Systems Analysis in Forest Resources: Proceedings of the 2003 Symposium
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Systems Analysis in Forest Resources:
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Compiled by
Michael Bevers and
Tara M. Barrett
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ABSTRACT


The 2003 symposium of systems analysis in forest resources brought together researchers and practitioners who apply methods of optimization, simulation, management science, and systems analysis to forestry problems. This was the 10th symposium in the series, with previous conferences held in 1975, 1985, 1988, 1991, 1993, 1994, 1997, 2000, and 2002. The forty-two papers in these proceedings are organized into five application areas: (1) sustainability, criteria and indicators, and assessment; (2) techniques and decision support for forest planning; (3) forest assessment and planning case studies; (4) fire suppression, fire planning, and fuels management; (5) harvest scheduling; and (6) mill supply and forest product markets.

KEYWORDS: Forest planning, forest management, forest modeling, operations research.
PREFACE AND ACKNOWLEDGMENTS

The 2003 symposium on systems analysis in forest resources was the 10th symposium in this series. Originated as a conference of the Systems Analysis Working Group of the Society of American Foresters, the first meeting was held in Athens, Georgia, in 1975. The second symposium was held again in Athens in 1985. The international success of these conferences has motivated additional meetings every 2 to 3 years since 1985, including systems analysis symposia in Asilomar, California (1988 and 1994), Charleston, South Carolina (1991), Valdivia, Chile (1993), Traverse City, Michigan (1997), Snowmass Village, Colorado (2000); and Punta de Tralca, Chile (2002). Future meetings are being planned in Brazil in 2005 and in the United States in 2006.

The 2003 symposium was made possible through the contributions of many people and organizations. Participating organizations included three Society of American Foresters scientific groups (the management science and optimization (E-4) working group, the economics, policy, and law (E-1) working group, and the technology assessment and future analysis (E-5) working group), scientific divisions of the International Union of Forest Research Organizations, the College of Forestry and Department of Statistics at Oregon State University, the Western Forestry and Conservation Association, the Forest Inventory and Analysis program at the Pacific Northwest Research Station, and the Natural Resource Assessment, Ecology, and Management Science work unit at the Rocky Mountain Research Station, USDA Forest Service.

We thank our program committee: Doug Brodie, Peter Ince, Darek Nalle, Kevin Boston, Matt Turner, John Sessions, and Jeff Arthur. We were grateful for the assistance of Masha Konoshima, Jules Comeau, Rafael de la Torre, Paul Dunham, Hamish Marshall, Glenn Christensen, Phil Lacey, and Demetrios Gatziolis. We appreciate the efforts of Robert Haight and Mikael Rönnqvist, who provided the keynote address, Andy Gray, who led the field trip, and John Hof, Peter Ince, and Dave Martell, who gave the general session talks. We thank Doug Brodie for his closing remarks. We recognize the session moderators including Pete Bettinger, Joe Buongiorno, Larry Davis, Matt Pelkki, Alan Murray, Darius Adams, Jeremy Fried, Mikael Rönnqvist, Marc McDill, Stephanie Snyder, and Marc Wiitala. Richard Zabel, Aimee Sanders, and Virginia Hokkanen helped with logistics. The Skamania Lodge in Stevenson proved to be an excellent facility for this meeting. The continued support and enthusiasm of participants in this symposium series is very much appreciated.

Mike Bevers and Tara Barrett, Compilers
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SUSTAINABILITY, CRITERIA AND INDICATORS, AND ASSESSMENT
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DECISION-SUPPORT SYSTEMS
FOR FOREST BIODIVERSITY: A REVIEW

EXTENDED ABSTRACT

Sean N. Gordon¹, K. Norman Johnson¹, Keith M. Reynolds², Patrick Crist³, and Nick Brown³

ABSTRACT

The primary objectives of this in-progress review are to (1) help potential decision support system (DSS) users find systems which meet their needs and (2) help DSS designers and funders identify unmet DSS needs in the area of forest biodiversity. Thirty systems clearly applicable to forest biodiversity issues were identified and reviewed against three themes: (1) classes of forest biodiversity indicators used, (2) major forest influences addressed, and (3) abilities to tackle complex political decisions. Preliminary results show few DSS model both coarse-scale forest and fine-scale species indicators. A number of forest modeling tools evaluate the influences of fire and biological threats on forest ecosystems, but these systems do not generally deal with related biodiversity effects. Only one system was found which attempts to integrate the influence of climate change. Very few DSS appear to have capabilities explicitly designed to address the often value-based, political nature of forest biodiversity decisions.

INTRODUCTION

Biodiversity is a major theme in ecosystem management and the first criterion in the internationally-recognized set of Montreal Protocol Criteria and Indicators. It has impacted both public and private forest management in the United States, primarily through the Endangered Species Act treatment of individual species, and more recently through voluntary forest certification standards. Biodiversity presents a complex challenge for forest managers, from policymakers to field foresters, due to its broad definition as “…diversity of ecosystems, the diversity between species, and genetic diversity in species” (Montreal Process 1998) and lack of a widely accepted operational definition.

Decision support systems are commonly defined as computer applications designed to help managers deal with complex problems. Previous reviews of DSS have focused on national forest plans (Schuster, Leefers and Thompson 1993), ecosystem management (Mowrer 1997; Rauscher 1999), and biodiversity in county-level planning (Johnson and Lachman 2001). This review focuses on forest biodiversity and attempts to address two basic questions:

1. What DSS exist that can help managers address forest biodiversity issues?
2. How well do these existing DSS cover the range of issues related to forest biodiversity?

METHODS

An initial inventory of available systems was developed from previous DSS reviews (Schuster, Leefers and Thompson 1993; Mowrer 1997; Rauscher 1999; Johnson and Lachman 2001; Barrett 2001; Lee, Meneghin, Turner, Hoekstra 2003) and the personal knowledge of the authors. We screened this inventory to a shorter review list based on evidence of...
design for or application to forest biodiversity issues. This evidence typically consisted of a mention of a forest biodiversity application in the previous reviews, the DSS’ own documentation or website.

A framework for reviewing the systems was developed through a scoping exercise based on semi-structured interviews with eight national-level experts on forest biodiversity. Issues expressed by the experts were grouped into three themes: (1) methods to characterize biodiversity, (2) influences on forest biodiversity, and (3) the often complex political nature of decisions related to forest biodiversity conservation. Themes 1 and 3 required further operational definition. We chose to operationalize theme 1 by generalizing the Montreal Process biodiversity indicators into indicator classes. Theme 2 influences were used directly: silviculture, land use change, climate change, biological threats, and fire. Theme 3 was operationalized by adapting three themes identified as deficient in an earlier DSS review by Mowrer (1997): interdisciplinary information integration, decision support at multiple spatial scales, and facilitation of social negotiation.

RESULTS AND DISCUSSION

Out of 114 systems in our current inventory, 30 systems have met our initial screening criteria and have been reviewed (table 1). An additional 26 systems are still in the screening process, due to late discovery or difficulty in locating current information. Of the 30 reviewed, only five DSS appear to integrate capabilities for both forest and biodiversity modeling. Ten systems focus on wildlife and biodiversity modeling, 12 on forest modeling, and three are general purpose DSS. The full inventory of systems is available on the project website (www.ncssf.org).

The Montreal biodiversity indicators can be roughly split into those covering forest structure and management and those emphasizing species-based measures. Forest modeling systems tend to cover the former and wildlife/biodiversity systems the latter. There appears to be potential for more formal linkages between these types of systems. The Willamette Basin Futures Analysis and the LANDIS forest DSS stand out in that they have established explicit links between forest growth and wildlife population modeling systems (PATCH and RAMAS, respectively).

While many of the combined forest-biodiversity systems model the effects of silviculture and land use change, none of these systems nor the biodiversity systems include tools to address the influences of fire, biological threats (pest, pathogens, invasive species) or climate change on biodiversity. The forest modeling systems frequently consider silviculture, fire, and biological threats, but they generally do not include mechanisms to address the impacts of these disturbances on non-tree organisms. LANDIS appears to be the only system with some designed capacity to model climate change effects.

Integration of biophysical, economic, and social information is possible in many of the systems but is only actively supported and structured in a few. NED and Restore both enable users to input their relative values for biophysical, economic and social goals and evaluate results accordingly. Similarly, many of the systems can be used at different scales but few provide coordinated products for decision makers at multiple scales. Previous surveys identified communication and consensus building as top needs, but we are finding these abilities difficult to judge. Some specific examples worth mentioning include the following: LMS integrates visualization tools at the stand and landscape scales; EZ-IMPACT is designed to integrate individual values in group decision processes; and the Willamette Basin Futures Analysis made extensive use of stakeholder groups in setting up model assumptions and visualization techniques in presenting model results.

A prime rationale for decision support systems is to facilitate a diffusion of decision support capacity, for example domain-specific knowledge (such as in forest growth simulators) or decision-aiding techniques (such as optimization). However, four of the five systems in our survey that include both forest and biodiversity modeling capabilities are large, regional-scale assessment efforts. As such, they are more prototypes than systems that could be easily transferred to others. In the same vein, the LANDIS system, whose capabilities stood out in a few of the review categories, has been designed more as a research tool rather than a system ready for diffusion.

ACKNOWLEDGEMENTS AND FURTHER INFORMATION

This study is being sponsored by the National Commission on Science for Sustainable Forestry. Our complete inventory of systems, criteria, and reviews is available through the projects section of the NCSSF web site: http://www.ncssf.org
Table 1—List of reviewed systems

<table>
<thead>
<tr>
<th>System focus</th>
<th>Abbreviated name</th>
<th>Full name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forestry &amp; biodiversity</td>
<td>CLAMS</td>
<td>Coastal Landscape Analysis and Modeling System</td>
</tr>
<tr>
<td>Forestry &amp; biodiversity</td>
<td>LUCAS</td>
<td>Land-Use Change and Analysis System</td>
</tr>
<tr>
<td>Forestry &amp; biodiversity</td>
<td>MRLAM</td>
<td>Multi-Resource Land Allocation Model (Umpqua Land Exchange)</td>
</tr>
<tr>
<td>Forestry &amp; biodiversity</td>
<td>NED</td>
<td>NED</td>
</tr>
<tr>
<td>Forestry &amp; biodiversity</td>
<td>WBAFA</td>
<td>Willamette Basin Alternative Futures Analysis (PNW-ERC)</td>
</tr>
<tr>
<td>Biodiversity</td>
<td>BMAS</td>
<td>Biodiversity Management Area Selection</td>
</tr>
<tr>
<td>Biodiversity</td>
<td>CAPS</td>
<td>Conservation Assessment and Prioritization System</td>
</tr>
<tr>
<td>Biodiversity</td>
<td>C-Plan</td>
<td>C-Plan</td>
</tr>
<tr>
<td>Biodiversity</td>
<td>MARXAN</td>
<td>MARXAN / SPEXAN</td>
</tr>
<tr>
<td>Biodiversity</td>
<td>PATCH</td>
<td>Program to Assist in Tracking Critical Habitat</td>
</tr>
<tr>
<td>Biodiversity</td>
<td>RAMAS</td>
<td>RAMAS Biodiversity Refuge GAP</td>
</tr>
<tr>
<td>Biodiversity</td>
<td>ResNet &amp; Surrogacy</td>
<td>ResNet &amp; Surrogacy</td>
</tr>
<tr>
<td>Biodiversity</td>
<td>Restore</td>
<td>Restore</td>
</tr>
<tr>
<td>Biodiversity</td>
<td>Sites</td>
<td>Sites/Site Selection Module</td>
</tr>
<tr>
<td>Forestry</td>
<td>FVS</td>
<td>Forest Vegetation Simulator</td>
</tr>
<tr>
<td>Forestry</td>
<td>INFORMS</td>
<td>Integrated Forest Resource Management System</td>
</tr>
<tr>
<td>Forestry</td>
<td>LANDIS</td>
<td>LANDIS</td>
</tr>
<tr>
<td>Forestry</td>
<td>LANDSUM</td>
<td>Landscape Successional Model</td>
</tr>
<tr>
<td>Forestry</td>
<td>LMS</td>
<td>Landscape Management System</td>
</tr>
<tr>
<td>Forestry</td>
<td>RELM</td>
<td>Regional Ecosystem and Land Management Decision Support System</td>
</tr>
<tr>
<td>Forestry</td>
<td>RMLANDS</td>
<td>Rocky Mountain Landscape Simulator</td>
</tr>
<tr>
<td>Forestry</td>
<td>SIMPPLLE</td>
<td>Simulating Patterns and Processes at Landscape Scales</td>
</tr>
<tr>
<td>Forestry</td>
<td>Spectrum</td>
<td>Spectrum</td>
</tr>
<tr>
<td>Forestry</td>
<td>VDDT / TELSA</td>
<td>Vegetation Dynamic Development Tool / Tool for Exploratory Landscape Scenario Analyses</td>
</tr>
<tr>
<td>Forestry</td>
<td>Woodstock</td>
<td>Woodstock, Spatial Woodstock &amp; Stanley</td>
</tr>
<tr>
<td>General</td>
<td>DEFINITE</td>
<td>DEFINITE</td>
</tr>
<tr>
<td>General</td>
<td>EMDIS</td>
<td>Ecosystem Management Decision Support</td>
</tr>
<tr>
<td>General</td>
<td>EZ-IMPACT</td>
<td>EZ-IMPACT</td>
</tr>
</tbody>
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LITERATURE CITED


SUSTAINABLE FOREST MANAGEMENT: CONTROL, ADAPTIVE MANAGEMENT, HIERARCHICAL PLANNING

Eldon A. Gunn

ABSTRACT

This paper reviews sustainable forest management, adaptive management and hierarchical planning from the perspective of control systems. If sustainable forest management is portrayed as monitoring and responding to indicators of sustainability, then it is a form of feedback control. Adaptive management is control aimed at learning the unknown dynamics of the system being controlled. Hierarchical planning aims at controlling complex systems by appropriate decompositions that emphasize the span of control of decision makers. The paper reviews some of the issues associated with these control systems and suggests that a view of sustainable forest management as a value system rather than a control system may be more productive. To effectively protect or enhance future productivity, a forest manager has to continuously improve current harvesting practices based on lessons learned from monitoring the effects of past practices—sometimes over long periods. Where possible, the effects should be measured directly rather than indirectly, e.g., monitoring not only the soil disturbance but also its effect on tree volume and quality. Such observations are likely to show that not all disturbance and soil changes from harvest operations are equal in their effects on site productivity and net value recovery, i.e., they can range from negative to insignificant to positive.

INTRODUCTION

Sustainable forest management (SFM) is often discussed as adaptive management with respect to a system of criteria and indicators (C&I). The image of a process of feedback control is embedded in many of these discussions. This paper attempts a brief review of some of the issues that this image raises.

The concept of criteria and indicators plays an important role in most discussions of SFM. Duinker (2000) has a useful introduction and critique of C&I with a particular emphasis on the Canadian process. The C&I of the Montreal Process (MPWG, 1998) have been summarized under the Canadian Council of Forest Ministers (CCFM, 2000). In the U.S., the Montreal Process has been less codified but still influential in establishing definitions of SFM (see USFS, 2002). Certification processes have driven industry’s efforts in SFM. The standard CAN/CSA Z809 A Sustainable Forest Management System (CSA, 2003) is based closely on the CCFM criteria. The Forest Stewardship Council certification (FSC, 2003) and the Sustainable Forestry Initiative are not focused on criteria and indicators to the same extent as CSA Z809, yet both have a strong flavour of this process. Closely connected with C&I for SFM is the notion of adaptive management, usually with reference to Holling (1978) and Walters (1986). Duinker and Trevisan (2003) discuss the dependence of SFM on adaptive management.

This paper first considers C&I and adaptive management as feedback control, a notion ingrained in the minds of many policy makers, but which, although present, is not a key part of Holling (1978) or Walters (1986) thought process. It then goes on to look at adaptive management as an approach to learning. Finally it looks at hierarchical planning and tries to place some of the SFM and adaptive...
management ideas in that context. Overall, the view of SFM as a control process is not seen as productive. The more hopeful perspective is as a value context for hierarchical planning.

**ADAPTIVE MANAGEMENT AS FEEDBACK CONTROL**

Adaptive management is often interpreted as feedback control (Figure 1). The idea is that by choosing appropriate indicators and setting target levels, by monitoring the values of these indicators, and by taking management actions whenever the indicators are not suitably close to the target, it is possible to sustainably manage the forest. The concept is like the thermostat that measures room temperature at some appropriate spot in the room, and issues commands to the heating/air conditioning system to make adjustments to maintain the temperature at the desired target comfort level. This “thermostat” idea is inherent in processes that emphasize setting targets for indicators. However, it is important to ask if the concept of target levels makes sense and, further, is it possible to manage a forest to keep it at the target level?

The answers to the above questions are not obvious. Davis and Barrett (1993) showed that, for various harvest scenarios, including doing nothing, habitat quality for a broad variety of species fluctuated strongly over the 200 year planning horizon with differing patterns of habitat quality increase and decrease. Bevers and Kent (1994) and Hof and Bevers (2000) have pointed out that sustainability does not imply constancy, but rather implies stable repeating patterns. If this is the case, then there are no specific levels to aim for.

Even if desirable indicator levels can be established, it may be unrealistic to expect a feedback process to maintain a stable system. The indicator state space is very large. For example, the CCFM group the indicators under six criteria with 22 main elements and 83 indicators (see table 1). Restricting ourselves to vegetation management reduces the indicator space, since many are not related to vegetation management. However, this is more than offset by the fact that many indicators involve multiple forest states. For example, consider CCFM indicator 2.2.1 Percentage and extent of area by forest type and age class. Choosing just three forest types (softwood, mixedwood, hardwood) and 6 age classes (0-20, 21-40, 41-60, 61-80, 81-100, 100+), this indicator implies 18 states to monitor. We are thus asking our control system to maintain a very large number of indicators close to chosen target values.

**CONTROL SYSTEM DESIGN**

The simplest control models are based on linear systems. Mathematically, a state representation linear system is:

$$\frac{dx(t)}{dt} = Ax(t) + Bu(t) + C \cdot x(t) + u(t) \cdot R^m,$$

where $x(t)$ is the state of the system and $u(t)$ is the control action. If this seems overly restrictive, recall that linear systems that involve higher order derivatives can always be represented this way by introducing new variables. For example, instead of just the position ($x$), we can have variables that refer to velocity ($v$) and acceleration with appropriate equations ($\frac{dx(t)}{dt} = v(t)$). The control system designer attempts to find a matrix $G$ that gives a feedback control $u(t) = G(\hat{x} - \hat{x}(t))$ in tracking a target input $\hat{x}$.

To design controllers for dynamic systems (see Dorf and Bishop (2001) or other standard texts for details), the systems must be *controllable* and *observable*. Simply put, controllability means that the system is capable of being

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**Table 1—Number of criteria, elements and indicators**

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Main elements</th>
<th>Indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – Biodiversity</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>2 – Ecosystem Health and Productivity</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>3 – Soil and Water</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>4 – Global Cycles</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>5 – Multiple Benefits</td>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>6 – Accepting Society’s Responsibility</td>
<td>5</td>
<td>19</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>22</strong></td>
<td><strong>83</strong></td>
</tr>
</tbody>
</table>
steered from any initial state to any other state in a finite amount of time. Observability means that, by observing the system outputs and controls over a fixed period of time, it is possible to calculate (uniquely) the initial state of the system. Both of these have quite specific technical characterizations (Dorf and Bishop 2001) that are unlikely to be satisfied in systems measured by “indicators”. The very term “indicator” arises because the complexity of forest systems is such that they are not observable and we only have partial knowledge of the “state” of the forest at any instant of time.

Control system designers cope with uncertainty by ensuring that the control system is stable. If the system is perturbed by some sort of outside influence, the control will bring it back to the desired state. If the elements of $G$ are not chosen properly, then a small perturbation in the system state away from the desired $\bar{x}$ can result in large oscillations in system response. For a given control matrix $G$, there is no a priori guarantee that a system will have an equilibrium; that if it has an equilibrium, that this equilibrium state is $\bar{x}$, and that this equilibrium is stable. The design problem is to try to find a $G$ that causes the system to have a stable equilibrium at $\bar{x}$ with a reasonably fast response to deviations. There exist linear systems that are impossible to control with simple position error feedback. To achieve stable control, capable of tracking a target, one often needs not just state information, but also information on the rate of change and some sort of time average of the state. This is referred to as PID control (Dorf and Bishop 2001). PID control implies measurement processes that are capable of measuring rate of change and time averages of indicators. Information also needs to be more or less instantaneous. Systems that are stable with no time delay between the acquisition of information and taking control actions can be unstable when such delays exist. Few forest indicators can be measured with estimates of rate of change and without substantial time delays.

Assuming controllability and observability, designing stable controllers for large dimensional systems is extremely challenging unless there are very special conditions. These usually amount to the existence of a few driving state variables for the system with the other states highly correlated to the drivers. There is always debate about what constitutes a large system. However, systems of the size implied by the C&I (80 indicators, many which are themselves multidimensional) would be considered large in the extreme.

Standard control theory establishes the control feedback through appropriate choice of the elements of $G$ along with some sort of control actuator (B). Even if we assume the system can be controlled stably, it is worth asking: “By what mechanism can public SFM processes make such design choices?” Note also that the feedback regulator operates with a fixed target $\dot{x}$ (or at least a target trajectory $\bar{x}(t)$) and a fixed gain matrix $G$. As discussed, it is unclear how one might set an $\bar{x}(t)$. It is also hard to imagine public processes that can resist fiddling with the $\bar{x}(t)$ and $G$.

Putting all this together, it is highly questionable that a process of setting indicator targets and responding to deviations from these targets to suggest new management actions can result in stable systems. We must look beyond this if the notion of C&I for SFM is to be seen as sensible. This conclusion may be surprising, but this is not the first time that a systems approach has overextended its legitimacy (Andrews 2001).

**ADAPTIVE MANAGEMENT AS A SEARCH FOR INFORMATION**

Walters (1986) recognizes natural resources problems as control problems and is well aware of problems raised above. The discussion in Walters is based on parsimonious models with few state variables. Nothing in Walters (1986) suggests the simultaneous consideration of 80+ state indicators. Walters, together with C.S. Holling, developed a process called adaptive environmental assessment, where a number of “key actors” participated in a model building process aimed at policy assessment. The outcome of this work was the recognition of important effects that “were only clearly evident over large spatial and/or time scales”. Uncertainty in the nature of stock dynamics was a major issue. An emphasis on the macro level process dynamics, aimed at senior managers, with a particular focus on uncertainty and risk, is characteristic of hierarchical planning.

Walters discusses his modeling in the context of feedback control, but it is a context illuminated by a dynamic programming point of view. The fundamental problem is to find $J(x)$, the optimal expected return of the system over the future (possibly infinite) given that the system is in state $x$ at the present time $t$. $J(x)$ is referred to as the cost-to-go function in dynamic programming. The fundamental equation is:

$$J(x) = \max_{u \in U(x)} \{ E_\xi[ g_t(x_t, u, \xi) + J_{t+1}(x_{t+1}(x_t, u, \xi))] \}$$

where $u \in U(x_t)$ is the set of allowable control actions in state $x_t$, $\xi$ is the random realization, $g_t(x_t, u, \xi)$ is the reward and $x_{t+1}(x_t, u, \xi)$ is the state that results from action $u$ this period. Fundamental to dynamic programming is the notion of tradeoff of expected present returns $E[g_t(x_t, u, \xi)]$.
versus expected future returns $E[J_t(x_{t+1}(u, \xi))]$. If a good estimate of the cost-to-go function is available, all sequential decision problems are two stage problems of making this tradeoff between present and future. Although dynamic programming is an almost ideal framework for decision analysis and optimization, it is worth noting that problems where the state vector $x_t$ is of dimension higher than 3 are computationally challenging.

SFM indicators are just that – indicators. They are imperfect information on the actual state of the forest. The observer has access to observations and has the capability to observe how these observations change over time in response to control actions. Bertsekas (2000) shows how, by replacing the concept of state by the information vector, one can reformulate problems with imperfect state information as a dynamic programming problem with perfect information. The information vector is the entire history of observations and control actions. The question of making an optimal decision for a given state is replaced with making an optimal decision for a given information vector. Implicit in this approach is a Bayesian updating of the probability of a given state based on a given information vector. However, unless the modeler can find a sufficient statistic that can stand in place of the information vector, imperfect information poses even more computational challenges.

Walters focuses on situations where the major uncertainty is in the underlying model of stock reproduction and growth. The state is made up of two components: one representing the measured state of the stock and another representing the true underlying growth model with prior probabilities on that state. If the control action is primarily aimed at the optimal exploitation of the stock using the current estimate of the underlying model, then we may never detect situations where the actual model is different from the estimate and a superior solution is possible. Walters focuses on actively adaptive policies where actions are taken with a primary purpose of learning about the system.

