Decision Support for Evaluating the U.S. National Criteria and Indicators for Forest Ecosystem Sustainability

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Abstract—*This paper describes and illustrates the use of the Ecosystem Management Decision Support (EMDS) system for evaluating the U.S. national criteria and indicators for forest ecosystem sustainability at the scale of Resource Planning Act (RPA) regions. The evaluation component of EMDS uses a logic engine to evaluate landscape condition, and the RPA-scale application demonstrates one practical approach to unifying knowledge for evaluation of forest ecosystem sustainability. EMDS (version 3.0.2) is an extension to ArcMap (ArcGIS 8.x), and is implemented as a general application framework that provides integrated decision support for environmental evaluation and planning at multiple spatial scales.*

In this study, national criteria two and six (productive capacity of forest ecosystems and socioeconomic benefits derived from forest management, respectively) were evaluated. Most data needed to evaluate criterion 2 were available in a recent national report, and results of evaluation indicate strong support for the proposition that productive capacity of forest ecosystems is adequate within all RPA regions. Evidence for suitable levels of socioeconomic benefits varied from weak to moderate across RPA regions, but conclusions were substantially influenced by missing data within all subcriteria.

Introduction

The 1992 Earth Summit (Rio de Janeiro, Brazil) enunciated principles for sustainable development of the world's forest resources (United Nations 1992). Subsequently, the 11 signatory nations to the 1995 Santiago Declaration, representing about 90 percent of the world's boreal and temperate forest cover, affirmed the recommendations of the Montreal Process that prescribed a set of seven criteria and 67 indicators for evaluating forest ecosystem sustainability (WGCICSMTBF 1995). Although the Montreal specifications provided relatively clear definitions of ecosystem attributes requiring evaluation, the Montreal Process did not prescribe how criteria and indicators (C&I) were to be interpreted to draw conclusions about the state of forest ecosystem sustainability. Reynolds (2001) suggested an approach to C&I evaluation based on a formal logic specification.

Gustafson and others (2003) discussed the potential use of logic models for ecological modeling in general. More specific examples of the possible uses of logic modeling in natural resource science include evaluating compatible resource uses (Reynolds 2002a), evaluating the social acceptability of decision processes (Reynolds 2002b), use of logic frameworks as a way to integrate diverse models (Reynolds 2003), and a way to integrate science and policy (Reynolds and others 2003a). Logic models also have been employed in decision support applications for landscape analysis and planning, including applications for design of biodiversity reserve systems (Bourgeron and others 2000), diagnosing departures in landscape structure and functioning (Hessburg and others 2004; Reynolds and Hessburg 2004), effectiveness monitoring (Reeves and others 2003; Reynolds and Reeves 2003), and watershed analysis (Reynolds and others 2000; Reynolds and Peets 2001).

Potential application of the Ecosystem Management Decision Support (EMDS) system for evaluating forest ecosystem sustainability has been described previously in a brief report (Reynolds 2001). This paper presents results on evaluating national criteria 2 (productive capacity of forest ecosystems) and 6 (socioeconomic benefits derived from forest management) at the scale of the Resource Planning Act (RPA) regions used by the U.S. Department of Agriculture, Forest Service in its periodic national reports.

Methods

Criteria and Indicators

Prabhu and others (2001) describe criteria and indicators as "information tools in the service of forest management" in the sense that they "can be used to conceptualize, evaluate, implement, and communicate sustainable forest management." For the purposes of this paper, I follow the definitions of C&I given by Prabhu and others (1999):

- Indicator: An indicator is any variable or component of the forest ecosystem … used to infer attributes of the sustainability of the resource and its utilization. Indicators should convey a 'single meaningful message.' This 'single message' is termed information. It represents an aggregate of one or more data elements with certain established relationships.
- Criterion: A standard that a thing is judged by. Criteria are the intermediate points to which the information provided by the indicators can be integrated and where an interpretable assessment crystallizes. Principles [for example, sustainability] form the final point of integration.

