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Integrated decision support for sustainable forest management in the United States: Fact or fiction?

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Abstract

Decision support systems have played a prominent role in the implementation of forest management since the early 1980s. However, whereas early systems were typically designed to address relatively simple management questions, more modern systems are increasingly being called upon to address the challenges posed by issues surrounding forest ecosystem management, sustainable forest management, and adaptive management. This paper considers some of the key requirements as they apply to forestry in the United States, and reviews recent decision support system designs in the United States, considering the extent to which they are satisfying the requirements, and opportunities for their continued evolution. The three systems discussed, NED, LMS, and EMDS, are typical of recent approaches to system design insofar as each has taken an evolutionary approach to system implementation in order to develop effective, integrated decision support for forest management in this new, complex problem domain. On considering the current state of system development for the three systems, it is concluded that significant progress has, in fact, been made in the last few years in providing support for evaluation and planning, although it is equally true that substantial opportunities remain for continued development to support plan implementation and forest ecosystem monitoring.
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Keywords: Decision support; Sustainability; Forest management; Ecosystem management; Adaptive management; NED; LMS; EMDS

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1. Introduction

The early to mid-1980s saw the rise to prominence of decision support systems in forest management in the United States (U.S.). Numerous expert systems were developed to assist with forest pest management, silvicultural prescriptions, and timber harvesting, among other things (Durkin, 1993). By the end of the decade, the value of decision support in forest management was well established, and decision support system developers had become relatively adept at delivering effective expertise for these small, well-defined problems. By the late 1980s, however, the scope of forest management began to expand dramatically as agencies, universities, and industry began to embrace new concepts like the hierarchical organization of ecosystems (Allen and Starr, 1982) and forest ecosystem management (Holling, 1978; Walters, 1986). With its emphasis on broad, holistic, integrated perspectives, the concept of forest ecosystem management posed serious new challenges to the delivery of effective decision support (Rauscher, 1999; Schmoldt and Rauscher, 1996). The challenge was further exacerbated by the still newer concept of sustainable forest management (SFM) that had risen to prominence, following the Earth Summit in Rio de Janeiro, Brazil in 1992, and by introduction of the adaptive management concept.

Twenty years after the initial appearance of decision support applications for forest management, it is appropriate to ask, “How are we doing?” or more specifically, “Has decision support been able to meet the challenges posed by forest ecosystem management, SFM and adaptive management?” In this paper, I consider some of the key requirements of ecosystem management, adaptive management, and SFM as they apply to forestry in the U.S., and review recent decision support system designs in the U.S., considering the extent to which they are satisfying the requirements, and opportunities for their continued evolution. Rauscher (1999) recently presented an excellent overview of the state of decision support for ecosystem management. Rather than present another broad overview, this paper discusses three major systems in some detail. The three systems are relatively mature in their development, relatively advanced in integrated decision support features, and representative of the state of the art in the U.S. The first two systems, the Landscape Management System (LMS, McCarter et al., 1998) and NED[1] (Nute et al., 2000, 2003; Twery et al., 2000, 2003), primarily provide decision support at the project level; that is, at the level management areas encompassing 10 s to 100 s of stands. LMS and NED are similar in that both use vegetation simulation components to project future landscape conditions. The third system, the Ecosystem Management Decision Support System (EMDS, Reynolds et al., 2003c), is a decision support framework for environmental evaluation and planning at any spatial scale.

2. What is a decision support system?

There is a natural human tendency to generalize the meaning of terms until they are no longer useful. For example, the term, knowledge base, originally meant a formal, typically logical, specification for the interpretation of information (Walters and Nielsen, 1988).

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[1] Author’s note: The name, NED, originally derived from Northeast Decision Model. The acronym has been retained, but the application is no longer referred to as the Northeast Decision Model.

However, the concept of a knowledge base now is commonly understood to include the stack of reprints on my desk. For the purposes of this discussion, I adopt the definition of a decision support system (DSS) from Holsapple (2003, p. 551):

> A computer-based system composed of a language system, presentation system, knowledge system, and problem-processing system whose collective purpose is the support of decision-making activities.

Two key attributes in Holsapple's definition are a problem-processing system and purposeful support of a decision-making process. A decision-making process is a method that guides an individual or group through a series of tasks from problem identification and analysis to design of alternatives and selection of an alternative (Mintzberg et al., 1976).

Systems that generally fulfil the Mintzberg and Holsapple definitions include multi-criteria decision analysis (MCDA) systems that implement the Analytic Hierarchy Process and similar MCDA methods, knowledge-based systems that provide a framework for applying procedural or reasoning knowledge to decision problems, and, perhaps somewhat more arguably, optimization systems. On the other hand, while geographic information, spreadsheet, and database systems may be critical components, or even the foundation, of a DSS, it stretches the definition of a DSS beyond usefulness to classify these types of applications as DSS. Numerous simulation systems have been developed to support many aspects of forest planning (Schuster et al., 1993), but most should be considered as potential tools in a DSS framework as opposed to DSS *per se*.