These ideas are closely related to what are often referred to as bandit problems. (see Puterman, 1994, Berry and Fristedt, 1985). The classic one-armed bandit problem involves a gambler with the choice of either not playing or paying an amount $c$ to pull a slot machine lever that pays an amount 1 with probability $q$ where $q$ is unknown. By playing, the gambler has the opportunity for Bayesian updating of the estimates of $q$. If the gambler concludes $q$ is unfavourable, he/she stops playing but then acquires no further information about $q$. Multi-armed bandit problems are a natural extension with several arms to pull, each with their own characteristic $q$. Bandit problems have been applied in project selection, and sequential clinical trials. They are difficult to solve since the state space is not a scalar but a density function on the $q$.

Duinker and Trevisan (2003) emphasize the contrast between passive and active adaptive management. Walters (1986) characterized passive adaptive management as the learning that occurs about the underlying system model in the course of implementing a policy. Duinker has used the phrase of “staying on the wrong road long and smart enough to know how and why it is wrong”. Active adaptive management is characterized as the deliberate use of management policies “that seek … some … balance between learning and short term performance: actions that perturb the system state and output in an informative manner may require giving up immediate harvests, accepting the risk that the system may not recover after some perturbations or simply living with temporal variation that is uncomfortable from a social and economic perspective” (Walters, 1986). Duinker and Trevisan note that some view active adaptive management as simply field trials or trial and error. The use of field trials in forest science is uncontroversial, but what Duinker and Trevisan, as well as Walters, mean by active adaptive management is the use of alternative strategies “employed at the large ecosystem level at a fully operational scale … intended to examine the effects of management strategies on the entire system” (Duinker and Trevisan, 2003). In the sense of large scale gaming with simulation models, a concept that dominates much of Walters (1986), there is again little of controversy here. In the sense of using actual ecosystems as experimental devices with the potential for significant failures, active adaptive management may raise significant moral questions (Lee, 1999). This is particularly troublesome when we consider the bandit problems. One pull of the lever tells you only that you won or lost that time. It takes many pulls of the lever to narrow estimates of $q$.

**HIERARCHICAL PLANNING SYSTEMS**

Hierarchical planning follows from the observation (Anthony 1965) that there is a natural hierarchy in decision problems and that this decision hierarchy often corresponds to the management hierarchy: i) Strategic Decisions: defining the role and nature of the enterprise and the resources that the enterprise will have available to it, ii) Tactical Planning: making the most effective use of the resources available to the enterprise, iii) Operational Control: detailed scheduling of weekly and shift level activities to make the system function. At each level, decisions are taken within the goals and objectives of the decision makers at that level. Decisions taken at one hierarchical level act as constraints.
on the lower level decisions. In turn, the process of planning and operating the lower levels feeds back cost and feasibility information on these constraints to the upper level decision processes (Figure 2).

Anthony’s (1965) main observation is that decision problems at each level differ in time horizon, management level, source and detail of information and the uncertainty and risk associated with the decision outcome. Table 2 indicates some characteristics of each type of decision problem. At all levels, decision-making is a dynamic process with information and plans constantly changing. However, information feedforward and feedback enables most organizations to function effectively.

As a modeling approach, hierarchical planning systems emphasize models that reflect the decision hierarchy and the decision structure. This leads to:

**Separate Models:** Upper level models are based on aggregate data, for long-term analysis. The upper level models provide appropriate constraints for lower level, shorter-term models.

**Rolling Planning Horizon Implementation:** Plans are developed for multiple periods but only the immediate decisions of that plan are explicitly implemented.

**Recognition of Uncertainty:** The most uncertain data is detailed information for time periods removed from the current period. Aggregate models broadly attempt to optimize the performance of the enterprise over time. Detailed scheduling models are run when more accurate information is available as to data and system state becomes available.

**Mirroring of Organizational Structure:** Each model is aimed at a specific level of management. The constraints

![Figure 2—Feedback process of Decision Hierarchy.](attachment:image.png)

**Table 2—Characteristics of hierarchical processes**

<table>
<thead>
<tr>
<th></th>
<th>Strategic analysis</th>
<th>Tactical planning</th>
<th>Operational control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective</td>
<td>Resource Acquisition</td>
<td>Resource Use</td>
<td>Execution</td>
</tr>
<tr>
<td>Time Horizon</td>
<td>Long</td>
<td>Middle</td>
<td>Short</td>
</tr>
<tr>
<td>Management</td>
<td>Top</td>
<td>Middle</td>
<td>Low</td>
</tr>
<tr>
<td>Scope</td>
<td>Broad</td>
<td>Medium</td>
<td>Narrow</td>
</tr>
<tr>
<td>Information</td>
<td>External/internal</td>
<td>External/internal</td>
<td>Internal</td>
</tr>
<tr>
<td>Level of Detail</td>
<td>Highly Aggregated</td>
<td>Mod. Aggregated</td>
<td>Very detailed</td>
</tr>
<tr>
<td>Uncertainty</td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
</tr>
<tr>
<td>Risk</td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
</tr>
</tbody>
</table>
provided from the upper level models correspond to the type of constraints that management normally experience on their own decisions.

Dempster and others (1981) have observed “hierarchical organizations, as well as hierarchical planning systems are a response to the nature of the problem being solved and to the need to reduce complexity and respond to uncertainty”. Complexity and uncertainty are characteristic of forest management. Gunn (1991; 1996) focus on hierarchical planning as a way of dealing with the uncertainty associated with the long-term tactical issues that arise in forestry. In this context, rolling planning horizons amount to using the linear programming or other long run tactical model as a way of estimating the cost-to go function, thus recovering the two-stage paradigm of dynamic programming. Gunn (1996) shows that, if forest systems are large scale with sufficient opportunities for recourse, the decision maker is justified in treating them as deterministic, so long as the implementation involves only the first period. Simple mean value estimates provides a near optimal assessment of the strategic choices being made. Others have showed similar results in different contexts. Dempster and others (1981), studying a job shop design/scheduling problem, showed that treating processing time as deterministic is optimal in the design problem as long as there are enough jobs. Sethi and Zhang (1994) show, for manufacturing systems subject to failure and repair, that treating machine availabilities as deterministic becomes optimal as the rate of failure/repair becomes fast relative to the rate of growth in demand.

Successful organizations typically have strategies for what business they are in and where they want to go with their business. This defines their goals and objectives, their value structure within which hierarchical planning proceeds. Planning models used in forest management are often referred to as strategic, but if examined closely, will be seen as tactical. The confusion arises because of the two roles of tactics in the decision hierarchy. The first role is to optimally use the resources provided through the strategic design. For a given strategic design, this provides a performance assessment of that design (as in Gunn 1991; Dempster and others 1981; Sethi and Zhang 1994). The second role is the feedback role. This provides sensitivity analysis on the resource constraints. Whether through shadow cost information (Paredes and Brodie, 1989) or through redeveloping tactical plans by explicitly changing constraints, tactical analysis is necessary to provide strategic decision makers with tradeoffs between their overall goals and constrained resources. For the strategic decision maker, this is essential information.

**SFM AS STRATEGY AND VALUE CONTEXT**

The “thermostat” model of adaptive forest management and even the passive/active adaptive management discussions are clearly tactical in their main themes. They involve making effective use of the resources of the forest enterprise, not with the acquisition of new resources. However this paper would argue that the proper view of SFM is inherently strategic; SFM defines the role and nature of the enterprise.

Mintzberg (1978) has studied the strategy formation process extensively. See Gluek and Jauch, 1984 for extensive references to his work. At the heart of Mintzberg’s discussion is the idea that strategy is not a computation, it involves the decision maker’s developing a concept of what it is they want to do and how they want to do it. Strategy is subjective, not objective. As Mintzberg (1978) observes, some strategy is deliberate and some strategy is unintended, what Mintzberg calls emergent.

The SFM C&I are values that enter into the worldview of a forest decision maker. By agreeing to use indicators of sustainability, the enterprise is giving expression to the values and social framework within which it operates. To some extent, these are values that can be seen as the “law of the land”. In Canada, forests are a provincial responsibility and all provincial forest ministers are members of the CCFM. Except for the four eastern provinces, most forest land is public land, under the control of these ministers, even when leased or licensed in some form to private enterprise. In another sense, SFM C&I can also be seen as reflecting a cost of doing business. In feudal times, one might debate the necessity of paying workers. Today, paying workers is a required cost of doing business. This has evolved to recognition that employers are responsible for standards of health and safety in the working environment and continues to evolve to recognition that business is also responsible for the maintenance of a healthy environment. However strategy is about more than obeying the law and dealing with the cost of doing business. Organizations define themselves by how they go about their business and the types of experiences they provide to their customers. The Montreal Process and the CCFM C&I define criteria by which governments and businesses that wish to make claims of sustainability would want to be examined. An important aspect of the C&I system is that it is directed at local level indicators; indicators that are specific to the particular environment in which the organization works. Another important point is the lack of prescribed levels or targets. As governments and enterprises attempt to position themselves with
respect to their practices of sustainability and environmental stewardship, they need tactical models to explore and assess their strategy and to provide the shadow costs on the resource restrictions inherent in this strategy.

Models such as RELM (Church and others 1994), Spectrum (Sleavin 1994) and DTRAN (Rose and Hoganson 1995) provide ways of assessing strategy as well as expressing the cost-to-go function for the future. From a strategic perspective, the RELM model in particular (but others also) allow the decision makers to focus on defining the resources available to the organization in terms of present conditions and in terms of the desired future conditions. The shadow-pricing framework of these models provides the appropriate mechanisms to assign marginal benefits/costs to modifying the ecosystem and other constraints. These marginal benefits are in terms of the objectives chosen by the analysts, which reflect the goals and objectives for the decision makers to whom they report. This is implicit in hierarchical planning; tactical models operate with the value structure of the strategic decision maker. Economists such as Arrow and others (2000) also argue for the use of marginal costs, but the value system there is the general theory of economic equilibrium.

No organization, public or private, is immune to the strategic context that SFM places them in as they develop their organizational strategy. The specific criteria, and the local level indicators of sustainability that are chosen by their own organization, or by bodies that either regulate or certify their organization, must be acknowledged and addressed. Some of these are simple (“we will obey the law”). Others are more complicated such as a strategy of being recognized as good corporate/organizational citizens, both for internal values and for marketing.

SUMMARY

By taking too literally the ideas of SFM as a control process and as adaptive management, we run the risk of exceeding the legitimacy of the systems approach (Andrews, 2001). By recognizing the role of the C&I of SFM as context, managers can proceed to develop their own strategy within this context. Implementing strategy in systems of the complexity found in forest management will require well-conceived hierarchical planning approaches.

LITERATURE CITED


METHODS FOR PROJECTING LARGE-SCALE AREA CHANGES FOR U.S. LAND USES AND LAND COVERS: THE PAST AND THE FUTURE

Ralph J. Alig

ABSTRACT

Over the past 25 years, renewable resource assessments have addressed demand, supply, and inventory of various renewable resources in increasingly sophisticated fashion, including simulation and optimization analyses of area changes in land uses (e.g., urbanization) and land covers (e.g., plantations vs. naturally regenerated forests). This synthesis reviews related research over the more than two decades since area projection modeling systems replaced expert opinion approaches in the national Resources Planning Act (RPA) assessments, as part of state of the art approaches for regional and national resources assessments. Such models reflect that key land base changes such as afforestation and deforestation are driven by quite different socio-economic factors. Projections of area changes are important for a wide range of natural resource analyses, including those for wildlife habitat, timber supply, global climate change, water, recreation, and others. The demand for applications in global change analyses has increased recently, and the synthesis addresses information needs in such macro assessments. Significant challenges in the research area in general include systematic integration of approaches and therefore findings across resource areas to support sustainability analyses. Another challenge is a unified view of future forest conditions constructed at a scale that serves all of these uses adequately.

INTRODUCTION

Over the past 25 years, renewable resource assessments have addressed demand, supply, and inventory of various resources at large spatial and over long temporal scales in increasingly sophisticated fashion, including simulation and optimization analyses of area changes in land uses (e.g., conversion of forests to agriculture or developed uses) and land covers (e.g., plantations vs. naturally regenerated forests). This synthesis reviews related research over the last quarter century since area projection modeling systems replaced expert opinion approaches in the national Resources Planning Act (RPA) assessments (e.g., Alig and Butler 2004, Alig and others 2003a).

It is important upfront to define what policy-relevant questions that land use and land cover research have been designed to answer, given the many demands for information about the current and future land base. The core research described here was designed to support periodic U.S. natural resource assessments mandated by the national Forest and Rangeland Renewable Resources Planning Act (RPA) of 1974, to support USDA Forest Service strategic planning and policy analyses. The RPA act requires that decadal national assessments, with mid-decade updates, include an analysis of present and anticipated uses; demand for and supply of the renewable resources of forest, range, and other associated lands; and an emphasis on pertinent supply, demand, and price relationship trends. Land use and land cover changes have important consequences for the future availability of timber, wildlife habitat, and other renewable resources and, therefore, are a critical component of this analysis.

The RPA act clearly defines the national assessment as a forward-looking exercise in examining resource conditions and services. The first RPA Assessment was carried out quickly around 1975 in response to the 1974 RPA...
legislation. Over the past 25 years, assessment efforts have addressed demand, supply, and inventory of various renewable resources in increasingly sophisticated fashion. Methods developed through the RPA in many areas define the state of the art approaches for regional and national resources assessments. One area that remains a significant challenge in the field in general is the systematic integration of approaches and therefore findings across RPA resource areas.

The 2000 RPA assessment is the most recent one and the context has broadened over time (USDA Forest Service 2001). Interest in sustainable management of the world’s forest resources was heightened by the United Nations Conference on Environment and Development in 1992. Since that time, various countries have joined together to discuss and attempt to reach consensus on ways to evaluate progress toward the management of their forest resources. The United States participates in the Montreal Process, designed to use a set of criteria and indicators for the conservation and sustainable management of temperate and boreal forests. The criteria provide a common framework for describing, assessing, and evaluating a country’s progress toward forest sustainability at the national level. The 2000 RPA assessment provides a broad array of information about the Nation’s forests and rangelands, including the current situation and prospective area changes over the next 50 years. Such information can help shape perceptions about whether we can sustain both increasing consumption of forest products and forest resource conditions (Alig and Haynes 2002). Related data illustrate the dynamics of our Nation’s land base, and how adjustments are likely to continue in the future. The projections of land use and forest cover changes also provide inputs into a larger system of models that project timber resource conditions and harvests, wildlife habitat, and other natural resource conditions (USDA Forest Service 2001). Current debates about sustainability involve both physical notions of sustainability and competing socioeconomic goals for public and private land management. The land-base changes also indicate the importance of viewing “sustainability” across the entire land base and across sectors, in contrast to the current typical sector approach, as in examining “sustainable forest management” (Alig and Haynes 2002).

This paper focuses on land use changes that involve forestry. Land use is the purpose to which land is put by humans, e.g., protected areas, forestry for timber products, plantations, row-crop agriculture, pastures, or human settlements. Land cover is the observed (bio)physical cover on the Earth’s surface, e.g., oak-hickory forest.

### REVIEW OF MODELS

Over the last 25 years, land use projections at large scales for RPA assessments have moved from an expert opinion basis (e.g., Wall 1981) to systematic models. Substantial population growth in the United States has been associated with an increase in the rate of conversion of forest and agricultural lands to residential, commercial, and industrial uses (Alig and others 1983, USDA SCS 1989, USDA NRCS 2001), increasing the importance of models that can aid in assessing future land use scenarios. An example of an improvement introduced by systematic approaches was the elimination of possible double accounting of land use changes when projections were done by sector (e.g., agriculture). With a total land base perspective and zero-sum constraints built in, systematic approaches ensured that land base totals would sum appropriately across sectors.

Availability of additional quantities and types of data was a major contributor to the expanded number of models developed over the last 25 years. A major boost was broad coverage in data collection by the Natural Resources Inventory (NRI) (e.g., USDA NRCS 2001) that provided a national snapshot of land use for a particular year. This was in contrast to the periodic forest inventories by state staggered across time in Forest Inventory and Analysis forest inventories (e.g., Rosson 2001). The NRI covers the entire nonfederal land base, with major land uses classified as cropland, pastureland, forest land, and urban and developed.

I next look at three classes of land use models that utilized NRI and other types of land use data. This review supplements and updates earlier ones by Alig and others (1984) and Parks and Alig (1988).

### Classes of Land Use Models

Land use models characterize human and natural influences on landscapes. Theoretical land use models are derived from rules that are assumed to govern human and natural processes. Typically profit-maximization is assumed as the goal of forest and agricultural commodity production. Theoretical models explore the types of land-use patterns that emerge from given sets of behavioral assumptions. Empirical land-use models can provide a test of theoretical models, using real world data to quantify model parameters and see how consistent they are with underlying hypothesized behavioral relationships. Empirical models can be used to predict how land use will change in response to changes in economic conditions and policies. Three basic types of empirical land-use models are econometric, mathematical programming, and simulation, each varying in their relative strengths and spatial and temporal scales.
Econometric Models—Econometric land use models are based on statistical methods that are used to quantify relationships between land uses and hypothesized determinants. Landowners’ profit maximization typically is the theoretical basis for these models—landowners are assumed to allocate land parcels to that use generating the highest land rent or present value of future profits. Models are estimated with data describing land use decisions and profits derived from alternative land uses. Additional variables may be included to control for land-use regulations and other factors that influence land use decisions. For example, land-use policies often are used to mitigate potential negative impacts of urbanization. Econometric land use models typically are estimated with sample plot data comprised of a random sample of parcels or aggregate data such as county-level observations of land use (e.g., Alig 1986, Plantinga 1996, Wear and others 1996, Hardie and Parks 1997, Kline and Alig 1999, Ahn and others 2000, Kline and Alig 2001). With the advent of satellite imagery and geographical information systems (GIS), econometric land-use models have been estimated using spatially-referenced plot or parcel-level data (e.g., Bockstael 1996, Wear and Bolstad 1998, Irwin and Geoghegan 2001, Kline and others 2001). Examples of explanatory variables in such models are rents (or proxies) for forestry, agriculture, and urban/developed uses.

The principal advantage of econometric land use models over other approaches is that they are based on the observed or revealed landowner behavior (e.g., Stavins 1999). In particular, they measure how landowners actually respond to observed changes in economic and other decision variables. Econometric models may capture the combined influence of several factors motivating land use decisions that may otherwise be difficult to describe in an explicit way. Because econometric models can be estimated with highly disaggregated data, such as plot or county data, they can generate land use projections at correspondingly fine spatial scales. Although estimation based on historical data is the strength of econometric models, it is also a weakness. Econometric models may not always yield accurate predictions outside observed historical ranges. For example, it may be difficult to use econometric models to predict consequences of a major land use policy change not within the bounds of historical data. In addition, factors influencing land use decisions that cannot be explicitly controlled for in the model estimation will be carried along in predictions of future land use changes.

Findings from econometric studies indicate that drivers for deforestation differ notably for those of afforestation and reforestation activities. Major determinants for deforestation associated with conversion to urban and developed uses in the United States are population and personal income levels. The rate and extent of urbanization are typically governed by such determinants that shift demand for urban and developed uses. Revealed behavior by landowners indicates that values for developed uses (e.g., deforestation for residential purposes) generally dominate those for rural uses such as forestry and agriculture (Alig and others 2004). Within the rural land base, relative land rents between forestry and agriculture affect deforestation (i.e., forest converted to agriculture), afforestation, and reforestation decisions. The significance of these findings for RPA Assessment and global climate change analyses is that policy deliberations recognize that the growth in developed area is not likely to be arrested, but rather may be diverted or relocated by policies offering preferential tax assessment or other traditional programs.

Implications regarding future policy deliberations about afforestation programs include focusing on incomes for rural land enterprises. A series of econometric studies offer insights about determinants of afforestation (e.g., Plantinga and others 1999) and reforestation activities (e.g., Alig and others 1990, Kline and others 2002).

Most econometric models of land use developed to date have been regional in nature, although Lubowski (2002) recently developed a national land use model. His work takes advantage of transition rates among major land uses, as identified by the NRI survey (USDA NRCS 2001). Modeling transitions among land uses, in contrast to net area changes, enhances analysis of land-based policies that can cause ripple effects across major uses. For example, Lubowski (2002) finds that rising government subsidies for agricultural crops restrained an increase in forest area in the Mississippi Delta area by 10% from 1982 to 1997. This approach is being tested in the 2005 RPA Assessment Update.

Mathematical Programming Models—Mathematical programming models of land-based economic sectors are a second land-use modeling approach. Mathematical programming describes land use allocations using numerical optimizing techniques to find the multi-market price and quantity vectors that either maximize or minimize the value of an objective function, resulting in an optimal land use allocation (e.g., USDA SCS 1989, Adams and others 1996, Alig and others 1998). Maximization or minimization of the objective function can be subject to sets of constraints that characterize the resource commodity production over time, initial land and resource conditions, availability of fixed resources, such as land, and policy constraints. Land is modeled as an input resource that moves among different sectors depending on relative land rents, in an optimization,
as contrasted to a positivistic approach (Alig and others 1984). This allows “what if” questions with respect to optimal land allocation to be investigated, based on selected or prescribed objective functions such as economic efficiency. Dynamic economic behavior pertaining to land use is investigated using intertemporal optimization by mathematical programming models (e.g., Alig and others 1998).

Advantages of the mathematical programming approach include its theoretical basis of market equilibrium, whereas econometric models can sometimes suffer from incorrect specifications of economic variables or omitted variables where data are not available to fully represent theoretical constructs. Mathematical programming models are better able to handle economic conditions outside of historical ranges, which facilitate evaluating new policies. However, such models may also be limited by data unavailability that affects representation of responses to policies. Programming models can incorporate a wealth of physical structural detail, which is important when physical structure strongly influences the behavioral response, such as existing forest age class structure and timber harvest behavior. Disadvantages of mathematical programming land use models are their high level of spatial aggregation, behavioral relationships are determined to a greater extent by the researcher, either based on assumed or revealed behavior, and greater difficulty in calibrating to recent historical trends where appropriate. Programming models based on intertemporal optimization also are less able to incorporate feedback effects due to biophysical processes and explicitly account for the spatial distribution of decision variables. However, the latter limitation can also apply to econometric models in some broad-scale applications.

Other Simulation Models—Another spatially explicit land use modeling approach is to simulate land use change using spatial land use data and sets of decision rules. For example, several studies have combined cellular automata models and spatial land-use data (e.g., Clarke and Gaydos 1998, Wu 1998, Webster and Wu 1999a,b). Cellular automata models generally consist of an action space, a set of initial conditions, and a set of behavioral rules. In land use modeling, the action space is a grid of cells where the state of each cell is one of a finite number of land uses, initial conditions are land uses described by a GIS base land-use layer, to which are applied decision rules that specify how land uses change over time. Decision rules typically are conditional on the initial land use as well as the land uses of surrounding cells.

Wu (1998) develops a cellular automata model of the transition from undeveloped to developed land in a province in China. At each time step in the simulation, a development suitability index is computed for each undeveloped cell. The index is a weighted average of distances to urban features such as transportation hubs and the degree of development in the neighborhood of the cell. Based on their suitability for development, cells are converted until an aggregate (and exogenous) “demand” is satisfied. Using a related approach, Landis (1995) simulated land development in the San Francisco Bay Area. The spatial unit of analysis is a Developable Land Unit—a polygon construct with similar environmental (e.g., slope) and policy (e.g., zoning) attributes. Developable land units are identified through the overlay of the corresponding GIS layers. Each undeveloped unit is scored according to its profitability for development, taking into account location-specific home sales prices and construction costs. As in Wu (1998), developable land units are “converted” according to profitability given exogenous demands for developed land.

The advantage of simulation methods is that they can provide very detailed information about spatial patterns of land use change and are very flexible with regard to the types of rules that govern change. Although decision rules adopted in some studies seem somewhat arbitrary, it is possible to specify rules consistent with empirical evidence. For example, an updated version of the Landis (1995) model incorporates a statistical model of urban land use change (Landis and Zhang 1998). Another example is the transition-based model by Theobald and Hobbs (1998), employing a single-step Markov transition function. This is in contrast to regression-based approaches that are used to understand underlying historical relationships. The principal drawbacks of simulation models relate to their data and computational requirements. These models have mostly been developed for individual urbanized areas. Such an approach is needed for modeling land use change in urban areas due to the importance of location and existing land use zoning in determining land development. When considering changes in the rural landscape, it may make sense to sacrifice spatial detail for broader regional coverage. This is particularly the case with econometric modeling since many important economic factors, such as prices, often exhibit little spatial variation.

Increasing Use of Spatial Analyses

With the increased interest in land use modeling, the geographic scales at which investigators have been working have expanded in both directions. More ecological assessments at finer scales have increased demand for land use and land cover projections that are spatially explicit, including investigations of forest fragmentation (e.g., Butler and others 2004) and ownership parcelization, i.e., an owner-
ship is subdivided into one or more ownerships. Spatial modeling is growing in its use and application in the natural resources because natural resource processes are spatially linked. Economists increasingly face opportunities to collaborate with ecologists and other scientists in multi-disciplinary research involving landscape-level analyses of socio-economic and ecological processes.

