An Overview of the Ecosystem Management Decision-Support System

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Abstract By way of introduction, this chapter provides a general overview of the Ecosystem Management Decision Support (EMDS) system, including a brief account of its development history, key factors that have motivated its development, and more central topics such as concepts, principles, and functionality. We conclude the chapter with discussions on applications involving multiple spatial scales, ways in which the technology can support the modern planning process, critical design factors behind the relative success of the system, and experiences drawn from design and use of the system.

Keywords Ecosystem management decision support · Environmental analysis · Planning · Logic model · Decision model · Spatial decision support · EMDS

1 Introduction

In the following section, we give a brief account of the history of decision-support systems (DSS) for the benefit of readers who may not have much formal background in the subject. There are many excellent texts on the subject, so the cursory description here is only to help place EMDS in the broader context. Next, we provide brief accounts of DSS in environmental management and the origins of EMDS.

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Chapters "Use of EMDS in Conservation and Management Planning for Watersheds through Measuring Biological Sustainability via a Decision Support System: Experiences with Oregon Coast Coho Salmon" of this volume present a diverse set of specific applications of EMDS in environmental analysis and planning. By way of introduction to these later chapters, this chapter provides a general overview of the system including a brief account of its development history, key factors that have motivated its development, as well as more central topics such as concepts, principles, and functionality. We conclude the chapter with discussions on applications involving multiple spatial scales, ways in which the technology can support modern planning processes, critical design factors behind the relative success of the system, and experiences drawn from design and use of the system.

2 The Origins of Decision-Support Systems

Early pioneering work in the DSS field was carried out at various institutions from the late 1950s to the late 1960s, including theoretical studies on decision making at the Carnegie Mellon Institute, work on the technical aspects of interactive computer systems at the Massachusetts Institute of Technology, and the first DSS applications at the Harvard Business School. Simon (1947, 1960) was instrumental in setting the stage for the evolution of DSS by providing the necessary context for understanding and supporting decision-making processes. Power (2008) provides an excellent historical overview on the origins of DSS, including descriptions of early work at Harvard by Scott Morton (1967, 1971), on computer-aided support for business managers; an historical turning point. Other important milestones in the conceptual development of DSS include the works of Scott Morton (1967), Gorry and Scott Morton (1971), Davis (1974), Keen and Scott Morton (1978), Sprague (1980), Bonczek et al. (1981), and Sprague and Carlson (1982). The work of Bonczek et al. (1981) is particularly significant because these authors articulated for the first time what has become the most enduring definition of a DSS. They identified four essential components that were common to all DSSs:

> 1. A language system (LS) that specifies all messages a specific DSS can accept; 2. A presentation system (PS) for all messages a DSS can emit; 3. A knowledge system (KS) for all knowledge a DSS has; and 4. A problem-processing system (PPS) that is the software engine that tries to recognize and solve problems during the use of a specific DSS (Power 2008).

3 Decision Support in Environmental Management

Environmental management has been a hotbed of DSS development since at least the early 1980s. By 1989, Davis and Clark (1989) were able to catalogue about 100 systems related to environmental management; subsequent reviews of systems suitable for forest management (Mowrer 1997; Schuster et al. 1993) catalogued many more. Somewhat later, Oliver and Twery (2000) and Reynolds et al. (2000) laid theoretical and practical groundwork for applying DSSs to the more formidable goal of ecosystem management.

The majority of what might be called first-generation systems for use in environmental management (1980s) were typically hard-coded, and designed to address relatively fine-focused and well-defined problems such as supporting silvicultural prescriptions (e.g., practices concerned with forest cultivation) for individual species (Rauscher et al. 1990), or pest management for specific pests on specific species (Twery et al. 1993), which partly accounts for the seeming plethora of systems by the mid 1990s. However, especially over the past 15 years, there has been a pronounced trend toward development of far fewer, but more general purpose, multi-functional systems like EMDS. This trend was significantly enabled by rapid advances in computing hardware and software systems engineering. Equally important, natural resource organizations have been called upon to effectively address the complex issues of ecosystem management (Rauscher 1999).

4 Development History

EMDS development began in 1994 as a research and development project of the Pacific Northwest Research Station, a unit of the US Department of Agriculture, Forest Service. Federal and university scientists from various institutions developed the initial design specifications for the system, and early versions were implemented under contract with the Environmental Systems Research Institute (ESRI).[1]

EMDS 1.0 was released in 1997. This version supported spatially explicit, logic-based landscape analysis, and was implemented as an extension to ESRI's ArcView 3.x geographic information system (GIS).

