.), but comes from expert specialists in a problem domain and their private knowledge of a field. The distinction between KB and expert systems is fuzzy at best because the concept of expertise is, itself, not well defined. Consequently, we will generally use the term KB system inclusively for subsequent discussion, and not worry about the distinction between KB and expert systems.

Knowledge-based systems are currently among the most visible products of AI. A KB system is a computer program capable of simulating that element of an expert's knowledge and reasoning that can be formulated into units of knowledge so that a computer can approximate an expert's ability to solve problems (Bowerman and Glover 1988, Harmon et al. 1988, Parsaye and Chignell 1988, Waterman 1986). Different KB systems formalize knowledge in different ways. Some of these different knowledge representations include rule- and frame-based systems (including object-oriented), semantic networks, and predicate logic, among others. Although the influence diagrams of Bayesian belief networks (BBNs) have much in common with semantic networks, BBNs are treated in a separate section of this paper because their underlying theory is fundamentally different.

A KB application codifies knowledge about how to solve a particular, well defined problem. KB applications are distinct from conventional analytical ones that operate on numerical data in that they combine a

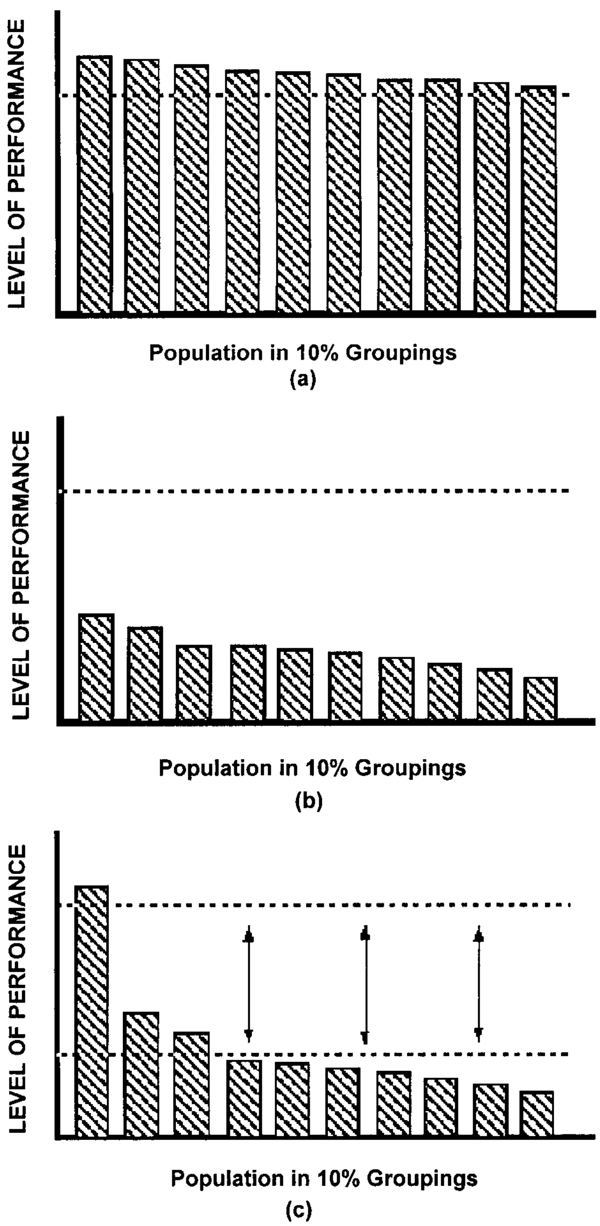

Fig. 4. Each of the three graphs contains a hypothetical population separated into 10 percent performance groupings. Each group's performance can be compared along the vertical axis. A dashed line across the top of the graph indicates a desired level of skill. All population groups function at or above the desired level in (a), all groups function well below desirable in (b), and a single group functions at the desired level in (c). In terms of increasing overall population performance, KBs would be valuable in (c), where there is a skilled group and also the potential to raise the mean (lower dashed line) skill level of other groups.

symbolic representation of knowledge with a reasoning procedure (the so-called inference engine) that can process that knowledge (Feigenbaum et al. 1988). Required knowledge and associated reasoning procedures are, in effect, models of the problem-solving expertise of human experts. A primary function of KB systems is to improve the problem-solving skills of the nonexpert (Fig. 4), i.e., to increase the level of productivity for a large number of people. In doing so, a KB system acts as an organized and accessible repository of the problem-solving knowledge accumulated by experts. Knowledge in this form is both scientifically organized and readily applicable to problem solving (management tasks).

Knowledge codified in KB systems typically represents the best thinking of recognized authorities, leading to problem solutions that are imaginative, accurate, and efficient (Waterman 1986). In addition to the immediate application of KB systems to solve problems, KB systems are also useful as (Schmoldt and Rauscher 1995):

- institutional memory, where they provide a permanent record of the best strategies and methods developed by staff;
- knowledge management devices, where they aid the collection, organization, synthesis, evaluation, and delivery of scientific knowledge;
- accountability documents, where they contain an explicit record of current decision-making that gives users and organizations objective justification for their decisions and actions;
- management checklists, where they ensure that all pertinent information is utilized appropriately for decision-making;
- training tools, where they contain the knowledge necessary to explain their reasoning processes to less experienced managers.