Spatial statistics investigates the relationship between a subject of interest and the subjects around it to determine if they are more related to each other than to other subjects that are farther removed. Using remotely sensed data can involve some degree of dependency between pixels, most likely in the form of positive spatial autocorrelation. Such dependence has potentially a dual impact on the analysis of image data. It can be a source of nuisance and error, when traditional statistical techniques involving assumption of independence of sampling units are applied. On the other hand, it can represent valuable information, which may be exploited as an image characteristic. Diffusion of recent advances in GIS technology and modeling/simulation tools has increased the application of quantitative techniques in investigating land use and land cover changes. Changes in land use and land cover can result from the interplay of complex factors; some causative factors (e.g., land owner characteristics) cannot be measured cost-effectively over large areas; and sophisticated techniques of data manipulation do not offset the adverse effects of unreliable input data. Quality of basic data remains an issue, possibly affecting reliability of modeled predictions.

Spatial land use models based on econometric estimation can be viewed as extensions of area-base models first developed by economists about two decades ago (e.g., Alig 1986, Hardie and Parks 1997, Kline 2003). Area-base models describe proportions or shares of land in forest agriculture, urban, or other discrete use categories, within well defined geographic areas (e.g., counties).

The need to consider spatial relationships has grown with increased populations across regional and national landscapes. An example is the hypothesis that increasing population density in forested areas will cause changes in timber management, including likelihood of timber harvest. More people in the woods will also affect fire suppression efforts and costs. Private forestlands in the United States face increasing pressures from growing populations, resulting in greater numbers of people living in closer proximity to forests. What often is called the forest/urban interface is characterized by expansion of residential and other developed land uses onto forested landscapes in a manner that threatens forestlands as productive socioeconomic and ecological resources. Prevailing hypotheses suggest that such forestlands can become less productive, because forest owners reduce investments in forest management. Kline and others (2003) developed empirical models describing harvest, thinning, tree planting, and forest stocking in western Oregon, as functions of stand and site characteristics, ownership, and building densities. They use the models to examine the potential impacts of population growth and urban expansion, as described by increasing building densities, on the likelihood that forest owners harvest, pre-commercial thin, plant trees following harvest, and maintain forest stocking. Empirical results support the general conclusion that population growth and urban expansion are correlated with reduced forest management and investment on private forestlands in western Oregon. Results have potential implications for both economic outputs and ecological conditions, as well as for wildfire risks at the forest/urban interface.

LINKAGES TO OTHER MODELS IN RESOURCE ASSESSMENTS

Land use models have increasingly been linked to other models in order to extend the power of both types of models. In the RPA context, the shift to land use models from expert opinion approaches started around the time that timber supply and demand “gap” models were being replaced in the early 1980s by equilibrium models. Feedbacks among assessment models are important in that changes in land uses and land covers affect the condition and characterizations of future forests, which in turn influence timber market conditions. Projections of market conditions from supply and demand models feed back into the area change models, as timber prices from equilibrium models from the timber assessment are one input into the RPA land use models (Alig and Butler 2004, Haynes 2003). In general, RPA specialists have a long history of exploring linkages among models for different resource areas (Joyce and others 1986).

In the timber supply case, Alig and others (1984) described potential linkages among models used to represent the following activities: land allocation, timber growth and yield, timber harvest, and timber investment. In recent years, additional modeling components have been added to model forest carbon, biodiversity, wildlife habitat, and other forest-based goods and services. Linkages reflect both spatial (e.g., interregional shifts in timber production) as well as temporal changes. Examples of other linkages to address in future work include land allocation decisions in a particular region that leads to impacts in other regions or
nations, affecting timber harvest decisions in other coun-
tries. In view of timber imports into the United States, this
requires a broad view of sustainability in a multi-national
context.

In addressing problems with complex biophysical, eco-
logical, and economic aspects, testing linkages among mod-
eling components is critical. Sensitivity analyses can reveal
critical linkages and information gaps and need for feed-
back loops. The holistic approach, with land use and land
cover changes as components, will vary depending on the
composition of the portfolio of policy-relevant questions
to be addressed. Data availability and accuracy are prime
concerns in such complex modeling, and monitoring of
land use and land cover at relatively frequent intervals is
warranted. An example is monitoring any migration of tree
species over space and time due to global climate change,
for use in land cover modeling.

PROPOSED NEXT-GENERATION
MODELS

To help improve analyses in future RPA Assessments
and global change assessments, I propose assessment mod-
ules to explicitly project the condition of land in the United
States (Alig and Wear 2003) (figure 1). This is at the core
of what the national RPA Assessment seeks to accomplish.
Characterizations of the future land base, including forest
and aquatic ecosystems, are required to conduct all supply
and demand analysis. For example, the timber assessment
projects changes in timberland area and forest cover types,
along with age class distributions and other vegetation
information, in order to project growth and yield and the
market-clearing outputs and prices for timber products.
Examples of specific land condition attributes are planta-
tions versus naturally regenerated forests, old versus young
forests, and interior versus fragmented forests. The public
has a direct interest in how forest conditions in their respec-
tive regions might change in the future. For example, pub-
lic concerns in response to the Southern Forest Resource
Assessment (Wear and Greis 2002) were largely focused on
the anticipated future condition of forests—e.g., plantations
vs. naturally regenerated forests.

In addition to information needs in the timber assess-
ment, the wildlife assessment relies on projections of forest
area, configuration, and condition. Salmon restoration
analyses require information on what is happening on the
entire land base, including urban areas where human activi-
ties may impact aquatic systems (e.g., fertilizer leakage
into streams). Similar data needs characterize assessment
activities in the areas of global climate change, water, and
recreation. Characterization of land condition will depend
on a comprehensive information needs assessment for
applications such as in the national RPA Assessments,
related global climate change assessments, and the U.S.
Climate Change Science Program’s plan (in process) for
land use and land cover research. Figure 1 largely repre-
sents current RPA linkages involving land use and land
cover modeling and opportunities exist to build in other
two-way flows of information between resource areas, such
as wildlife management that could influence vegetation
management.

A primary need in global change assessments is to test
models of drivers in land use and use them for projections
of land condition. Analysts working on global change have
a large body of land use theory, models, and empirical
results to draw upon from applications in other areas of
inquiry (e.g., RPA Assessment land use and land cover
analyses). They can also draw upon both econometric
models of revealed behavior, as well as optimization models
(e.g., Adams and others 1996). Use of both modeling types
can be designed to be complementary, and can address
questions regarding land resource allocation and potential
for reallocation. In the global climate change context, mod-
elers are closer to dealing with a closed system, but face
significant data gaps, such as consistent and comprehensive
time series of consistent land use and land cover data.

One complication in past RPA assessments and global
climate change assessments has been the lack of a unified
view of future land conditions constructed at a scale that
serves all of these assessment areas adequately. Attaining
the ideal unification is a substantial undertaking, and this
could be aided upfront by an assessment of common infor-
mation needs. An example of a possible case study in the

Figure 1—Schematic depicting conceptual framework for land condition
projection system.
land condition context would focus on methodologies that model the evolution of land base conditions at the FIA plot level, and then scale to aggregate levels using plot expansion factors (Prestemon and Wear 2000). Such analyses could be updated on an annual basis as the continuous FIA inventory is implemented. Access to plot locations would be a critical element for the work to proceed along this track. Modeling at more aggregate levels will also be considered, as land markets are effectively analyzed at large enough scales where prices are formed. Sufficiently large scales are also necessary for addressing certain policy-relevant questions, such as whether land allocation in one region or country leads to increased timber imports from other regions or countries, e.g., land set asides for spotted owl and increased timber imports from Canada (Wear and Murray 2003). Micro- and macro-scale analyses can be linked, such as having city-scale or subregional analyses tied to larger scale regional or national studies.

A modeling system that can generate land base condition projections could provide for forest ecosystems a thorough and unified description of anticipated change in the extent, structure, and condition of the nation’s forests at useful regional and subregional scales. At the same time, such a system could augment economic measures, useful when investigating changes in land markets and analyzing trends in land values. Land prices embody information on relative valuations by different sectors of the economy. For example, valuation of land currently in forest and agricultural uses in some areas is strongly influenced by trends in developed areas (e.g., Shi and others 1997).

**Global Change Assessments**

Improvements for global climate change analyses will require enhancements in climate change projections, production function information and ecological translations of climate-change effects, land owner behavior modeling, and socio-economic effect determination (e.g., equity). Key feedbacks also warrant more attention, such as between land use changes and climate change impacts. Uncertainty in projecting climate change impacts on land use and land cover include any carbon dioxide fertilization impact, interactions with air pollution on productivity under climate change, and impacts of climate change on abiotic and biotic disturbances (e.g., extreme events, insects, disease, fire regimes). Several studies have employed linkage of different modeling systems to investigate how changes in forest productivity may translate into impacts in the forest sector under climate change (e.g., Joyce and others 1995, Alig and others 2002). A key information gap appears to be empirical estimates of production function changes, including any migration of tree species. Sensitivity analyses in a systems analysis approach can aid in determining critical components, and linkages among those components (Sohngen and Alig 2000).

In reality, land use choices often involve a complex interaction of factors, including the initial land endowment of the owner, landowner characteristics, institutional influences (e.g., local zoning), and the economic and policy context in which the land use choices are made. Changes in the area of any of the major land use classes relate to demographic, economic, biophysical, and policy factors (Alig 1986), so that the suite of factors need to be considered in global climate change assessments. Projections of forest-land and timberland areas are based on projections of relevant demographic and economic factors, which are more likely to change in the future than biophysical factors. Current policies can be frozen in place in an initial conditions run or baseline, so that we can examine where the current policy trajectory (e.g., no U.S. action or implementation of policy for mitigating climate change) would lead, and then examine sensitivity of projections to certain policy-related assumptions.

Risk and uncertainty considerations include changes in technology. Impacts from global warming in some cases may be partially offset by technological changes, such as genetic stock improvements to boost forest carbon sequestration efforts. Other technological changes may also allow more output from input of land, especially in regional climates favorably affected regarding crop or forest production. The net outcome can not be easily forecast. Some scenarios may arise where forest use might be better able to compete with other major rural land uses, such as agriculture (e.g., Alig and others 2002).

Land use models based on historical data will not be as well suited to simulate global climate change as mathematical programming models if future events are outside the range of historical data. Changes in productivity for crops and forests may change slowly, although some hypothesize certain thresholds beyond which actions may accelerate. Global climate change will also affect the relative risk of land-based enterprises, given uncertainty of the magnitude, duration, and deleterious nature of such events.

Multidisciplinary research increasingly has striven to examine the impacts of land use and land cover changes on ecological conditions and processes brought about by timber harvesting, land use change, or other human-caused disturbances. However, these efforts can be costly and time-consuming. Planning upfront is critical for effectively augmenting land use and land cover analyses in both the general RPA.
and specific global climate change applications. A streamlined and relatively inexpensive approach enabling managers and policymakers to anticipate, describe, and plan for potential land use impacts on habitat and other goods and services is desirable.

**Land Cover Monitoring and Projections**

Another key part of land base changes is changes in major forest cover types. Although detailed discussion of them is outside the scope of this paper, I will describe some examples of modeling issues for land cover monitoring and modeling. Analogous to the snapshot of land-use information by USDA’s NRI, land cover modeling would benefit from periodic nationwide estimates of changes in forest cover. A start down that path is the National Land Cover Data mapping project (an output of the Multi-Resolution Land Characteristics Consortium). This project will produce an updated version of the National Land Cover map for the year 2002, providing the means to conduct multi-temporal analysis.

A key goal of any forest cover monitoring program is to understand the processes affecting changes in forest cover. This would enable projections about future trends in forest cover and tie them to the local demands, forest investment (e.g., Alig and others 2003b), timber trade, and global issues of concern such as global change and biodiversity. The availability of modern technology of remote sensing and GIS makes this task feasible. The models should include the spatial component of the landscape and human activities. These new GIS data layers could be combined in models to obtain various indices that most likely influence or are influenced by human use of the land such as: (1) bio-physical and climatic factors, (2) fragmentation indices (e.g., perimeter/area ratios of forest area), (3) transportation networks (e.g., roads, rivers, railways), (4) population density and its rate of growth, and (5) socio-economic and political factors (e.g., land tenure, market availability, GNP/capita).

**Sustainability Assessments**

Many users and interests rely on the common land base, and myriad questions are asked about land conditions and sustainability prospects. Numerous approaches have been developed to address such questions, and land use planners, geographers, natural resource managers, and others have other information needs at spatial and temporal scales other than the primary ones for RPA and global climate change assessments. However, large-scale assessments provide a context for smaller scale inquiries, and aid in addressing policy-relevant questions. Other papers at this symposium pertain to smaller scale inquiries on the common land base. Regardless of scale, studies need to work toward common assumptions (e.g., population growth), consistent definitions, and sufficient use of statistical guides. Studies at different scales can inform each other, and this prospect can be enhanced if standard protocols are in place.

The common land base is competed for by different sectors of the economy, thereby complicating efforts to view sustainability from a single sector, such as “forest sustainability.” A broad view could foster resolution of important forest and rangeland health issues through design of integrated decision systems that involve ecological, political, economic, and institutional factors. Focal areas include ecological risk assessment, socio-economic modeling, and policy/decision analysis—particularly as they relate to forest and rangeland productivity, fish and wildlife habitat, and human communities. Crucial to this endeavor is the ability to bridge multiple disciplines, recognize multiple values, and analytically evaluate risks and tradeoffs associated with various scenarios for improving the health of forests, rangelands, and related natural resources. The ability to articulate prospective outcomes for both short- and long-term time frames to policy makers and resource managers is also pivotal.

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**LITERATURE CITED**


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A NONPARAMETRIC METHOD FOR DEFINING AND USING BIOLOGICALLY BASED TARGETS IN FOREST MANAGEMENT

Kevin R. Gehringer

ABSTRACT

Forest policy increasingly relies on the use of biologically determined criteria to quantitatively define desirable forest conditions as targets for forest management. Nonparametric procedures for defining targets and performing assessments relative to those targets have been developed. The target definition and assessment procedures were applied to the problem of defining targets for riparian zone forest management. Four target definition and assessment scenarios were considered: 1) basal area per acre, 2) conifer basal area per acre, 3) trees per acre and quadratic mean diameter, and 4) trees per acre, quadratic mean diameter, and average tree height. Targets were defined using riparian stands having ages between 100 and 180 years. Assessments were performed using stands having a minimum age of 80 years and using acceptance levels of 95%, 90%, 80%, and 50%. Acceptance percentages computed for each scenario were all at least 75% of their respective acceptance levels, with the majority of values being at least 88% of their acceptance levels.

INTRODUCTION

Forest policy increasingly relies on the use of biologically determined criteria such as trees per acre, stand density indices, average tree sizes, species composition, or basal area per acre to quantitatively define a set of desirable forest conditions as a target or reference condition for forest management. Management objectives defined by a set of target criteria may include desirable habitats, clean water, or aesthetically pleasing forests. Effective target criteria must be representative of the desired forest conditions, must be associated with data that are readily obtained, must be easily computed, and must be easy to use with an objective assessment procedure to determine whether the desired forest conditions have been achieved for a particular forest management scenario.

Representative target criteria must recognize the inherent variability of forest ecosystems, whether managed or unmanaged, and their multidimensional nature. These two objectives may be achieved by using multiple, quantitative stand parameters and their distribution as the basis for defining a desired forest conditions target. Using the distribution allows a neighborhood of acceptable values to be used when specifying a target. Using multiple quantitative parameters to describe the desired forest condition provides a more detailed description than could be obtained using any single parameter or parameter value, thereby increasing the likelihood of actually achieving the desired conditions.

Recognizing the relationship between target definition and assessment is also essential for the development of effective target criteria and an objective assessment procedure. The target definition and assessment procedure are linked through the distribution of parameters used to describe the desired forest conditions. Consistent target definition and assessment procedures must, therefore, be based upon the underlying distribution of parameter values describing the desired forest conditions.

Interest in the problem of defining targets for forest management was motivated by the new forest practices...
rules for riparian areas in Washington State. The new rules, known as the Forests and Fish Rules (FFR), were established in 1999 based on the recommendations of the Forests and Fish Report (FFR 1999; WFPB 2001). The primary objectives of the FFR include providing support for harvestable levels of salmonids and the long-term viability of other species, compliance with the Endangered Species Act, meeting or exceeding water quality standards defined by the Clean Water Act, and maintaining the economic viability of the state’s forest industry (FFR 1999).

The biological and water quality objectives of the FFR for western Washington are based in part on a desired future condition (DFC) target for riparian forest stands along potentially fish-bearing streams. Along these streams three buffer zones are defined: a 50 foot no-harvest buffer adjacent to the stream, an inner zone where timber harvest is allowed subject to restrictions ensuring the development of the DFC, and an outer zone where up to 20 trees per acre must be left after harvest. The total buffer width is determined by the site potential tree height and can vary from 90 ft to 200 ft based on the site class. The inner zone extends from the core zone to either 67% or 75% of the total buffer width depending on stream size (FFR 1999; Ehlert and Mader 2000; Fairweather 2001; WFPB 2001). The primary rules for riparian areas in Washington State.

Unmanaged, mature riparian forests were identified as the DFC for western Washington under the FFR, where a mature riparian forest stand was defined to have a reference age of 140 years, the midpoint between 80 and 200 years (FFR 1999; Fairweather 2001; WFPB 2001). The FFR further specifies the DFC targets as site-class specific minimum conifer basal area per acre (CBA) limits. Commercial harvest in the inner buffer zone is permitted only if the post-harvest stand conditions for the combined inner and core zones meet or exceed the minimum CBA target when projected to an age of 140 years using a stand simulator (FFR 1999; Fairweather 2001). Initial estimates of the minimum CBA values were obtained for each of five Douglas-fir (Pseudotsuga menziesii) site classes based on data from a sample of riparian stands in western Washington. The data were supplied by the Forest Inventory and Analysis (FIA) program, the forest industry, and the Olympic and Mount Baker-Snoqualmie National Forests (Moffett and others 1998; FFR 1999; Ehlert and Mader 2000; Fairweather 2001).

The selection of CBA to quantify DFC targets was motivated by the desire for simplicity and the need to recognize the variability of riparian forest structures that provide adequate function for streams (FFR 1999; Ehlert and Mader 2000; Fairweather 2001). The moderate to low stand densities, relative to managed upland stands, and the generally larger diameter trees found in mature riparian forests were some of the key structural features that the DFC targets were intended to represent (Fairweather 2001). Further, CBA was assumed to adequately describe the structural characteristics of a mature riparian forest, and when the target levels of CBA are present, the desired stream functions, in particular the production of large woody debris and shade, are also assumed to be present (FFR 1999; Ehlert and Mader 2000; Fairweather 2001). Assuming that the structure of a mature riparian forest can provide adequate stream function may be reasonable. The use of minimum mean CBA values by site class as target criteria may, however, oversimplify the problem of representing the structure of a mature riparian forest: the targets may be too restrictive or they may not adequately discriminate between conditions that are desired and those that are undesirable.

Given the potential importance of quantitative targets in forest management, biologically and statistically consistent target definition and assessment procedures are necessary. Such procedures have been developed for use with multiple, coupled forest stand parameters using a minimal number of assumptions. A nonparametric approach was used to specify the procedures since the actual parameter value distribution is unknown. The target definition and assessment procedures do not make direct use of a reference age, as was done in the FFR, other than for selecting data for a target. The forest structure is emphasized, rather than a specific point in time, since achieving a desired forest structure sooner than the reference age may be possible and beneficial.

The target definition and assessment procedures and implementations of them are described next. The procedures are then demonstrated by defining riparian management targets within the paradigm of the FFR for western Washington. Finally, a brief discussion of some of the potential benefits of using multiple parameters to define targets and perform assessments is then provided.

METHODS

A forest stand may be described using quantitative values for a specified set of forest stand parameters, including but not limited to: site index, slope, aspect, stand density, average tree diameter, average height, basal area, volume, species composition, distance to the nearest stream, or measurements of the individual trees comprising the stand. For a particular application the set of parameters used may be large, possibly consisting of a tree list with spatial coordinates for the location of each tree and individual tree measurements, or small, consisting only of stand density
and average diameter, volume, or basal area per acre. For any specific set of parameters there exists a joint, or simultaneous, distribution of their quantitative values for some collection of forest stands.

Let $k \geq 1$ be the number of quantitative parameters used to describe a forest stand, and let $x = [x_1, x_2, ..., x_k]^T$ be the vector of quantitative parameter values for a stand, where each $x_j, j = 1, 2, ..., k$, represents one parameter value and superscript $T$ indicates the transpose of the vector. A collection of $N$ forest stands may then be represented by a set of parameter vectors $x_i, i = 1, 2, ..., N$. The distribution of parameter vectors for this collection of forest stands is then described by some unknown probability density function (p.d.f.) $f(x)$.

**Target definition and assessment**

Given parameter vectors for a collection of forest stands, a target region may be defined based on probabilities derived from the unknown p.d.f. for their distribution. A target defined in this way will be called a probability based target. Such a target definition must take into account two factors. First, the target should use the most likely parameter values, those with the largest p.d.f. values. The most likely values then form the center of the target, which is not necessarily near the mean value. Second, the extent of the target should be defined using an acceptance region derived from the p.d.f. for a desired probability of hitting the target (Duda and Hart 1973; Mardia and others 1979; Zar 1996). These objectives are met simultaneously by choosing an acceptable level of error specifying the probability of not hitting the target, analogous to the selection of an $\alpha$ - level in the classical statistical hypothesis testing context (Mardia and others 1979; Zar 1996).

The natural way to define a probability based target is to use the likelihood contours or level sets of the p.d.f. $f(x)$. Let $p$ be the probability of not hitting the target, or the probability of error. The probability of hitting the target is then given by $1 - p$, and a target having a $(1 - p) \times 100\%$ chance of being hit may then be defined as

$$T_{1-p} = \{x \mid f(x) \geq c \text{ and } \int_{\{y \mid f(y) \geq c\}} f(y) \, dy = 1 - p\},$$

where $c \in [0, \text{max}\, f(x)]$ is a value defining a level set or contour of the p.d.f. $f(x)$, for $p \in [0,1]$. The first condition in the target set definition, $f(x) \geq c$, guarantees that the most likely values from the domain of the p.d.f. $f(x)$ are used first. The second condition in the target set definition, $\int_{\{y \mid f(y) \geq c\}} f(y) \, dy = 1 - p$, guarantees that the target set obtains the desired acceptance level $(1 - p) \times 100\%$. The values of $x$ such that $f(x) = c$ define the critical contour for the target $T_{1-p}$.

An assessment procedure consistent with this target definition may now be obtained. The procedure simply determines whether a parameter vector $y$ is contained within the target set for the desired acceptance level. If $y \in T_{1-p}$ then $y$ is statistically indistinguishable from the target at the $(1 - p) \times 100\%$ acceptance level and is considered acceptable. If $y \not\in T_{1-p}$ then $y$ is statistically different from the target at the $(1 - p) \times 100\%$ acceptance level and is considered unacceptable. An assessment of this type will be called a probability based assessment.

Assuming that the unknown p.d.f. $f(x)$ is continuous, unimodal, and symmetric, the problem of identifying critical contours for the target $T_{1-p}$ is simplified. With these assumptions the critical contours of $f(x)$ are defined by standardized distances from a central value $x^c$, which could be the mean, median or mode. Thus, to define a target only a standardized critical distance $d_{\text{crit}}$ from the central value $x^c$ for a specified $(1 - p) \times 100\%$ acceptance level needs to be determined.

The critical distance $d_{\text{crit}}$, then, determines whether a parameter vector $y$ is indistinguishable from the distance based target $\{d \mid \Pr(d, d_{\text{crit}} - 1 - p)\}$. The subscript $d$ indicates that the $(1 - p) \times 100\%$ target is defined using the p.d.f. $f^d(d)$ based on a distance function $d(x,x^c)$ and not on the contours of the p.d.f. of the actual distribution (Mardia and others 1979). A parameter vector $y$ is, then, acceptable relative to the target if its standardized distance $d_y$ from the central value $x^c$ is less than the critical distance, $d_y < d_{\text{crit}}$ for a distance function $d(x,x^c)$. An observation is unacceptable otherwise.

Under these simplifying assumptions the mean, median, and mode are coincident. In a more general setting, say without the symmetry assumption, the three central values would all be different. In this situation the mode, as the most likely value, should be used as the central value in the target definition and assessment procedures.

**Implementation**

Let $X = \{x_1, x_2, ..., x_M\}$ represent a set of parameter vectors $x_j = [x_{j1}, x_{j2}, ..., x_{jk}]^T$ containing the values for the $k$ forest parameters of interest for a collection of $M$ forest stands. The $M$ parameter vectors in the set $X$ are used to represent the p.d.f. $f(x)$ and, subsequently, to define a target $T_{1-p}^d$. Let $Y = \{y_1, y_2, ..., y_N\}$ represent a set of $N$ observed parameter vectors $y_j = [y_{j1}, y_{j2}, ..., y_{jk}]$ containing values
for the $k$ forest parameters of interest that are to be assessed relative to the target data set $X$. The objective is to determine which of the observation vectors $y$ are indistinguishable from the target data set $X$ for a $(1 - p) \times 100\%$ acceptance level and a level of error $p$, where $0 < p < 1$. Let $x^c$ represent a central value, the mean, median or mode from the target data set $X$, and let $d(x, x^c)$ be the distance function used to obtain standardized distances from the central value $x^c$ for a vector $x$.