In addition to C&I, it is also necessary for subsequent discussion to define measurement endpoints. Some national indicators are simple; their definition suggests an obvious one-to-one correspondence between an indicator and a measure for that indicator. However, definitions of some indicators are more complex in the sense that they represent a synthesis of two or more data elements, which I refer to subsequently as measurement endpoints.

Data Sources

Most data used as measurement endpoints in this study were obtained from the 2003 national report on sustainable forests (Anonymous 2003). Some socioeconomic data, primarily used to normalize data on measurement endpoints obtained from the 2003 report, were obtained from the U.S. Census Bureau. Data available in the 2003 report were not adequate to evaluate productive capacity of non-timber forest products, so data for measurement endpoints related to this indicator were provided as subjective likelihoods from an expert source (Susan Alexander, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, personal communication).

The Ecosystem Management Decision Support System

EMDS version 3.0.2 (Reynolds 2002c; Reynolds and others 2003b) is a decision support system for integrated landscape evaluation and planning. The system provides decision support for landscape-level analyses through logic and decision engines integrated with the ArcGIS® 8.x geographic information system (GIS, Environmental Systems Research Institute, Redlands, CA). The NetWeaver logic engine (Rules of Thumb, Inc., North East, PA) evaluates landscape data against a formal logic specification, designed in the NetWeaver Developer System, to derive logic-based interpretations of ecosystem conditions such as sustainability. The decision engine evaluates NetWeaver outcomes (and data related to feasibility and efficacy of land management actions) against a decision model for prioritizing landscape features. This study did not use the planning component of EMDS, so it is not discussed further here. However, its potential use in conjunction with the evaluation component is considered subsequently in the Discussion.

Representing the National Criteria and Indicators in Logic

The criteria for productive capacity and socioeconomic benefits include four (table 1), and 19 (table 2) indicators, respectively. Each table presents the logic as an outline of topics for conciseness, but the logic structure of topics is actually represented graphically in NetWeaver during logic design (fig. 1). With 19 indicators and many more measurement endpoints, the full logic structure for socioeconomic benefits is too large to present even in outline form, so the outline (table 2) only presents a summarized overview of this topic.

In a logic-based approach, topics for evaluation have associated propositions (tables 1and 2), which evidence may tend either to support or to refute. The statement of a proposition is free-from text, and, particularly for topics higher in a logic structure that deal with relatively abstract concepts, this statement may be somewhat generalized. However, the logic construct of the topic (fig. 1), together with those of its underlying topics, makes the meaning of each proposition relatively precise in the sense that requirements for support of a proposition are well defined.

The representation of any problem evaluated by NetWeaver can be seen as a logical argument if each proposition is regarded as testing a conclusion, in which case the topics on which it depends may be regarded as

Table 1. Logic outline for U.S. national criterion 2, forest productive capacity.

Topic name[a]	Proposition
Forest productive capacity (AND)[b]	Forest productive capacity is adequate.
Forest land (CALC)[c] (indicator 2.10)	Productive forest land area is a suitable proportion of total forest land area.
Forest volume (CALC) (indicator 2.11)	Volume of nonmerchantable timber on productive forest land is not excessive.
Removals (CALC) (indicator 2.13)	Annual harvest volumes do not significantly exceed annual increment.
Nontimber forest products (UNION)[d] (indicator 2.14)	Productive capacity of nontimber forest products is adequate.
Edibles[e] (UNION)	Productive capacity of edible products is adequate.
Animals[f] (UNION)	Productive capacity of animals is adequate.
Plants[g] (UNION)	Productive capacity of key plants is adequate.

[a]Terms in parentheses following a topic name indicate operators by which topics at the next lower level of the outline are combined. When applicable, the national indicator designation (Anonymous 2003) with which the topic is most closely associated is indicated underneath the topic name.

[b]The AND operator indicates that topics at the next level in the outline are treated as limiting factors. The result of the evaluation is biased toward the most limiting factor.

[c]Topics followed by the CALC operator indicate elementary topics that evaluate the results of mathematical operations on one or more measurement endpoints. Mathematical details are omitted for brevity.