3. DSS applications in U.S. forestry

FORPLAN (Barber and Rodman, 1990; Johnson et al., 1986), a linear programming system for non-spatial harvest scheduling on large areas, has been the primary forest planning system used by the U.S. Department of Agriculture, Forest Service since the mid-1970s. FORPLAN and its successor, SPECTRUM (Mowrer et al., 1997), which supports spatial allocation of FORPLAN solutions, are still widely used, particularly in the western U.S. There have been some criticisms of these systems on technical grounds (Hoekstra et al., 1987), but perhaps their greatest liability is the difficulty of adequately communicating the technical basis of solutions to a public that has grown skeptical, if not distrustful, of land management agencies over the last 25 years or more.

Initial successes with alternative forest management DSS applications, emphasizing improved facilities for explanation of conclusions or recommendations, were achieved with applications that focused on narrow problems. Some prominent early examples include a red pine forest management advisory system (Rauscher et al., 1990) developed for the mid-western U.S., an expert system for monitoring gypsy moth outbreaks and managing spray-control programs in the eastern U.S. (Twery et al., 1993), and an expert system for evaluating and managing hazard and risk of spruce beetle outbreaks in southcentral Alaska (Reynolds and Holsten, 1997).

Early efforts in the U.S. to deliver effective DSS for forest management were relatively successful; a number of early applications in addition to FORPLAN are still widely used today. However, the 1990s ushered in a more challenging era for DSS developers. Beyond the need for applications to help managers communicate analytical results more effectively to broad audiences, this period also saw the introduction of policies, initiatives, and concepts promoting ecosystem management, adaptive management, and ecosystem sustainability. These three topics are closely interconnected, but can be viewed as evolutionary steps in forest management thinking, with each adding another layer of complexity to the challenge of delivering relevant decision support. The following section considers some of the most important challenges and possibilities.

3.1. Ecosystem management

Ecosystem management became official policy of the U.S. Department of Agriculture, Forest Service in 1992 with then-Chief Dale Robertson's directive to the agency to "strive for balance, equity, and harmony between people and land . . . by sustaining what Leopold (1949) called the land community." Other federal land management agencies in the U.S. likewise adopted an ecosystem management policy at about the same time. An ecosystem management perspective focuses on maintaining ecosystem health and integrity, and production of goods and services, to the extent that the latter is compatible with the former (Callicott, 1993). Health has been taken to be the capacity of ecosystems to maintain their functions (Costanza et al., 1992), whereas integrity is concerned with maintenance of ecosystem structures within their natural range of variation (Callicott, 1993).

A rich literature has accumulated around the topic of ecosystem management and its implications. Distilled to the essentials, ecosystem management might be described as management informed by a somewhat holistic understanding of the components of ecosystems in terms of their attributes, functions, and interdependencies. But now we come to the crux of the matter; ecosystem based management sounds good, but how does one actually *do* it? Moreover, in the context of this paper, what must decision support systems be able to do to support ecosystem management?

An obvious place to start is the development of well-defined methods to evaluate the status of an ecosystem as a basis for management decisions. Recent evidence suggests, however, that science and management are not yet adept at performing this preliminary step. A critical examination of recent bioregional assessments conducted in the U.S. since 1992 (e.g., Anonymous, 1996; FEMAT, 1993; Hann et al., 1997; Quigley et al., 1996; SNEP, 1996) should convince most readers that, although a wide array of disciplinary perspectives were reflected in these assessments, and many insightful analyses were performed, convincing evidence of truly integrative synthesis is lacking. At least a few participants in these efforts have acknowledged this short-coming (Johnson et al., 1999).

Lack of a clear conceptual framework in ecosystem management has been apparent. As Rauscher (1999) has noted, ". . .ecosystem management remains primarily a philosophical concept. . ." I suspect that many scientists involved in DSS development for natural resource management would agree with Rauscher's assertion, but I am inclined to disagree at least a little. The literature on SFM has sharpened concepts about the topics that need to be considered in ecosystem management, and the literature on adaptive management has sharpened concepts on how to actually implement ecosystem management.