The $k$ -dimensional empirical distribution was assumed for the parameter vectors $x_i$ in the target data set $X$, and the distance function

$$d(x, x^c) = (x - x^c)^T S^{-1}_{xc}(x - x^c),$$

where $S^{-1}_{xc}$ is the inverse of the variation matrix $S_{xc} = (S_{ij})$, and

$$S_{ij} = \frac{1}{M-1} \sum_{r=1}^{M} (x_{ri} - x_{cj})(x_{ri} - x_{cj})$$

for $i, j = 1, 2, ..., k$ was used to compute standardized distances from a central value. The critical distance $d_{crit}$ for a $(1 - p) \times 100\%$ acceptance level was computed in three steps. First, the central value $x^c$ and the variation matrix $S_{xc}$ were computed from the $M$ parameter vectors $x_i$ in the target data set $X$. Second, the standardized distances $x_i^d = d(x_i, x^c)$ were computed for the $M$ parameter vectors $x_i$ in the target set $X$. Third, the index for the critical standardized distance,

$$i_{crit} = \begin{cases} 1, & \text{if } p = 0 \\ (1 - p)M, & \text{if } 0 < p < 1 \\ M, & \text{if } p = 1 \end{cases}$$

was computed, and $d_{crit} = x_{i_{crit}}^d$, where $\lfloor x \rfloor$ is the floor function, returning the largest integer less than or equal to $x$, and $x_{i_{crit}}$ denotes the $i_{crit}^th$ order statistic, $x_{1}^d \leq x_{2}^d \leq ... \leq x_{M}^d$, for the set of target distances (Mardia and others 1979; Serfling 1980; Zar 1996).

An assessment of the parameter vectors $y_j$ in the observation data set $Y$, relative to the target data set $X$, was performed in two steps. First, standardized distances from the central value $x^c$ were computed for the observed parameter vectors $y_j$, $y_j^d = d(y_j, x^c)$. Second, the observed distances $y_j^d$ were compared to the critical distance $d_{crit}$. If $y_j^d < d_{crit}$, then the observed parameter vector $y_j$ is statistically indistinguishable from the target data set for a $(1 - p) \times 100\%$ acceptance level, and is considered acceptable. A parameter vector is considered unacceptable otherwise.

**Application**

Following the paradigm of the FFR, the target definition used here was based on mature riparian forest stands having a midpoint age of 140 years and a minimum stand age of 80 years, giving an approximate upper age boundary of 200 years (FFR 1999; Ehlert and Mader 2000; Fairweather 2001; WFPB 2001). Four compatible target definition and assessment scenarios were considered. The same sets of stands were assigned to the target and observation data sets for all scenarios, making the only differences among the scenarios the parameter vector components used. The stand parameters used were: basal area per acre (BA), conifer basal are per acre (CBA), trees per acre (TPA), quadratic mean diameter (QMD), and average tree height (H). The parameter vectors used in each of the four scenarios are listed in table 1.

Letting $s = 1, 2, 3, 4$ be the assessment scenario number, define $A^s = \{a_1, a_2, ..., a_N\}$ to be a set of $N$ available parameter vectors $a_i$ from a sample of mature riparian forest stands. Identify a subset $A_{target}$ of $A^s$, $A_{target} \subset A^s$, containing $M$ of the available parameter vectors as the target data set for each assessment scenario. The sets $X = A_{target}$ and $Y = A^s$ then, define the target and observation data sets, respectively, for each scenario. Assessments of the observation data set $Y$ relative to its respective target data set $X$ were then made for each scenario. The modes of the target data sets were used as the central values in all assessments. Mode estimates were computed using the mean update algorithm (Thompson 2000).

Assessments for each scenario were performed using acceptance levels of 95%, 90%, 80%, and 50%. Acceptance percentages were computed for each assessment scenario and acceptance level as $(N_{starget}^s / N) \times 100\%$, where $N_{starget}^s$ is the number of acceptable observations for each acceptance level and scenario $s$. Finally, as a measure of the performance of the assessment procedure, relative acceptance percentages, the ratio of the acceptance percentage to the acceptance level, were computed. In the example, the target data set and the observation data set were selected from the same unknown distribution, that of a mature riparian stand, so the empirical acceptance percentages and the acceptance levels should be similar.

**DATA DESCRIPTION**

The mature riparian forest data used to define targets for this analysis were obtained from the Forest Inventory and Analysis (FIA) program of the U.S.D.A. Forest Service. The data were collected by the Pacific Resource Inventory, Monitoring, and Evaluation (PRIME) program of the FIA,
and contain forest inventory data collected from all owner-
ships except national forest and reserved areas (Woudenberg
and Farrenkopf 1995). The FIA PRIME database was used
for this analysis since it was readily available and because
it was one of the data sets used in the original DFC analy-
sis for the FFR (Moffett and others 1998; Fairweather 2001).
The FIA PRIME database was not restricted to unmanaged
stands, but data from this source were considered sufficient
for the purpose of demonstrating the target definition and
assessment procedures, and highlighting the benefits of
using multi-parameter targets within the paradigm estab-
lished by the FFR.

The FIA PRIME data were collected using a stratified
sampling scheme with two levels: the plot and subplot.
Each plot has multiple subplots whose measurement data
are intended to be aggregated to estimate plot level param-
eters (Woudenberg and Farrenkopf 1995). The number of
subplots per plot varied over time due to changes in the
sampling protocols, but five subplots has been the standard
number since 1994 (Woudenberg and Farrenkopf 1995).
The data for the analysis consisted of subplots that met
the following four criteria: 1) Subplots were at least 80 years
of age as indicated by the FIA age class codes; 2) Subplots
were within 215 ft of a stream; 3) Subplots were classified
by the FIA as timberland; 4) Diameter at breast height (d.b.h)
and height measurements for each tree were both greater
than zero. These data selection criteria were largely moti-
vated by a consideration of the original Forests and Fish
DFC analysis (Moffett and others 1998; Fairweather 2001).

These criteria yielded tree data from 127 subplots con-
tained in 47 unique plots. The number of subplots obtained
for each plot varied from one to five with almost equal
frequencies making an analysis at the plot level infeasible.
The selected subplots were all from plots having five sub-
plots distributed over an area of approximately 6.67 acres.
Using the subplots directly simply increases the observed variability in com-
puted stand parameters. The subplot data still provide an
unbiased random sample of riparian forest stands, with the
caveat that subplots associated with the same plot are not
independent.

Tree data extracted from the PRIME database included
the d.b.h., height, species, and TPA represented by each
sampled tree. The data were originally in metric units and
standard conversion factors were used to obtain English
units for this analysis. After the data were extracted and
converted to English units, the individual tree data from
each subplot were filtered to remove trees having d.b.h.
values less than 4 inches to reduce the influence of very
small trees on stand density. The stand parameters of inter-
est were computed using standard formulas and relation-
ships. Numerical summaries of the stand parameters for the
127 riparian subplots appear in table 2, and a summary for
the 42 subplots having stand ages in the range of 100 to
180 years appears in table 3.

For the assessment scenarios the observation and target
data sets, $A_s$ and $A_{target}$, were defined to be the whole data
set and the subset of the riparian data having stand ages in
the range of 100 to 180 years, respectively. The statistical
summaries indicate that the target data sets and the obser-
vation data sets are in general agreement, and a visual
inspection of the data sets indicated that the target data
were well distributed throughout the range of the larger
observation data for each assessment scenario.

RESULTS

Acceptance percentages and relative acceptance per-
centages for the four assessment scenarios and the four
acceptance levels are presented in table 4. A strong corre-
spondence between the acceptance level and the computed
acceptance percentages clearly exists. The acceptance per-
centages decrease as the acceptance levels decrease in all
cases for all of the target definition and assessment scenar-
ios. Further, the computed acceptance percentages were all
at least 75% of their respective acceptance levels, with the
majority being at least 88%, as indicated by the relative
acceptance percentages.

DISCUSSION

The overall performance of the probability based target
definition and assessment procedures was quite good. Trends
in the acceptance percentage results are in strong agreement
with expectations; acceptance percentages decreased for
each of the four target definition and assessment scenarios

<table>
<thead>
<tr>
<th>Scenario (s)</th>
<th>Parameter(s)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>1 BA</td>
</tr>
<tr>
<td>2</td>
<td>1 CBA</td>
</tr>
<tr>
<td>3</td>
<td>2 TPA, QMD</td>
</tr>
<tr>
<td>4</td>
<td>3 TPA, QMD, H</td>
</tr>
</tbody>
</table>
as the acceptance levels decreased. Exceptions to the expected trends occurred for the higher dimensional parameter vectors, which may be explained by the relatively small size of the target data sets, which contained only 42 points. The small target data set limits the achievable resolution for computing critical distances and probabilities: the procedures assume a continuous p.d.f., but the parameter vectors are discrete points, providing only an approximation to the distribution. These artifacts may be reduced by increasing the size of the target data set.

The behavior of the acceptance percentages and the high degree of agreement between the acceptance levels and the acceptance percentages would seem to indicate that any of the four targets could be used to successfully define a target for riparian forest management. A comparison of how well each of the targets performed in terms of identifying riparian stands that would have met the desired forest condition: a mature riparian forest with moderate to low stand densities and larger average tree sizes is warranted. The comparison is based on assessments at a 90% acceptance level. The 90% acceptance level was used since the 95% acceptance level may not be restrictive enough and the lower acceptance levels may be too restrictive. Only the CBA based basal area assessment results are presented here for consistency with the FFR. Results for BA were similar.

The CBA based assessment results had an acceptance percentage of 88.2%. A histogram of the CBA values from the observation data set appears in figure 1 along with the

<table>
<thead>
<tr>
<th>Table 2—Stand summary for the 127 riparian subplots defining the observation data sets in the four assessment scenarios.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable</td>
</tr>
<tr>
<td>BA (ft² ac⁻¹)</td>
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<tr>
<td>CBA (ft² ac⁻¹)</td>
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<tr>
<td>H (ft)</td>
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<tr>
<td>QMD (in)</td>
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<tr>
<td>TPA</td>
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</tbody>
</table>

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<tr>
<th>Table 3—Stand summary for the 42 riparian subplots defining the target data sets in the four assessment scenarios.</th>
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<tr>
<td>Variable</td>
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<tr>
<td>BA (ft² ac⁻¹)</td>
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<tr>
<td>CBA (ft² ac⁻¹)</td>
</tr>
<tr>
<td>H (ft)</td>
</tr>
<tr>
<td>QMD (in)</td>
</tr>
<tr>
<td>TPA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4—Acceptance percentages (relative acceptance percentages) for the four target definition and assessment scenarios.</th>
</tr>
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<tbody>
<tr>
<td>Parameter(s)</td>
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<tr>
<td>BA</td>
</tr>
<tr>
<td>CBA</td>
</tr>
<tr>
<td>TPA, QMD</td>
</tr>
<tr>
<td>TPA, QMD, H</td>
</tr>
</tbody>
</table>
acceptance region boundaries and the mean and mode for the target CBA values, 215.1 ft²/ac⁻¹ and 136.3 ft²/ac⁻¹ respectively. CBA values between the acceptance region boundaries are considered acceptable. The acceptance region clearly captures the most likely CBA values, rejecting only the largest CBA values on the upper tail of the distribution. Using this figure alone the performance of the target relative to the desired stand density and tree size criteria cannot be determined. The CBA assessment results are plotted in figure 2 using the corresponding TPA and QMD values. The unacceptable stands appear along the TPA-QMD self-thinning curve, where the highest basal area values are generally found. They are also located near the central portion of the TPA and QMD distribution, along its edge. The acceptable stands are distributed throughout the range of TPA and QMD values with no apparent discrimination between stands of high density and low density. In fact, the highest density stands are considered acceptable under the CBA assessment. This CBA assessment, therefore, failed to identify stands that meet the desired conditions. This result was anticipated, and it clearly demonstrates the difficulty of targeting a desired forest condition using CBA, or BA, as the sole parameter.

The TPA and QMD based assessment had an acceptance percentage of 84.3%. The assessment results appear in figure 3, with the mean and mode vectors for the target TPA and QMD being 190.0 TPA and 18.7 inches and 175.2 TPA and 16.0 inches respectively. The acceptable stands for this assessment are clustered about the center of the TPA-QMD distribution, indicated by the mode. High density stands with small tree sizes and low density stands with very large tree sizes are identified as unacceptable relative to the target.
The TPA and QMD assessment, therefore, succeeded in identifying stands meeting the desired conditions.

The TPA, QMD and H based assessment had an acceptance percentage of 81.1%. The assessment results appear in figure 4, with the mean and mode vectors for the target TPA, QMD, and H being 190.0 TPA, 18.7 inches, and 99.1 ft and 1750.1 TPA, 15.3 inches, and 78.3 ft respectively. As with the TPA and QMD assessment, the acceptable stands are clustered about the center of the TPA-QMD-H distribution, and both high and low density stands have been identified as unacceptable relative to the target. The TPA, QMD, and H assessment, therefore, also succeeded in identifying stands meeting the desired conditions.

The assessment procedures make no value judgments; they simply identify stands that are far from the target mode.

If, for example, the low density, large tree forest structures are desirable, then a second tier assessment could be performed to accept them. If used in this way the primary assessment identifies stands that are indistinguishable from the target and stands that need further consideration, the unacceptable stands. In a management context, the acceptable stands from a primary assessment could be used to determine appropriate management strategies, whereas the unacceptable stands could be used to identify management strategies that need further investigation or refinement.

CONCLUSIONS

The uses of quantitatively defined targets and assessment procedures to identify desired conditions and to assess management practices relative to the desired conditions in forest management, or other areas of natural resources
management, are likely to increase in the future. Target
definition and assessment methods must allow for the vari-
ability inherent in natural systems and provide for flexi-
bility in the attainment of the desired conditions. Further,
effective target definition and assessment methods must be
biologically and statistically consistent. Biological consis-
tency is necessary to ensure that the defined targets are re-
levant, representative of actual conditions, and achievable.
Statistical consistency is necessary to ensure the correct
interpretation of inferences derived from the target defini-
tion and assessment procedures.

The nonparametric target definition and assessment
procedures described automatically take into account the
inherent variability of a desired forest structure, as identi-
fied by a representative data set, and they may be used with
parameter vectors of any dimension. The procedures are
both statistically and biologically consistent. Statistical
consistency is obtained by using the underlying distribution
of parameter values as the basis for the target definition and
assessment procedures. Biological consistency is obtained
by using actual data for relevant parameters to define the
target and perform assessments. Methods like those pre-
sented here provide an effective conceptual framework that
may enable scientists and policy makers to focus on identi-
fying the relevant biological issues, rather than setting
potentially arbitrary targets for management.

ACKNOWLEDGEMENTS

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**LITERATURE CITED**


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SENSITIVITY ANALYSIS ON SUSTAINABLE FOREST MANAGEMENT CRITERIA AND INDICATORS IN FOREST DEVELOPMENT PLANNING: AN APPROACH USING MULTI-CRITERIA OPTIMIZATION

Thomas Maness and Ross Farrell

ABSTRACT

This paper describes the use of a multi-objective optimization model for creating forest development plans in the East Kootenay area of British Columbia. The planning model determines appropriate harvest levels and management treatments on planning units to satisfy stakeholder objectives related to the criteria and indicators of sustainable forest management. The model uses indicator targets and thresholds and determines the degree of goal satisfaction using fuzzy-sets. The paper illustrates how the model can be used to conduct sensitivity analysis on the relative impact of the various criteria as an aid in a participatory planning process. Results of a case study are shown to demonstrate use of the model in a sustainable forest development planning context.

KEYWORDS: Multi-objective planning, fuzzy sets, goal programming.

BACKGROUND

The vast majority of productive timberland in British Columbia is public land. There are 37 timber supply areas (TSA’s) and 34 tree farm licenses (TFL’s), which cover about 90 million hectares of public land in British Columbia. TFL’s are 25 year agreements with a company responsible for designing and carrying out a management plan. TSA’s are large forested areas, usually with multiple licensees. Each licensee has rights to harvest a specific volume of timber, or Annual Allowable Cut (AAC) every year. Under proposed legislation in BC, licensees in each TSA will be required to collaboratively conduct a timber supply analysis at least once every 5 years.

The purpose of the timber supply analysis has been to project the volume of timber available for harvest. Advanced forest level models based on simulation and heuristics are used to project timber supply based on the inventory information, expected growth and management practices (Nelson 2003). Sensitivity analysis is performed to determine the impact of various uncertainties that affect timber supply. The sensitivity analysis is conducted by varying one variable at a time over a natural range, and noting the impact on timber volume projections.

While this type of sensitivity analysis is useful, this paper addresses three areas of concern from current modeling methods used in BC. First, economic outputs are measured solely in terms of timber volume. The changing timber size and quality distribution have an important impact on economic sustainability, and this is not considered. Second, important ecological and social indicators are usually treated as constraints rather than as opportunities, although Lui et al. (2000) have made important contributions in this area and forest models used in practice are evolving. Third, it is well known that many indicators are clearly complementary (such as ecological representation and old growth), some
are clearly competitive (such as visual quality and timber supply), and in some the degree of complementarity is unknown.

This paper describes a decision support system (DSS) that was designed to create and evaluate management scenarios using a set of criteria and indicators for sustainable forest management. We illustrate the use of the model in a Timber Supply Area (TSA) in British Columbia, and we give an example of how the model can be used to conduct sensitivity analysis to determine the relative impact of SFM indicators for use in a participatory planning process and for investment planning.

The Planning Area

This Invermere Timber Supply Area (TSA) is located in the Rocky Mountain Trench at the headwaters of the Columbia River. It is a highly scenic area and contains a number of national and provincial parks, as well as a destination ski resort. The small communities in the region are highly dependent on the forest industry. The TSA comprises 1,110,700 hectares located in the interior dry belt of Southeastern British Columbia. It contains 6 biogeoclimatic zones. The timber harvesting land base consists of 22% of the total area. Major reductions are taken for parks and reserves (25%), non-productive forest land (31%), and inoperable areas (16%). The forest types on the TSA range from dry open stands of ponderosa pine (PP Zone) and interior Douglas-fir (IDF) at low elevations to Englemann spruce – subalpine fir (ESSF) at higher elevations. Lodgepole pine commonly occurs in the montane spruce zone (MS) due to the fire history in the region. There are 6 animal species listed as threatened and 19 species listed as vulnerable that potentially occur in the TSA. Threatened species include the southern population of woodland caribou and Swainson’s hawk, endangered species include grizzly bear, Rocky Mountain bighorn sheep, sandhill crane and bull trout (MOF 2000).

Timber from the TSA supplies three sawmills. In addition wood chips are sold to a local pulp mill, and logs are traded to an LVL plant located in another region of BC. The current allowable annual cut was set in 1996 at 581,570 cubic meters (m$^3$). The long term sustainable cut level is projected to decline to 426,880 m$^3$ over the next 3 decades as older stands are harvested. The transition from an older natural forest to younger managed stands leads to obvious concern about the ecological, social and economic sustainability of the TSA.

The TSA consists of 34 Landscape Units (LU), based roughly on watershed boundaries. Each LU consists of approximately 12,000 polygons with an average size of 2 hectares, but a great deal of variation in size. This paper concerns the chart area that was assigned to Slocan Forest Products Company, which has one sawmill located in Radium Hot Springs, BC.

The Modeling Approach

Models for multi-objective forest management planning have been created using multi-objective linear programming and goal programming (Weintraub and Bare 1996, Bare and Mendoza 1988, Mendoza and others 1987, Rustagi and Bare 1987, Van Kooten 1995, Varma and others 2000). These methods require the model users to fix a “weight” or “priority” for each of the objectives. However, these objectives are often imprecise, conflicting and non-commensurable. Consequently, the weights are increasingly more difficult to obtain as the number of objectives increase.

An alternative approach to multi-criteria forest planning uses fuzzy set theory. Fuzzy constraints have been applied to single objective harvest scheduling with non-declining even flow constraints (Hof and others 1986; Bare and Mendoza 1990), for carbon balancing in forestry and agriculture (Krcmar and others 2001) and for multi-criteria forest harvest planning (Mendoza and Sprouse, 1989).

Our decision support system is built around a decomposed linear programming model with a MINMAX optimization framework. The SFM indicators are modeled using fuzzy membership functions in the tactical (master) LP. Rather than having criteria weights, this approach uses targets, thresholds and triggers. Targets are the desired outcomes for each goal. Thresholds are the minimum acceptable outcome for each goal. Triggers are the management activities that occur on the ground to change the achievement levels of the goals. We call this optimization structure the “3T Approach”.

Forest planning models typically have log volume (or log value) maximization as the objective pertaining to timber. However, most manufacturing facilities perform best with a mix of diameters, lengths, species and grades suited to their technology and markets that they serve. To maximize the economic benefits, planning units that give the correct mix of logs would be chosen for harvesting. Other planning units may have higher values for other objectives. For this reason, an operational LP is called as a subroutine to determine the optimal manufacturing decisions and return the marginal log values to the tactical LP.

Early manufacturing models that used LP with decomposition techniques are described in Mendoza and Bare.
The forest planning and manufacturing models are linked using a hierarchical planning (HP)\(^2\) framework described by Paredes (1996). HP in our model refers to separating the planning problem into temporal contexts, and integrating separate models for each one. This allows each model to focus on the objectives that are important at that level. Sequential HP models are described by Jamnick and Robak (1996) and Ogweno (1994). These models operate from the top down in one direction, so they do not find a global optimum. To ensure global optimality our model is linked through the use of shadow prices on logs.

**METHODS**

**Creation of Planning Units**

It is impractical to use individual forest polygons for tactical planning. They are too small, and there are too many of them. Groups of polygons called cut blocks could not be used either as these are not created until an area has actually been scheduled for harvest. For this reason we created the Stewardship Unit (SU), a homogeneous planning unit of variable size, ranging from 0.02 hectares to 1,114 hectares depending on the characteristics. The average SU is 180 hectares. The SU’s were created by manually amalgamating contiguous polygons that had similar attributes. The GIS dataset for the Invermere TSA was obtained from Interior Reforestation Co. Ltd. in Cranbrook BC, in December 2002. GIS data for the TSA is organized by polygon. The timber type inventory data was obtained from the BC Ministry of Sustainable Resource Management in February 2002.

**Commercial Species**

The following are the principal commercially important tree species in the region.

- Lodgepole pine (*Pinus contorta* var. *lattifolia*) – 40.7%
- White spruce (*Picea glauca*) / Englemann spruce (*Picea engelmannii*) – 13.0%
- Douglas-fir (*Pseudotsuga menziesii*) – 28.7%
- Western larch – (*Larix occidentalis*) – 7.2%
- Subalpine fir (*Abies lasiocarpa*) – 4.3%
- Western redcedar (*Thuja plicata*) – 0.2%

**Sawmill and Product Information**

The lumber mill modeled in this study is Slocan’s Radium Division sawmill located in Radium Hot Springs, BC. The mill produces commodity dimension, J-Grade and machine stress rated lumber products with 50% of their production in the latter two categories. The mill has 180 employees, employs 60 contract loggers, and produces 150 million board feet per year. The mill also produces 71,000 bone dry units of wood chips annually.

Logs are trucked over public roads to the mill’s log yard. About 30% of the mill’s logs are cut-to-length, the balance are cross cut in 2 manual bucking lines. Primary breakdown consists of 3 sawing lines: a high speed small log canter, a canter twin and a carriage headrig for larger high quality logs. Three large kilns provide adequate drying capacity.

**Development of Criteria and Indicators**

The choice of criteria and indicators (C&I) used for SFM depends on the scale on which our judgments about sustainability are made. The broad principles for international sustainable development were developed in the 1992 Earth Summit (United Nations 1992), and followed up by the Montreal Process (1995), and Canadian Council of Forest Ministers (1997, 2000). While the Canadian Council of Forest Ministers C&I provide a good framework of the important principles for sustainable development, they fall short of defining operational criteria for local or regional management decisions (Reynolds 2001; Brang and others 2002). Effective criteria for management planning must be practical and simple, and they must make common sense (Bunnell 1997).

We conducted a comprehensive review of the SFM C&I published by the Canadian Council of Forest Ministers (1997, 2000), and the C&I developed by a local study in the West Kootenay region of BC (Robinson 2002). Indicators selected for inclusion were required to meet operational standards adapted from Bunnell (1997). Our study used the 4 criteria and 12 indicators listed in table 1. Targets and thresholds were developed for each indicator based on expert judgment. A full description of the indicators and rationale for choosing them can be found in Maness (2003).

**Mathematical Formulation**

**Tactical Planning Model**

The tactical planning model is a multi-objective linear programming model with a “fuzzy formulation”. We use a MAXMIN formulation which maximizes the degree of satisfaction with the least satisfied indicator. The full mathematical formulation of the model can be found in Maness and Farrell (2004).

\(^2\)A thorough review of HP techniques applied to forest management can be found in Weintraub and Davis (1996).
Operational Planning Model

The operation planning model used is a decomposed crisp linear programming model that maximizes net revenue from sawmilling operations given a log distribution. The model contains a bucking and sawing simulation model that generates activities using column generation. The mathematical formulation and full details of the model can be found in Maness and Norton (2002).