[d]The UNION operator indicates that topics at the next level in the outline are treated as incrementally contributing to the evaluation of their parent topic. The result of the evaluation is a weighted average, in which poor performance in one topic can be partially compensated by good performance on others.

[e]The edibles topic includes evaluation of berry and mushroom production capacities, both of which are elementary topics.

[f]The animals topic includes evaluation of production capacities for game and fur-bearing animals, both of which are elementary topics.

[g]The plant topic includes evaluation of production capacities for medicinal and decorative plants, both of which are elementary topics.

Table 2. Logic outline for U.S. national criterion 3, socioeconomic benefits.

Topic name[a]	Proposition	Frequency of missing values (%)
Socioeconomic benefits (AND[b])	A suitable level of socioeconomic benefits are being derived from current management of forests.	
Production[c] (indicators 6.29 to 6.34)	Current levels of production of forest products are adequate.	30
Recreation[d] (indicators 6.35 to 6.37)	Types and amounts of recreational opportunities are adequate.	34
Investment[e] (indicators 6.38 to 6.41)	Level of investment in the forest sector is adequate.	33
Cultural resources[f] (indicators 6.42 and 6.43)	Cultural, social, and spiritual needs are being satisfied.	50
Employment[g] (indicators 6.44 to 6.47)	Employment conditions in the forest sector are adequate.	51

[a]Terms in parentheses following a topic name indicate operators by which topics at the next lower level of the outline are combined. When applicable, national indicator designations (Anonymous 2003) with which the topic is most closely associated is indicated underneath the topic name.

[b]The AND operator indicates that topics at the next level in the outline are treated as limiting factors. The result of the evaluation is biased toward the most limiting factor.

[c] The production topic is a subcriterion of criterion 6, and includes evaluation of value and volume of wood and wood products production (indicator 29), value and volume of nonwood forest products (indicator 30), supply and consumption of wood and wood products (indicator 31), value of wood and nonwood products as percent of GDP (indicator 32), degree of wood product recycling (indicator 33), and supply and consumption of nonwood forest products (indicator 34).

[d] The recreation topic is a subcriterion of criterion 6, and includes evaluation of: area of forest land managed for general recreation and tourism (indicator 35), number and types of facilities available for general recreation and tourism (indicator 36), and number of visitor days attributed to recreation and tourism (indicator 37).

[e] The investment topic is a subcriterion of criterion 6, and includes evaluation of: value of investment (indicator 38), level of expenditure on research and development and education (indicator 39), use of new technology (indicator 40), and rate of return on investment (indicator 41).

[f] The cultural topic is a subcriterion of criterion 6, and includes evaluation of: area of forest land managed to protect the range of cultural, social and spiritual needs and values (indicator 42), and non-consumptive use of forest land (indicator 43).

[g] The cultural topic is a subcriterion of criterion 6, and includes evaluation of: direct and indirect employment in forest sector (indicator 44), average wage and injury rates (indicator 45), viability and adaptability to changing economic conditions (indicator 46), and area of forest land used for subsistence (indicator 47).

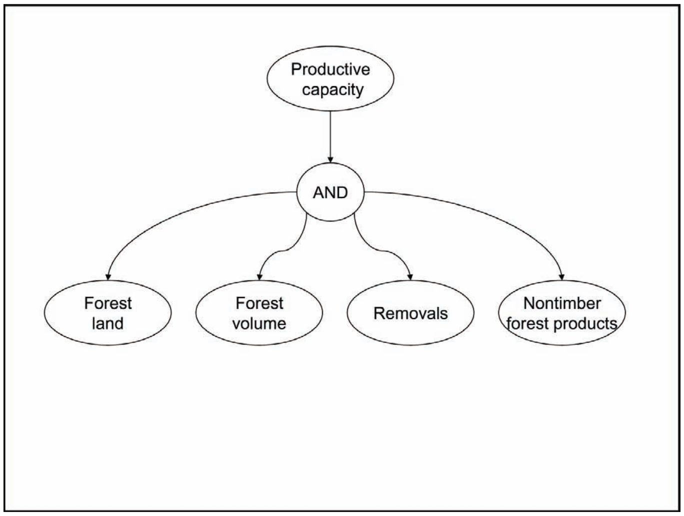

Figure 1. Graphic representation of a logic model in NetWeaver. Strength of evidence for the proposition that forest productive capacity is adequate depends on strength of evidence for its four premises, forest land, forest volume, removals, and nontimber forest products. Each premise similarly represents a topic to be evaluated for its strength of evidence. Partial details for the four premises are outlined in table 1.