3.2. Sustainable forest management

The Statement of Forest Principles was adopted by world leaders at the 1992 Earth Summit (Rio de Janeiro, Brazil). A key principle is that forests should be sustainably managed to meet the social, economic, ecological, cultural, and spiritual needs of present and future generations. Various national and international programs have been implemented to develop and apply sets of principles, criteria and indicators (C&I) for assessment of SFM in the U.S. (Abee, 1999; Darr and Delfs, 2000), Canada (Apsey, 2001; Hall, 1999; Ram and Prasad, 2001), Europe (Loiskekoski and Halko, 1994), and elsewhere (Lust and Nachtergale, 2000). As of 2000, 149 countries were involved in nine different processes related to development of criteria and indicators for SFM (Wilkie, 2001). The increasing importance of SFM C&I as tools for policy and management at national and regional scales is underscored by the fact that national inventory systems are now being adapted to directly support C&I assessment (Barker et al., 1996; Reams et al., 1999). Similarly, extension of SFM C&I to the level of forest management units (e.g., the operations level) for certification of management practices, forests, and forest products also has received considerable attention in the past few years from the Forest Stewardship Council and similar organizations (Burger, 2000a, 2000b; Sips, 1997; Wallis et al., 1997).

For purposes of later discussion, it will be helpful to distinguish between DSSs that provide strong versus weak tests for evaluation of SFM. In a strong test, indicators are evaluated not only for the forest resource, *per se*, but for a possibly wide range of other values such as water and air quality, wildlife habitat, socioeconomic, and other benefits. I use the term, strong test, to indicate that a minimum number of assumptions are made about relations between forest resource condition and other resource values. A strong test of SFM is likely to be expensive (requiring extensive monitoring), time consuming, and applied by government agencies at national and regional scales. A weak test, in contrast, might focus on evaluation of the forest resource *per se*, and assume that adequate maintenance of forest age- and structure-class distributions over time will provide suitable conditions for sustaining other resource values. The weak test of SFM is likely to be relatively inexpensive, and easy to apply for local government agencies and private forest industries.

3.3. Adaptive management

Perhaps the clearest explanation of what decision support systems need to provide to managers is encapsulated in the concepts of adaptive management (Walters, 1986; Walters and Holling, 1990). Bormann et al. (1993) and Maser et al. (1994) describe adaptive management as a continual cycle of monitoring, evaluation, planning, and action (Fig. 1). Rigorous application of the cyclic process supports management by experimentation, recognizing that knowledge currently available to guide management decisions is always incomplete. Rauscher (1999) presents an overview of the adaptive management process with implications for decision support:

- Planning: The planning process of Mintzberg et al. (1976) is a useful supplement to the adaptive management model (Fig. 2), the endpoint of which is a set of goals and constraints that guide the action phase (Fig. 1) of the process.

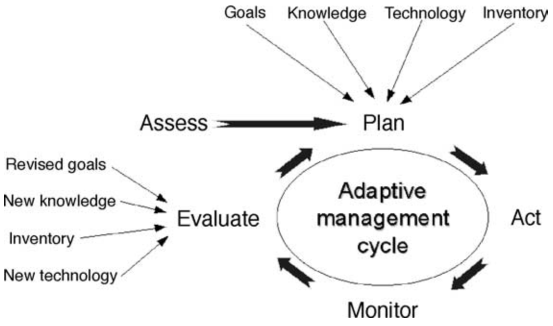

Fig. 1. The adaptive management process, after Maser et al. (1994). The process is typically conceived as a continuous cycle of monitoring, evaluation, planning, and action. Hypothesis testing provides the basis for adaptation, and is a fundamental feature of the process. Testable hypotheses are formulated in the action stage, evaluated in the evaluation stage, and results are used to adapt management in the subsequent planning stage.

- Action: This phase prescribes how, when, and where to implement activities to achieve the identified goals within the constraints. Identifying suitable hypotheses concerning expected outcomes of actions is critical at this stage to support the experimental nature of management actions and promote efficient learning.
- Monitoring: This phase must be informed through adequate documentation developed in the action phase of the process because different personnel may be involved in the