Post-optimization analysis from the operational model yields return-to-log (RTL) values for the logs input into the sawmill. The RTL values change as a function of the species and size of the logs that are delivered. Consequently, the tactical and operational models were solved iteratively using a hierarchical framework.

Linking the Models

Figure 1 shows a flowchart of the overall process for developing a management plan. First the GIS polygons are

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Table 1—Criteria and indicators chosen for the planning model. From Maness and Farrell (2004).

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Measured variable</th>
<th>Trigger</th>
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</thead>
<tbody>
<tr>
<td>Criterion I – Biological richness and its associated values are sustained</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Full range of ecosystem types are represented</td>
<td>Number of hectares of types deemed under-represented by experts</td>
<td>Indicator value can only be retained by preservation in current state</td>
</tr>
<tr>
<td>2. Ungulate winter range represented in unmanaged state</td>
<td>Number of hectares of unmanaged UWR</td>
<td>Indicator value can only be retained by preservation in current state</td>
</tr>
<tr>
<td>3. Old-growth forests are represented</td>
<td>Percentage of area in required forest types considered mature and old</td>
<td>Indicator value is retained up to a 30% net harvest removal</td>
</tr>
<tr>
<td>Criterion II – Forest productivity is sustained</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Annual removal of forest products relative to the volume determined to be sustainable</td>
<td>Annual harvests</td>
<td>Harvest volumes are constrained by the Annual Allowable Cut (AAC)</td>
</tr>
<tr>
<td>Criterion III – The flow of economic benefits from the forest is sustained</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Net profitability is sustained (proxy tax revenues)</td>
<td>Revenue (RTL values based on harvested log distribution)</td>
<td>Links between tactical and operational model.</td>
</tr>
<tr>
<td>6. Total employment in all forest sectors is sustained</td>
<td>Cost (Based on harvest costs)</td>
<td>Employment coefficients per cubic meter</td>
</tr>
<tr>
<td>7. The provincial government continues to receive portion of benefits</td>
<td>Direct employment determined by operation activities</td>
<td>Stumpage payments to government</td>
</tr>
<tr>
<td>Criterion IV – Forest management supports ongoing opportunities for quality of life benefits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Availability of recreation opportunities – 3 types:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Fishing</td>
<td>Number of recreation features by type</td>
<td>Indicator value can only be retained by preservation in current state</td>
</tr>
<tr>
<td>9. Camping</td>
<td></td>
<td></td>
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<tr>
<td>10. Hiking</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11. Visual quality of managed landscape is acceptable to stakeholders</td>
<td>Visual quality objective (VQO) scores for each stewardship unit from no value (0) to maximum value (10)</td>
<td>Current VQO and harvest treatment. Based on guidelines by Picard and Sheppard 2001.</td>
</tr>
<tr>
<td>12. Community watershed are sustained and protected</td>
<td>Number of hectares of community watersheds</td>
<td>Indicator value is retained up to a 25% net harvest removal</td>
</tr>
</tbody>
</table>
aggregated into stewardship units (SU’s). Next, the forest cover type data is used to generate a stand and stock table for each SU. Taper curves are used to determine the tree shape.

An expert is identified for each indicator used in the model. Before running the model, the expert analyzes the input data and the objectives of the stakeholders, and specifies the required target and threshold for each indicator. This information is added to the database.

The DSS is solved using a hierarchical planning framework. Trees are bucked into woods length logs based on return-to-log values (shadow prices from the operational LP). The tactical model determines which areas will be harvested with which treatments considering all of the criteria and indicators. The log information is passed to the operational model, which runs the sawmill optimally based on that log distribution. Return-to-log values are then determined, and the tactical/operational sequence is re-executed until a global optimum is reached. At this point
the DSS is completed and the optimal scenario is prepared for stakeholder review.

In practice, stakeholders would review the output to determine if criteria have been sufficiently met. If not, targets and thresholds are reviewed, negotiated and modified, and a new scenario is built as above. The process continues until stakeholders are satisfied or all options have been explored.

**Harvesting treatments**

The ten different management treatments considered by the DSS are listed in table 2. Selection cuts operate at a 50% retention level. The model assigns harvesting prescriptions to stewardship units taking account of the targets, thresholds and triggers for each criteria and indicator. Each harvesting prescription has an associated harvesting cost based on the harvest method (clear-cut or selection-cut) and the net harvest volume. Selection-cuts are more expensive than clear-cut systems and cost increases are incurred as net harvest volume decreases. Costs are also adjusted according to the likely harvesting system that would be used in each stewardship unit, determined by analysis of terrain data extracted from the GIS.

**RESULTS & DISCUSSION**

Results are organized in 2 sections. The first section shows the results of the base case scenario, where the model was used to prepare a 5 year forest development plan for the 2 landscape units. The second section shows the results of the sensitivity analysis, where an optimal solution was found for each indicator separately, and the effects on all other indicators was noted.

**Base case targets, thresholds and results**

The base case scenario was prepared for the first five-year planning period using the annual allowable cut to constrain harvest volumes from each of the landscape units. The scenario required two iterations of the tactical and operational LP’s to generate a global optimum solution based on the updated RTL values and the indicator targets, thresholds and triggers.

The RTL values for each iteration of the operational model are shown in figure 2. Iteration 1 increased RTL values for SED’s of nine inches and over, while SED’s less than nine inches have decreased in value. This result is intuitive as the tactical LP seeks to harvest SU’s that provide a more optimal log distribution, therefore increasing volumes of the larger SED’s that generate greater profit.

The RTL values adjust to reflect the more balanced log distribution showing an increase for large SED’s and a decrease for small SED’s.

The harvesting treatments prescribed by the global optimum solution to the tactical LP for each of the landscape units are shown in table 2. Only one harvest treatment is applied to LU 27. Approximately 14% of LU 27 is prescribed a 20% clear-cut and the remainder is preserved. Approximately 98% of LU 29 is preserved with the remainder allocated to 5 different treatments. The largest treatment is a 100% clear-cut prescribed to 1% of the LU area.

Table 3 shows the targets and thresholds with the result and satisfaction score for each of the 7 indicators that had threshold below the target. The threshold percentages specify the minimum acceptable values as a percentage of the target for each indicator. The criterion II indicator (forest productivity is sustained) is modeled as a hard constraint that ensures harvest volumes do not exceed the annual allowable cut for each landscape unit. Consequently this indicator has no target or threshold values. Four other indicators were deemed critical in the base case scenario and were fixed in the base case run. This means their minimum acceptable value is equal to the target for that indicator, thereby ensuring that they are sustained in their current state (in other words they were hard constraints also). These four indicators were: ecosystem type representation, old-growth forest representation, visual quality of the landscape, and protection and sustainability of community watersheds. However, for the sensitivity analysis in the next section all indicators were considered variable.
For illustration, the thresholds for ungulate winter range, fishing, hiking, camping, employment and benefits to the government were set at 90% of the target. The threshold for net profitability was set at 75% of the target as it was anticipated that this indicator would be the most difficult to satisfy (at its target level) when balancing the needs of all the other indicators.

Table 3 shows the achievement level and percent for each of the 7 indicators. The achievement level is related directly to the membership function. Since all membership functions were linear in this study, the achievement level represents the percentage achieved between the threshold and the target. It is the actual fuzzy indicator used in the model. The achievement percent reported in table 3 is the percent of the target that was achieved (between zero and the target).

Three indicators failed to achieve the target. Ungulate winter range achieved a level of 0.95, while both hiking and net profitability achieved the minimum level of 0.34. Experience with the model has shown that using the MAXMIN approach the achievement level will always be equal for 2 or more indicators at the lowest level (the minimum). This represents the balance point. None of the indicators at the lowest level can be raised without decreasing at least one of the others. This is an important feature of the MAXMIN fuzzy approach—it identifies all the indicators at the balance point.

It is interesting to note that even though profit does not attain its target value, the other economic indicators (employment and benefits to government) were fully satisfied. This occurs because both employment and government benefits are a function of harvest volumes rather than a direct function of sawmill profitability. This is an important result because even though volume can be sustained,
the decreasing timber quality over time is unable to sustain profitability. This factor is often overlooked in long range timber planning. In this case the high quality timber that would sustain profits is located in high recreation value areas.

From these results we conclude that profitability and hiking are the most critical indicators in the base case scenario, with ungulate winter range falling next in line. This was checked out with the forest company and was found to indeed be the case on these landscape units. If the model was used in a participatory decision making context the output of the base case scenario would be reviewed by all stakeholders to determine if criteria have been sufficiently met. If not, the targets and thresholds would be reviewed, negotiated and modified, and a new scenario would be defined. When reviewing this information the forest company had an important insight – they may decide to invest to hiking trails as a way to improve their profitability. This is an interesting outcome of using this type of model.

The scenario evaluation model can also be used to generate a number of alternative solutions with different target and threshold settings. This allows decision makers to explore a variety of options in the context of a “what-if” analysis.

**Indicator Sensitivity Analysis**

The way in which the indicators impact one another was investigated by conducting a series of runs where the threshold level for one indicator is set at the target, while the thresholds for all others are relaxed at 50% of the target. This forces the model to achieve the target for the designated indicator and maximizes the minimum of the remaining indicators. Eleven runs were made in total, one for each indicator.

Table 4 shows the results from the sensitivity analysis. Each row represents the results from a single run with the indicator listed in column 1 set at the target. The corresponding achievement level for each indicator is reported under the appropriate column. Recall that when the achievement level equals 1.00 the indicator has attained the target value.

The lowest achievement level score (0.51) was incurred (by the hiking indicator) when profit is constrained to the target. The next lowest achievement level is obtained when the community watershed indicator is set at the target, in which case both profit and hiking indicators are reduced to a satisfaction score of 0.72 (this identifies the two balancing indicators).

<table>
<thead>
<tr>
<th>Indicator</th>
<th>ECO</th>
<th>UWR</th>
<th>OLD</th>
<th>PFT</th>
<th>EMPL</th>
<th>BNFT</th>
<th>FISH</th>
<th>HIKE</th>
<th>CAMP</th>
<th>CWAT</th>
<th>VIS</th>
<th>MINIMUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. ECO</td>
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<td>0.94</td>
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<tr>
<td>2. UWR</td>
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<tr>
<td>3. OLD</td>
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<td>5. PFT</td>
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<td>6. EMPL</td>
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<tr>
<td>7. BNFT</td>
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<tr>
<td>8. FISH</td>
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<td>9. HIKE</td>
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<td>10. CAMP</td>
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<td>11. CWAT</td>
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<td>12. VIS</td>
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</table>
Decision makers can make inferences about the trade-offs between specific indicators using this information. For example when profit is maximized, the hiking indicator is most affected, i.e. hiking incurs the lowest achievement level. It is also evident that the community watershed indicator has the biggest single impact on profit levels when this indicator alone is maximized. In this case profit drops to an achievement level of 0.72.

**CONCLUSION**

There are many factors that must be considered when generating sustainable forest development plans. Sensitivity analysis is a key component to identify solutions that satisfy a wide range of stakeholders. Using the DSS illustrated in this paper, stakeholders and a panel of experts could collaborate in the decision making process to generate potential development plans. Stakeholders would review the output to determine if criteria have been sufficiently met, and if not, the targets and thresholds could be reviewed, negotiated, and modified, and a new scenario defined. The process would continue until stakeholders are satisfied or all options have been explored. In addition, forest products companies would receive feedback on which areas they should invest in to assure timber supply and future profits. Such investments may include those undertaken to satisfy non-timber objectives, as has been illustrated in this paper. This type of win-win investment is in the true spirit of sustainable forest management.

Research and development on this model is ongoing in both Northern and Southern British Columbia. Much work remains to be done before the model reaches its full potential. Researchers are currently expanding the planning horizon to several rotations, refining the indicators, adding new indicators, solving much larger areas, and adding road networks to the model.

**LITERATURE CITED**


PARTICIPATORY MODELING AND ANALYSIS
OF SUSTAINABLE FOREST MANAGEMENT: EXPERIENCES
AND LESSONS LEARNED FROM CASE STUDIES

Guillermo A. Mendoza¹ and Ravi Prabhu²

ABSTRACT

Participatory approaches to natural resource management and development have become widely accepted as the most effective instruments for achieving sustainable resource management particularly in the developing nations. This paper presents a participatory modeling framework that is consistent with participatory methods of assessing sustainable forest management. Under this participatory modeling framework, a number of techniques have been developed aimed at: 1) communicating the concept of sustainable forestry to local communities, 2) soliciting direct input and active participation of local communities in the planning and decision-making process, and 3) seeking active involvement of local stakeholders in the formulation of the models and in their implementation for generating strategies and action plans. These models include: multi-criteria analysis, cognitive mapping, qualitative, and quantitative system dynamics. The models can be stand-alone models, or they can be combined together to constitute a more robust and flexible planning framework. These models have been applied to a number of case studies in the Philippines, Indonesia, Zimbabwe, and Ontario, Canada. Experiences and lessons learned from a selected set of applications are described in the paper.

INTRODUCTION

The concept of sustainability has become prominent in almost all natural resource management situations. Its great appeal has dominated discussions about resource utilization, conservation, biodiversity, and many other resource development and management issues. Despite some lingering differences and confusion about the meaning and essence of sustainability, there is widespread acceptance that it is, in principle, a noble goal that all resource management must strive for. Consequently, the literature is now very rich with reports and discussions about its meaning and practice (Floyd et al 2001; AF&PA, 1995; Ferguson, 1996; Munasinghe and Shearer 1996; Maser 1994). Over the last few years, significant amount of effort, resources, and initiatives worldwide have been dedicated to the implementation of sustainable management of forests and other natural resources (FSC, 1994; IUFRO 1997; Varma et al. 2000). For example, one of the most common initiatives is the development of criteria and indicators for assessing and monitoring sustainability (ITTO 1992; IUFRO 1997; Maser 1994; Mendoza and Prabhu 2000a,b).

The practice of sustainable resource management has also brought new paradigms in terms of how it is implemented at the field level. Traditionally, resource management has often been entrusted to experts and professionals who exert enormous influence in how forests and other resources are managed. Local communities and other stakeholders have, in the past, been marginally involved in the planning and decision-making process that ultimately affect how the resources were managed. This traditional management paradigm has, over the last decade, been debunked or considered ineffective and unable to address the challenges posed by sustainable resource management. In its place, the paradigm of participatory or collaborative management has been widely accepted as a more appropriate and effective paradigm for natural resource management.
particularly in the developing nations. Consequently, there now exists a large body of resource management and development literature describing and advocating the practice of participatory approaches to resource management (Chambers and Gujit 1995; Selener 1987; Saxena et al. 2002; Richards et al. 1999).

This paper describes modeling approaches to support the participatory or collaborative management paradigm. Participatory approaches have been described in a significant body of literature and will not be rehashed here (Chambers and Gujit, 1995; Selener 1987; Saxena et al. 2002). The paper however, will briefly describe the principle of participatory or collaborative modeling in general and also describe how it has been applied in a number of case studies.

THE NEED FOR PARTICIPATORY MODELING

Participatory approaches described and reported in the literature have taken many different forms with their glossary of terms, concepts, and analytical constructs. Some of the more popular or better-known approaches include: participatory rural appraisal (Chambers and Gujit, 1995), participatory action research (Selener, 1997), community-based resource management, co-management, joint forest management, adaptive management, integrated resource management, and other similar terms (Sarin, 1995; Misra 1997). While subtle differences exist among these methods, they have fundamental similarities and commonalities in terms of their general process and the nature of issues and problems they are designed to address, which generally include: multiple stakeholders and their multiple interests, plurality of perspectives, and the empowerment of local communities and stakeholders. Also common to these approaches is the prerequisite for direct and active involvement of stakeholders in the planning, decision-making, and actual management of the resources.

While these approaches have been widely accepted and promoted by many national and international agencies, both governmental and non-governmental, they have also received general criticisms from practitioners, management, and development scientists. Much of the criticisms revolved around the apparent lack of rigor, structure, and analytical framework provided by these approaches. On one hand, the strength of these approaches lies on the highly transparent and open-ended exploration of the issues, problems, and objectives that characterize the complex environment typical of many resource management situations. The weakness, on the other hand, stems from an apparent lack of a structured or systematic framework with which management strategies in general, and action plans in particular, can be evaluated for purposes of making decisions or choices among competing management alternatives.

Resource management often includes many components and stakeholders each of which has their own demand in terms of resources, uses, goods, and services. To effectively manage the resource, it is imperative that stakeholders’ concerns are addressed individually and collectively in a manner consistent with the resource’s ability to meet these demands without compromising its future productivity. Hence, in one way, comprehensiveness that allows the accommodation of multiple interests, uses, and products, is desirable. On the other hand, choice of optimal alternatives would almost certainly be impaired or impossible to identify in light of the complexity surrounding the comprehensive scope of resource management. Faced with such broad scope, potentially large number of alternatives and their intricate relationships, processes and impacts, it is almost imperative to have a mechanism or framework for evaluation. Modeling, in general, offers such a framework.

Modeling, to be effective under a participatory management environment, must be transparent and within the reach and grasp of local communities and stakeholders who often are not familiar with, or do not have the experience and technical know-how about, models. Historically, modeling has been the exclusive domain of scientists and experts in part because most models are complex and require some expertise to formulate and develop. Moreover, traditional models referred to as ‘hard systems models’ by Checkland (1981), are generally very structured and formalized requiring sophisticated analytical constructs and mathematical functions. Because of these restrictions, it is not advisable or appropriate to use a complex modeling environment as the platform for participatory modeling. On the contrary, for modeling to be able to offer genuine analytical support for participatory management, it must be simple and transparent for local stakeholders and at the same time it must be of sufficient rigor that enables more in-depth analysis capable of accommodating the breadth and depth that characterizes the scope and complexity of natural resource management.

The type of analysis, insights, and decisions that can reasonably be expected from a group, community of stakeholders, or under a participatory setting is worth noting. As pointed out by Checkland (1981, 1988), most traditional models are designed to ‘seek’ the ‘best’ or ‘optimal’ solution to a perceived problem. Clearly, the issues surrounding sustainable forest management are too complex to presume
that an optimal solution can be identified, particularly when there are other stakeholders involved. Under these conditions, models must be viewed as ‘problem structuring’ tools, rather than ‘problem solving’ methods. Hence, results of analysis and insights from participatory models are generally broad and tend to be strategic in nature rather than operational or tactical. These models are generally designed as tools to ‘understand’ the problem rather, make decisions with respect to optimal ways of solving the problem (Checkland, 1981).

PLURALISTIC AND QUALITATIVE SYSTEMS MODELS

As pointed out above, because of their rigid assumptions and generally restrictive nature, traditional models do not suitably match the type of modeling and participatory process required in analyzing sustainable forest resource management. However, current methodologies in participatory management are also inadequate because they are inherently qualitative and do not offer any systematic framework by which natural resource management strategies and alternatives can be analyzed.

While traditional models on one hand, and current participatory approaches on the other hand, have their limitations when used as stand-alone methods, they nonetheless have desirable features that can enhance sustainable management of forest resources. The systematic approach of traditional models and the stakeholder-focus of participatory approaches, are notable strengths of the two methods that can be combined to form a modeling framework suitable for analyzing sustainable forest management consistent with the principles of participatory management.

The need for more flexible and still rigorous methodology particularly for human-dominated systems, such as the case of public natural resource management or community-based forest management, have been advocated by a number of management practitioners and scientists. Checkland (1984,1988) was perhaps the first to propose the use of what he calls ‘soft systems methodology’ as an alternative to traditional scientific management method, which he referred to as following the ‘hard systems’ paradigm. He characterized the scientific management paradigm as highly mechanistic, reductionist, and functionalist in orientation. Recognizing that these characteristics do not conform with messy and ill-defined problems (e.g. complex human systems coupled or interacting with natural systems) he developed a soft systems methodology purposely designed to accommodate the anomalies and externalities that arise when dealing with human-centered systems. Following the same school of thought, other authors advocated similar approaches such as value-focused thinking (Keeney, 1992), robust planning methodologies (Rosenhead, 1989), Strategic Options Development (Eden, 1988, 1989), and qualitative system dynamics (Coyle, 2000; Wolstenholme, 1999). Mendoza and Prabhu (2003a) describe some of these methodologies in the context of community-managed forests. The following sections describe three general methodologies and how they are used in the context of sustainable forest management.

Cognitive Mapping and Analysis

Cognitive maps are essentially loosely structured ideas laid out purposely for understanding basic relationships and dynamics of a system. The process begins with generation of ideas or concepts with direct and active participation of all stakeholders. This process is very similar to participatory rural appraisal techniques. However, cognitive mapping goes beyond simple listing of essential ideas concepts. These ideas are organized into a ‘map’ showing the relationships and interactions between and among these ideas. These relationships are organized following a layout of nodes and arrows (i.e. nodes represent concepts or ideas and arrows denote the interactions or linkages between these ideas).

Mendoza and Prabhu (2003b) describe an application of cognitive mapping on a community-managed forest in Zimbabwe. In this case study, three groups representing three villages were convened to assess the sustainable management of the Mafungautsi forest whose boundary encompasses the community forests managed by the villages. The modeling process started with an open-ended discussion of issues and factors affecting the management of their forests. In addition to ‘listing’ these issues or factors, the villagers were also asked to indicate the connections or relationships between these factors using lines and arrows. The process was facilitated by a team of local scientists who are familiar with the forest its history and ecology. Each idea or factor was discussed and debated. Often, original ideas were revised, re-stated, or sharpened to make them more meaningful, central, and relevant to the overall objective of sustainable forest management. Moreover, each connection or relationship denoted by arrows also went through group scrutiny.

The cognitive map generated by the villagers served as an excellent learning and communication tool. Viewing the map they themselves generated kindled the villagers’ awareness and appreciation of the extent and complexity of managing their forest in a sustainable manner. They found it instructive to see the factors and issues in a systems-oriented view instead of a simple ‘listing’ as is often done
using other participatory methods described in the published literature such as participatory rural appraisal (Chambers and Gujit, 1995), and participatory action research (Selener, 1997). For further or more in-depth analysis of the cognitive map, the methods described by Eden and Ackermann (1998) were used. Specifically, three significant analytical results were pursued. First, is the concept of ‘domain’ of a factor. This reflects the extent of influence or tactical significance of a factor. This is determined from the cognitive map by simply examining the number of nodes affected by, or directly connected to, a given factor. Another significant concept is the ‘centrality’ of an indicator. This reflects the ‘strategic significance’ of a factor, which can be determined by simply examining the scope of influence of a factor through its direct and indirect connections. Finally, the third concept is the ‘criticality’ of a node, which is determined by examining the number of ‘critical nodes’ connected to a factor.

The three model insights described above seemed to be quite meaningful and helpful for the three villages. They quickly recognize that these three insights can serve as a guide to them as they prepare action plans for their forests. For example, they realize the significance of a ‘central or strategic’ factor when it comes to focusing on those factors that they can affect the most and can get the most favorable impact. The ‘critical factors’ were also viewed as highly in need of mediation or urgent attention. The tactically significant factors were also viewed as factors that they, individually or as a group, can start to influence positively for more immediate impact.

Qualitative and quantitative system dynamics

The cognitive maps described are essentially a first attempt to structure the essential elements or components of a system. Clearly, the objective of developing a cognitive map is just to lay the overall relationships of factors or elements of a system. For some applications, this may be sufficient level of analysis, however, in some situations particularly where there is more information, knowledge, or experience about the different factors or elements, it may be possible to structure the cognitive map as ‘influence diagrams’. In other words, the relationships are described in terms of causalities between nodes connected by an arrow. In this case, the concept of system dynamics is appropriate (Forrester 1961, 1999).

System dynamics is a general term associated to the study of the dynamic behavior of a variety of complex systems (Coyle, 2000). Typically, influence diagrams using nodes and directed arrows are used to denote this dynamic behavior. In addition, the relationships sometimes referred to as feedback loops or causality diagrams, are either positive or negative as shown in Figure 1. The diagram can serve as ‘sense’ making device for the purpose of identifying dynamic causality relationships. The potential advantages of qualitative inference diagrams showing causal loops was described by Wolstenholme (1999) as follows: “Causal loop qualitative model enhances linear and ‘laundry list’ thinking by introducing circular causality and providing a medium by which people can externalize mental models and assumptions and enrich these by sharing them. Furthermore, it facilitates inference of models of behavior by assisting mental simulations of maps”.

Purnomo et al (2003) used a number of influence diagrams to examine the criteria and indicators of a community-managed forest in Indonesia. Figure 2 shows an example of a causality loop diagram generated by a focus group representing two indigenous tribes living within a forest concession-area located in Kalimantan, Indonesia. In this study, selected members and representatives from the two villagers were asked to serve as a team that will examine the sustainability of their forests. Following the principles of participatory action research, the villagers were asked to participate in a historical examination of their forests, and in the process, generate a set of relevant indicators that could be used to evaluate and monitor the sustainability of their forests. During the group modeling process, mental maps or cognitive maps were generated following participative or collaborative modeling procedures as described by (Richardson and Anderson, 1995; Vennix, 1996). The modeling process, debate, and iterative presentations of causality maps eventually led to a group model. An example of this is shown in Figure 2. With the generated set of indicators, the villagers, along with some scientists, were asked to provide input with respect to: a) the current condition of the indicators, and b) projections about the desired condition of the forest with respect to the set of indicators. These projections are not meant to be accurate; they are meant only to show crude comparative analysis and projections between the status quo and projected desired future conditions.