5.2 What Is the Value of KB Systems in Ecosystem Management?

Land managers routinely use knowledge from many scientific and technical disciplines to deal effectively with the problems and decisions that confront them. Staying informed on current research and development in all relevant fields is virtually impossible. Each year, thousands of scientific articles, technical reports, research notes, handbooks, newsletters, and bulletins are published with potential application to forestry (Anderson et al. 1981). It is unreasonable to expect land management professionals to examine, organize, synthesize, and apply this vast and diverse array of information to their management problems with thoroughness and consistency. There is simply not enough time, and often the information is not in an easily usable form for practicing foresters (Nicholls and Prey 1982), nor is it possible to have a full-time expert available from each of the many specialized disciplines needed to support management decisions (Schmoldt and Rauscher 1994). As land management philosophy transitions from managing separate resources independently to managing the ecosystems that support those resources, the difficulties inherent in integrating a wide variety of technical disciplines are magnified.

Past approaches to supplying decision-making expertise to land managers have included operations research, statistics, and simulation. However, many modern land management problems do not lend themselves to precise quantification. Many types of decisions are based, instead, on judgment and experience, and such problems are difficult to quantify. Often, a land manager must answer "what" types of questions that require selecting one of several alternative activities, including to do nothing — what to plant, when to harvest, what to inventory, improve fish habitat or not. The decision-maker is further hampered by often incomplete and uncertain information associated with the technical domains involved in land management. Many aspects of the physical and biological environment are unknown, or only known with limited certainty. Decision-making, based on uncertainty and ignorance, demands that one surrender the expectation that answers are absolute or optimal. KB systems overcome many of the limitations of quantitative methods that require hard numbers and discrete decision boundaries (Schmoldt and Martin 1986, Schmoldt and Rauscher 1995).

Initial evaluations of the potential value of KB systems in natural resource management (Martin 1980, Rauscher 1985, Rykiel et al. 1984, O'Keefe 1985, Schmoldt and Martin 1986) concluded that application areas were plentiful and potential benefits were significant. In the 1980s, thousands of KB systems were developed in a wide variety of problem domains (Smart and Knudsen 1986, Walker and Miller 1987). Articles on AI and KB systems in natural resource management began to appear in significant numbers in 1983 (Davis and Clark 1989). A more recent survey, reporting on 74 projects worldwide (Rauscher and Hacker 1989), showed an increasing number of prototype systems nearing completion, suggesting the emergence of KB systems as major problem-solving tools in natural resource management. Durkin (1993) catalogued more than 100 KB systems in the environmental sciences. Particularly pertinent to this discussion, Martin (1980), Rykiel et al. (1984), and O'Keefe (1985) envisioned an important role for KB systems as components of larger decision-support systems in the future. This has, in fact, become the case with decision-support systems such as INFORMS (Williams et al. 1995), EMDS (Reynolds et al. 1996), and NED (Rauscher et al. 1995). Knowledge-based systems have evolved into another accepted computational tool to aid decision-makers, along with simulation, geographic information systems, and other computer-based technologies.

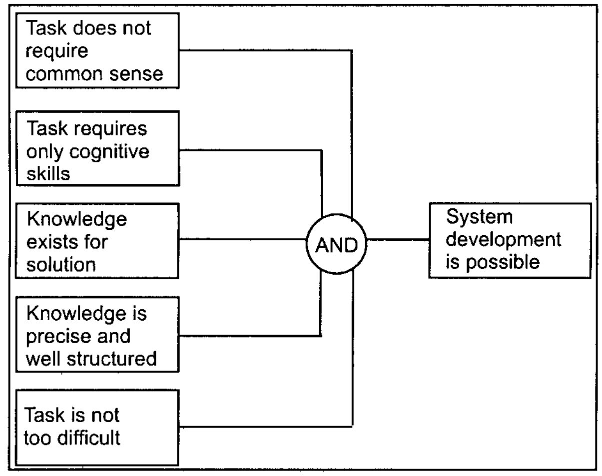

Fig. 5. Considerations of feasibility for system development (after Waterman 1986).

Within the context of ecosystem management, KB systems have two unique advantages over other decision-support tools. They can be designed: (1) to utilize uncertain and inexact knowledge, and (2) to help managers learn from experience, to improve their decision-making skills over time. KB systems can provide solutions to problems in which data are lacking or unreliable because decision boundaries are no longer fixed and inflexible. This capability is important for ecosystem-based management because severely limited inventory and monitoring activities have resulted in a paucity of resource information. This data limitation, with its resulting uncertainty, will likely continue into the foreseeable future. While learning capabilities in current KB systems are crude, proper system design can lead to improved system performance based on monitoring of successes and failures. As land management organizations move toward an adaptive management model, decision support software that can be modified in response to feedback is not just desirable, but essential.

5.3 When Are KB Systems Appropriate?

Figure 5 summarizes characteristics of a problem domain that are required to make KB system development possible. A more detailed, analytical approach to resolving this issue is provided by Laufmann et al. (1990).

5.3.1 Feasibility

One of the most important — and obvious — requirements is that extensive knowledge exists for solving problems within the domain of interest. Other requirements deal with the characteristics of the problem that the system will solve. An important characteristic is that the task not be extremely difficult. If solving a typical problem requires days or weeks, there is a good chance that it is too difficult or too complex for a KB system approach. If the task can be segmented into smaller, shorter, relatively independent subtasks, however, each subtask might be a candidate for KB system development.

