Using logic to evaluate forest ecosystem sustainability

Keith M. Reynolds, USDA Forest Service, Pacific Northwest Research Station
Sean N. Gordon, USDA Forest Service, Pacific Northwest Research Station
K. Norman Johnson. Oregon State Univ., College of Forestry, Dept. of Forest Resources

“All models are wrong; some models are useful” (Box 1979, p. 212).

Introduction

In this paper, we have three objectives: 1) to illustrate the utility of a logic-based approach to evaluating the sustainability of forests and their benefits using the Montreal criteria and indicators (C&I), 2) to identify the roles of science and policy in this effort, and 3) to illustrate application of C&I with a prototype model designed for the US 2003 Report (USDA Forest Service, 2004). To accomplish these objectives, we present a prototype logic framework for using C&I in assessing sustainability, highlight the policy choices that must be made in this construction, and discuss some of the lessons we learned along the way.

Criteria and indicators

Prabhu et al. (2001) describe C&I 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, we follow the definitions of C&I given by Prabhu et al. (1999a). In addition to C&I, it is also necessary for subsequent discussion to define measurement endpoints. Some Montreal indicators are simple; their definition suggests an obvious one-to-one correspondence between an indicator and a metric for that indicator. However, definitions of some Montreal indicators are more complex in the sense that they represent a synthesis of two or more data elements, which we refer to as measurement endpoints.

Any indicator or criterion implies a model and set of assumptions that relates the indicator to more complex phenomena and comes with an obligation to make explicit both the metric and the underlying model (Hammond et al. 1995; Adriaanse 1993). Relatively little research to date has focused on developing formal representations of indicators and their interrelations as a basis for actually evaluating sustainable forest management (SFM) despite recent widespread interest in developing and applying C&I for evaluating SFM (Prabhu et al. 2001). However, a few efforts have been experimenting with use of semantic networks and similar types of representation (Colfer et al. 1996, Haggith et al. 1998, Prabhu et al. 1999b). In this paper, we consider the use of a logic-based network representation for evaluating the Montreal C&I as a way to cope with the semantic vagueness inherent in natural language (Zadeh 1976). Our primary

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1 This paper is an abbreviated version of Reynolds et al. (2003), but with addition of results from a prototype model.
objective is to show how representation in formal logic can help reveal the myriad
decisions involved at the science/policy interface of SFM, as well as enhance the
transparency and consistency of evaluations.

Montreal criteria and indicators

The Montreal specifications provide relatively clear definitions of biophysical,
socioeconomic, and institutional attributes requiring evaluation (WGCICSMTBF 1995).
However, design of evaluation procedures that allow interpretation of the Montreal C&I
is one of the major technical issues that remain to be resolved (Raison et al. 2001). The
design of any model that purports to evaluate sustainability with respect to a set of
criteria and indicators must necessarily incorporate value judgments and other subjective
elements (Prabhu et al. 2001), and this is no less an issue for biophysical aspects as it is
for socioeconomic ones (Lélé and Norgaard 1996). We discuss several specific aspects of
subjective design elements in the context of logic models in the section, Model design
issues.

Conceptual frameworks

Sustainability is fundamentally a human construct (Franklin 1993). Hence, any discussion
of resource sustainability is strongly conditioned by human values and objectives.
Following Davis, et al. (2000), six elements are needed to assess the sustainability of
values in which we are interested:

1. Specific conditions or outcomes to be sustained (the indicators).
2. A measure for each condition or outcome.
3. Calculation of the level of the indicator over some time period using the selected
measure.
6. A monitoring program.

Both science and policy are needed to apply this framework. Policy decisions are needed
to select the values of interest and the methods for assessing sustainability. Science is
needed to specify indicators and measurement endpoints, develop reference conditions
(e.g., step 4), and specify a monitoring plan. Successfully completing these tasks requires
the joint effort of policy makers and scientists, with significant interaction between the
two groups.

Representation of what we think we know about ecosystems often is problematic and,
while scientific frameworks are valuable organizing tools (Johnson et al. 1999), a basic
difficulty is that the framework concept itself is ill-defined. What constitutes a useful
framework? Too often, the term connotes a conceptual model with no well-defined,
underlying syntax so the problem specification is semantically vague at best, and
unintelligible at worst. One way to cope with semantic vagueness (lexical uncertainty) is
by constructing a formal logic with well-defined syntax and semantics. Interpretation of
data by a logic processor can then provide a consistent evaluation of system states and processes represented in the model.