its premises. Thus, fig. 1 can be interpreted as "forest productive capacity is adequate to the degree that each of its four premises is satisfied." Each premise contributes some strength of evidence for the conclusion about forest productive capacity. The measure for strength of evidence is a continuous-valued, dimensionless metric that originates with the evaluation of elementary topics (for example, forest land in table 1) that evaluate data (measurement endpoints) as evidence at the lowest levels of the logic. Reynolds and others (2003a) provide additional details about evaluating data as evidence and about basic logic operators such as AND and OR. The key point here, however, is that data in elementary topics are evaluated for the strength of evidence they provide with respect to reference conditions that ideally have been derived from scientific studies and perhaps policy considerations.

Derivation of the Logic

The basic structure for the logic (tables 1 and 2) was originally developed by the author to correspond as closely as possible to the topic outline suggested by the Working Group on Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests (WGCICSMTBF 1995). However, the WGCICSMTBF topic outline did not include specifications for how topics might be combined through logic operators, so initial suggestions for synthesizing information with logic operators also were developed by the author (tables 1 and 2). A panel of internationally recognized authorities on issues of forest ecosystem sustainability was convened to review the resulting logic structure as an initial check on its reasonableness. Among others, the panel included John Gordon (Yale), Jerry Franklin (University of Washington), Norm Johnson, and Hal Salwasser (Oregon State University). Specific formulations for propositions at the lowest levels of the topic hierarchy (tables 1 and 2) were subsequently developed by the author. A key principle in formulating each proposition was that the relevant metric being evaluated by a topic should be normalized whenever possible. So, for example, rather than evaluating the absolute values of forest growth increment and harvest volume (components of indicator 2.13 in table 1), the Removals topic tests the proposition that there is a suitable ratio of growth increment to removals.

Results

Logic-based interpretation of data from the 2003 report (Anonymous 2003), census data, and expert opinion indicated strong support for the proposition that overall productive capacity of forest ecosystems within the four RPA regions was adequate (fig. 2). In fact, evidence indicated full support for the three premises associated with the forest land, forest volume, and removals topics (table 1). On the other hand, evidence for adequate productive capacity within non-timber forest products fell within a range that could be characterized as moderate

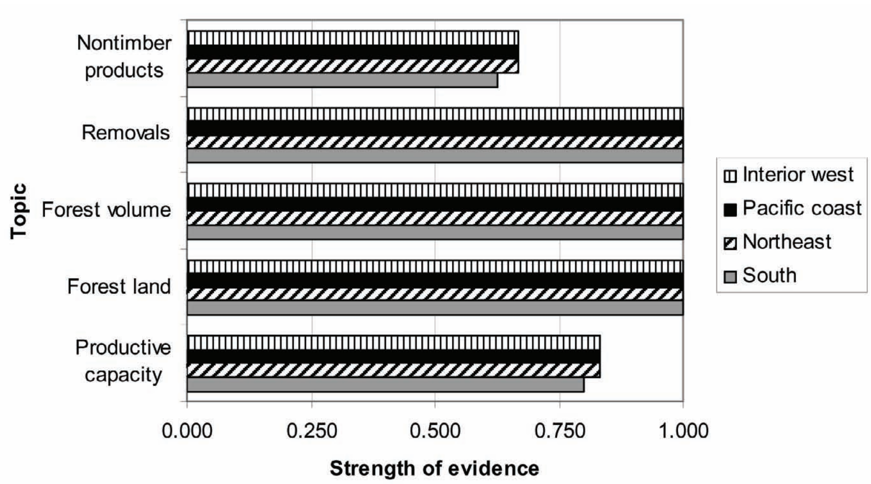

Figure 2. Evidence for adequate productive capacity of forest ecosystems in RPA regions of the U.S. Strength of evidence for the premises of productive capacity (table 1, fig. 1) also are shown.