Task difficulty also relates to how well the problem domain is really understood — that is, the degree to which existing problem-solving knowledge can be made explicit and is well structured. If the task is so poorly understood that it requires basic research to develop solutions, KB system engineering will not work. It also will not work if the solution depends heavily on use of common sense reasoning, because KB programs perform poorly under these circumstances.

5.3.2 Justification

Just because it is possible to develop a KB system for a particular task does not mean that it is necessarily desirable to do so. There are four basic ways to justify a KB system development effort (Fig. 6). KB system development can be justified when the task solution has a very high payoff. For example, a KB system for ecosystem management might significantly improve the planning process in a U.S. Forest Service Region or National Forest, resulting in savings worth millions of dollars over a planning cycle. If there is a reasonable possibility of a high payoff, development is probably a good idea.

KB system development is justified when human experts are regularly unavailable to do the job. Often human experts are scarce, and their time is very much in demand. This problem is compounded when similar expertise is required at many locations at the same time. In this situation, a KB system is a relatively cheap and effective way to multiply existing expert resources. Indeed, it may be the only cost-effective alternative.

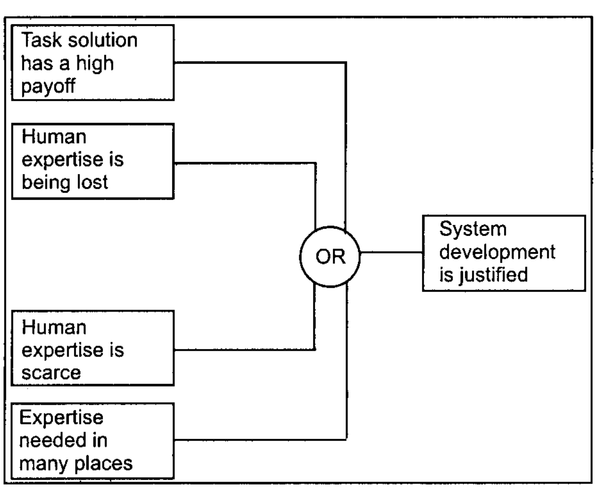

Fig. 6. Justification for system development (after Waterman 1986).

KB systems also are justified when significant corporate knowledge is likely to be lost from an organization through personnel changes, such as retirements, job transfers, and downsizing. Such events frequently disrupt management processes because highly valuable expertise can be lost. The institutional memory capability of a KB system can minimize or even eliminate this problem.

5.3.3 Nature of the Problem

The key factor determining when it is appropriate to develop a KB system is the nature of the problem to be solved. It must be a problem that can be solved naturally by manipulating symbols and symbolic structures. As discussed previously, the ability to deal with symbolic reasoning is one characteristic that sets KB systems apart from more conventional programs. Most real-world problems do, in fact, require symbolic reasoning. Problems that can be wholly solved with algorithms (formal procedures that guarantee the correct solution every time) are not good candidates for KB system development. For example, there are many different algorithms for making forest yield projections, and it would be more cost-effective to solve such a problem with a conventional analytic program.

In a sense, the KB systems approach is the last resort. If the problem can be solved algorithmically, then those methods should be used. If it's too poorly specified for conventional, quantitative techniques, KB systems may be appropriate. In other circumstances, KB systems might be used effectively in the context of an ecosystem management decision support system by assisting users with the appropriate application and interpretation of a complex configuration of conventional models. For this latter case, the KB system would serve as an intelligent front-end for these other models.

6 EXAMPLES OF DECISION SUPPORT SYSTEMS

The state of the art in the development of decision support tools and systems specifically for ecosystem management is still rudimentary. Several systems are in various stages of development and implementation. Even though most developing systems are relatively untried, there is still great benefit to examining the variety of approaches and experimenting with systems that are still early enough in the development stage to be influenced by potential users. Thus, if you find something that is close to what you need in the descriptions that follow, contacting the developer and offering your situation as a potential test case may get you the help you need and improve the decision support software at the same time.

The next 18 subsections provide a synopsis of computer-based tools designed to assist managers in various parts of the decision process in the context of ecosystem management. The tools vary considerably in their approach and comprehensiveness. The list is not exhaustive, because new tools are constantly under development. In Section 6.19, we briefly consider coordinated use of several of the systems discussed in previous sections to achieve some measure of integrated decision support for adaptive ecosystem management.

6.1 ArcForest

ArcForest is an ARC/INFO and Oracle-based software product comprising a set of integrated functions to support forest management planning and improved decision-making. ArcForest's functions, organized into modules and subprocesses, include: Forest and Land Records Management, Query, SurfaceView, Map-Composer, Planning-Eligibility, Planning-Define Planning Area, Planning-Allocation, and System and Data Administration. Together, these processes provide a forest vegetation inventory and maintenance system and support for strategic and operational management for harvesting and silviculture and roads planning.

Contact: Keith Jones, ESRI Canada -Victoria, 1010 Langley Street, 2nd Floor, Victoria, BC, Canada V8W lV8 (Tel: 604-383-8330, Fax: 604-383-3846, e-mail: kjones@esri.com).