**Using logic models as design frameworks**

Logic models (or knowledge bases) provide a formal specification for organizing and interpreting information, and are a form of meta database. As a meta database, a logic model helps ensure consistency in interpretation of data across time and space. Such models can be designed for broad geographic application, by taking some care in their design. In our design of a specification for evaluating SFM, we use the NetWeaver Developer system (Rules of Thumb, North East, PA) that represents a problem in terms of propositions about topics of interest and their logical interrelations. In design of a NetWeaver model, a topic for analysis is translated into a testable proposition. For example, if the topic is forest sustainability, the associated proposition might be as simple as “The forest ecosystem is sustainable.” The statement of the proposition by itself is inherently vague because sustainability is an abstract concept. However, the full formal logic specification underlying a proposition makes the semantic content of the proposition more clear and precise (Figure 1 and 2). The biophysical, socioeconomic and framework topics (Figure 2) are logical premises of forest sustainability. The proposition about forest ecosystem sustainability evaluates as *true to the degree that* integrity of the biophysical environment, suitable socioeconomic conditions, and a suitable institutional framework exist. The phrase, “true to the degree that,” emphasizes that strength of support for propositions in logic models is evaluated by “evidence-based reasoning.” This form of reasoning can be implemented with fuzzy math (Reynolds et al. 2003), a branch of applied mathematics that implements qualitative reasoning as a method for modeling lexical uncertainty (fuzzyTech 1999).

The logical discourse on forest ecosystem sustainability is extended by providing a logic specification for each premise. Each iteration of discourse extends the logic structure another level deeper by defining a logic specification for each topic in the level above. The process generally proceeds from abstract to concrete propositions, with premises of a particular proposition tending to be less abstract than that proposition. Eventually, each logic pathway ends in a premise, or set of premises, each of which can be evaluated by reference to data. Pathways in a logic model can thus be construed as a cognitive map of the problem that provides a formal data specification. However, this specification not only describes what data are to be evaluated, but how the data are to be interpreted and synthesized to arrive at conclusions.

The semantics of a logic model are easily conveyed to broad audiences in graphic form. A group of specialists, representing diverse disciplines, can easily collaborate in the design of a complex logic model, because the structure and its graphic representation provide an effective basis for organizing discussion. During model evaluation, conclusions and explanations of their derivation are intuitively traced through the evaluated state of a logic model to communicate effectively with both policy makers and other interested parties. Effective communication between model designers, scientists, and policy makers is especially important in the context of designing a logic model for
evaluating SFM, because many aspects of model design reflect important policy decisions concerning how sustainability is to be evaluated.

The design of logic models involves both interpretation of data and synthesis of information. Here, we focus on the synthesis dimension. One of the more significant challenges that has emerged for all countries preparing and presenting national reports on SFM is how to distill the volumes of information collected into the kinds of major conclusions that policymakers and, ultimately, the public care about. For example, the Montreal Process specifies nine indicators concerned with biodiversity. A few of these biodiversity indicators involve dozens of measurement endpoints that must be synthesized to generate an index for the indicator. However, even if we take for granted that suitable indices exist for the nine Montreal biodiversity indicators, there is still the question, what does this set of indices tell us about the status or trend of biodiversity? Formal logical argument, structured in terms of successive levels of conclusions and premises, as discussed above, can provide useful answers to such higher order questions by imposing levels of organization that succinctly “tell a story” in relatively intuitive terms.

Prabhu et al. (2001) emphasize the need for transparency in models that evaluate C&I for SFM because any such model 1) embodies important policy decisions in its specification, and 2) depends on value judgments and critical assumptions that require documentation. For example, the specific arrangement of C&I within a logic framework reflects value judgments concerning the relative importance of components being evaluated, and thus constitutes an important policy decision. We have already mentioned how the graphical representation used in logic models facilitates discussion on the design of models and the derivation of conclusions. Equally important, such a framework also can provide an extensive set of documentation attributes for each topic in a model, including description of the proposition, explanation of the proposition, technical authorities, literature citations, and assumptions.

**Model design issues**

*Implications of model organization*

Most representations of C&I for evaluating SFM are arranged hierarchically (Prabhu et al. 2001), and this is true in the case of the Montreal C&I (WGCICSMTBF 1995). However, Prabhu et al. (2001) emphasize the value of a more general network representation such as that used in logic models, which allows cross-linkage among indicators and perhaps other intermediate topics. In our current prototype of the Montreal C&I logic, for example, evaluation of community viability (indicator 46) depends on indicators 13 and 44 as well as data elements related to other indicators (Figure 3). This ability to represent interdependencies among indicators means that the logic can account for both mutual dependencies and tradeoffs.