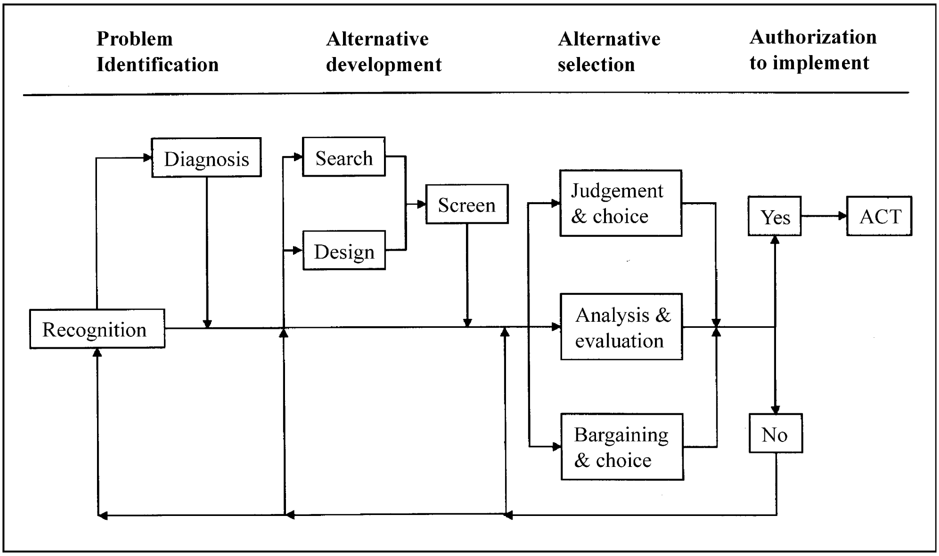

Fig. 2. The Mintzberg planning process (Mintzberg et al., 1976), after Rauscher (1999). The Mintzberg process presents a general approach to planning, representing all, or at least most of, the classic variations on any planning process. Planning proceeds through the four steps of problem identification, alternative development, alternative selection, and a final decision to either implement the selected alternative, or cycle back to one of the first three steps. In each of the first three steps, multiple pathways are possible.

two phases, or personnel may change over time, and because monitoring may extend for years after implementation.

- Evaluation: Hypotheses are tested in the evaluation phase by comparing actual and expected outcomes. Results from this phase provide a starting point for the next iteration of planning.

4. Recent lines of development

All three systems discussed here are Microsoft Windows®[2] applications. For each system, the discussion first summarizes key features, and then considers the degree to which the application can address the needs of decision support for sustainable forest management and adaptive management. In the following, I have deliberately omitted explicit consideration of how the three systems support ecosystem management on the grounds that ecosystem management is more a philosophical foundation than a methodology, whereas the focus of sustainable forest management and adaptive management is on making ecosystem management concepts operational.

4.1. LMS

The landscape management system (LMS) integrates landscape-level spatial information, stand-level inventory data, and distance-independent individual tree-growth models to project changes on forested landscapes over time. The core component of the application coordinates the execution of, and flow of information between, more than 20 programs, including a variety of utilities for data management such as formatting, classification, summarization, and exporting.

A wide variety of software applications are available to support decision-making in the forest management, including databases, growth and yield models, wildlife models, silvicultural expert systems, financial models, geographical information systems, and visualization tools (Schuster et al., 1993). Typically, each application has its own interface and data format, so managers must learn each interface and manually convert data from one format to another to use combinations of tools (Nute et al., 2003). Considering the scope of topics that may need to be addressed in a typical ecosystem management problem, and consequently the need to run several to many applications, manual orchestration of the entire analysis process can quickly become a significant impediment. LMS relieves this problem by managing the flow of information through predefined pathways that are programmed into its core component.

Stand projections in LMS are performed with variants of the forest vegetation simulator (FVS, Crookston, 1997) or ORGANON (Hester et al., 1987). A variety of utilities report stand projection information in tables and graphs, and projection information can be delivered to the ArcView geographic information system (GIS, Environmental Systems Research

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[2] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Institute) for additional spatial analysis, or to the stand visualization system (SVS) or to the Envision landscape visualization system (McGaughey, 1997).

4.1.1. *Sustainable forest management*

LMS provides a partial, weak test of SFM by providing various tabular and graphic views of forest inventory projections over time, given proposed management scenarios. The test is partial because the system currently lacks components to interpret and synthesize projection information, leaving these tasks to the discretion of the user.

4.1.2. *Adaptive management*

LMS is fundamentally a silvicultural planning system, with its core functionality geared toward stand and landscape projection for project-scale applications. The capabilities for stand and landscape visualization integrated into LMS mean that at least some of the important consequences of proposed management alternatives can be effectively communicated to a broad audience in an intuitive graphic form. Basic integration with ArcView affords opportunities for spatial analysis of management alternatives, although LMS does not interpret the meaning of predicted values or provide explicit methods for application developers to integrate their own specifications for interpretation. In other words, LMS presents results, but does not attempt to evaluate them; evaluation is left to the user.

In some respects, LMS support for monitoring is moot in the current version, because its monitoring requirements are largely prescribed by the needs of the projection components of the system. On the other hand, overall functionality of the system could readily be extended to include more comprehensive support for the weak test of SFM, and by inclusion of explicit decision models for evaluation of alternatives. Finally, an interesting feature of this projection-based approach to planning is that actions in the implementation phase of the adaptive management process are implicit in the design of alternatives. That is, the set of actions to pursue are determined by selection of a preferred alternative.