6.2 AR/GIS: Active Response Geographic Information System

AR/GIS is a multi-user GIS tool used for place-based negotiations. The user interface is designed for use by non-technical decision-makers. The tool is based on developing a linkage between an electronic meeting system and GIS. Meeting participants interact with laptop computers to assess the current status, develop decision criteria, and propose geographically based proposals/scenarios. Individual recommendations are collected via a local area network for group discussions, negotiations, and decisions. Decision rational for final recommendations are recorded automatically using the electronic meeting functionality.

Contact: Brenda Faber, CIESIN, 1201 Oakridge Dr., Suite 100, Ft. Collins, CO 80525 (Tel: 970-282-5475).

6.3 CRBSUM

The Columbia River Basin SUccession Model (CRBSUM) simulates broad-scale landscape vegetation changes as a consequence of various land management policies. It was designed to compare the effects of alternative management strategies on vegetation dynamics. This model can be used to (1) predict future landscape conditions as a result of alternative management plans, (2) investigate the interaction of disturbance processes with vegetation dynamics, (3) map the distribution of disturbances on the simulation landscape, and (4) spatially describe the composition and structure of future landscapes. CRBSUM is a spatially-explicit, deterministic model with stochastic properties that simulates changes in vegetation cover types and structural stages on landscapes over long time periods using probabilities. The successional pathways comprise the heart of the CRBSUM simulation engine. There is a successional pathway for each Potential Vegetation Type (PVT) recognized on the simulation landscape.

Contact: Bob Keane, IFSL, P.O. Box 8089, Missoula, MT 59807 (Tel: 406-329-4846, Fax 406-329-4877, DG: B.KEANE:S22L01A).

6.4 EMDS

EMDS provides knowledge-based decision support for landscape-level ecological analyses. Knowledge bases in EMDS represent knowledge of how analysis topics relate to ecosystem functions, processes, and data. Given a set of selected topics, the system determines data requirements, retrieves existing data, and evaluates the state of the selected topics. Because EMDS uses symbolic reasoning, topic states can be partially evaluated with incomplete data. EMDS also uses its knowledge of relations to prioritize the value of missing data. The knowledge base system is linked to GIS; states of topics, ecosystem function and state, and variousviews of missing data can all be displayed on maps.

Contact: Keith M. Reynolds, PNW Research Station, Corvallis Forestry Sciences Lab, 3200 SW Jefferson Way, Corvallis, OR 97331 (Tel: 541-750-7434, Fax: 541-750-7434, email: reynoldsk@fsl.orst.edu).

6.5 FVS (Forest Vegetation Simulator)

Starting with inventories of existing primary vegetation, FVS (also known as the Prognosis Model for Stand Development) provides simulated estimates of the future states of primary vegetation. The model can represent a large number of alternative management activities. In the growth and yield literature, the model is termed an "Individual tree, distant-independent growth model." This simulator includes an extensive set of submodels, including the Parallel Processing Extension and various other extensions to the base model that represent shrubs, insects, diseases, and/or fire fuels, behavior, and effects.

Contact:: Nick Crookston, Intermountain Research Station, 1221 South Main, Moscow, ID 83843 (Tel: 208-883-2317). Gary Dixon, Timber Management Service Center, 3825 E. Mulberry, Ft. Collins, CO 80524 (Tel: 970-498-1814). Bov Eav, FHTET, 3825 E. Mulberry, Ft. Collins, CO 80524 (Tel: 970-498-1784).

6.6 GypsES

GypsES, a tool for organizing and evaluating information to be used in gypsy moth control, suppression, prevention, or eradication efforts, is built around visual display of information through the GRASS GIS and several simulation models. GypsES provides decision support by identifying areas of concern, recommending areas to monitor, recommending areas for suppression, and producing maps and tabular summaries. The GypsES system uses GRASS to handle all geographic data, and an original database system that reads any .dbf file. It includes a generalized report generator that uses information from both the GIS and the database. It also includes an original on-screen map-editing facility called MapEdit, which edits raster, site, and vector files. The three major components of the GypsES system are Hazard Rating, Survey, and Treatment. The Hazard Rating component classifies susceptibility to defoliation, estimates vulnerability to damage, determine hazard from gypsy moth based on management priorities, and determines current risk based on insect populations. The Survey component works in two different modes, Eradication and Suppression, according to the situation. In Eradication mode the system provides advice on setting and collecting data from pheromone traps. In Suppression mode the system provides similar advice on egg mass surveys and data management. The Treatment Component allows the user to draw spray blocks based on risk ratings, supports decisions by incorporating budgetary constraints in recommendations, and incorporates timing estimates from the phenology model to help plan suppression specifications. Also incorporated are a spray deposition model to assist in designing spray blocks and a simulation model for estimating damage to stands from defoliation.

Contact: Dan Twardus, USDA Forest Service, 180 Canfield Street, Morgantown, WV 26505-3101 (Tel: 304-285-1545).

6.7 INFORMS

INFORMS is a DSS that supports landscape and project-level planning by integrating needed planning tools into a user-friendly interface. Easy and logical user access is provided to data management, GIS, modeling, and knowledge-base tools. The INFORMS framework allows relatively easy custom configuration to accommodate the variety of tools, planning methods, and databases used across USDA-FS Ranger Districts nationwide. The functions supported by INFORMS include project definition, scoping, pre-alternative analysis, alternative creation, post-alternative analysis, and document preparation. The design is based on extensive analysis of user requirements using CASE methodology.