Organization of topics within the current Montreal design specification has important policy implications. For example, many colleagues have found the highest-level organization (Figure 2) quite acceptable, but an alternative representation is quite
possible (Figure 4), and these two representations of sustainability would produce very
different evaluations. The five biophysical criteria in the current specification are
subsumed under the biophysical topic (Figure 2). This specification effectively asserts
that the collective evidence from all biophysical criteria is equal, in terms of strength of
evidence for sustainability, to the collective evidence from criterion 6 or criterion 7. The
alternative representation (Figure 4) puts much greater emphasis on the biophysical
criteria, asserting that the collective evidence of each biophysical criterion (1-5) is equal
to that for criterion 6 or criterion 7.

**Synthesis of information**

Evaluation of any criterion for SFM involves multiple indicators. Therefore, the
definition of a criterion (Prabhu et al. 1999a) stresses the need for integration of
information in evaluating any SFM criterion. In the case of the Montreal C&I, integration
of information may, in fact, extend many levels deep (e.g., Figure 2 and 4). The
specifications of the employment topic (Figure 3) and biodiversity (criterion 1, Figure 5)
illustrate another design issue with significant policy implications: the choice of how to
integrate information. The most commonly used logical operators for combining
elements in NetWeaver are AND, OR, and SUM. That a logic model requires us to
explicitly assign an operator at each synthesis step reveals critical information that is
often left undefined in less formal descriptions.

The computation implemented by the NetWeaver AND operator effectively evaluates the
set of topics that are arguments to the operator as limiting factors. That is, the result of
the AND operation is constrained by the least favorable component. A three-legged stool
is a useful visual analogy to the AND operator: if one leg is removed (a line of evidence
evaluates as fully false), the stool topples.

The SUM operator, commonly associated with calculations in the Montreal logic model,
effectively asserts that the topics in the set of arguments to the SUM operator can
compensate for one another. For example, in the evaluation of the ecosystem diversity
topic (Figure 5), if the proposition for indicator 2 evaluates as unsupported, but
propositions for indicators 3, 4, and 5 evaluate as fully supported, then the strength of
evidence for suitable ecosystem diversity evaluates to 0.75 on a scale of [0, 1].

The OR operator is the functional opposite of AND. In this case, the three-legged stool is
magical, and will continue to support weight as long as any one of the legs is functional.
Figure 4 uses an OR operator to combine community viability with community
adaptability: socio-economic goals are likely to be met if either the community can
continue sustainably as it is or it can successfully adapt to new conditions.

**Reference conditions for quantitative measures**

“Possibly one of the biggest challenges facing researchers currently is the identification
and quantification of … [reference conditions]” for SFM indicators or more specific
measurement endpoints (Prabhu et al. 2001). In the context of endpoint evaluation,
reference conditions provide a context for inferring the meaning of observed values at
step 4 in the process of Davis et al. (2000). Perhaps more often than not, the specification of reference conditions for interpreting observed values of endpoints used in evaluation of SFM will require scientifically-based judgments in lieu of more precise calculations. Fuzzy membership functions provide an effective approach to representing such qualitative or semi-quantitative relations (Zadeh 1976). Figure 6 demonstrates a fuzzy membership function that compares old-growth forest cover to its probable historical extent. Scenarios evaluated that are clearly outside the historical range of less than 20 or greater than 80 percent receive values of zero in the model, while those in the 40-60 percent range receive full credit (+1), and remaining intermediate values partial credit.

Reference conditions for evaluating some endpoints might be applicable to a national level application of C&I. However, it is probably much more typical that reference conditions will need to vary with biogeographic or socioeconomic context. The examples we present subsequently decompose the US national analysis into more homogeneous regions that have been delineated for purposes of the USDA Forest Service’s periodic RPA (Resources Planning Act) assessment.

Other design issues

The previous three subsections have addressed some of the most fundamental issues of logic design in the C&I context. Other important issues that we will simply mention here, but perhaps discuss in the presentation, include:

- Weighting topics
- Use of qualitative measures
- Reliability of data
- Precision of available knowledge
- Availability of data

Examples of model application to date

An initial prototype application was developed in 2002, covering criteria 2 and 6 (Figure 2), and based on earlier draft versions of the first US national report (USDA Forest Service 2004). Reynolds (2003) demonstrated a small portion of the prototype, focusing on modeled interdependencies related to forest productive capacity. Since publication of the national report, we have continued to compile data for a larger prototype covering criteria 1, 2, 3, 5, and 6. In the following, we only offer a broad overview of current prototype results because the full model contains so many logic topics and data elements that a detailed description is far beyond the scope of this brief report.