Version 2.0, released in 1999, added a major new component, dubbed the "Hotlink browser," to the logic-processing component by which system users could graphically trace the logical derivation of model conclusions in an intuitive graphic interface. Whereas version 1.0 had essentially been a "black box," version 2.0 made the inner workings of the logic processor transparent to end-users, which significantly increased interest among users.

The ESRI product line began undergoing a major transformation in the late 1990s, culminating in the contemporary ArcGIS, which first appeared around 2002. Production on EMDS 3.0 began in 2000 to keep pace with the new object-based implementation of ESRI products. In addition to the original EMDS code being re-implemented in Microsoft Visual Basic to support the new ArcObjects

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

framework of ArcGIS, EMDS 3.0 introduced another major component that supported decision modeling as a complement to the logic modeling. At the release of version 3.0 in 2002, EMDS now provided an integrated solution to landscape analysis and planning.

Between the release of version 4.1 in 2009 and the release of version 3.0 in 2002, another major milestone in EMDS development occurred: In 2005, the USDA Forest Service and the University of Redlands (Redlands, CA; www.institute.redlands.edu/emds) signed a memorandum of understanding, under which the university (and the Redlands Institute, in particular) would assume the stewardship of EMDS. More or less contemporaneously, commercial software developers who had been instrumental in delivering the logic and decision components of the system agreed to join the Forest Service and university in a private non-profit development consortium now known as the EMDS Consortium.

Finally, at the release of version 4.2, no new functionality was introduced, but several enhancements were implemented: Version 3.0 code was re-implemented in Microsoft.net, which represents an important intermediate step toward eventually delivering the system as a web service ("EMDS 5.0 and Beyond"). Other major enhancements included implementation of a companion stand-alone edition that runs independently of ArcMap; a new, more intuitive interface built on the workflow concept; and project structures implemented around geodatabases and contemporary database management systems, such as SQL Server and Microsoft Access.

5 Motivations

In recent decades, significant global attention has focused on addressing current and potential future problems with the sustainability of ecosystems, especially since release of the Brundtland Report (WCED 1987). This Report brought international attention to the concept of sustainable development defined through environmental protection, economic growth, and social equity. The subsequent United Nations (UN) Conference on Environment and Development (UNCED 1992 in Rio de Janeiro), and its successor in Johannesburg in 2003, have sharpened the focus and galvanized resolve at many levels of government from international forums like the UN down to local levels. Natural resource management agencies at many levels have adopted principles of ecosystem management, based on their best current understanding of ecosystem dynamics, and are beginning to adapt their management practices accordingly.

The concept of ecosystem management (Overbay 1992) has been with us now for about 30 years. The terms "ecosystem management" (Jensen and Everett 1994), "adaptive management" (Holling 1978; Walters 1986), and "sustainable management" (Maser 1994) are closely connected with each other in the natural resource literature. Ecosystem management has been defined as

> The careful and skillful use of ecological, economic, social, and managerial principles in managing ecosystems to produce, restore, or sustain ecosystem integrity and desired conditions, uses, products, values, and services over the long term (Overbay 1992).

There are many other definitions of ecosystem management in the literature, many of which describe it as a plan or strategy. However, we prefer Overbay's definition (i.e., the use of principles) on the grounds that few if any of the extant descriptions, regardless of how detailed, actually describe a process indicative of planning or strategizing. On the other hand, adaptive management (Holling 1978; Walters 1986) describes a process for implementing ecosystem management, which is why we say that these two terms are closely connected: one describes a set of principles for managing ecosystems, while the other describes a process for the implementing these principles. Subsequently, we shall refer to the two concepts collectively as adaptive ecosystem management (Everett et al. 1994). The Overbay definition also is succinct: it is clear from the definition that the goal behind the application of these principles is ecosystem sustainability in the broad sense of the Brundtland Report (WCED 1987).