4.2. *NED*

NED version 2.0 assists natural resource managers with project level planning and decision-making processes, and is designed to be used by a forest management professional as a communication tool for working with forest landowners. NED is a goal-driven DSS that implements the Mintzberg et al. (1976) multiple-criteria decision analysis process. Resources currently addressed include visual quality, ecology, forest health, timber, water, and wildlife. The system is adaptable to a range of applications from small private holdings to cooperative management across multiple ownerships. NED supports a five-step process:

1. Identify and define goals and their measurement criteria.
2. Inventory the property being managed.
3. Design alternatives to manage the land and satisfy the goals.
4. Simulate the impact of each alternative to visualize how the forest will look under each alternative.
5. Evaluate how well each alternative satisfies the hierarchy of goals.

Extensive hypertext support provides information about resource goals, desired conditions that support the goals, data used to analyse forest condition, and detailed information about the program itself and the rules and formulae used to produce analyses.

NED uses a blackboard architecture and semi-autonomous agents to manage a variety of applications for the user (Nute et al., 2003). In the blackboard approach to problem solving, the current state of the solution is maintained in a global data store (e.g., the blackboard), agents with specialized knowledge contribute their knowledge, incrementally building up a solution, and a controller agent implements one or more solution strategies to orchestrate when and how other agents contribute to the solution (Nii, 1989). The specialized agents participating in a blackboard solution are said to be semi-autonomous, as opposed to autonomous (Maes, 1991), because they carry out their tasks under the supervision of a controller. In their simplest form, semi-autonomous agents have state (they “know” certain facts), and behaviour (they perform certain tasks when certain states are recognized). Each specialized agent in NED, for example, has the procedural knowledge, or methods in the sense of object-oriented design (Booch, 1995), needed to operate a class of decisions support tools needed in forest management. The simulation agent sets up input for growth and yield models and interprets model output. The GIS agent merges information with an ArcView shape file and invokes ArcView to display the information. The visualization agent generates input for SVS and Envision (McGaughey, 1997). The NED blackboard is implemented as a database with integrated Prolog clauses, and is managed by a controller agent. The interface agent provides access to all applications in the system through a single user interface. Additional agents support development of alternative treatment plans; provide analysis of timber, wildlife, water, ecology, and visual goals; generate a wide variety of reports relevant to forest management. The net effect of tool integration in LMS and NED is similar: transparent flow of information among collaborating system components, resulting in improved ease of use for end users. However, from a development perspective, the agent architecture of NED more readily supports continuing system evolution by better facilitating integration of new decision support tools as they become available.

4.2.1. Sustainable forest management

Goal-driven systems such as NED assist the user in creating an explicitly defined goal hierarchy (Rauscher et al., 2000). A goal is an end-state to be achieved or sustained, and to which people are willing to allocate resources. Goals form a logical hierarchy with an ultimate, all-inclusive goal at the top, sub-goals at intermediate levels, and a special goal, desired future condition, at the bottom (Keeney and Raiffa, 1993). A desired future condition, as used in NED, is a goal statement containing a single variable that measures some observable state or flow of the system being managed (Nute et al., 2000). The most recent version of NED provides a flexible method for defining and implementing custom goals for any particular application (Nute et al., 2003). Thus, NED supports the strong test of SFM at the project scale because users can directly evaluate the distributed effects of changes in an arbitrary number of observable states and processes.

4.2.2. Adaptive management

Given a set of goals (step 1, above), and inventory data on variables needed to evaluate the goals (step 2), an analysis of current condition in NED permits evaluation of the goal hierarchy to determine strengths and weaknesses of the current condition of the property. Knowing which goals have or have not been achieved allows managers to design alternative courses of action that may improve the situation (step 3). Various simulation models are used to forecast the future state of the forest property, given a certain set of management activities and the natural growth and change of the existing forest ecosystems (step 4). NED uses the forest vegetation simulator (Crookston, 1997), for example, to forecast future forest conditions. Given several possible, simulated future forest conditions, it is then possible to evaluate how well each future state of the forest satisfies the original goal hierarchy (step 5). NED provides numerous tabular and graphical reports to help in this evaluation, but alternative selection currently is done ad hoc by a professional forester in consultation with the landowner and perhaps other stakeholders. NED evaluations support the strong test for SFM, but there is only partial support for planning, given the lack of an explicit decision-modelling component for alternative selection. The system provides partial support for the implementation phase of adaptive management because management actions are well defined, given a selected alternative regime of stand treatments. Similarly, NED provides partial support for the monitoring phase because monitoring requirements follow from the specification of the goal hierarchy.

4.3. EMDS

The ecosystem management decision support (EMDS) system (Version 3.0), developed by the U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, is an extension to ArcMap (ArcGIS 8.x, Environmental Systems Research Institute, Redlands, CA) that provides integrated decision support for environmental evaluation and planning at multiple spatial scales (Reynolds et al., 2003c). System architecture is based on the Microsoft Component Object Model (COM) specification, which supports the evolutionary design and implementation of complex systems by establishing communication standards that facilitate collaboration among system components (Potter et al., 2000). The practical significance of conformance to the COM specification is the ease with which the functionality of applications can be extended by integration of new components, as is well illustrated by the extensibility of ArcGIS itself via COM-based extensions.