Figure 7 presents a synthesis of the five biophysical criteria (Figure 2), but with the conservation criterion ignored due to lack of data. Many indicators for these criteria were evaluated by reference to observed values from the previous RPA assessment, and therefore are based on interpretation of trend. However, we note some interesting exceptions to interpreting trend below.
Figure 8 provides a further decomposition of forest biodiversity (criterion 1) in terms of indicators organized into subcriteria. Figure 9 repeats the information presented in Figure 8, but in the native modeling environment of NetWeaver. The NetWeaver interface offers a convenient way to “drill down” through the evaluated state of the logic structure (Figure 9) to trace the derivation of conclusions.

Figure 10 provides a further decomposition of the evaluation of contributions to the global carbon cycle (criterion 5). All indicators for this criterion were evaluated by reference to observed values from the previous RPA assessment, and therefore are based on interpretation of trend. Use of trend data in this criterion proved to be problematic in part because there was a strong shift in timber production from the west coast to the southeast US over the period being evaluated.

Figure 11 shows the overall synthesis for the socioeconomic criterion, based on subcriteria for production capacity, employment, recreation, and investment. The cultural subcriterion under this criterion was ignored due to lack of data.

As noted, not all indicators were evaluated in terms of trend. A few examples, relative to evaluating biodiversity (criterion 1), include the following:

- For indicator 2 (extent of area by forest type and by age class or successional stage), data based on three size classes (sawtimber, pole timber, seedling/sapling) were used as surrogates for successional stage. The 2003 report (USDA Forest Service 2004) states that "A balance of forest types at diverse successional stages is considered essential to providing forest landscapes that are both sustainable and capable of providing desired outcomes for both wildlife and human use." Therefore, instead of using data from a previous year as a reference, we evaluated the data against Hill's index, which combines the percentages in all three size classes into an index of evenness.

- For indicator 3 (extent of area by forest type in protected area categories as defined by IUCN or other classification systems), we used a reference range (±2%) centered around 10% protected area for each forest type, which has been widely adopted in international fora (e.g., the World Parks Congress in 1992).

- For indicator 7 (status of forest dependent species at risk of not maintaining viable breeding populations), we evaluated the proportion of area within an RPA region containing species designated as at risk of extirpation, specifying a reference range of 5 to 20%, corresponding to evidence scores of 1 and 0, respectively.

- For indicator 8 (number of forest dependent species that occupy a small portion of their former range), the 2003 US report uses species range reductions based on NatureServe data. Species range reduction is based on species extirpations by State. To calculate regional numbers, we calculated a weighted average of extirpations based on the State's percent of total regional forest area. Here, we used a reference range of 0 to 10 extirpations, corresponding to evidence scores of 1 and 0, respectively.
The above examples of more absolute reference conditions in the current prototype logic were only intended as examples. However, it seems quite possible that sensible reference ranges for these, and probably other, indicators could be developed by thoughtful deliberation between policymakers and scientists. Finally, there are other avenues for developing reference ranges that deserve further attention. For example, the question of what harvest volume (removals, indicator 13 under productive capacity) is sustainable has been debated since the concept of sustained yield forestry was first introduced. For national assessments, the traditional approach in the US has been to compare removals with net growth. It may be easier to specify reference ranges for normalized metrics, such as ratios of measurement endpoints for two or more indicators (e.g., harvest measures versus measures of net growth),

**Some lessons learned**

- Many aspects of evaluating sustainability cannot be answered by science alone. Policy makers have a critical role to play in model design.
- Data on SFM is a necessary, but not a sufficient, condition for setting policy.
- Semantic vagueness is an important issue in evaluation of C&I for SFM.
- The collection of topics, and the manner in which they are evaluated, depend on geographic scale.
- Desired future conditions are not a suitable basis for evaluating sustainability.

**Recommendations**

The issue of whether or not to interpret indicators of SFM has been hotly debated for at least the past 10 years. This issue needs to be resolved. There is no escaping the basic problem that any such analysis cannot be executed with anything approaching perfect objectivity; judgment, which is inherently subjective, is an essential ingredient when knowledge is less than perfect. If senior scientists and policy analysts, with decades of training and experience in the subject matter pertinent to SFM, are unwilling to interpret and synthesize data on sustainability to help develop policy recommendations, then who can, considering the substantial scientific and technical knowledge requisite to any informed decisions on this topic? Scientists and policymakers should not shrink from bringing logical rigor to the task of assessing SFM for fear that their models are wrong. As Box (1979) pointed out, they are, but such models can nonetheless constructively sharpen the necessary public discourse.