By about 20 years ago, the integrated concept of adaptive ecosystem management had been enthusiastically embraced by both the scientific and management communities of the natural resource disciplines. Then-Chief of the Forest Service (US Department of Agriculture), Dale Robertson, declared in 1988 that henceforth the National Forest System was to be managed according to the principles of ecosystem management. Heads of other federal natural resource agencies in the US and elsewhere soon followed suit, and managers set about implementing ecosystem management, often with the eager assistance of scientists who appreciated the experimental nature of active adaptive management (Lee 1999) in particular. Integrated ecological assessments (Christensen et al. 1996) were designed to provide a structured process from formulation of issues to assessment to implementation to adaptive management (Bourgeron et al. 2009). Some 25 years following the Brundtland Report, however, it probably is safe to say that managers and scientists now generally feel a sense of disillusionment with adaptive ecosystem management. There are few good examples in which active adaptive management has been successfully implemented, and progress in learning to manage complex ecosystems more effectively by this approach has been agonizingly slow. Slowing the implementation of ecosystem management is the argument that the general use of the historic range of variability as a reference is not always achievable. Consequently, a shift from ecosystem management to ecosystem stewardship has recently been advocated to sustain the capacity to provide ecosystem services under conditions of uncertainty and change (Chapin et al. 2009a, b). Ecosystem stewardship explicitly includes the acknowledgement of tradeoffs between efficiency and flexibility and between immediate and long-term benefits (Chapin et al. 2009b; Liu et al. 2007). In practice, most of the methodologies used in ecosystem stewardship are shared with ecosystem management. In particular, EMDS is particularly well positioned to assess uncertainty and the trade-offs mentioned above.

You may well be wondering what all of the above has to do with EMDS. In many ways, the swirling maelstrom of principles, methods, and objectives briefly alluded to above in the period from 1985 to 1995 was in fact the context within which the system was conceived (ca 1994). In this context, many good ideas were being advanced, and even a few great ones. Unfortunately, few if any advanced beyond a conceptual model, and the utility of such models is almost always limited by their vagueness, ambiguity, and imprecision (Gustafson et al. 2003). Even as specifications for EMDS were beginning to take shape, it was already becoming clear that successful application of adaptive ecosystem management was turning out to be elusive. Thus, a primary motivation behind EMDS design from the beginning was delivery of a practical decision-support system for adaptive ecosystem management.

6 Concepts and Principles

A few key concepts and principles pertinent to EMDS are discussed in this section as a prelude to subsequent discussion on EMDS structure and functionality.

6.1 Decision-Support System

For the purposes of this volume, we 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 fulfill the Mintzberg and Holsapple definitions include multi-criteria decision analysis (MCDA) systems that implement the Analytic Hierarchy Process (AHP) and similar MCDA methods. These knowledge-based systems provide a framework for applying procedural or reasoning knowledge to decision problems, and, perhaps somewhat more arguably, to optimization systems. However, 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 DSSs. Numerous simulation systems have been developed to support many aspects of planning (see, for example, Schuster et al. 1993), but most should be considered as potential tools employed in a DSS as opposed to DSSs per se.

6.2 Logic and Inference

By the start of the 20th century, important milestones had been reached in what we now recognize as modern science. Russell (1903) had laid the foundations of modern set theory and logic. Although Popper (1934) is perhaps most commonly associated with the principles of modern hypothesis testing, it was Peirce (1931–1935) in the 1890s who described the essentials of hypothesis testing that are still with us today. Peirce drew upon classical logic (Aristotle, 350 BCE) to develop a theory of inquiry, in parallel with the early development of symbolic logic for which he is much better known, to address contemporary challenges in scientific reasoning. Peirce's theory describes three fundamental modes of reasoning: abductive, deductive, and inductive inference.

Most contemporary scientists get sufficient training in the principles of deductive (a conclusion is derived from premises known to be true) and inductive (a conclusion is inferred from multiple observations) inference, so these terms need no detailed explanation here. However, abductive inference (inference based on robust explanation) is probably less familiar because it represents the path of inference less traveled in modern science. It is certainly much less emphasized. Abductive inference is concerned with the initial stages of scientific inquiry, and could be thought of as hypotheses that explain observed phenomena. Conceptual models are one example of what is meant by abductive inference. At one time or another, most scientists dabble in conceptual models because abductive inference is, as suggested by Peirce, an important part of the scientific process. Abductive inference has powerful heuristic value, often quickly leading to researchable hypotheses that would otherwise resist surfacing via deductive or inductive methods. Nonetheless, abduction has been largely ignored as a formal mode of inference by the scientific community, at least within disciplines concerned with natural resource management because it is usually conducted in an informal manner (e.g., conceptual models), and is therefore not perceived by scientists as rigorously scientific. Modern knowledge-based systems overcome many of the inherent limitations of less formal approaches to abductive inference.