Mendoza and Prabhu (2003b) reported another case study describing the application of qualitative system dynamics. The case study involved a community-managed forest located in Midland Province of Zimbabwe. In their study, they used a computer-assisted decision support system called Collaborative Vision Exploration Workbench or COVIEW (http://www.cifor.cgiar.org/acm/pub/co-view.html). This system is organized and structured following a system dynamics framework as shown in Figure 3. As can be seen from Figure 3, the system has the objective in the middle,
Figure 1—Components of causal loop diagram (Source: Purnomo et al. 2004).

Figure 2—Causal loop diagram of management of forest as perceived by its stakeholders (Source: Purnomo et al. 2004).
which is reflected as the main resource in Figure 3. The attainment of the objective is dependent on both favorable factors and unfavorable factors considered detrimental to the objective. These factors are structured following the SWOT (Strength, Weaknesses, Opportunities, and Threats) concepts familiar in strategic management. Framing the issues and concerns in this manner helped the villagers identify internal (Strengths) as well as external (Opportunities) factors that contribute to the attainment of their objectives, as well as internal (Weaknesses) and external (Threats) factors that undermine the attainment of their objective. The indicators are the variables that reflect the status of the resource being managed in general, or a given objective in particular. Clearly, the qualitative system dynamics shown in Figure 3 is not sufficiently ‘formalized’ to allow simulation in terms of specific scenarios based on alternative strategies. At this level of formalization, more simplistic analysis such as those described by Purnomo et al. (2003) can be used. Or, it may also be desirable to focus on those aspects of the problem that are sufficiently understood whose relationships can be quantified or formalized.

Based on the qualitative system dynamics described in Figure 3, a simpler and quantifiable portion of the model was examined in more detail. This allowed the development of a quantitative system model, which was then used as the simulation model to evaluate different management alternatives and strategies presented to, and analyzed by, the villagers facilitated by a team as proposed by Vennix (1996).

The Co-View decision support system has a ‘Bridge’ component that allows the system dynamic diagram to be converted to a system dynamics model that is transparent to the stakeholders. The ‘transformed’ model then becomes the vehicle with which stakeholders can ‘analyze’ impacts of different scenarios using another component of Co-View called ‘Power to Change’. The simulation afforded the villagers a chance to examine alternative management scenarios, both long term and short term.

**Multi-criteria Analysis**

Multi-criteria Analysis (MCA) is an umbrella approach that encompasses a number of methods, both qualitative and quantitative. As its name implies, MCA is a structured framework by which management problems that involve a number of criteria or objectives can be systematically evaluated and analyzed within the context of rational decision-making. Because of its capability to accommodate multiple criteria and multiple decision makers or participants, it offers a convenient framework for assessing sustainable forest management. Mendoza and Prabhu (2000a,b) were one of the first to recognize the potential of this approach in sustainable forest management. Since their seminal work, a number of applications have been reported describing case studies where MCA was used as the organizing framework with which sustainable forest management were implemented (Varma et al., 2000). Perhaps the most significant application environment under which MCA was applied is the development of criteria and indicators for sustainable forest management. One of the more recent application is the use of MCA as a tool to evaluate sustainability as part of the Provincial State of the Forest Report (SOFR).
Ontario Ministry of Natural Resources (OMNR) is required to put together a report every five years documenting the status or condition of its forest particularly with respect to how sustainable the Ontario forest is being managed. It is a report that is meant to inform the general public of the current condition of the forest and the trends evident from repeated and consistent measurement of indicators. To provide a framework for such an assessment, MCA was examined as one possible approach. Mendoza (2002) describes the concept and principles used in this assessment. The results of the analysis are reported by BioForest Technologies, Inc. (2003). In this analysis, MCA was used as an assessment tool to evaluate the relative significance of indicators and their contributions to the overall sustainability of the Ontario forests.

CONCLUSIONS

It is now widely accepted that participatory methods are the most effective approaches to achieve sustainable resource management. Increasingly, local communities are demanding more voice and influence in the manner public forests are managed. This calls for more active and direct participation from a number of stakeholders who are affecting, or affected by, the forest. In response to such changing management paradigms, participatory methods have been proposed. However, to date, while many of the existing participatory methodologies are strong in terms of inviting participation, they but are still lacking in terms of providing a structured framework by which debate about management alternatives and strategies can be sufficiently analyzed and evaluated. While formal methods of analysis like many traditional analytical models can offer such structured framework, they are often too mechanical, overly simplistic and rigid in their assumptions, and generally lack the flexibility and ‘robustness’ necessary for participatory analysis. On the other hand, many of the recent participatory methods like participatory rural appraisal, though they are inclusive and generally meet requirements of participation, are often lacking in rigor for more in-depth analysis. This paper proposed an alternative approach using participatory modeling as a more suitable framework for analyzing more complex problems like sustainable resource management within the context of managing public forests. The participatory modeling framework proposed in this paper combines the strength of participatory rural appraisal by taking advantage of local knowledge through active participation of local communities, and the analytical capabilities of structured modeling. Three general models were presented for this purpose: 1) cognitive mapping, 2) qualitative and quantitative system dynamics, and 3) multi-criteria analysis.

Experiences gained from a number of applications indicate that in general, a soft modeling paradigm is capable of enhancing both planning and the decision-making processes necessary to implement participatory management. Its transparent nature allows for more inclusive participation of local stakeholders. Nothing is hidden beyond the complexities of the model as is often the case for more sophisticated models. This is one of the significant lessons learned from the case studies; that is, transparency is critical to build trust, confidence, and integrity of any planning exercise.

The models described in this paper are simple yet powerful in terms of ‘externalizing’ relevant aspects of sustainable forest management. Because of their relative simplicity, they brought modeling within the comfortable reach of local stakeholders. Unlike traditional models that historically have been in the exclusive domain of modeling experts, the models described in this paper are simple enough for local stakeholders to understand. Consequently, local stakeholders were able to confidently participate in the entire process: from formulation to more in-depth analysis. This was made possible also in part because of the adoption of the group modeling process suggested by Vennix (1998), particularly the emphasis on team facilitation.

Feedback received from many participants have generally been favorable with respect to the use and potential of the models described in this paper. Because the overall process itself (not just certain stages) is participatory, the participants often share ownership of the model, as well as the insights, results, and decisions made stemming from the application of the models. We believe this is in large part because the participants have higher confidence in the analytical results generated because they understand the inner workings of the model, which they themselves helped put together. This increases the likelihood that policies developed, actions plans generated, and decisions made following the participatory modeling and analysis process will be adopted.

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TECHNIQUES AND DECISION SUPPORT FOR FOREST PLANNING
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HATT: THE HEURISTIC ALGORITHM TEACHING TOOL FOR ADVANCED FOREST PLANNING COURSES

Pete Bettinger¹

ABSTRACT

The Heuristic Algorithm Teaching Tool (HATT) is a Windows®-based computer program developed to support an advanced forest planning course at the University of Georgia. The procedures available within HATT include basic implementations of Monte Carlo simulation, simulated annealing, threshold accepting, tabu search, and genetic algorithms. The Model I forest planning problem that can be solved with HATT is relatively simple: achieve the highest even-flow of timber harvest volume over a three-period planning horizon, using a unit restriction model for 1-period green-up concerns. The number of management units that can be modeled is flexible, as are the yields used to describe forest conditions. The problem size is only limited by a computer’s RAM. HATT was developed in Visual Basic, perhaps the easiest programming language to learn. Students are encouraged to modify the program to enhance the heuristic search processes (e.g., add intensification techniques), to model larger problems (e.g., those with more time periods), or different problems (e.g., maximize net present value, maximize habitat, area restriction adjacency).

INTRODUCTION

Forest planning is evolving, and while the traditional mathematical programming solution techniques (linear programming, integer programming, etc.) are still being used to assist in the decision-making processes associated with the scheduling of forest management activities, other non-traditional heuristic techniques are also being evaluated for their usefulness. The reason for the exploration into non-traditional techniques is mainly due to the combinatorial nature of today’s forest management problems. Spatial constraints, integer decision variables, and complex physical or biological effects models are increasingly seen as critical aspects of forest plans. The traditional mathematical programming solution techniques can locate optimal solutions to a number of complex forest planning problems, but may find solving increasingly complex problems difficult, if not impossible. Therefore, heuristic programming techniques are viewed as, perhaps, viable alternatives that allow the development of forest plans that recognize spatial constraints and complex physical or biological relationships between activities and the environment.

Most advanced forest management courses in U.S. forestry schools emphasize an expansion on the usage of traditional mathematical programming solution techniques. Larger and more complex linear and integer models are evaluated, and goal programming formulations are introduced. Few schools offer an examination of heuristic techniques. Those that do include the University of Georgia (Advanced Forest Planning), Oregon State University (Combinatorial Optimization), and tangentially, Ohio State University (Special Topics in Quantitative Geography). One of the major drawbacks of doing so is the limited availability of heuristic algorithm software. Given this, students need a background in computer programming in order to develop their own heuristics, since heuristic techniques are generally based on computer program logic, and not explicit formulations of equations representing an objective function or constraints. In fact, most of the knowledge gained from the use of heuristic techniques is through research projects and applications to real world forest planning efforts (e.g., Sessions and others 1998, Bettinger and others 2003). This paper introduces the Heuristic Algorithm Teaching Tool (HATT, Bettinger 2003), a Visual Basic program that could...
facilitate the integration of heuristic techniques into advanced forest planning courses. HATT includes a suite of heuristics in their basic implementation, and thus provides a framework of computer program logic that can be expanded upon to solve more difficult planning problems or to generate more efficient solutions.

SYSTEM REQUIREMENTS

The HATT model was developed within Microsoft Visual Basic 6.0. In order to run the HATT executable program, a computer with a Windows® 95/98/ME/NT/2000/XP operating system is required. Computers equipped with other operating systems may also be able to run HATT, however, this has not been tested. If Visual Basic is available on the computer being used, students and teachers can modify the HATT program. If Visual Basic is not available, yet users desire to run the executable program, the installation package must be used to set up the program, since it will require a few dynamic link library (.dll) files that are usually not available on computers where Visual Basic has not been installed.

HATT requires two input data files, one describing the condition of the landscape being modeled, and the other describing the adjacency relationships among landscape management units. The file that describes the landscape condition is a comma-delimited ASCII file with the following format for each line of data:

management unit, area, potential volume

Management unit is an integer, the remaining values are real numbers. The potential volumes represent the timber volume per unit area that is available for a clearcut management activity if the management unit is not clearcut in any of the other time periods. The length of a time period is an assumption made by the user. The yields should reflect the appropriate volumes for each stand grown over the length of the time periods.

The file that describes the adjacency information is also a comma-delimited ASCII file, with the following format:

management unit, adjacent management unit

Each of these values are integers. Adjacency can be defined as the user wishes, yet must be reflected in the data contained in the adjacency data file. The three basic types of adjacency relationships in forestry include management units that share an edge, management units that share both an edge and a point, and management units whose edges are within some proximity of one another.

The size of problem that can be modeled with HATT is only limited by the amount of RAM available on a computer, as all data are stored in arrays at run time.

PROGRAM STRUCTURE AND ALGORITHMS

HATT attempts to solve a forest management problem where one desires to schedule the highest even-flow of timber volume over three time periods, yet no harvest areas can be adjacent to each other during the same time period.

OBJECTIVE FUNCTION

The objective function consists of maximizing an even-flow harvest volume (i.e., scheduling harvest volume as close as possible to a target harvest volume) over three time periods. HATT attempts to do so by minimizing deviations from a target harvest volume. Users must first decide what the target harvest volume will be for the area. Each of the HATT search algorithms then schedules harvests such that the accumulated timber volume in each time period is as close to the target as possible. Deviations from the target are squared to prevent ambiguous solutions. For example, one solution with a large deviation of harvest volume in one time period (while keeping the other two periods close to the target volume) may be seen as good as another solution with equal deviations in all three time periods (where the sum of the deviations is the same as the solution with one large deviation) if none of the deviations are raised to a power. The objective function, therefore, is to minimize the squared deviations in periodic harvest volumes from a target harvest volume:

Minimize

$$\sum_{t=1}^{T} TV_t - \sum_{i=1}^{N} (a_i v_{i,t} x_{i,t})^2$$

Where:
- $t$ = a time period
- $T$ = the total number of time periods
- $TV_t$ = the target harvest volume during time period $t$
- $a_i$ = the area of management unit $i$
- $v_{i,t}$ = the volume per unit area of management unit $i$ during time period $t$
- $x_{i,t}$ = a binary variable indicating whether (1) or not (0) management unit $i$ was clearcut during time period $t$
Constraints

Two constraints are explicitly recognized in the HATT program. First, all decision variables are integers, and management units can only be harvest once during the three time periods.

\[ \sum_{t=1}^{T} x_{i,t} \leq 1 \quad \forall i \]  

[2]

Second, adjacent timber harvests are prohibited from being scheduled for harvest during the same time period. This constraint utilizes the unit restriction model described by Murray (1999) to prevent adjacent harvests within the same time period.

\[ x_{i,t} + x_{j,t} \leq 1 \quad \forall i, t, j \in N_i \]  

[3]

Where:

\( N_i \) = set of all management units adjacent to management unit \( i \)

Heuristic solution algorithms

Five heuristic algorithms are available within HATT to assist in developing forest plans. They are Monte Carlo simulation, simulated annealing, threshold accepting, tabu search, and genetic algorithms. Each of these is represented in HATT using a very basic interpretation of their processes. HATT provides the structure for students to build upon the basic interpretation, allowing incorporation of intensification or diversification processes that could lead to better solutions, and other modifications that could allow one to solve more complex problems. Of course, students will need to understand how to develop programming logic in Visual Basic to accomplish this.

Monte Carlo simulation—Within the Monte Carlo (MC) simulation algorithm, a randomly generated solution is produced (fig. 1), and its objective function value (solution value) calculated. If the solution value is better than the best solution value, the solution becomes the best solution and is reported at the end of a number of iterations.
defined by the user. When a solution is being developed (fig. 2), a set of unscheduled management units is defined. This set represents all management units that have not yet been scheduled, and does not include any management units that are precluded from harvesting due to the incremental harvests scheduled around it and the resulting adjacency problems. For example, if a management unit has three neighbors, and they are scheduled in periods 1, 2, and 3, the management unit is precluded from harvest because doing so would violate the adjacency constraint. Management units are scheduled randomly, and once the unscheduled set is empty, the process has completed an iteration (i.e., a forest plan has been developed). All that is required of the user is to define a target harvest volume and the number of iterations to develop with this heuristic. See Clements and others (1990), Nelson and Brodie (1990), Boston and Bettinger (1999), and Bettinger and others (2002) for a more detailed description of Monte Carlo simulation applications in forestry.

Simulated annealing—Simulated annealing (SA) began to be used in a widespread manner in the early 1980s (Dowsland 1993), yet the ideas that form the basis for SA were first published by Metropolis and others (1953) in an algorithm to simulate the cooling of materials in a heat bath—a process known as annealing. The SA search process begins with users defining the initial annealing temperature, the number of iterations to model at each temperature, and the cooling rate of the temperature. As each activity is scheduled, the process determines whether to change the temperature (fig. 3). When the temperature gets below 10, the process stops and the best solution is reported. During the scheduling of activities (fig. 4), a management unit and time period are selected at random, the adjacency constraint
is assessed, and if needed, the simulated annealing criteria assessed. As in other SA applications, if a randomly drawn number is smaller than

\[
\exp(-\frac{\text{proposed solution value} - \text{best solution value}}{\text{temperature}})
\]

the proposed change to the solution is accepted. If the solution had resulted in the best solution found, the changes would have been automatically accepted. If the change to the solution is not acceptable, the process reverts to the previous solution. The initial temperature must be high (10,000,000 or so) for the problem at hand. Proposed solution values minus best solution values will be on the order of 10,000,000 or more during the first several iterations, given the objective function and inefficient solutions that are developed initially, thus the test statistic will yield a reasonable value (other than 0) only if the initial temperature is very high. See Bettinger and others (2002), Boston and Bettinger (1999), Lockwood and Moore (1993), and Öhman and Eriksson (2002) for a more detailed description of simulated annealing applications in forestry.

**Threshold accepting**—Threshold accepting (TA) was introduced by Dueck and Scheuer (1990), and requires users to specify the target harvest volume, initial threshold level, the number of iterations per threshold that will be modeled, the change in the threshold, and the number of unsuccessful iterations that may be attempted per threshold. As each activity is scheduled, the process determines whether to change the threshold (fig. 5). When the threshold is equal to or less than 0, the process stops and the best solution is reported. During the scheduling of activities (fig. 6), a management unit and time period are selected at

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**Figure 5**—The basic threshold accepting process within HATT.

**Figure 6**—A more detailed examination of the “schedule activities” process within the threshold accepting process of HATT.
random, the adjacency constraint is assessed, and if needed, the threshold accepting criteria assessed. Here, the number of unsuccessful choices (either due to adjacency violations or failing the TA test) are tracked. If the number exceeds a number specified by the user, the threshold is reduced and the process continues. This aspect of TA prevents the search process from wasting time with unacceptable changes to solutions. See Bettinger and others (2002, 2003) for a more detailed description of threshold accepting applications in forestry.

**Tabu search**—The tabu search (TS) was introduced by Glover (1989, 1990) and within HATT is represented as a process requires that users define the target even-flow volume level, a tabu state (the number of iterations each management unit / time period choice will be tabu after incorporation into a solution), and the total number of iterations to run the model. After the development of an initial random solution (fig. 7), the process develops a neighborhood of choices that contain only those management unit / time period changes that do not violate the adjacency constraint (fig. 8). The neighborhood consists of the potential objective function values, holding everything else constant, of changing the harvest timing of a single management unit. In addition, the aspiration criteria is examined in the development of a neighborhood. Here, if a choice is tabu, yet may lead to a solution better than any other previous solution, it can be chosen. Once a choice has been made, the tabu states of all management unit / time period choices are updated, and the process continues. See Bettinger and others (1997, 1998, 2002), Boston and Bettinger (1999), Brumelle and others (1998), Caro and others (2003), and Richards and Gunn (2000) for a more detailed description of tabu search applications in forestry.
Genetic algorithm—The genetic algorithm (GA) search process was initially described by Holland (1975), and within HATT begins by developing a population of feasible solutions (the actual number defined by the user) using a Monte Carlo process. The objective function value (fitness) of each solution is determined, then the search process “evolves” (fig. 9). In this search process, the very best solution (parent) is selected from the population, and mated with a randomly chosen partner (fig. 10). Each solution is “split” at a randomly chosen point, and two children are created from the recombined portions of each parent. For example, assume parent A had harvest timing values (time periods of harvest) for 5 management units, listed as periods 1,2,0,2,3, and parent B had harvest timings lists as 2,0,1,3,1. If the parents are split after the second management unit value in these vectors, then recombined, child AB would represent the harvest timings for the 5 management units as 1,2,1,3,1, and child BA would represent them as 2,0,0,2,3. These new solutions may be mutated randomly depending on the rate of mutation set by the user. Adjacency constraint violations would also be examined. If either child results in an infeasible solution, it is rejected. The child with the highest fitness value, as measured by the objective function value, is retained. It then replaces a randomly chosen parent in the population, and the search continues for a number of iterations set by the user. The user, therefore must define the target even-flow harvest volume, the population size, the total iterations the model must run, and the mutation rate. See Boston and Bettinger (2002), Falcão and Borges (2001), Lu and Eriksson (2000), and Mullen and
Butler (2000) for a more detailed description of genetic algorithm applications in forestry.

PROGRAM APPLICATION IN ADVANCED FOREST MANAGEMENT COURSES

The HATT program is available over the Internet at www.forestry.uga.edu / Warnell / Bettinger / planning / index.htm. Along with an executable version of HATT, the actual Visual Basic code is available, as are two example data sets, and a GIS database associated with the example data sets. There is no user manual associated with this software - the only documentation is this paper. The HATT code contains numerous comments (fig. 11), with the aspiration that people other than the author can follow the processing of information. However, the program was not supported with grant or contract funds, so documentation may seem incomplete to more savvy computer programmers.

Using the “west” example data set, the five heuristics were used to attempt to achieve an even-flow volume of 31,000 units per time period (a volume near the relaxed [no adjacency constraint] linear programming solution to optimal even-flow). The time periods implied in this data set are 10 years long, and the volumes are in thousand board feet (MBF) per acre. The best results from 20 runs of each of the five heuristic algorithms are noted in table 1.

DISCUSSION

A forest planning problem with an even-flow objective and an adjacency constraint is not an easy problem to solve, and some of the heuristic techniques, in their basic implementation, do not seem to perform very well. However, the intent of the HATT model was to demonstrate the basic techniques, then encourage students to either (1) modify the algorithms (with intensification or diversification processes) to solve the problem faster and more efficiently, or (2) explore variations in each algorithm's parameters to locate those that seem to be the best for each problem, thus examining the sensitivity of each algorithm to changes in parameters. In many cases, the selection of appropriate search parameters will require numerous trial runs.

As a test of the notion that some of the algorithms, in their basic implementation, do not seem to perform well in solving the even-flow, adjacency planning problem, the adjacency file was altered to indicate that none of the management units had adjacent neighbors (e.g., the adjacency data for unit was 1,0). This represents a relaxed version of

Figure 11—An example of the programming code documentation available within HATT.
the problem described above, yet continues to use integer
decision variables. The GA algorithm, for example, was
run for 10,000 iterations with a population size of 500, and
a mutation rate of 0.01. One solution we found had an
objective function value of 11,459.7 (volumes of 31,008.04,
31,045.15, and 30,903.27). The difficulty that the GA algo-
rithm has with this problem is that the vector of harvest
timings for management units is arranged 1-n, yet the adja-
cency relationships are not as orderly. Management unit 1,
in fact, is adjacent to management unit 48. Thus this algo-
rithm encounters numerous adjacency violations in the
children as parent solution vectors of harvest timings are
split and recombined.

Since the underlying Visual Basic code is available for
students to examine, the process of understanding how the
heuristic algorithms work is facilitated. This is a less desir-
able substitute for actually developing an algorithm from
scratch, but will hopefully engage those who are hesitant to
learn and use computer programming techniques. In addi-
tion, it may encourage students to modify the algorithms to
solve more complex planning problems, such as those with
area restriction adjacency constraints or complementary block
wildlife habitat goals (as in Bettinger and others 2002).

**LITERATURE CITED**

Bettinger, P. 2003. Heuristic Algorithm Teaching Tool (HATT). Warnell School of Forest Resources, University of Georgia, Athens, GA.


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**Table 1—Values of the best single solution from 20 runs of each of the five heuristic algorithms.**

<table>
<thead>
<tr>
<th>Value</th>
<th>Algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MC&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Period 1 harvest</td>
<td>31,180.48</td>
</tr>
<tr>
<td>Period 2 harvest</td>
<td>31,532.88</td>
</tr>
<tr>
<td>Period 3 harvest</td>
<td>30,457.25</td>
</tr>
<tr>
<td>Obj. func. value</td>
<td>611,112</td>
</tr>
</tbody>
</table>

<sup>a</sup> Monte Carlo simulation: Iterations = 10,000.
<sup>b</sup> Tabu search: Tabu state = 150; Iterations = 10,000.
<sup>c</sup> Threshold accepting: Initial threshold = 10,000,000; Iterations per threshold = 1; threshold change = 1,000; Unsuccessful iterations per threshold = 1,000.
<sup>d</sup> Simulated annealing: Initial temperature = 11,000,000; iterations per temperature = 20; cooling rate = 0.98.
<sup>e</sup> Genetic algorithm: Population size = 1000; Iterations = 10,000; mutation rate = 0.01.


SPATIAL SENSITIVITY ANALYSIS: AN APPLICATION OF HARVEST TO A SPECTRUM ALTERNATIVE

Larry A. Leefers¹, L. Jay Roberts¹, and Eric J. Gustafson²

INTRODUCTION

Spectrum and its FORPLAN predecessor are widely used tools for developing harvest schedules (Hoekstra and others 1987; Greer 1997). HARVEST has been used to simulate a number of spatial effects of different management strategies over time. For example, Gustafson and Rasmussen (2002) conducted simulation experiments on an 84,111-acre (34,053-ha) portion of the Hoosier National Forest in southern Indiana using a baseline harvest target of 2,613 acres (1,058 ha) per decade for eight decades. The simulations focused on the interactions of adjacency constraints, spatial dispersion, and size of harvest units. Harvest unit size was the most important factor in reducing harvests below the cutting targets. Smaller 4.45-acre (1.8 ha) harvest sizes significantly reduced the cutting levels achieved in comparison to 44.5-acre (18 ha) cuts. Adjacency constraints had a significant, but smaller, effect on accomplishing harvest targets, and the harvest dispersion method (described below) had only a negligible effect.

Planners on the Chequamegon-Nicolet National Forest in northern Wisconsin created seven alternatives in their recent forest plan revision process. Each alternative was analyzed using Spectrum. As part of their species viability analysis, HARVEST was used to calculate various spatial statistics and to display maps of transformed landscapes (Gustafson and Rasmussen 2002, Leefers and others 2003).