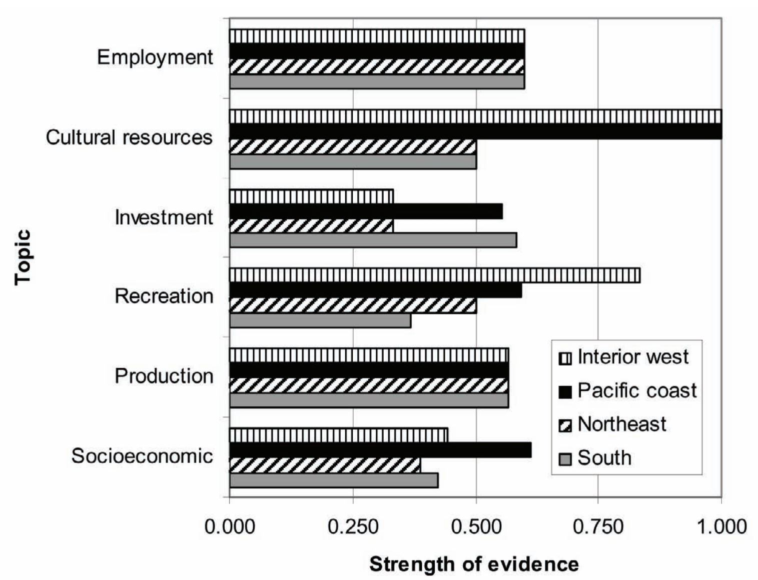

Figure 3. Evidence for suitable levels of socioeconomic benefits derived from forest management in RPA regions of the U.S. Strength of evidence for the premises of socioeconomic benefits (table 2) also are shown.

(fig. 2), and this result constrained the overall evaluation of forest productive capacity due to the influence of the AND operator (fig. 1) that treats individual premises as potentially limiting factors.

Overall strength of evidence for suitable levels of socioeconomic benefits derived from forest management varied from weak to moderate across the four RPA regions (fig. 3). However, the relatively poor performance on this criterion was partly due to negative conclusions about indicators. Instead, the lower levels for strength of evidence in this case are often attributable to significant data gaps in all subtopics (table 2). The influence of missing data on evaluation of production (table 2), for example, is typical. The production topic includes indicators 6.29 to 6.34 (although indicator 6.32 is not used in the current logic model) which are organized within the three subtopics, wood production, production of non-timber forest products, and recycling (indicator 6.33). Data were not available on recycling, and this lack of evidence constrained the strength of the conclusion about production, given available evidence, because strength of evidence on the other two subtopics was moderately strong.

Discussion

A Framework for Science, Policy, and Communication

Perhaps one of the most useful aspects of a logic-based approach to evaluating forest ecosystems is that logic provides a formal framework within which possibly numerous interdependent issues of science and policy can be organized to guide the needed dialogue between scientists and policymakers to perform an evaluation (Reynolds and others 2003a). Conceptual models can be very useful in the initial design stage of a logic-based approach, but, as Gustafson and others (2003) have discussed, they have significant limitations when used as stand-alone modeling solutions. In particular, lack of a formal structured logic in typical conceptual models can result in the entities and their relations being semantically vague at best and unintelligible at worst. Although formal logic frameworks are not entirely immune from such problems, they are far less prone to them. In fact, the graphical form of logic representation is not only a powerful form of communication among model developers, but an intuitive medium in which to explain the results of evaluations to audiences who may have little or no technical background in modeling (Reynolds and Reeves 2003).

Missing Data

The 2003 report on the state of forest ecosystems in the U.S. (Anonymous 2003) was a landmark publication with respect to the scope of the ecological and socioeconomic indictors that it attempted to address. However, not too surprisingly, even given several years of preparation to produce this report, there were numerous data gaps. An important contributing factor was that the scope and complexity of questions being asked about forest ecosystem had increased dramatically over the past 20 years. Indeed, missing data is a recurrent issue in most modern programs of landscape monitoring and assessment. In this particular study, all data on forest productive capacity were available in one form or another, but there were significant data gaps in all subcriteria of the socioeconomic criterion (table 2).