The evaluation component of EMDS, implemented by Rules of Thumb (North East, PA), uses the NetWeaver logic engine (also Rules of Thumb) to evaluate knowledge bases (*sensu* Walters and Nielsen, 1988), represented by networks of topics, concerning the state of landscape features. In design of a NetWeaver model, a topic for evaluation is represented by a testable proposition. The statement of a particular proposition may be quite vague. For example, in the SFM context, the statement, “The forest ecosystem is sustainable,” clearly is relevant, but also quite vague. However, the formal logic specification underlying a proposition makes the semantic content of the proposition clearer and more precise (see Reynolds et al., 2003 for an extended example). The proposition about forest ecosystem sustainability evaluates as *true to the degree that* its premises are satisfied. The phrase, “true to the degree that,” reflects an approach to problem specification that might be termed “evidence based reasoning,” and is implemented in NetWeaver models with fuzzy math (Miller and Saunders, 2002), a branch of applied mathematics that implements qualitative reasoning as a method for modelling lexical, as opposed to stochastic, uncertainty (Zadeh, 1975a, 1975b, 1976).

The planning component, implemented by InfoHarvest (Seattle, WA), evaluates analytic hierarchy process (AHP) decision models (Saaty, 1992), components of which may optionally implement the simple multi-attribute rating technique (SMART, Kamenetzky, 1982). AHP models structure a decision problem as a hierarchy of criteria and subcriteria, and have been widely used for about 25 years in business and government for setting priorities, decisions about resource allocation, and alternative selection. Typically, in the AHP method, weights on a set of subcriteria are derived as the eigenvector solution to a matrix of pair-wise comparisons of relative importance among subcriteria with respect to their contribution to a parent criterion. The SMART method evaluates attributes of alternatives with utility functions and, in the context of landscape planning, facilitates evaluating an arbitrary number of alternatives.

Logic models and decision models used in EMDS are built by application developers with the NetWeaver Developer (Rules of Thumb) and Criterium DecisionPlus (CDP, InfoHarvest) applications, respectively. The complete suite of applications (EMDS, NetWeaver Developer, and CDP) collectively provides a general application framework. An individual EMDS project may include evaluation and planning at multiple spatial scales, and networks of dependencies between scales can be designed by application developers by summarizing model outputs from one scale and passing them as inputs to models at coarser or finer scales. For example, knowledge base outputs from a biophysical evaluation of watersheds and a socioeconomic evaluation of counties may be summarized for input to the evaluation of biophysical provinces or ecoregions.

4.3.1. Sustainable forest management

EMDS can support the strong test for SFM because it is not difficult in practice to design logic models for large, complex, and abstract problems with NetWeaver Developer (Reynolds, 2001). An early prototype model (Reynolds, *unpublished*) provides a logic-based evaluation of SFM at national or regional scales for all 67 indicators specified in the Montreal Process (WGCICSMTBF, 1995). A report on a much more advanced prototype, focusing on indicators for Montreal criteria 2 and 6 (productive capacity and socioeconomic benefits, respectively) and actually implemented in EMDS for regional-scale evaluations, is in preparation (Reynolds, in press).

4.3.2. Adaptive management

Evaluation of each SFM topic in a NetWeaver logic model is based on evaluation of a proposition concerning the topic and recursion through successive layers of underlying premises (Miller and Saunders, 2002). Propositions can be construed as hypotheses, but their metric, strength of evidence, is grounded in the theory of lexical uncertainty (Zadeh, 1975a, 1975b, 1976), which is concerned with uncertainty about the definition of events, as opposed to probabilistic uncertainty, which is concerned with uncertainty about the likelihood of events. Rigorous statistical tests of individual outcomes are problematic in lexical uncertainty, so this could be seen as a weakness of a logic-based approach in the context of rigorous support for the adaptive management process. However, EMDS is fundamentally a landscape analysis system in which evaluations are typically performed on hundreds, perhaps thousands, of landscape features. In the landscape context, rigorous statistical testing is no longer problematic, because hypotheses can be framed, for example, in terms of the significance of shifts in frequency distributions of the evidence metric for a proposition (for a population of landscape features) between time periods, and standard statistical tests, such as the Kolmogorov–Smirnoff test, can be applied in this context.