The purpose of this paper is to (1) describe HARVEST spatial allocation options, stand cutting approaches, and spatial analyses, (2) explain linkages between Spectrum

ABSTRACT

The Chequamegon-Nicolet National Forest (CNNF) in northern Wisconsin analyzed several forest plan alternatives using Spectrum, a linear programming model developed by the USDA Forest Service. Spatial analyses of the Spectrum results were assessed using HARVEST (Gustafson 1997; Gustafson and Rasmussen 2002), given the spatial restrictions of plan alternatives. Metrics related to interior forest habitat, edge habitat, and patch size were generated. For these alternatives, CNNF standards and guidelines were used in defining forest openings, harvest sizes, harvest dispersion, green up intervals, and buffers. Sensitivity analyses are sometimes used in a linear-programming context to explore the implications of changing constraints (acres harvested, areas protected) or model inputs (prices, costs, productivity, etc.), but often comparisons between alternatives dominate analyses. We examine one CNNF (Spectrum) alternative, but change a variety of spatial assumptions in HARVEST to see their effects on selected spatial metrics, and their consistency with the Spectrum harvest solution. Some assumptions yielding different spatial configurations are equally consistent with Spectrum results; usually 92-95 percent of Spectrum results can be simulated with HARVEST. In other cases, assumptions lead to significant deviations from the Spectrum solution and may require additional, more constrained Spectrum analyses that will yield more satisfactory spatial results.
and HARVEST, and (3) illustrate effects of changing assumptions regarding edge creation and spatial allocation options. One Spectrum-based forest plan alternative for the Nicolet National Forest in northern Wisconsin is used for all HARVEST simulations. The Nicolet National Forest has approximately 600,000 acres (243,000 ha) of national forest land within its larger proclamation boundary that includes private lands as well.

**HARVEST SPATIAL ALLOCATION OPTIONS, STAND CUTTING APPROACHES, AND SPATIAL ANALYSES**

HARVEST is a spatial simulation model that requires four input maps: stand age, forest type, management area, and stand boundaries. These are raster-based maps that, when combined, stratify an area for many common forest management purposes (for example, harvesting). In our case, the pixel or cell is 98.4 feet X 98.4 feet (30 m X 30 m) or .222 acres (900 m$^2$). Details regarding HARVEST parameters are presented in Gustafson and Rasmussen (2002) and are available in the User’s Guide for Version 6.0 of HARVEST at the USDA Forest Service North Central Research Station website (http://www.ncrs.fs.fed.us/4153/).

**Spatial Allocation Options**

HARVEST has three spatial allocation options: dispersed, clustered, and “oldest first.” Each of these is subject to management area, forest type, minimum age and optional adjacency restrictions. For example, within a management area for a given forest type, stands that are old enough to harvest cannot be cut because they are adjacent to recent harvests. Different forest types typically have different minimum age restrictions based on their life history and typical management practices for the species. Forest stands, one of the HARVEST map inputs, are the focus in applying harvests. HARVEST uses the chosen option to select stands for cutting until the target acreage has been harvested, or until no stands remain that satisfy restrictions.

The dispersed method selects stands independently of each other (that is, randomly) to harvest for the designated forest type(s) that are old enough to harvest within the management area(s). If the harvest target acreage is not met, then the next acceptable stand is selected randomly. The clustered method chooses a focal stand for harvest. Additional harvests are attempted in stands that are neighbors of its neighbors, potentially creating a halo of harvested stands around the focal stand. Of course, nearby stands must satisfy the same HARVEST restrictions as the focal stand. If nearby stands are harvested and the target acreage has not been exceeded, a new focal stand is randomly selected and the process is repeated. “Oldest first” selects from the stands within the management area of the designated forest type that are old enough to harvest in order of decreasing age.

**Stand Cutting Approaches**

Once a stand is selected for harvest, three cutting approaches are available. The first approach, “stand filling,” cuts all of the cells in the stand. The second approach is controlled by mean, standard deviation of harvest size, and maximum/minimum harvest size—these parameters are used to randomly generate a harvest block size from a truncated normal distribution. Harvest blocks are generated around a single pixel chosen randomly within the stand to be harvested. Adjacent pixels are sequentially added to the harvest block by randomly choosing from all adjacent pixels within the stand. If the entire stand is cut before the target block size has been reached, HARVEST will begin cutting in an adjacent stand that also satisfies all restrictions. If no such stand exists, the harvest process is truncated. The final approach, group selection, chooses stands using the dispersed method, and then harvests small openings (groups of pixels or patches) within those stands. The number of openings harvested in a stand during each entry is calculated by HARVEST as a user-specified proportion of the size of the stand. These small harvests are randomly placed within the stand to mimic group selection.

Stands are selected for harvesting if the average stand age is greater than or equal to the minimum harvest age for the forest type. Initially all pixels within a stand are the same age. However, because partial stands can be cut, pixels within a stand can have different ages and average stand age is calculated for the stand weighted by the area in each age. Thus, HARVEST may encounter stands that are old enough to cut, but pixels that are too young. However, HARVEST cannot cut pixels within a stand that are younger than the minimum harvest age—instead, older pixels within the stand are located and harvested.

HARVEST can simulate traditional rotation-based cutting, where stands are cut periodically at some specified interval that mimics a linear programming Model I formulation (Johnson and Scheurman 1977). When the user selects the re-entry feature associated with a dispersion method, HARVEST ensures that re-entries occur automatically for the same stands, using the parameters set during the initial entry. If re-entry is not specified, HARVEST has more flexibility in choosing where future harvests occur—this is similar to the Model II pooling concept in linear programming (Johnson and Scheurman 1977).
Spatial Analyses

HARVEST calculates a number of standard spatial statistics. Alternatively, map files can be imported into different GIS environments and other spatial statistics software can be used for analysis. Standard analyses incorporated in HARVEST include calculation of forest interior and edge habitat, and patch analysis.

Interior and edge habitat are calculated for the forest area based on openings, permanent or temporary due to green up restrictions following harvests, and buffer size around the openings. Area totals are calculated by summing the number of pixels in openings, buffers and interior forests. The buffer size, a multiple of the pixel width, simulates the effects of proximity to the opening (or edge) on plants and animals. Edge effects are the result of microclimatic and ecological differences between two adjacent habitats. These coarse habitat characteristics are calculated for the entire planning area.

Patches can be calculated for the entire planning area or for individual management areas. They can be defined simply by age classes or by a combination of age classes and forest types. For example, patches may be defined for regenerating, young, mid-seral, mature, and late-seral age classes. For more fine-scale patch details, forest type can be added, too.

LINKING SPECTRUM AND HARVEST

HARVEST provides a simple, yet powerful tool for spatial analyses of strategic forest plan alternatives. One of its main drawbacks is that for large problems, manual input for creating the input data used to run HARVEST would be very tedious and prone to error. We have largely addressed this by developing Spec2Harv, a program for converting Spectrum output to HARVEST input (Gustafson and others 2003).

Spec2Harv uses a Spectrum output file that identifies how much harvesting occurs over time by analysis unit. Spectrum models must be designed to correspond with inputs required by HARVEST. Hence, Spectrum analysis units must be linked to management areas, forest types, and forest type ages—these correspond to three HARVEST map inputs.

By using an algorithm that recognizes the pattern of harvests and crosswalk tables that allow the two models to communicate, most inputs are automatically transferred from Spectrum to HARVEST. Several management area and forest type inputs are then completed and a HARVEST script is generated. The script can be edited with a word processor to facilitate sensitivity analysis. For example, “dispersed” and can be changed to “clustered” for the entire script and a new HARVEST simulation can be run.

SPATIAL SENSITIVITY ANALYSIS FOR AN ALTERNATIVE ON THE NICOLET NATIONAL FOREST

Sensitivity analysis is commonly used in linear programming work to analyze the consequences of changing assumptions, constraints, costs, and prices. In fact, linear programming computer software is designed to show the effects of changing certain parameters on the value of the objective function. Sensitivity analysis may be even more important for spatial problems because juxtaposition, proximity and other factors may be crucial to the acceptability of management plans. For example, a feasible aspatial Spectrum solution may call for 1,000 ac (400 ha) to be harvested. However, guidelines may specify that the cuts should be 40 ac (16 ha) in size and not adjacent to other harvests. The latter may not be spatially feasible due to the locations of the proposed cuts; HARVEST can be used to examine the spatial feasibility.

Method

Rather than comparing spatial simulation results for a variety of harvest schedules generated using Spectrum, we analyzed effects of changing assumptions regarding specification of buffer width, what constitutes an opening, and how the cuts are spatially allocated for one forest plan alternative on the Nicolet National Forest. These simulations are intended to illustrate the utility of HARVEST in analyzing different standards and guidelines. For the purposes of this paper, only forest interior and edge habitat were considered over the 10-decade planning horizon.

The base case for comparisons uses the “oldest first” spatial allocation because forest managers indicated this most closely mirrors their management when harvests are involved. Most harvests were based on the following parameters: a truncated normal distribution pattern with a mean harvest size of 25 acres (10 ha), a standard deviation of 15 acres (5.9 ha), a maximum harvest size of 40 acres (16 ha), and a minimum harvest size of one acre (0.4 ha). For a small number of management areas, larger mean harvest sizes were used.

Adjacency restrictions were used in all simulations; that is, stands adjacent to recently harvested areas could not be cut until two decades passed for the green up period. Private lands within the forest boundaries were included in calculations for forest interior and edge habitat. The private lands
were classified based on 1992 Landsat Thematic Mapper (TM) data which has a 98.4 foot (30 m) square resolution. Forested cells on these lands were assumed to have closed canopies for the 10-decade simulation.

HARVEST was used to calculate forest interior and edge habitat at the current time and in decades 5 and 10 for the base case. Three different distances for defining edge effects were used: 98.4, 196.8, and 295.2 feet (30, 60, and 90 m). By examining these analytical results, we derive an understanding of the effect of distance on edge effects and habitat when only permanent and temporary openings are considered. However, other features such as roads and water may also create edge effects, so additional simulations included roads and water as features influencing edge. The cumulative results of these forest features help us understand how habitat effects differ based on how we define buffers.

Most sensitivity analyses conducted in this study were performed by analyzing one Spectrum-HARVEST simulation—one set of multi-period age maps. In those simulations, HARVEST was used to conduct analyses based on changing assumptions on buffer width and forest features. In other cases, such as the no-cut buffers around roads, new Spectrum-HARVEST analyses were required. These analyses were facilitated by using a word processor to edit the HARVEST script file which has all the parameter and data inputs for HARVEST (for example, we changed “Clustered” to “Dispersed”).

HARVEST simulates Spectrum harvest schedules, but does not perfectly match the schedule due to spatial restrictions. So it is important to understand the effect of different spatial parameters in HARVEST on the achievement of Spectrum harvest targets. For purposes of this paper, the sensitivity of spatially allocating Spectrum results is explored by changing the harvest dispersion method and by creating no-cut buffers around roads. The former will provide insights regarding “oldest first,” dispersed, and clustered harvesting, whereas the latter will illustrate the effects of systematically restricting harvests from more and more of the forest.

Results

Edge habitat was defined initially as area bordering temporary and permanent forest openings, and the edge width was varied to examine its effects. Then edge habitat was expanded to include areas around roads, and finally water was also included. There is over a five-fold change in edge habitat when the buffer is expanded to 295.2 feet (90 m) and openings, roads, and water are assumed to create edge when compared to a narrow buffer and openings only (table 1). Moreover after existing openings, roads have a much greater effect on edge than water. Roads were the dominant feature affecting edge (table 2). Edge habitat diminished over time due to the large current, or decade 0, area influenced by recent harvests; relative to the current condition, projected harvests will decline leading to less edge in future decades (fig. 1). And, of course, forest interior increased with the decreases in edge habitat by decade 10.

As noted by Gustafson and Rasmussen (2002), the dispersion method also influences habitat. For this case study, however, dispersion method did not have much influence on area of edge habitat (table 3). “Oldest first” created the least amount of edge, and dispersed and clustered approaches were very similar in total, but distinct in detail. In fact, with the narrow buffer of 295.2 feet (60 m), the dispersed approach created only 1,000 acres (400 ha) more edge habitat than the clustered approach. The clustered approach was designed to concentrate harvests more and thereby decrease overall edge, but the effect on edge does not appear until the buffer width is increased to 590.4 feet (180 m).

Comparisons between dispersion methods are complicated due to the random placement of harvests. Moreover, for the base case, or “oldest first,” approximately 95 percent of the 10-decade, 205,901-acre (83,361 ha) Spectrum harvest target was accomplished by HARVEST. For the dispersed and clustered approaches, 94 percent was achieved. Overall, regardless of forest features, decreased edge habitat is due principally to lower Spectrum-projected harvest levels in decade 10 relative to recent harvests which are reflected in the current conditions (tables 1 and 2).

The preceding results treated creation of forest edge and interior habitat as effects determined by forest features, buffer width, and dispersion method. However, we can also restrict the location of harvesting by creating no-harvest zones around certain features thereby reducing potential harvest area. So another type of sensitivity analysis can examine the effects of changing the size of the no-harvest buffer on habitat. For these comparisons, the base case uses the “oldest first” dispersion method and a buffer definition for assessing habitat based on a 295.2 feet (90 m) buffer around openings, roads, and water; the base case has a no-harvest buffer of 0 feet (0 m).

As the no-harvest buffer around roads expands from 0 to 98.4 to 196.8 to 393.6 feet (0 to 30 to 60 to 120 m), area of edge habitat increases (table 4). In effect, harvests are being pushed away from the extensive road network (which is creating edge habitat) and into the forest interior thereby increasing edge. Total forest area increases as well due to
Table 1—Effects of forest features and buffer width on area of edge habitat for current conditions on the Nicolet National Forest, in thousands of acres.

<table>
<thead>
<tr>
<th>Buffer width (feet)</th>
<th>Forest features</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Openings only</td>
</tr>
<tr>
<td>98.4</td>
<td>47</td>
</tr>
<tr>
<td>196.8</td>
<td>90</td>
</tr>
<tr>
<td>295.2</td>
<td>132</td>
</tr>
</tbody>
</table>

Table 2—Effects of forest features and buffer width on area of edge habitat in decade 10 on the Nicolet National Forest, in thousands of acres.

<table>
<thead>
<tr>
<th>Buffer width (feet)</th>
<th>Forest features</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Openings only</td>
</tr>
<tr>
<td>98.4</td>
<td>23</td>
</tr>
<tr>
<td>196.8</td>
<td>45</td>
</tr>
<tr>
<td>295.2</td>
<td>68</td>
</tr>
</tbody>
</table>

\(^a\) Base case.

Figure 1—Area of edge habitat over time on the Nicolet National Forest based on openings, roads, and water features and buffer width.
lower harvest levels which allow current temporary openings to revert back to forest. As in the other sensitivity analyses, these results are complicated by the relationship between Spectrum and HARVEST. Due to the reduced area available for harvesting, only 92 percent, 90 percent, and 85 percent of the Spectrum target could be achieved by HARVEST for the 98.4, 196.8, and 393.6 feet (30, 60, and 120 m) no-harvest buffer, respectively. As a consequence, the areas of edge habitat created with the 196.8 foot (60 m) and 393.6 foot (90 m) no-harvest buffers were almost identical. This was due to the reduced harvesting in the latter simulation. Hence, no-harvest buffers have a fairly dramatic influence on the ability of HARVEST to satisfy Spectrum targets in this situation because of the extent of the road network.

### DISCUSSION

The application of HARVEST to Spectrum outputs was pioneered by USDA Forest Service personnel at the North Central Research Station and on the Chequamegon-Nicolet National Forest (Leefers and others 2003). Spatial sensitivity analyses in this paper highlight the importance of defining edge in analyses. Edge and forest interior habitat effects are greatly influenced by the definition.

For any given buffer width and features included in defining edge, the total area of forest interior habitat increased over time. This is attributed in large part to initial conditions which have more area of temporary openings than succeeding periods. As the green up period returns recent harvests to forest, new additions increase the area of forest interior more than it is diminished by future harvests.

Considering the effects of edge based solely on permanent and temporary openings provides the smallest amount of edge habitat and largest amount of forest interior habitat. Of course, these amounts vary over time and by buffer width. Smaller buffer widths yield more forest interior habitat and less edge because edge around an opening is based on perimeter length and buffer width. If roads on the Nicolet National Forest create edge, then their influences are much more far reaching than those of openings due to the extensive road system.

Table 3—Effects of dispersion method and buffer width on area of edge habitat in decade 10 on the Nicolet National Forest, in thousands of acres.

<table>
<thead>
<tr>
<th>Buffer Width (feet)</th>
<th>Dispersion method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Oldest first</td>
</tr>
<tr>
<td>295.2</td>
<td>225</td>
</tr>
<tr>
<td>590.4</td>
<td>407</td>
</tr>
</tbody>
</table>

*a* Edge is based on openings, roads, and water features.

*b* Base case.

Table 4—Effects of no-harvest buffer width around roads on area of edge and forest interior habitat in decade 10 on the Nicolet National Forest, in thousands of acres.

<table>
<thead>
<tr>
<th>No-harvest width (feet)</th>
<th>Habitat</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Edge</td>
</tr>
<tr>
<td>0</td>
<td>225</td>
</tr>
<tr>
<td>98.4</td>
<td>246</td>
</tr>
<tr>
<td>196.8</td>
<td>249</td>
</tr>
<tr>
<td>393.6</td>
<td>249</td>
</tr>
</tbody>
</table>

*a* Edge is based on oldest first dispersion method and openings, roads, and water features.

*b* Area of simulated openings varies slightly for each simulation.

*c* Base case.

Though not presented in detail for this paper, specific interactions of HARVEST and Spectrum are generated for each Spectrum analysis unit, identifying where problems in allocating Spectrum harvests occurred. These results may be used to redefine Spectrum constraints, if needed, to better align model results. Managers may be satisfied with allocating 95 percent of the Spectrum target spatially with HARVEST, or they may require more consistency and new Spectrum results. Diagnostic tables are available to facilitate this process.

Currently, HARVEST does not track changes in forest type, but Spectrum does. As a result, both models are needed to address conversion and succession. Modifications to HARVEST may allow us to track forest type changes in future versions.
It is clear that future harvest scheduling models will increasingly be linked to spatial models. The Spectrum-HARVEST approach provides one straightforward alternative. It does, however, require coordinated development of both models so that desired analyses can be completed efficiently.

**LITERATURE CITED**


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MAGIS EXPRESS: SPATIAL MODELING FOR TIMBER AND ACCESS PLANNING

Janet Sullivan, Greg Jones, Judy Troutwine, Kurt Krueger, Hans Zuuring, Bruce Meneghin

ABSTRACT

MAGIS eXpress is a modeling system for spatially-explicit analysis of timber harvest scheduling and access management. GIS (Geographic Information System) layers are imported and used as the basis for formulating harvest and access models. Access issues that can be addressed include new road construction, existing road reconstruction, and road decommissioning. Vegetation growth is based on ‘vegetative pathway’ principles. Data are viewed, scenarios developed, and results analyzed using state-of-the-art ArcGIS map input screens. A MAGIS eXpress solution includes the schedule of harvest activities and associated volumes, present net value, values predicted for individual treatment units, and the predicted vegetation distribution, including standing volume. A sample problem is presented to illustrate MAGIS eXpress uses and features.

INTRODUCTION

Forest managers are increasingly in need of GIS-based planning tools for developing projects that are both economically efficient and environmentally beneficial. Integrated management, from the strategic level down to operational planning, across multiple objectives and over the long-term, is more cost effective than independent planning at various stages (Aspinall and Pearson 2000, Bellamy and others 1999, Hahn and others 2001, Jakeman and Letcher 2003). Projects including timber harvest in particular need to be planned with strategic or tactical consideration of the transportation problem. Software is available to determine optimal rotation times and maximize economic benefit both at the strategic level (Gustafson 1999) and at the tactical level with commercial software packages available (Mowrer 1997), but which does not consider access costs.

Conversely, operational-level planning software is available for supply-chain or traffic flow problems, but which assumes the user already knows which units are to be harvested (Chung and Sessions 2002). If the problems are considered together, a more complete picture of the problem emerges: an in-depth analysis of scheduling alternatives that will improve efficiency and minimized adverse environmental effects, leaving managers less vulnerable to criticism about data and information used to develop projects. With increased pressure on public land managers to provide economic and ecological justification for harvest projects, the use of analytical tools has become critical for efficient planning. Planning tools need to be flexible, fast, easy-to-use, and address the relevant economic issues for efficient planning.

We present here a software application: MAGIS eXpress, which was developed to address this need. MAGIS eXpress is an application for timber harvest scheduling which selects harvest activities on user-defined treatment units, with access and road ‘management’ considerations. MAGIS eXpress is an explicit model of timber harvest and road access issues. It addresses the need for incorporating access issues, including modeling of activities such as road maintenance or road improvement to reduce pollution sources, and temporary closure or permanent decommissioning of roads.
MAGIS eXpress is an offshoot of the more robust ecological modeling tool, MAGIS, which, in addition to timber products, can incorporate non-timber outputs, including wildlife habitat, sediment and water yield, fire risk indexes, and other forest health issues. Economic benefit is the major criteria for selecting harvest schedules and access, but other resource values and environmental effects can be used as constraints.

Optimization is complimentary to other approaches that include simulation modeling, and ‘blackboard’ applications that make it easier to modify and collaborate on project design, with or without simulation (Argent and Grayson 2003). A common theme is the need for spatially explicit information, either within the model or in the solution; MAGIS eXpress incorporates many GIS-related input screens and solution displays.

**Software Description and Features**

MAGIS express is a PC-based, spatially explicit, timber harvest and network access modeling system that allows the user some flexibility in the ways that costs are accounted, and significant flexibility in defining treatment regimes and rules for treatment options. The user creates all the basic definitions, imports GIS data for a specific project area, and runs scenarios that are customized for the specific problem. Because it is spatially explicit, MAGIS eXpress features many map-based interfaces for data entry, scenario definition, and solution display that assist the user in setting up the planning problem in a meaningful manner.

The following seven custom GIS interfaces facilitate validation and import of geospatial databases, user-assignment of planning area feature attribute values and model specifications, assignment of user-selected scenario presets, and viewing of scenario solution values:

- Multiple, task-specific interactive maps.
- Custom task management controls side-by-side with the interactive maps.
- Custom, single- or multiple-feature, filtered selection tools.
- Custom interactive tables and table editing tools for single or multiple records.
- On-the-fly feedback of user decisions, both in map and table displays and status bar displays of attribute values.
- Customizable legends for user-defined categories for nominal or numeric attribute values.

Interface designs are implemented via ESRI ArcGIS ArcObjects as Microsoft Visual Basic standalone ActiveX user controls or ArcMap VBA projects. The standalone ActiveX controls are embedded in and managed by Microsoft Visual FoxPro forms launched by the MAGIS VFP framework.

Users can make decisions about treatment unit and road options using GIS-based queries and selection tools. Solutions are fully displayed using both maps and tables.

**Basic Operating needs**

In its final configuration, MAGIS eXpress will have a dedicated solver incorporating both simulated annealing and heuristic algorithms. Currently, it is functioning with a commercial linear programming and mixed integer programming solver package which is launched from the MAGIS eXpress application.

MAGIS eXpress runs in any PC-based Microsoft operating system. The GIS-based graphical interfaces rely on ArcGIS capabilities and objects; ArcGIS must be installed on the same computer. Any PC computer with the capability to run ArcGIS can run MAGIS.

**Model Parameters**

A MAGIS eXpress model consists of four main components: the planning framework, project area, effects functions, and scenarios. The planning framework is the definitions of the parameters for the model, including activity-costs, timber products, management regime definitions and rules for assignation to individual treatment units as options, and the vegetation pathways. These pathways consist of individual states linked either by succession or by management activities; a stand exists in a given state until it is changed by succession or management action into a new state. Trajectories from state to state are determined by habitat-type group, and length of time in a given state. Selection of management actions can change the projected species components of the state, setting the stand down a different pathway.

The Project Area data model consists of the specific geographic area, represented as two GIS coverages: a polygon coverage and a road network coverage. Each coverage needs to be attributed with specific information determined by the definitions in the planning framework (for example, the vegetation growth model has a set of pathways using definitions of dominant species, size class and density: the polygon coverage vegetation attributes have to match these definitions.). Each treatment unit polygon has one or more management options, in one or more time periods. Each treatment unit with management options has ‘connections’
to the network (loading nodes). As units are selected for harvest, traffic from the harvest is loaded onto the network. If the loading point is on a 'proposed' road, or a road that requires reconstruction before it can carry traffic, the road options for those construction or reconstruction options are selected as well. The model selects the least cost route to the ‘exit’ or final demand node, and keeps track of the total amount of traffic (of each type) by road segment and for each period. Each coverage has specific criteria and attributes it needs to have before being used in a MAGIS model.

The effects functions are the items of interest, defined by the user, that are to be calculated as part of the solution. The types include: 1) harvest quantities, either as a total, or by product, 2) net costs, either total or split out by type, 3) net revenues, also split or lumped as the user sees fit, and 4) area control, which is the acreage of land in user-defined conditions. These include acres of activity (groups), acres by vegetative state characteristic (acres of large or v-large size class, for example), and acres by management schedule. Length control functions report miles of road by activity type (again, user-selected criteria) for example, miles of new construction, or miles of road decommissioning.