In a logic context, data are evidence, and missing evidence does not preclude a useful evaluation, but constrains the strength of conclusions (fig. 3). In the present study, for example, it is possible to conclude that available evidence indicates there is at least weak to moderate support for the proposition that levels of socioeconomic benefits derived from forest management are adequate across the four RPA regions. To appreciate the value of this partial answer, consider that 50 to 70 percent of the data on subcriteria of the socioeconomic criteria were available, and that none of the available data led to the conclusion that the levels of socioeconomic benefits were inadequate.

Perhaps just as importantly, logic engines such as that integrated in EMDS can interpret interdependencies in data and analysis topics to calculate a measure of the influence of missing information, and this information can readily be incorporated into simple decision models to evaluate the priority of missing information, taking into account its influence and other logistical considerations, such as how expensive it might to acquire the missing data (Reynolds 2002c, Reynolds and others 2003b).

Additional Lines of Future Development

The current application could easily be extended in two potentially useful respects.

First, the present example illustrates evaluation at a single spatial scale. However, EMDS applications can accommodate multiple spatial scales. Reynolds and Peets (2001) have illustrated integrated evaluation across multiple spatial scales in the context of watershed assessment for salmon habitat restoration. In the present context, virtually all of the indicators for criteria 2 and 6 could be evaluated at the scale of States, and State-scale results summarized to RPA regions as area-weighted averages. More generally, evaluations of criteria can be parsed among scales as necessary. For example, the biodiversity, global carbon cycle, and institutional framework criteria (1, 5, and 7, respectively) are most likely best evaluated at the broader scale of RPA regions. Multiple scales can be employed within a single EMDS application in other ways as well. For example, evaluations of criteria 2 and 6 at the scale of National Forests might be superimposed on their corresponding regional evaluations to place the Forest-scale evaluations in their broader regional context.

Second, the present paper does not consider analysis of management priorities for maintenance or restoration of forest ecosystems within the RPA regions. However, EMDS includes a planning component that uses a decision engine to evaluate planning models built with Criterium DecisionPlus® (CDP, InfoHarvest, Seattle, WA). The CDP models implement the analytical hierarchy process (AHP, Saaty 1994), the simple multi-attribute rating technique (SMART, Kamenetzky, 1982), or a combination of the AHP and SMART methods. Reynolds (2000) provided a detailed example of applying AHP and SMART to develop priorities for salmon habitat restoration. Reynolds and Hessburg (2004) provided an example of decision modeling with CDP in conjunction with EMDS applications.

The distinction between the evaluation and planning phases of analysis as implemented in EMDS has important consequences for users developing management applications because it simplifies the overall analytical problem into two simpler problems. In evaluation, the question of interest is, "What is the state of the system?," whereas, in planning, the question is, "Which areas are the highest priority for management?" Decomposing the problem is this way avoids confusion in the assessment process by cleanly separating issues about the current state of a system from issues about where management or restoration activities ought to occur. An important side effect of this problem decomposition is that logistical considerations about the feasibility or efficacy of potential management activities are easily accommodated within the planning component.

Conclusions

Evaluating forest ecosystem sustainability within a formal logic framework illustrates one practical approach to unifying knowledge within a large, abstract problem domain. Some specific benefits that derive from the logic-based approach include 1) a rigorous approach to problem specification that simultaneously expedites dialog among model developers while facilitating communication of model results to non-technical audiences in intuitive terms, 2) effective use of partial information in the early stages of monitoring when information is often incomplete, and 3) the availability of metrics for evaluating the influence of missing information which can help optimize how data gaps are subsequently filled.

Within the broader context of a decision support framework, knowledge unification in a logic framework can be viewed as a form of knowledge integration. Additional practical examples of integration within a decision support framework include the ability to link scales of evaluation, and the ability to explicitly link the evaluation and planning phases of adaptive management (Reynolds and Hessburg, 2004; Reynolds and Peets, 2001).

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