Contact: Steve Williams, Forest Health Technology Enterprise Team, Forest Health Protection, 3825 E. Mulberry Street, Fort Collins, CO 80524 (Tel: 970-498-1500).

6.8 KLEMS: Klamath Landscape Ecosystem Management System

KLEMS is a suite of analysis tools designed and written in close association with land managers at the Forest Service District level to assist in answering fundamental questions in support of management decisions at landscape scales. The tools are designed for use by resource specialists in developing, analyzing, and communicating suggested alternative management actions. The central purpose of the KLEMS development team efforts is to better understand the questions that must be answered, and then design tools to help answer them.

Contact: Robert J. Laacke, US Forest Service, Pacific Southwest Experiment Station, 2400 Washington Avenue, Redding, CA 96001 (Tel: 916-246-5455).

6.9 LANDIS

LANDIS is a spatially-explicit model of forest landscape disturbance and succession. This model simulates forest overstory vegetation succession and response to disturbance on landscapes ranging from thousands to tens of thousands of hectares. LANDIS explicitly predicts regeneration, sprouting, and growth of cohorts of trees based on a series of probabilistic equations. Fire and wind disturbance are modeled as probabilistic events. LANDIS is currently calibrated for northern Lake States species. Calibration for Missouri Ozarks in progress. A submodel to simulate management disturbance is under development.

Contact: David J. Mladenoff, Department of Forestry, University of Wisconsin, 1630 Linden Dr., Madison, WI 53706-1598 (Tel: 608-262-1992 or 608-221-6326). For Missouri Ozark Variant, contact: Stephen R. Shifley or Frank R. Thompson III, North Central Forest Experiment Station, USDA Forest Service l-26 Agriculture Bldg., University of Missouri, Columbia, MO 65211-0001 (Tel: 573-875-5341).

6.10 MAGIS: Multi-Resource Analysis and Geographic Information System

MAGIS is a modeling system for integrating ecological and social information and scheduling management practices spatially and temporally for a landscape. A wide variety of management practices can be accommodated, including alternative silvicultural methods, various logging methods, and practices such as prescribed burning and creating snags for wildlife. In addition, MAGIS contains a transportation component for addressing issues involving roads. Possible network practices include construction or reconstruction, closing, obliteration, and mitigation activities for reducing environmental effects.

Contact: J.G. Jones, Research Forester, Intermountain Research Station, USDA Forest Service, Forestry Sciences Lab., P.O. Box 8089, Missoula, MT 59807 (Tel: 406-542-4167). W. Wood, Forest Economist, Montana DNRC, 2705 Spurgin Road, Missoula, MT 59801 (Tel: 406-542-4232). H.R. Zuuring, Director of Geographic Information Systems Laboratory, School of Forestry, University of Montana, Missoula, MT 59812 (Tel: 406-243-6456).

6.11 NED

NED is a set of decision-support tools for natural resource management in the eastern United States. It is designed to help landowners and managers answer four questions:

What do you want?
What do you have?
What can you do to get what you want?
How can you tell if you succeed?

To answer these questions it draws on a multiple-resource knowledge base that includes aesthetics, ecological values, timber, water, and wildlife. It seeks to provide users with as much information and control over the decision process as possible, beginning with identifying goals, forest inventorying, management prescription, and modeling future conditions. NED uses a prescription design system to incorporate management goals for multiple objectives, analyze current forest conditions, produce recommendations for management alternatives, and predict future conditions under different alternatives. NED assists in evaluating silvicultural decisions at a project level using landscape-scale factors.

Contact: Mark J. Twery, USDA Forest Service, PO Box 968, 705 Spear Street, Burlington, VT 05402 (Tel: 802-951-6774).

6.12 RELMdss: Regional Ecosystem and Land Management Decision-Support System

RELMdss is designed to be an integration, analysis, and display tool for the generation and implementation of forest and land-use plans. RELMdss currently operates in the Windows environment on a personal computer. One of the key features of RELMdss is that potential plans are depicted through the use of map-based displays to facilitate rapid comprehension of results. The effects of various existing or proposed allocations, standards and guides, and treatment schedules can be evaluated relative to meeting multiple objectives or desired future conditions across several time periods and scales. RELMdss provides not only optimization models that allow the user to interactively adjust activity or constraint levels, but also includes management and display of hierarchical planning linkages. RELMdss provides the necessary tools for managing different levels of data and displaying the data in one system simultaneously. An additional feature is its capability to display and interpret planning information externally generated by other systems along with map-based overlay features such as roads and streams and images or pictures of actual landscapes.

Contact: Richard Church, NCGIA, Department of Geography, University of California, Santa Barbara, CA 93106 (Tel: 805-893-4217, email: church@geog.ucsb.edu).

6.13 SARA: Spreadsheet-Assisted Resource Analysis

SARA is a set of programs and templates for a free-form procedure for matrix generation and report writing to build and evaluate solutions of linear programming models of forest ecosystem planning. The programs work with any commercial spreadsheet and linear programming solver. The most common programs used are QuattroPro and EXCEL for spreadsheets and CWHIZ and LINDO for linear programming solvers. SARA programs can directly construct a bottom-up hierarchical planning model by pulling alternative solutions for sub-units as the integer decision variables into an aggregate model for the larger planning unit.