Results from an evaluation feed directly into the planning component of EMDS, if a CDP decision model has been developed for the particular scale of evaluation. CDP, together with its EMDS planning component, provide extensive support for implementing the Mintzberg decision process (Fig. 2) discussed earlier, including setting priorities, explaining the derivation of conclusions, checking model robustness, and providing trade-off analyses. Implementation of the Mintzberg decision process in EMDS is somewhat unusual, because the planning component treats the landscape features of the problem as its alternatives, obviating the need for a search for, and design of, alternatives.

EMDS 3.0 provides partial support for the implementation and monitoring phases of adaptive management. Well designed decision models provide full strategic support for selecting landscape features in which to focus management activities, and partial tactical support for selection of specific management activities in specific landscape features (the latter, based on trade-off analysis results). Planned, near-term enhancements to the system include more comprehensive support for tactical decisions based on portfolio-modelling techniques for generating coherent, optimal, multi-alternative management plans. Finally, a NetWeaver logic model can be thought of as a meta database insofar as it is a specification for the interpretation of information. Among other things, the logic structure specifies the data requirements for evaluating the propositions associated with its networks, so the logic structure for evaluation provides at least a partial specification for the monitoring phase. Further, each network object in the logic has an associated set of attributes for documenting hypotheses and assumptions identified in the action phase.

5. Conclusions

What can be concluded about the current state of development of integrated decision support for sustainable forest management in the U.S.? There are both technological and institutional aspects to the answer.

From a technical perspective, the three systems discussed in this paper represent significant advances in integrated decision support for SFM. They also represent a range of capabilities with respect to decision support, and each occupies a relatively distinct niche (Table 1). With its central focus on silvicultural projections at the project scale, LMS is well suited for SFM evaluation in private land-management applications in which most of the attention is naturally on silvicultural properties of decisions and for which a weak test for SFM may be sufficient. Although NED similarly focuses on the project scale, its additional support for testing goal satisfaction suggests that it is quite feasible to develop strong tests of SFM at the project scale, and NED may well be the preferred application for agencies that need to explicitly consider additional indicators in project-scale planning. EMDS similarly supports the strong test for SFM, and functions equally well at the project scale, so there is, in effect, some niche overlap between NED and EMDS, but there also are intriguing possibilities for the two systems to operate collaboratively. For example, EMDS supports integrated evaluation and planning across multiple spatial scales, but it has no intrinsic capabilities for stand projection; however, stand projection and goal satisfaction results from NED can be provided as inputs to an EMDS application as a starting point for evaluations spanning a series of progressively coarser scales. EMDS and LMS are more distinctly different, but could equally well work collaboratively.

None of the three systems reviewed currently provide comprehensive decision support for the full adaptive management process. EMDS and NED each provide strong support for the evaluation and planning phases, but explicit support for formal hypothesis testing in the evaluation phase would be desirable. LMS currently provides only minimal support for evaluation. EMDS provides modest support for at least some aspects of implementation and monitoring, but provision of enhanced capabilities in these two areas remains a fertile area for continued development. Current planning for a subsequent version of NED includes implementation of the Analytical Hierarchy Process (Saaty, 1992) as a way to objectively select an alternative and to perform sensitivity analyses on goals (Rauscher and Twery, *personal communication*). Addition of an AHP component to NED would further strengthen its support for planning, but would not duplicate planning functionality in EMDS because the definition of an AHP alternative in the two contexts is distinctly different. In EMDS, landscape features such as watersheds or provinces constitute alternatives, whereas, in NED, an alternative would be a specific set of stand treatments.

Overall, good progress has been made on developing decision support components to handle the evaluation and planning phases of adaptive management (Tables 1 and 2), but providing full support for the process will require closing the loop on the cycle (Fig. 1). Major outstanding technical issues include development of design specifications to provide support for managing the implementation and monitoring phases. Design issues related to these two phases are likely to be at least as complex as those associated with design for evaluation and planning, and also are likely to be very different in important respects. For example, evaluation and planning are typically performed over short time spans and in close temporal proximity to each other, but implementation and monitoring are recurrent activities that may be spread over many years in a typical adaptive management cycle. Speculating a little, one might imagine a collection of new system components, such as task-scheduler and task-management agents, running quietly in the background, helping to assure that implementation plans are staying on track, that data is updated and summarized, and perhaps even helping spot evidence that might trigger initiation of a new cycle. It is difficult to overstate the significance of decision support implementations for these phases of the process. When we have learned how to provide practical support for these phases, we will have closed the loop, and forest managers will be able to provide convincing demonstrations of adaptive management.