NetWeaver ("NetWeaver") was first developed in 1991 to ease knowledge engineering tasks by giving a graphical user interface to the ICKEE (IConic Knowledge Engineering Environment) inference engine developed at Pennsylvania State University by Bruce J. Miller and Dr. Michael C. Saunders. The first iterations were simply a visual representation of the logic model stored in a LISP-like syntax. NetWeaver quickly evolved into an interactive interface in which the visual environment was also capable of editing the models and saving them in the ICKEE file format. Eventually NetWeaver became "live" in the sense that it could evaluate the models in real time.

A NetWeaver logic model graphically represents a problem to be evaluated as networks of topics, each of which evaluates a proposition. The formal specification of each topic is graphically constructed, and composed of other topics (e.g., premises) related by logic operators such as *and*, *or*, *not*, etc. NetWeaver topics and operators return a continuous-valued “truth value,” that expresses the strength of evidence that the operator and its arguments provide to a topic or to another logic operator (Miller and Saunders 2002). The specification of an individual NetWeaver topic supports potentially complex reasoning because both topics and logic operators may be specified as arguments to an operator. Considered in its entirety, the complete logic specification for a problem can be thought of a mental map of the logical dependencies among propositions. In other words, the model amounts to a formal logical argument in the classical sense (Halpern 1989).

Cognitive theory suggests that human beings have two fundamental modes of reasoning: logical and spatial (Stillings et al. 1991). Interesting things happen when logic is implemented graphically.

First, the knowledge of individual subject-matter experts engaged in knowledge engineering often is not fully integrated when dealing with complex problems, at least initially. Rather, this knowledge may exist in a somewhat more loosely organized state, a sort of knowledge soup with chunks of knowledge floating about in it. A common observation of knowledge engineers experienced in graphically designing knowledge bases is that the process of constructing a graphic representation of problem-solving knowledge in a formal logical framework seems to be synergistic, with new insights into the expert’s knowledge emerging as the process unfolds.

Second, synergies similar to those observed in organizing the reasoning of individual subject-matter experts can also occur in knowledge engineering projects that require the interaction of multiple disciplines. For example, many different specialists may be involved in evaluating the overall health of a watershed. Use of a formal logic system, with well-defined syntax and semantics, allows specialists to represent their problem solving approach in a common language, which in turn facilitates understanding of how all the various perspectives of the different specialists fit together and accomplish an evaluation.

6.3 Knowledgebase (or Logic Model)

In modern parlance, the concept of a knowledgebase is now commonly understood to mean an organized body of information. For example, many software companies offer knowledgebases on their web sites to assist users with various aspects of using the software. However, as originally defined by Walters and Nielsen (1988), the term meant a formal specification for the interpretation of information. In this volume, the term knowledgebase is used in the latter sense, and is synonymous with the term “logic model,” which some knowledgebase-system developers prefer as more descriptive. Hereafter, in the remainder of this chapter, we use the term logic model, but we use it interchangeably with knowledgebase.

In terms of the Holsapple (2003) definition of a DSS, logic models represent the knowledge system. The problem-processing system (or engine) is the DSS component that processes the logic model to generate interpretations of the state of a real-world system that is being modeled. Ideally, the construction of a logic model is under the control of the engine, which guarantees that the model is ontologically committed to the engine (Gruber 1995). In other words, the model conforms to the semantics and syntax of the engine.

Logic models can be rule-based, object-based, or some combination of the two. In either case, they implement a reasoning process that supports formal arguments (Halpern 1989). In simplest form, a logical argument can be represented by a conclusion (or proposition) that is to be tested, and a set of premises, each of which contributes evidence for or against the conclusion.

6.4 Decision Model

Environmental assessments provide essential background information about ecosystem states and processes, and are thus a useful starting point for applying adaptive ecosystem management. As a logical follow-up to ecological assessment, managers may wish to identify and set priorities for ecosystem maintenance and restoration activities. Decision models such as the AHP (Saaty 1992) and the Simple Multi-Attribute Rating Technique (SMART; Edwards 1977; Edwards and Newman 1982) provide a bridge from assessment to planning by helping managers to establish rational priorities for management activities ("Criterium DecisionPlus").

Environmental assessments generally deal with a broad array of topics that include biophysical, social, and economic dimensions. Ideally, the same circumspection should carry over into processes used to identify and set priorities for maintenance and restoration activities derived from an assessment. AHP and SMART decision models are discussed together in this chapter because they complement each other in the design of large and complex decision models.