Because the essential data and model building are done within a commercial spreadsheet, it is easy and inexpensive to share an understandable analysis process with all interested constituencies, which greatly enhances model credibility and consensus building. SARA is easily connected to GIS and related data bases on the input and output sides of the linear program. SARA has been extensively tested in teaching, large-scale research models to determine economic-ecological tradeoffs, and in landowner strategic planning applications over the past 5 years.

Contact: Dr. Greg Biging or Dr. Larry Davis, CAMFER, 145 Mulford Hall, University of California, Berkeley CA 94702 (Tel: 510-643-2028, Fax: 510-643-5438).

6.14 SIMPPLLE: SIMulation of Patterns and Processes at Landscape scaLEs

SIMPPLLE consists of an object-oriented design that allows for flexibility in the level of detail used to characterize existing vegetation and the processes that drive change. Using processes (insects, diseases, wildfire) and management treatments, the system provides simulated change in vegetative states. The system includes interaction between processes and vegetative patterns. Numerous stochastic simulations provide the means to understand and quantify the variability in landscapes to help determine realistic desired future conditions. Stochastic simulations provide the basis for evaluating alternatives within the context of a dynamic landscape.

Contact: Jim Chew, RWU 4151, Intermountain Research Station, 800 Block East Beckwith, P.O. Box 8089, Missoula, MT 59807 (Tel: 406-542-4171).

6.15 SNAP: Scheduling and Network Analysis Program—"SNAP" II+ and III

SNAP is designed to assist in the scheduling and transportation planning for harvest areas. Using certain rules, it can schedule the harvest for up to 30 time periods considering costs, revenues, several species, alternative destinations, non-adjacency requirements, and transportation systems. SNAP attempts to either maximize present net worth or minimize discounted costs. SNAP combines pattern generation and network analysis to find feasible solutions—both of units that are selected for harvest and those that are not selected. Both even and uneven-aged management can be modeled. In addition to normal non-adjacency rules, SNAP can aggregate units during pattern generation to form "super polygons" subject to maximum size of disturbance limits. Also, units may be excluded from harvest and wildlife corridors may be created by connecting sets of polygons that conform to the eligible seral stages defined by the user. Two version are available: II+ is capable of handling 1,000 polygons with 3,000 links. SNAP III is capable of handling 5,000 polygons, 10,000 road links, 20,000 stream links, 50 time periods, 100 polygon attributes, and 250 seral stages.

Contact: Dr. J. Sessions and J.B. Sessions, Oregon State University, Forest Engineering, Corvallis, OR 97331-5706 (Tel: 503-737-2818, Fax: 503-737-2668).

6.16 SPECTRUM

SPECTRUM, an evolution of FORPLAN, is a linear programming-based forest planning model used to optimize land allocation and activity and output scheduling for a forest over a specified planning horizon. It includes a data entry system, model manager, matrix generator, and report software. A commercial LP package is used to solve the LP matrix generated by SPECTRUM. The matrix generator reads and interprets model data, and creates rows and columns for the LP software to solve. The report utilities interpret the LP solution and produce a series of reports and data base files. Applications can be designed to schedule management treatments to achieve ecosystem management, financial, or other goals.

Contact: Kathy Sleavin, Forest Service Ecosystem Management Group, 3825 E. Mulberry, Fort Collins, CO 80524 (Tel: 970-498-1833).

6.17 Terra Vision

Terra Vision is a new conceptual and technological approach to the design and function of natural resource management decision support systems. It results in positive, constructive changes in perspectives about land planning and land use decision-making by both landowners and interested constituencies. Terra Vision is a comprehensive, generally applicable set of tools and approaches to support strategic planning and policy analysis for natural resource ecosystems to achieve both ecological and economic goals. It was crafted in 1995 to support the preparation of sustained yield plans for Louisiana-Pacific Corporation's 500,000 acres of timberland in California. Terra Vision is new technology that utilizes the best of contemporary computer, data management, GIS, and multimedia presentation technology.

Contact: Dean Angelides, VESTRA Resources, 962 Maraglia St., Redding, CA 96002 (Tel: 916-223-2585, Fax: 916-223-1145, e-mail: dean@vestra.com).

6.18 Woodstock

The Woodstock Forest Modeling System is a modeling system for building harvest scheduling, vegetation management, and ecosystem models. Models can be simple inventory projections (with or without binary search), Monte Carlo simulations, or generalized Model II linear programs.

Contact: Remsoft Inc., 620 George Street, Suite 5, Fredericton, New Brunswick, CANADA E3B 1K3 (Tel: 506-450-1511, Fax: 506-459-7290, email: remsoft@nbnet.nb.ca).

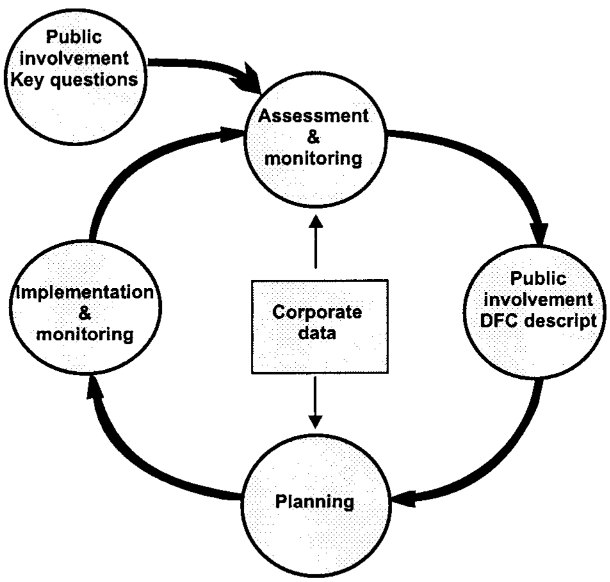

Fig. 7. Modified version of the adaptive management process based on considerations of decision support.