If there is agency-level interest in further developing a logic-based approach to interpretation and synthesis of national C&I, then

- A good next step would be a national-level policy review of model organization and strategies for interpreting and synthesizing sustainability information.
- We need to accept the need for reference conditions and shift a portion of the scientific and technical energy on indicator measurement to developing them.
Literature Cited


Figure legends

Figure 1. Key to logic symbols used in subsequent figures.

Figure 2. Partial logic specification for evaluating sustainability of a forest ecosystem. Each premise has its own logic specification that may extend many more levels. NetWeaver knowledge bases are graphically built from modular components like this, simplifying incremental development of complex models. Only the first three levels of network structure are illustrated.

Figure 3. Logic specification for evaluation of the employment topic under the socioeconomic criterion (criterion 6). Community viability depends on (e.g., is cross-linked to) indicators 13 and 44 as well as data elements of other biophysical indicators related to wood production (indicators 29 and 31) and production capacity (indicators 11 and 12).

Figure 4. An alternative (partial) logic specification for evaluating sustainability of a forest ecosystem. In this representation, biophysical criteria assume more importance compared to Figure 2.

Figure 5. Additional level of detail of the logic specification for the biodiversity criterion, illustrating the AND and SUM operators which represent different philosophies about how information combines.

Figure 6. Deriving a fuzzy membership function for suitability of old-growth forest cover from statistical information. The probability curve shows the estimated probability density for old-growth forest in the Oregon coast range for the past 3,000 years (adapted from Wimberley and Spies in Davis et al. 2001, p. 12). The superimposed fuzzy membership function maps percent cover values into a measure of suitability. Dashed reference lines indicate thresholds used to define reference conditions for the fuzzy membership function.
Figure 7. Evaluation of Montreal criteria 1, 2, 3, and 5 by Resources Planning Act regions, based on data from the 2003 US national report (USDA Forest Service 2004). Criteria 1, 2, 3, and 5 are biodiversity, productive capacity, ecosystem health, and global carbon cycling, respectively. Evaluation of criterion 4 (conservation) was disabled for this example due to most data being missing at the present time.

Figure 8. Evaluation of Montreal criterion 1 (biodiversity) by Resources Planning Act regions, based on data from the 2003 US national report (USDA Forest Service 2004). Results for biodiversity (criterion 1 in Figure 7) are further decomposed into the subsets of indicators that make up its premises.

Figure 9. An alternative view of Figure 8, illustrating the NetWeaver representation of the biodiversity criterion and the subsets of indicators that make up its premises. Color coding of logic topics corresponds to the strength of evidence, which is also indicated in the figure, next to each topic.

Figure 10. Evaluation of Montreal criterion 5 (contribution to global carbon cycling) by Resources Planning Act regions, based on data from the 2003 US national report (USDA Forest Service 2004). Results for carbon cycling (criterion 5 in Figure 7) are further decomposed into the subsets of indicators that make up its premises.

Figure 11. Evaluation of Montreal criterion 6 (socioeconomic wellbeing) by Resources Planning Act regions, based on data from the 2003 US national report (USDA Forest Service 2004). The topmost map shows the overall evaluation of socioeconomic benefits, and other maps represent subcriteria, which are treated as premises of criterion 6. Evaluation of cultural benefits (an additional subcriterion of criterion 6) was disabled for this example due to most data being missing at the present time.
Numeric ID for Montreal criteria
Math or logic operator
A simple datum named n or a numeric constant with a value of n

Logic switch that maps a set of ordinal values (A, B, and C) into a set of numeric constants.
Logic model topic with complex proposition.
Logic model topic whose proposition is evaluated by a fuzzy node.
Logic model topic that performs a mathematical calculation. The optional [{-m, n}] ornament indicates a set of fuzzy arguments.
A list of one or more topics that read ordinal data, and map the ordinal value to NetWeaver’s fuzzy membership scale.

Figure 1

Figure 2
Indicator 47
Subsistence area

Indicator 44
Employment rate

Indicator 45
Injury rate

Indicator 46
Commm. viability

Indicator 45
Wage rate

Indicator 46
Commm. adaptability

AND

Indicator 47
Subsistence area

Indicator 44
Employment rate

Indicator 45
Injury rate

Indicator 46
Commm. viability

Indicator 45
Wage rate

Indicator 46
Commm. adaptability

AND

Figure 3

Figure 4
Figure 5

Figure 6
Figure 7

1. Biodiversity
2. Productive Capacity
3. Ecosystem Health
4. Northeast
5. Carbon Cycle

Evidence:
- Red: No support
- Pink: Very low
- Light pink: Low
- Undetermined
- Light green: Moderate
- Dark green: Strong
- Black: Full support
Figure 8
Figure 9
Figure 10
Figure 11