7 EMDS Environment

At version 4.2, EMDS runs on 32- and 64-bit versions of Windows XP, Windows Vista, and Windows 7. In addition, there are two editions of EMDS 4.2. The ArcMap edition, similar to version 3.0, is implemented as an extension to ArcMap, whereas the new stand-alone edition has a custom interface implemented by the Redlands Institute (University of Redlands, Redlands, CA) and runs directly on ArcEngine. The advantage of the ArcEngine edition over the ArcMap edition is that the user interface is greatly simplified (for the GIS-averse), and licenses are an order of magnitude cheaper. On the other hand, the stand-alone edition foregoes immediate access to the full geoprocessing power inherent in ArcMap. Both editions of version 4.2 are compatible with the ArcGIS 9.2, 9.3, and 10.0 platforms.

8 Core EMDS Components

EMDS integrates a decision engine from InfoHarvest, Inc. (www.infoharvest.com) and a logic engine from Rules of Thumb, Inc. (www.rules-of-thumb.com) as core components. The NetWeaver engine ("NetWeaver") performs logic-based evaluation of environmental data, and logically synthesizes evaluations to infer the state of landscape features, such as watersheds (e.g., watershed condition). The decision engine ("Criterium DecisionPlus") prioritizes landscape features with respect to user-defined management objectives (e.g., watershed restoration), using summarized outputs from NetWeaver, as well as additional logistical information considered important to the decision maker(s).

9 Project Structure

Each EMDS project has a well-defined structure that can be summarized as follows:

- A project may contain one or more assessments. An assessment is defined by the user by a set of spatial data layers and a spatial extent selected on those layers. Different assessments are required when the layers participating in the assessments represent different combinations of layers, different extents selected on the same set of layers, or the same combinations of layers but with data from different assessment dates.
- Each assessment may contain one or more analyses. Each analysis has an associated logic model specified by the user. Generally, there is a one-to-one association between assessments and analyses, but multiple analyses can be run in the same assessment to compare structural variants of a logic model.
- Each analysis may contain one or more scenarios. Users are not allowed to alter the data inputs to an analysis after the assessment area has been defined, but data and logic structure can be edited within scenarios to explore "what-if" types of questions.
- Each analysis or scenario may contain one or more decision analyses. Generally, there is a one-to-one association between analyses or scenarios and their associated decision analyses, but multiple decision analyses can be run in the same logic analysis or scenario to compare structural variants of the decision model.

10 EMDS Functionality

The previous section on project structure implies some rather obvious basic functionality (e.g., create assessments, create and run analyses, etc.). However, some functionality falls outside the scope of the structural description, and some of the implied functionality bears further elaboration.

10.1 Analyses and Scenarios

To set up an analysis, the user chooses one or more topics from the logic outline to be included in the analysis. When the run command is executed, the logic processor first traces the logic dependencies from the highest logic level(s) selected down to the data requirements as defined in the logic model. Data requirements from the logic model (names and aliases) are then matched against the names and aliases of attribute fields in the spatial data layers previously associated to the assessment by the user. A name-matching dialogue is then presented to the user to aid them in reviewing, correcting, or filling in matches, as necessary, before an analysis is run.

Once a logic analysis or scenario has been run, any data input or evaluated logic topic can be displayed in the map pane of the system interface. Other functions associated with analyses include:

- Customization of map symbology, which persists within the scope of a project.
- Querying of landscape features to display the evaluated state of the logic in a graphic interface provided by the logic engine.
- A utility to review missing data, and derive priorities for missing data.
- Exporting of map products to various graphic formats.
- Creation of additional scenario(s) based on the current analysis.

10.2 Decision Models

After a logic-based analysis or scenario has been run to evaluate the state of landscape features in the assessment area, this same set of features can then be prioritized for management activities. This is generally based on summarized results generated from the logic-based analysis, as well as any additional data inputs that may be technically or logistically relevant to a decision. Examples of data inputs that may not be considered in the logic evaluation, but that may enter into the decision phase, include factors related to environmental consequences or effects, performance criteria, feasibility or efficacy considerations, and social or economic cost or benefit consideration, among others.

The decision component of EMDS is called the Priority Analyst, which is responsible for configuring a decision model, and displaying its results. The configuration and display tasks are each handled by an associated wizard. Within the configuration wizard, the user is guided through a series of dialogs to:

- Assign a Criterium DecisionPlus (CDP, InfoHarvest, Seattle, WA) model to the decision analysis.
- Map field names between the CDP model and the attribute table generated by the logic engine.
- Optionally, adjust weights on decision criteria.
- Specify options for error handling.