6.19 Case Study: Coordinated Use of Systems for Ecosystem Management

Many of the systems discussed in previous subsections of section 6 are complementary to one another with respect to supporting the complete adaptive management process (Fig. 7, a modified version of Fig. 2 presented earlier in this chapter). Figure 8 superimposes a subset of the systems discussed in Section 6 and some of the tools discussed in section 4 onto the basic processes (Fig. 7) as an example of how collections of tools and systems can be used to support at least major components of the complete process.

In our example (Fig. 8), the analytic hierarchy process (AHP, Section 4.4.3) is first used to decide what key questions (that have been synthesized from public input) will be carried forward into an assessment of the current status of ecosystem states and processes in, say, a region. The AHP model in this context would specify criteria and subcriteria that are the basis for selecting among candidate key questions, given a common set of attributes that characterize each key question. A selection process is generally necessary because a typical public involvement process prior to assessment can easily generate many more questions than can feasibly be addressed. The AHP provides a rational basis for choosing among candidates, and provides useful documentation for superiors and clients to justify the basis for the decision.

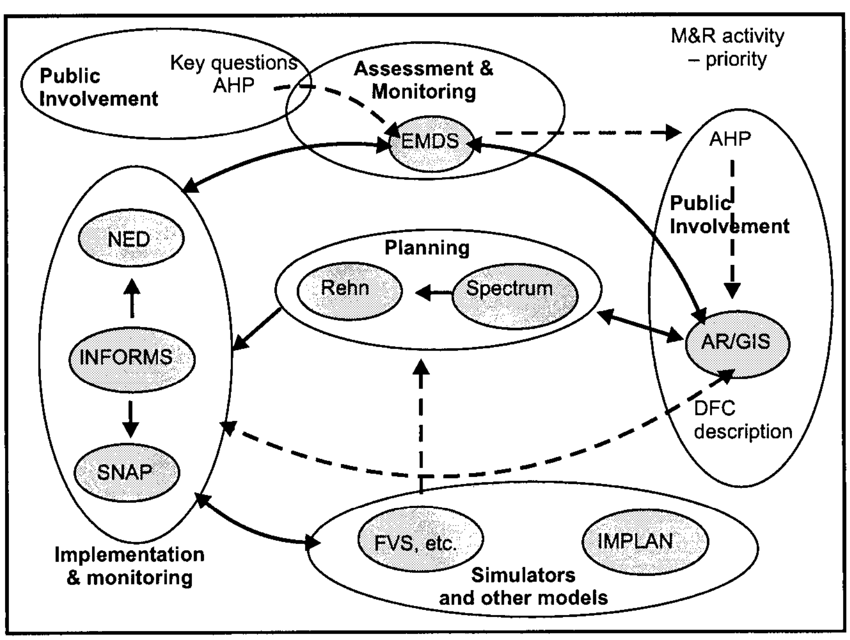

Fig. 8. Integration of systems and tools to support the adaptive management process of ecosystem management.

Given a set of key questions that have been selected, the NetWeaver knowledge base system in EMDS (Section 6.4) is then used to construct one or more knowledge bases that address the set of key questions. One of the virtues of knowledge- based representation, and that of NetWeaver in particular, is that a single knowledge base can include any or all topics that are logically related to one another, thus facilitating integrated analysis. Following knowledge base development, EMDS is then used to provide an assessment of current conditions across the region.

Assessment of current conditions provided by EMDS provides a starting point for a new public involvement process aimed at developing desired future conditions. As suggested (Fig. 8), the AHP might be used as a preprocessor (for example, to choose among basic strategies that initially are not spatially explicit), or information from EMDS might be used directly by AR/GIS (Section 6.2) to develop spatially explicit scenarios of alternative desired future conditions. AR/GIS not only facilitates collaboration among a small group, such as a planning team, that might develop an initial set of scenarios, but also facilitates communication with the public.

AR/GIS can be used to develop scenarios for any spatial scale, so the diagram (Fig. 8) indicates two general pathways from AR/GIS to other systems. If the analysis area is small (e.g., a watershed) decisions reached with AR/GIS may be directly implementable on the landscape, in which case AR/GIS output can provide a starting point for design of management activities using systems such as INFORMS (Section 6.7) or NED (Section 6.11). On the other hand, if the planning area is large (e.g., an administrative region such as a National Forest), decisions reached with AR/GIS are likely to be too general for immediate implementation. In this latter case, more traditional planning systems such as SPECTRUM (Section 6.16) may be used to analyze the implications of planning alternatives in greater detail. Several of the systems discussed in previous subsections of section 6 are flexible enough to be applied to a range of spatial scales and so may provide data inputs to either broad-scale planning systems such as SPECTRUM or may provide inputs to more project-oriented systems such as INFORMS. A few examples of systems and tools that may serve information to other DSSs at various scales include FVS (Section 6.5), KLEMS (Section 6.8) and SIMPPLLE (Section 6.14).