The institutional perspective is at least as important as the technical one. Two key concerns emphasized by Rauscher (1999) in this context were support for public involvement in the planning process in some fashion and institutional capacity. The public cannot be effectively engaged in the process if the underlying subprocesses of a DSS and the conclusions they support are not readily understandable. While the three systems discussed here take somewhat different approaches to this issue, all three emphasize visual, intuitive communication of complex information. For example, both NED and LMS use advanced stand- and landscape visualization tools to help people visualize some of the practical consequences of proposed management actions. EMDS, on the other hand, emphasizes visualization and

Table 1
Comparison of basic system attributes

Attribute	Decision support system		
	LMS	NED	EMDS
Basic unit of analysis	Stand	Stand	User-defined unit[a]
Typical spatial extent	100 to 50,000 acres	100 to 50,000 acres	User-defined extent[b]
Spatial scales[c]	Stand and landscape	Stand and landscape	User-defined range
Emphasis of decision support	Silviculture properties of landscape	Silviculture properties of landscape and user-defined topics[d]	User-defined topics[d]
Basis of evaluation[e]	User interpretation	Goal satisfaction	Strength of evidence
Basis of planning	Simulated future	Simulated future	Current condition[e]
Alternatives	Stand treatment regimes	Stand treatment regimes	User-defined landscape units

[a] In a geographic context, the basic units of analysis in EMDS may be point, line, or area features.

[b] Spatial extent of analysis in EMDS may range from small landscapes (e.g., watersheds) to continents.

[c] The basic unit of analysis in LMS and NED is a stand, and the objective of analysis is decision support for the collection of stands that compose a property or set of properties. An EMDS project may span multiple scales (for example, stand, watershed, province, etc.), and results of evaluations at two or more scales may contribute synthesized information to another, coarser scale.

[d] User-defined topics include any topic of interest for which an evaluation is desired, and whose evaluation can be specified by a logical argument (for example, forest ecosystem sustainability, watershed health, etc.).

[e] Evaluation of simulated futures is left to the discretion of the user in the current implementation of LMS. NED uses goal satisfaction to evaluate both current and simulated future conditions. Logic networks in EMDS perform an evaluation function similar to that in NED, but implemented with fuzzy logic (Zadeh, 1975a, 1975b, 1976) to express strength of evidence on a continuous scale. Planning in EMDS typically is based on evaluation of current conditions, but simulated future conditions also could be provided by LMS and NED as a basis for planning.

interpretation of models and model results. Institutional capacity is an important consideration because the ability of organizations to field DSS systems can be fatally constrained by lack of required expertise to develop and use applications built with them. Particularly in a complex subject area such as decision support for SFM, achieving a suitable balance between ease of use and adequately addressing the inherent complexity is no small task. All three systems are still relatively new, so to some extent the jury is still out on this question. However, NED already is widely used in the eastern U.S., and has been successfully field tested over a 3-year period to evaluate feasibility of application on both public and private forest lands ranging in size from 35 to over 7000 ha (Twery, *personal communication*). Perhaps I am an optimist, but the NED field tests and personal experiences to date with

Table 2
Comparison of system support for phases of the adaptive management process

Phase	Decision support system		
	LMS	NED	EMDS
Evaluation	Weak	Strong	Strong
Planning	Moderate	Moderate	Strong
Implementation	Weak	Weak	Weak
Monitoring	Weak	Weak	Weak

EMDS tend to reinforce my sense that the level of complexity in these systems will not prove to be a significant issue limiting their application in the field.

The focus of this paper has been on systems developed more recently, but it also is worth considering how systems such as FORPLAN and SPECTRUM, which continue to be widely used in broad scale strategic forest planning, might be used in conjunction with systems such as EMDS, LMS, and NED. The two classes of system are not substitutes for one another; they were designed to address distinctly different problems, and, with the exception of EMDS, operate at distinctly different spatial scales. However, practical design principles for integrated, multi-scale analysis and planning in the EMDS context (Reynolds, 2001) are easily generalized to combinations of systems collaborating across spatial scales. For example, an accepted FORPLAN/SPECTRUM solution might provide broad contextual information to finer-scale analyses and planning activities performed by EMDS, LMS, or NED. Synthesized information from the fine scale can flow equally well in the other direction. The principles are practical insofar as they only depend on loose couplings of systems, based on analysis and specification of information flows. Lastly, as an example of system collaboration within scale, an EMDS evaluation of a proposed FORPLAN/SPECTRUM solution could make the ecological implications of complex optimization solutions much more accessible to a broad audience.

The task posed to the DSS development community, to deliver effective, integrated decision support for sustainable forest management, was too large and complex to be achieved in a single development cycle. It has required, instead, an incremental and adaptive approach to system design. While substantial opportunities remain for continued development, to better meet the needs of SFM and adaptive management, significant progress has been made in the last few years. In answer to the question posed in the title of the paper, the claim is more fact than fiction, but there is still much work to be done.

6. Applications cited

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Landscape Management System: http://lms.cfr.washington.edu/index.html
NED: http://www.fs.fed.us/ne/burlington/ned/

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