A second display wizard presents the user with a set of tabs in which to review:

- The overall priority score derived for each landscape feature in the assessment.
- The derivation of criterion scores in terms of the contributions made to a criterion by its subcriteria.
- An analysis of model sensitivity or, conversely, model robustness.
- How unit changes in data inputs trade for one another in terms of changing priority scores (tradeoff analysis).

Tables and graphs displayed in the tabs of the display wizard can be exported to a variety of formats. The configured model, including all input records, can be exported to CDP for further analysis. In addition, upon exiting the display wizard, a map of priority scores can be output to the map pane of the system interface.

10.3 Multiple Spatial Scales

Many contemporary decision problems in natural resource management cannot be adequately addressed at a single spatial scale. For example, watershed analysis may require analysis of watersheds and of stream segments within watersheds (Gallo et al. 2005). Similarly, a national forest fuels analysis may require analysis of forest units and regions (Reynolds et al. 2009). Other types of problems may suggest the need for three or more scales of analysis that must be spatially integrated. EMDS projects support multi-scale analyses to the extent that multiple scales of analysis can be accommodated within a single project, but this functionality could be developed further. Currently, it is left to the user to manage integration across scales. However, it is not difficult to conceive of a wizard feature that could assist with scale integration.

10.4 System Role in Adaptive Ecosystem Management and Planning Processes

So far as we are aware, no one has yet fully exercised the capabilities of EMDS with respect to supporting adaptive ecosystem management in particular, or planning processes more generally, so this section is more prospective in nature as opposed to an historical account.

The adaptive management process has been described as a cycle that begins with monitoring and then proceeds through evaluation, planning, and implementation (Holling 1978; Walters 1986). However, any cyclical process requires initialization (i.e., there is always a cycle 0). The process has traditionally been launched by recognition (within the natural resource community) of a significant environmental concern. This leads to identifying key questions that need to be addressed, and an enumeration of data requirements that should be addressed by monitoring. The manner in which data requirements are derived is important. If it is done in an ad hoc or undisciplined way, there is no formal roadmap that traces the dependencies between key questions, intermediate ecosystem states and processes that influence those questions, and a logical trace to needed data. The latter situation is inherently problematic because of the time typically needed to acquire the relevant data. If 5 years have elapsed, half the scientists, specialists, and resource managers initially involved in the process are likely to have moved on, and those that are left may well have lost track of the original rationale, and are left wondering what to do with the data.

Logic models can be a significant aid, in this context, by providing a formal specification that maps the dependencies from key questions, through all the intermediate states, down to data (i.e., a roadmap). Such models serve as a form of institutional memory. A significant point here is that modeling is often an afterthought, when in fact we argue that it should be the first step in the process, in which case the data requirements are derived from the model specification. Furthermore, if the process is implemented in the manner suggested, there is also a clear specification of what to do with the data once they are collected and it's time to evaluate the state of the ecosystem.

In the spatial context of EMDS, the basic products of evaluation are maps of NetWeaver scores, as well as distributions of NetWeaver scores for the set of features that comprise the assessment area. One approach to planning is to employ the Priority Analyst to derive strategic priorities for the management of the landscape features, given the summary results from the logic evaluation and other logistical information important to managers, as discussed earlier. However, there are alternative approaches to planning that can be implemented in EMDS. For example, given the current observed state of the landscape, there may be multiple competing alternative strategies that might be implemented to restore it to a more desirable state. If the consequences of these strategies can be projected into the future (e.g., with simulation systems), and the results attributed back to the GIS layers that fed the original EMDS analysis, one can evaluate the performance of each of the alternatives relative to each other and the original system state (each alternative would be represented by an EMDS assessment). Although one might visually compare the maps associated with each alternative, a more straightforward approach would be to compare the distribution of outcomes across alternatives. In fact, using the distribution data from the assessment of each alternative, standard statistical tests could be brought to bear. With respect to the planning phase, simply comparing the distribution of outcomes of alternatives may not be sufficient. As with more basic EMDS analyses, there may be additional logistical factors that need to be considered, in which case the application of decision models may again be useful. However, the Priority Analyst is no longer the appropriate tool in this case, because it deals with priorities of spatial features, whereas the evaluation of a set of strategic alternatives as described above is no longer a spatial problem. Here, one could revert to the more classical application of CDP models.