Up until this point, we have begged the question of why Fig. 7 differs from Fig. 2. From the perspective of decision support, it seems reasonable to partition the decision support functions related to monitoring between systems that support implementation and systems that support assessment (evaluation). For example, it would be logical for a system such as INFORMS, which is used to design management activities for implementation, to include tools for designing and maintaining monitoring programs. Moreover, EMDS, for example, can evaluate data from monitoring programs. Thus, monitoring inputs to EMDS effectively closes the loop in the cyclical process of adaptive ecosystem management. It is worth emphasizing here, however, that decision support for design and maintenance of monitoring programs in particular is conspicuously lacking and represents a significant hole in existing decision-support capabilities.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Barriers to Decision Support

Some biases and problems in decision-support technology that need to be recognized as barriers to good decision-making include:

- Decision processes often deal poorly with unanticipated outcomes because decision-makers are too focused on benefits and desired outcomes.
- Misuse of information can corrupt the decision-making process.
- People see decisions separate from organizations because the decision-making process is so diffuse. Each organization needs clear mandates and goals, including the broad concept of ecosystem stewardship.
- Move away from hierarchical decision-making to lateral or more flexible decision-making.
- Decision support is not simply a collection of computer-based tools, but an integrated, logical process in which a particular tool or system *may* be useful. Don’t create additional tools and processes that won’t be effective or efficient.
- We need to provide training to deal with sophisticated tools, to obtain informed consultant advice and assistance, and to utilize groups already well versed in using specific tools.
- Many decisions are political and have more to do with power than with information, values, and perceptions.
- In group decision-making, how do we develop responsibility and accountability? How do we make ourselves stick to the decision?

- Techniques and tools used in decision support systems provide the decision-maker and stakeholders a clearer understanding of the issue and its solutions, but all tools have the potential to be misused. Peer review or other objective processes are needed to ensure that tools are accurate and objective, and used appropriately.

7.2 Successes in Decision Support

Some basic concepts that promote successful application of decision support technology and lead to good decision-making include:

- Tools help the process and analysis of decisions, but the decision is made by people.
- Decision-making is incremental. Decision-makers are forming and adjusting viewpoints throughout the process. Things are not, and should not, be viewed as written in stone.
- Decision-making is dynamic. The world is changing as decisions are being discussed.
- Integrate and share power and responsibility between stakeholders, organizations, and agencies.
- Document the rationale behind decisions. The organization and decision-makers can then learn from their mistakes because it is possible to go back and examine the way the decision was made.

7.3 Promising Possibilities

There are, it seems, at least four levels at which decision support can be improved.

- For the individual manager or management team, section 4.0, Decision-Support Tools, discusses a variety of specific tools. Managers may find that specific aspects of the decision process that historically have posed thorny problems for them can be markedly improved by the application of these tools.
- Section 6 briefly summarizes the features and capabilities of 17 systems that have been developed to deal with major elements of the overall decision process. All of these systems have been designed to tackle some major problem associated with ecosystem management. Some provide alternative solutions for essentially the same problem, and most are highly complementary, but none provides a comprehensive solution. On the other hand, developers increasingly are talking amongst each other, looking for ways to provide more completely integrated solutions.
- Steady, incremental improvements in decision support will emerge naturally along lines 1 and 2, above, but the pace of incremental improvement can be markedly accelerated if state and federal agencies, industry, and perhaps other groups are willing to invest in development of a framework decision support system that provides a unifying logical construct for tool and system developers. Figure 8, which illustrates coordinated use of various systems and tools, suggests interesting possibilities. The concept of framework systems is relatively new, and is closely identified with the new methods of object-oriented analysis and design that now predominate in the software development industry. This type of development is by no means trivial; it requires major commitment. On the other hand, the potential payoffs, already well demonstrated in commercial software development, are enormous.
- Successful implementation of decision support technology is necessarily an organizational issue. Improvements along lines 1, 2, and 3 are helped or hindered, depending on whether or not there is adequate organizational commitment to development, training, and maintenance.

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THE AUTHORS

Keith Reynolds
USDA Forest Service
Pacific Northwest Research Station
3200 SW Jefferson Way
Corvallis, OR 97331, USA

Jennifer Bjork
Cumberland Island NS
P.O. Box 806
Saint Marys, GA 31558, USA

Rachel Riemann Hershey
USDA Forest Service
Northeastern Forest Experiment Station
5 Radnor Corporate Center, Suite 200
Radnor, PA 19087, USA

Dan Schmoldt
USDA Forest Service
Southern Research Station
Brooks Forest Products Center
Blacksburg, VA 24061, USA

John Payne
Bureau of Land Management
222 West 7th Avenue #13
Anchorage, AK 99513, USA

Susan King
USDA Forest Service
Northeastern Forest Experiment Station
5 Radnor Corporate Center, Suite 200
Radnor, PA 19087, USA

Lee DeCola
US Geological Survey
12201 Sunrise Valley Drive, MS521
Reston, VA 20192, USA

Mark Twery
USDA Forest Service
Northeastern Forest Experiment Station
P.O. Box 968
Burlington, VT 05402, USA

Pat Cunningham
USDA Forest Service
Pacific Northwest Research Station
3200 SW Jefferson Way
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