EMDS also has a potentially useful role to play in assessing plan performance. To set the stage, let us suppose that an initial landscape evaluation was performed at year 5 (we are continuing the earlier example, and assuming it took 5 years to get to the first evaluation), and, following a planning exercise, a strategy for landscape improvement was selected and implemented. It is now 5 years later (year 10), the monitoring data have been updated to reflect the current landscape condition, and managers want to assess how well the plan is performing. This situation differs in only minor details from the discussion about comparing the expected performance of alternative management strategies. Whereas prior analysis compared expected outcomes of the alternatives, now analysis is comparing two realizations of the evaluated system state over time. Thus, here again, standard statistical tests could be applied to draw inferences about the significance of changes in the distribution of outcomes. Continuing the earlier discussions about the impact of time, 10 years have elapsed from start to present, there has been almost a complete turnover of staff, and the argument for methods that instill institutional memory into the process become more compelling.

11 Critical Factors in the Success of EMDS

The following five factors have been critical in the success of the EMDS system, and provide some additional insights into the functionality of the system.

11.1 Generality

EMDS is a framework within which developers can design customized applications that implement logic and decision models to address many different kinds of questions related to natural resource management, and at whatever spatial scale(s) may be relevant to associated questions. Because of its implementation as a general framework, EMDS has been used in numerous natural resource applications around the world since 1997 (for a fairly comprehensive compilation of published accounts see http://en.wikipedia.org/wiki/Ecosystem_Management_Decision_Support). The design of EMDS as a general solution framework accounts for much of the success of the system since its introduction in 1997.

11.2 Transparency

Rational and repeatable processes are a foundation of decision support, but are not sufficient to achieve maximum effectiveness. EMDS design also has placed a premium on transparency, and we argue that this has been another key ingredient in the relative success of the system as a tool for decision support. Transparency has two important dimensions. First, models should be fully self-documenting in terms of revealing data limitations, underlying assumptions, and particulars of development, with this information accessible to users via the system interface. Second, logic and decision engines should be able to reveal the derivation of answers, via an intuitive user interface, so results can be transmitted to stakeholders who may have limited technical expertise in the subject area. As an example, EMDS solutions have been used to address important national issues in the US precisely because senior agency officials were able to effectively communicate results to Congress or federal oversight agencies.

11.3 Simplification

Logic and decision models in an EMDS application complement one another. A logic model focuses on the question, "What is the state of the system?" A decision model focuses on the question, "Given the state of the system, what can be done about it?" Logistical issues of significance to managers are not pertinent to the first question, but they are important to the second. One consequence of separating the overall modeling problem in EMDS into two complementary models has been that each model is rendered conceptually simpler. The logic model only evaluates the status of a system according to its attributes, whereas the decision model primarily considers attributes of special interest to resource managers. In addition, a logic model can be used as a preprocessor to a decision model, which leads to better handling of the abstractions and complexities of modern natural resource management decisions.

11.4 Abstraction and Complexity

Logic-based approaches to environmental analyses have proven useful in EMDS for accommodating the levels of abstraction and complexity commonly encountered in contemporary decision-support contexts. Abstraction is an issue even in problems that are predominantly biophysical in nature. For example, watershed analysis, wildfire potential, and landscape integrity are all examples of decision-support topics that are both inherently abstract and complex, but essentially biophysical in scope. The application of logic to such problems has been successful in EMDS because the only limitation to use of logic is that one must be able to reason about solutions in terms of chains of conclusions and underlying premises. The case for logic-based solutions becomes still more compelling when the complexity of the problem increases with the need for integrated analyses spanning biophysical, social, and economic dimensions.

12 Experiences in Design and Use

At version 4.2, EMDS is a fully operational decision-support system for environmental analysis and planning, but, by design, it remains a work in progress. The original vision for the system was that it ultimately should provide complete support for the full adaptive management process, but complete specification of such a system, following concepts of waterfall design, was considered impractical, and the development team opted instead to implement an incremental and evolutionary approach to design, following the principle of "build a little and test a little." Based on logic-based processing, versions 1 and 2 implemented decision support for monitoring and evaluation. However, as these early versions were put into application by users, we soon observed that users were attempting to simultaneously evaluate environmental conditions and derive priorities for management (e.g., planning). Such approaches created considerable confusion about how to model the problem. Only after some reflection on these use cases did it become apparent that providing for a separate but complementary decision component might have the potential to simplify integration of evaluation and planning. Subsequent experiences with version 3, which added a decision engine to support planning, confirmed the utility of the solution.

More recently in 2009, EMDS analyses to support budget allocation for forest-fuels management for the US Department of Interior led to recognition of another opportunity by which to improve and extend the functionality of the system. Between 2007 and 2009, solutions had been designed by Department scientists, technical specialists, and mid-level managers to set priorities for level of effort with respect to forest fuels treatment. The set of models was primarily oriented toward biophysical considerations, but included some additional socioeconomic factors as well. Nevertheless, senior managers were primarily interested in using the modeling results to allocate budgets to agencies and regions of the Department. Conflating these two different purposes could easily lead to undesirable outcomes because the existing solutions did not explicitly account for economic and institutional factors needed to support budget allocation decisions. Discussions around this dilemma lead to the realization that a manifold was needed, that is, an additional layer of decision models that consumed results from the existing decision process, to process the multiple purposes for which solutions were being developed.

13 Conclusion

One of the advantages of an application development platform like EMDS is that it enables users to decompose complex, multi-dimensional analysis and decision-making processes into manageable components that conceptually frame and transparently present planning results. Decision-support systems like EMDS require users to formally represent how they logically structure a problem analysis, which allows them to more effectively communicate the rationale of decisions made on the basis of their analyses. Once they are built, logic models can be readily adapted in the future, based on new information, and what has been learned from applied activities. Hence, EMDS applications are highly useful adaptive management tools, as well.

EMDS is an application development framework within which users can design logic and decision models to address many different kinds of questions related to landscape evaluation, at whatever spatial scale(s) may be relevant to their questions (Reynolds et al. 2003). EMDS was intentionally designed for the purpose of integrating environmental analysis and planning processes. Models developed in EMDS can provide decision support for multi-level and multi-dimensional landscape analyses through the use of logic and decision engines integrated with the ArcGIS1 9.2, 9.3, and 10.0 geographic information systems (GIS, Environmental Systems Research Institute, Redlands, CA).

The NetWeaver logic engine evaluates landscape data against a logic model designed by the user in the NetWeaver Developer system (Miller and Saunders 2002), to derive logic-based interpretations of complex ecosystem conditions. A decision engine evaluates outcomes from the logic model and other feasibility, valuation, and efficacy criteria related to management actions, against a decision model for prioritizing landscape treatments in light of these criteria, built with its development system, CDP. CDP models implement the Analytic Hierarchy Process (AHP; Saaty 1992), the Simple Multi-Attribute Rating Technique (SMART; Kamenetzky 1982), or a combination of the two processes.

The logic and decision models in EMDS are complementary; the logic model focuses on the question, “What are the states of the system?”, and the decision model focuses on the question, “Given the states of the system, what might be done about it?” Logistical issues are not pertinent to the first question, but they are vital to the second. One consequence of separating the overall modeling problem into two complementary models is that each model is made simpler: the logic model considers the status of the topics under evaluation; the decision model takes the status of the system and then places it in social and operational contexts that can further inform decision-making. The decisions rendered need only be partially based on system conditions; they can also be based on social context and human values. Decision-makers set priorities for treatment or remedial action using the AHP and/or SMART utilities in CDP. After priorities have been fully derived by the decision model, decision-makers can then review the results and observe the relative contributions of ecological states and social contexts to alternative decisions. This may be accomplished either through sensitivity analysis or by developing various management or treatment scenarios that alternatively weight priorities as they might contribute to a decision. Users adjust the weightings when evaluating alternative scenarios and their trade-offs.

The process of landscape evaluation can be simply rendered or include representative complexity. This feature is critical to ecosystem evaluations because system structure and functionality may exist at several scales that are influential to species large and small, their habitats, and other ecological patterns and processes. A failure to consider the contributions of potential management treatments on conditions, patterns, or processes at these scales can have a large, distributed impact. Thus, having a platform like EMDS allows the user to develop and structure knowledge about the levels and dimensions of landscapes, and how various components interact, enabling them to substantially increase the quality, complexity, and transparency of their thinking. It also enables them to catch themselves in non-critical or erroneous thinking because the logic representing how they think about their systems is formally specified, and can be reviewed and adapted with learning. When outputs of the logic or decision models are revealed that are inconsistent with expectations, the user can then delve into the structure of the logic to determine where the error(s) occurred. This is often an iterative process and it results in improved reasoning and model representation.

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