To define a scenario, the user selects one of two possible objective functions (maximize PNV or minimize total cost), and sets constraints using any of the defined effects functions. There is no explicit limit on the number of constraints that can be used; any of the cost, revenue, and area control functions can be used. For example, a constraint could be set for a specific number of acres in the entire area to be in the saw size class. This could be used to control the amount of old growth or new growth, as the user requires.

The scenario setup allows the user to create, solve, and save any number of individual scenarios. Each scenario consists of the objective function, constraints, and preselected decision variables. Constraints are limits (upper or lower) placed on other defined effects functions (most effects functions are available for this use). Preselected decision variables are road network or treatment unit options that the user either sets into or excludes from the solution. The user may choose to set any number of constraints and decision variables.

Example Problem: Upper Belt Planning Area

This example problem will be used to schedule two alternatives in addition to the No Action alternative using MAGIS eXpress, based on the idea that a combination of harvest and non-harvest treatments can be used to improve forest health and reduce risk of catastrophic fire.

Goals will be set based on forest vegetation stand-structure classes and economics. Analysis of the No Action simulation indicates the direction of the vegetation pattern without management intervention. If desired, instead of using the MAGIS eXpress vegetation simulation, one could run a No Action simulation using SIMPPLLE (same GIS, same pathways, but with disturbance processes factored in) to determine a more realistic projection of vegetation patterns over time, and use the outcomes of the SIMPPLLE projection to set the vegetation pattern constraints for the MAGIS eXpress scenario.

The Upper Belt Planning area is an actual planning area on the Helena National Forest, in Montana. Timber is mostly lodgepole pine or mixed lodgepole pine and Douglas-fir. The vegetation description in the model includes a simple set of ‘pathways’ (total 109 records), with three species groups; four size classes (Saw, Mix, Pole, and SeedSap); and seven density classes (including the non-stocked category). The planning area is approximately 47000 acres of mostly forested land, within Forest Service administrative boundaries. There is an established road system with two main exit points (north to one mill, south to a different mill). For access, a harvest systems engineer designed an extensive system of proposed roads, to illustrate what could be done if all areas were accessible by road. Activity-costs and harvest specifications for three levels of harvest (a commercial thin, a more aggressive commercial ‘restoration’ thin, and a regeneration harvest) and a flat rate for log prices were entered in the model. Some areas are not considered for harvest because they are too rocky, too steep, or both.

No Action: This scenario is created by maximizing the acres of No Action in period 5 and setting the road cost constraint to zero. The results of the No Action scenario suggest explicit parameters for developing alternatives.
Results: In the No Action scenario, we see that, given successional changes (but no disturbance processes are modeled here) there is a predicted increase overall in large size class, and a decrease in the early successional size classes. If we assume that a mixture of large (saw), pole and seedsap size classes is more desirable, and the ‘mix’ size class is less desirable from a fire risk standpoint, the user would adopt this strategy.

Scenario 1: The objective function is set to minimize costs, and constraints are set on the relative mix of size classes as follows: Large is to comprise 70% of the acres, Seedsap and Pole comprise 15% of the acres each, and Mix is set to 0% of the acres. These specific goals are to be reached by the third decade of the planning horizon.

Results of Scenario 1: Vegetation constraints were met within the time allotted, but with a total projected cost of
62.5 million dollars, with almost 30 miles of new road construction in each of the first two decades. This is not acceptable because the cost is too high and there are too many miles of road construction with negative environmental impacts, so there is a need to limit the miles of new road construction and still achieve (or come close to achieving) the vegetation management goals.

Scenario 2: Minimize costs with the same vegetation constraints, and allow no new road construction.

Results of Scenario 2: Vegetation constraints were not able to be met with the road construction constraint (apparently many stands with the mix size class are inaccessible.) However, some shift towards the ‘ideal’ goal is still possible. Total projected cost is now 3.44 million dollars, with some reconstruction costs. There has been a tradeoff for the ideal vegetation pattern goal, for one with fewer economic (and environmental) costs. One can analyze this new solution and then explore additional modifications by entering new constraints, or, using the vegetation management goals that
are achievable, set up a new scenario that maximizes present net value (rather than minimizing costs) to achieve the same vegetation patterns. There are now many possibilities where predicted outcomes are calculated quickly and consistently, allowing the development of feasible alternatives that are determined by different combinations of objectives and constraints.

CONCLUSIONS

The example problem illustrates how a MAGIS eXpress model can be used to efficiently schedule harvesting and road access with vegetation management goals (not strictly ‘timber production’) and use constraints to modify scenarios to reach management objectives. MAGIS eXpress can assist forest planners and timber sale designers in building feasible, economically efficient alternatives that address forest health, vegetation management, fuels treatment considerations and access problems, including road maintenance, removal, and new road construction.

LITERATURE CITED


ASSESSING LANDSCAPE CONTIGUITY IN RESERVE DESIGN

Alan T. Murray¹, and Xiaolan Wu²

ABSTRACT

Contiguity is a vital property of spatial structure in landscape design, particularly forest and habitat reserve planning. While it is well recognized that contiguity represents the ability to travel from any point within a region to any other point within that region without leaving the region, it is typical that associated landscapes in this context, natural or planned, are not contiguous. As a result, contiguity measurement must account for relative degree of fragmentation in a landscape. This paper proposes a measurement approach for assessing the relative degree of contiguity based on mathematical and spatial theories. Empirical applications of this measure are provided to illustrate the advantages of the approach.

INTRODUCTION

There are many ways in which landscape characteristics are sought to be summarized, particularly in this age where spatial information is readily available through geographic information system (GIS) technologies. Examples include shape, compactness and contiguity in lands being acquired for managed productivity, development or preservation. Often what is of interest is a single measure reflecting a two (or three)-dimensional pattern. Of course driving this need for quantitative measures is the fact that spatial variation in patterns can be observed and visualized using GIS, and as such relative comparison of alternative landscapes is critical in management planning.

In this paper we are interested in examining contiguity and how it has been approached in the context of land use planning. Contiguity is inherently a spatial property indicating whether specific parcels of land are mutually interconnected (Wright and others 1983). The notion of contiguity has been an important consideration in nature reserve design, and land use planning more generally (Nalle and others 2002; Williams 2002).

A number of measures of contiguity have been utilized in the literature, though authors have been quick to recognize they are only proxy approaches. Much of the reason for this is that contiguity has been narrowly defined as a binary concept, where parcels of interest are either mutually interconnected or they are not (Wright and others 1983; William 2002). Such a definition offers little help in characterizing a landscape that is fragmented to some degree.

This paper reviews approaches that have been used to model contiguity in land use planning and nature reserve selection. The spatial implications of existing approaches are detailed. Given the limitations of existing approaches, we develop a spatial measure for quantifying contiguity. Empirical results are presented to illustrate the validity of this measure. Finally, conclusions are provided.

APPROACHES FOR MODELING CONTIGUITY

A range of approaches have been suggested in the literature for addressing contiguity concerns in spatial models. Most can be characterized as implicit approaches designed

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to encourage contiguous configurations of land for a designed use. However, modeling approaches have been explicitly structured to ensure contiguity in developed plans.

One of the first attempts to characterize and model spatial structure in the context of land use planning was the work of Wright and others (1983). It was recognized that “land acquisition has a continuous border or it has not”, reflecting the binary nature of contiguity (Wright and others 1983). To model contiguity, the notion of internal, external and open borders was introduced as a way to track formed edges of acquired land. With this, it is possible to minimize total perimeter of border and thereby promote a contiguous collection of land. When edge/border length is minimized, this most certainly will lead to a contiguous arrangement of land. However, the minimum total edge length for a specified land area occurs when a circle is formed. As such, the use of a border minimizing approach has a spatial bias seeking a circle-like configuration of land. This is actually a compactness approach.

Williams and ReVelle (1998) introduced mathematically the concept of core and buffer in acquired lands in the context of nature reserve design. A core area represents land that is an interior portion of the reserve, while a buffer area is that land on the border (but still in the reserve). The idea here is actually to represent border using buffer lands (as they are by definition on the periphery), which is nothing other than the concept of perimeter discussed previously. Thus, the model developed in Williams and ReVelle (1998) attempts to minimize total cost of acquired parcels such that a specified number of core parcels is selected, but a parcel cannot be counted as core unless it is surrounded by either core or buffer parcels. Thus, boundary buffer parcels must first be acquired before core parcels can result. When parcel costs are equivalent, such a minimization approach is nothing other than the edge/border approach. As such, there is a spatial bias to produce more circle-like arrangements of land as this produces minimum cost.

Also focused on nature reserve design, Nalle and others (2002) proposed a modeling approach that combined contiguity and compactness. What they proposed was an approach that sought to minimize distance between acquired parcels and maximize interior shared edges. The focus on maximizing interior shared edges represents their approach to model contiguity. However, the minimum shared edge length results in a circular shaped configuration of acquired land parcels, which is a spatial bias reflecting compactness rather than contiguity. While contiguity is promoted, it is not explicitly being modeled.

Another line of work can be characterized as imposing contiguity explicitly in the modeling framework. Cova and Church (2000) constrain selected sites to be contiguous using a rooted shortest path approach. The result is in fact one contiguous collection of acquired land parcels. Williams (2002) relaxes the stipulation of only one contiguous collection of land, but ensures that each resultant cluster be constrained to be contiguous. This is achieved by representing the land parcels for potential acquisition as a planar graph. With this, a primal/dual graph approach can be structured to impose contiguity. As such, the approach of Williams (2002) considers fragmented clusters (specified a priori) and imposes contiguity for each cluster.

In summary, existing approaches either use proxy measures to implicitly model contiguity or impose contiguity explicitly. The implicit approaches detailed above do promote contiguity, but they have an unintended spatial bias that produces compact land configurations. This may be problematic in some land use planning situations, as compactness is not equivalent to contiguity. Alternatively, one may want to optimize contiguity rather than strictly enforce it completely as done in Cova and Church (2000) or Williams (2002). The rationale for contiguity optimization is that fragmentation is often an unavoidable outcome, but ensuring the greatest degree of contiguity in acquired lands is desirable.

DEVELOPING A NEW MEASURE OF CONTIGUITY

In structuring a measurement approach for assessing contiguity, there are a number of underlying properties that such a measure should have. First, the measure should be relatively consistent in order to allow comparative assessment of alternative land use patterns for a given region. Second, the measure should be meaningful across various landscapes. Finally, the measure should preserve conceived notions of contiguity, varying in the range (0,1). As such, complete contiguity would be indicated by a value of 1.

The proposed approach utilizes graph theory (see van Langevelde and others 1998) and spatial interaction modeling (see Fotheringham and O’Kelly 1989). Figure 1 depicts the basic representational transformations that we rely upon in the quantification of contiguity. Figure 1a shows a raster representation of a region, where the shaded cells represent land parcels to be acquired. As such, we would like to be able to assess the relative degree of contiguity in this spatial configuration. As a first step, figure 1b shows the associated contiguity graph for our land use pattern, where each node represents a land parcel and an arc indicates a cluster.
of nodes (defined when two parcels form a contiguous cluster). If the graph is disconnected, complete contiguity is not achieved. Using the contiguity graph, we can identify a graph representing connected clusters using a minimum spanning tree of the clusters based upon the underlying grid structure (fig. 1a). This graph is shown in figure 1c. Thus, what results to this point is the observed connectivity (fig. 1b) and a measure of the relationship between independent clusters (fig. 1c). If we observe that complete contiguity of these parcels would result in the graph shown in figure 1d, then an approach to assess relative contiguity may be derived.

Consider the following notation:

\( i, j = \) indices of clusters (entire set denoted \( \Omega \));

\( n_i = \) number of parcels in cluster \( i \);

\( d_{ij} = \) minimum spanning tree distance from cluster \( i \) to cluster \( j \);

\( r = \) distance decay parameter.

With the above notation, a contiguity index is proposed as the following:

\[
C = \frac{\sum n_i (n_i - 1) / 2 + \frac{1}{2} \sum_{i \neq j} n_i n_j (d_{ij})^r}{\sum_{i \in \Omega} n_i (\sum_{i \in \Omega} n_i - 1) / 2}
\]

The numerator reflects intra- and inter-cluster connectivity. The first component of the numerator accounts for the observed number of intra-cluster arcs. The second component of the numerator accounts for potential spatial interaction of pairs of clusters. Notice that the minimum spanning tree distance between two clusters is raised to the power \( r \). This is a standard way of treating distance decay in spatial interaction modeling (see Fotheringham and O’Kelly, 1989). The denominator reflects the graph that would result if the parcels where contiguous.

**EMPIRICAL EVALUATION**

In order to assess the relative merits of this measure of contiguity, we now present a number of empirical examples for comparison. The distance decay parameter utilized here is \( r=2 \). Further, it is assumed that raster cell widths are 5 km. Cell neighbors are those cells sharing a non-zero length common boundary, which excludes diagonals.

Figure 2 depicts a range of spatial configurations of acquired land use parcels. Indicated beneath each configuration is \( C \), the relative contiguity. It is clear that different configurations are more or less contiguous than others, and the proposed measure appears to do an adequate job of reflecting the spatial variation in contiguity.
CONCLUSIONS

This paper has reviewed the concept of contiguity and detailed how contiguity has been approached in land use modeling. A measurement approach for assessing relative contiguity was developed based upon graphic representation of land use parcels and concepts of spatial interaction. Empirical results were presented to illustrate that the proposed approach provided measures that conform to visual expectations of spatial variation. Further research is needed to confirm the degree to which this measure is reliable. In addition, further research is needed to assess capabilities for integrating this measure in a land use planning model.

ACKNOWLEDGEMENTS

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LITERATURE CITED


DESIGNING AN INTEGRATED FOREST PLANNING SYSTEM FOR THE FOREST INDUSTRY: AN APPLICATION IN PORTUGAL

Rui Pedro Ribeiro¹, José G. Borges², Carla M. Pereira³, Pedro M. Sousa³ and João P. Lé⁴

ABSTRACT

Organizations currently face the challenge of managing the integration of very diverse Information Systems (IS) in their Information and Communication Technology (ICT) infrastructure. Ineffective IS architectures may lead to poor planning. An approach to architecture of an Integrated Forest Planning System (IFPS) that can best adapt both to the organizational system and to the strategy of a forest industry is presented. The Zachman framework is used to enterprise architecture planning encompassing business modeling and data, applications and technology architectures. Emphasis is on the definition of an IFPS that can facilitate the insertion, retrieval and update of data, models and technology by the industry organizational system to address the complexity of its forest management decision processes and its planning goals. Results of an application to a major European pulp and paper group are presented. Results suggest that this approach contributed to define an IFPS that may adequately support the vertically integrated forest industry management planning processes and objectives.

KEYWORDS: Forest industry, forest management, information systems, information and communication technology, enterprise architecture planning.

INTRODUCTION

Research on vertically integrated forest industry management planning has traditionally focussed on the development of modeling techniques to address specific business processes (e.g. Barros and Weintraub 1982, Gunn and Rai 1986, Gadow 1989, Burger and Jamnick 1991, Walters 1997, Falcão and Borges 2002, Troncoso and Garrido 2004). For modeling purposes, these business processes have generally been classified into three major groups: strategic or long-term planning, tactical or medium-term planning and operational planning. The forestry literature also reported modeling efforts to address the interrelations and the trade-offs between planning levels (e.g. Hoganson and Rose 1982, Gunn and Rai 1986, Weintraub and Davis 1995). Epstein et al. (1999) and Carlsson and Ronnqvist (in press) further focussed on modelling applications and information systems (IS) used by forest industries to address business processes within their supply chain. Carlsson and Ronnqvist (in press) pointed out that forestry has relatively few advanced IS as compared to other industrial sectors. Moreover, to our knowledge, no study has addressed the definition of an enterprise architecture plan that may provide business models and data, applications and technologies architectures to support effectively the vertically integrated forest industry management planning.

Yet organizational systems bedevilled by redundant, fragmented and inconsistent IS can hardly have an accurate understanding of management problems. An effective data-to-information strategy requires that the improvement of modeling techniques and of corresponding software applications to address specific business processes in a forest industry is framed by an ICT development plan. As Strassmann (1997) pointed out, managing the integration
of diverse IS within an organizational system ICT infrastructure is as important as the investment on new applications and technology. An effective ICT architecture is key for that integration and to good planning. It provides a guide for the structure and place of information within an organization (Davenport e Prusak 1997). It enables the discovery and the elimination of redundancy in the business processes reducing IS complexity (Cook 1996). It becomes the bridge between business and technical domains (Young 2001) thus contributing to the alignment between the forest industry IS and business management strategies.

The approach to architecture of an Integrated Forest Planning System (IFPS) discussed in this paper focuses on the need to integrate business processes such as strategic, tactical and operational planning and on the need to develop an ICT infrastructure to effectively support them. Accordingly, it addresses too forest industry organizational system issues. The Zachman framework is used to enterprise architecture planning encompassing business modeling and data, applications and technology architectures. Emphasis is on the definition of an IFPS that can facilitate the insertion, retrieval and update of data, models and technology by the industry organizational system to address the complexity of its forest management decision processes and its planning goals. After describing the approach, results of an application to a major European pulp and paper group are discussed. Preliminary results suggest that this approach contributed to define an IFPS that may adequately support the vertically integrated forest industry management planning processes and objectives.

**MATERIALS AND METHODS**

**The case study – the Portucel Soporcel Group**

The Portucel Soporcel Group (PSG) is one of the five largest European producers of uncoated woodfree paper (http://www.portucelsoporcel.com/). It has a productive capacity that exceeds 1 x 10^6 tonnes of paper and 1.2 x 10^8 tonnes of pulp and has an annual turnover of 1,000 x 10^6 euros. The PSG is the largest Portuguese forestry owner. It manages 1.5% of the Portugal’s land, 4.1% of the country’s forests and 15.6% of its eucalyptus forest. Because of its characteristics, the *Eucalyptus globulus* Labill is the preferred species for pulp and paper production. This vertically integrated forest industry manages about 138 x 10^3 ha of property, of which the eucalyptus plantations occupy 76%, and it is responsible for a diversity of forestry assets spread over 172 local districts from North to South of Portugal. The PSG also manages forest areas in the Açores and in Argentina (about 400 ha each). The production is carried out at three mills in Portugal (Setúbal, Figueira da Foz and Cacia) with 1950 employees. The most important market for PSG is Europe (http://www.portucelsoporcel.com/).

A typical eucalyptus prescription for raw material supply encompasses a plantation that may leave a number of trees per hectare ranging from 1,000 to about 1,700. A full rotation may include up to 2 or 3 coppice cuts, each cut being followed by a stool thinning that may leave an average number of shoots per stool ranging from 1 to 2. Harvest ages range from 10 to 20. In Portugal, eucalyptus maximum mean annual increment may reach up to 30 m^3/ha/year at the age of 10 years in the first cycle, in the northern coastal region. In other regions, average eucalyptus productivity may decrease to less than 8 m^3/ha/year. Productivity may increase up to 10% in the second cycle and it declines afterwards. Thus, generally, the final harvest occurs at the end of the third cutting cycle after which the site is converted into a new eucalyptus stand.

One of the Group’s priorities is its strategy of integration. This framework prompted the development of a project aiming at the definition of architecture for an Integrated Forest Planning System that might effectively support strategic, tactical and operational planning and project and budget control business processes to manage eucalyptus forests owned or rented by this vertically integrated forest industry. The project was developed in 2002 over a period of 3 months.

**Enterprise architecture of an Integrated Forest Planning System for the Portucel Soporcel Group**

Spewak (1992) defined enterprise architecture (EA) planning as the process of defining architectures for the use of information in support of the business and the plan for implementing those architectures. The concept of EA encompasses a set of basic components (Figure 1) that are present in different EA frameworks (e.g. Zachman 1987, Macaulay 2004): Business Architecture (BA), Information Architecture (IA), Application Architecture (AA) and Technological Architecture (TA). An EA framework guides the architectural process from BA to TA. Specifically, for that purpose the Zachman framework crosses the views of participants involved in the planning, conception, building, using and maintaining activities of an organization’s IS with the data, applications, technology and people components of IS. The reader is referred to Zachman (1987) for a detailed description of this framework.

The human component of information systems is prominent in the EA planning process. The project team involved both consultants from the consortium Link/ Metacortex/ISA...
and actors in PSG involved in forest management planning. For example, all actors in PSG involved in the business participated in the development of the BA. Both the information technology (IT) and the forest resources management departments were permanently involved in the EA planning process. In this project over 60 all-day meetings and workshops took place. The number of persons per meeting ranged from 7 to 10. Some people were present in all meetings (e.g. project manager, forest management planning director, IT director). Some people were present in the meetings when business issues related to their expertise were addressed (e.g. financial area, forest inventory, forest operations).

Business modeling is instrumental for BA, i.e. for the definition of PSG forest planning business strategies, processes, and its functional requirements. It encompassed three main stages. Firstly, the project team (PT) defined the scope of business modeling. It was decided that the IFPS should encompass strategic, tactical and operational planning and project and budget control business processes to manage eucalyptus forests owned or rented by this vertically integrated forest industry. Secondly, the characterization of current business processes involved the analysis of PSG documentation, preliminary meetings and modeling workshops with PSG staff. The workshops further enabled the definition of how PSG wants to carry out forest management planning in the future. Thirdly, the PT inventoried central and departmental IS that support current PSG forest planning processes.

The IA is instrumental for identifying what PSG needs to know to run its forest planning business processes. It described the data’s logical aspects, as well as the management of data resources at a macro level. It encompassed three stages. Firstly, workshops conducted a systematic analysis of the future IFPS business processes to identify both the information entities needed to support them and the PSG information systems where these entities are managed. Secondly, entity-relationship (E-R) diagrams were drawn to illustrate IA views from the perspective of IFPS business processes. Finally, each entity was characterized by its relevant attributes and an IFPS data dictionary was organized.

The AA is instrumental for identifying the applications needed to manage information entities in order to fulfill business processes requirements. It encompassed four stages. Firstly, workshops conducted a systematic analysis of the future IFPS business processes to identify the entities manipulated by each activity. Secondly, cluster analysis of the resulting CRUD matrices (Figure 2) grouped business activities according to information entities they manipulate. Thirdly, workshops used both the business processes knowledge base and the results of cluster analysis to define the applications that might support each process, the way they should interface with each other and to identify main data repositories needed. Finally, each application was described in detail.

The TA is instrumental for providing information about the technical foundation to support the BA, IA and AA. It was conducted according to some general principles (e.g. the priority of business needs; the importance of re-using current PSG technology, of the geographical information systems support, of the modular concept, of using hardware and software open standards whenever possible, of using ergonomic and intelligent human/machine interfaces, of using 3-tier application architecture and of introducing security mechanisms). TA selected and inventoried relevant technological areas (e.g. network infrastructure, servers and workstations, management information systems, decision systems, helpdesk) and recommended technological solutions to support the IFPS. The EA process ended with the definition of an implementation/migration plan.

RESULTS

The BA provided a knowledge base about current forest planning at PSG (Figure 3). It encompasses two loosely tied business processes: strategic and operational planning. The former is based on a simulation procedure that does not support systematic scenario generation and analysis. The latter involves two stages that are managed by the GPS central planning department and by its regional divisions, respectively (Figure 3). The lack of integration between these business processes prompted the definition of how the PSG organizational system wants to manage its eucalyptus area in the future (Figures 4 and 5). It was decided
Figure 2—Fragment of a CRUD matrix to identify and cluster business processes activities according to the way they manipulate information entities (C – create, R – read, U – update, D – delete).

<table>
<thead>
<tr>
<th>Activity (A) vs Entity (E)</th>
<th>CRUD</th>
<th>CRUD</th>
<th>CRUD</th>
<th>CRUD</th>
<th>CRUD</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1 -Aggregate strategic information</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A2 -Aggregate strategic constraints</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A3 -Strategic planning</td>
<td>R</td>
<td>P</td>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A4 -Strategic simulation validation</td>
<td>R</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A5 -Strategic simulation analysis</td>
<td>R</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A6 -Analysis strategic information</td>
<td>R</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A7 -Organize strategic scenarios</td>
<td>R</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A8 -Aggregate tactical information</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A9 -Organize tactical constraints</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A10 -Organize tactical constraints</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A11 -Tactical planning</td>
<td>R</td>
<td>R</td>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A12 -Tactical simulation validation</td>
<td>R</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A13 -Tactical simulation analysis</td>
<td>R</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A14 -Analyze tactical information</td>
<td>R</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A15 -Organize tactical scenarios</td>
<td>R</td>
<td></td>
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</tr>
</tbody>
</table>

Figure 3—Current business processes. The symbol D identifies an information source. The symbol A identifies a business process activity.
Figure 4—Fragment of future business model detailing strategic, tactical and operational planning. The symbol D identifies an information source. The symbol A identifies a business process activity.

Figure 5—Fragment of future business model detailing work and budget monitoring. The symbol D identifies an information source. The symbol A identifies a business process activity.
that the future model should integrate and align all business processes. Strategic or long-term planning will provide the framework for all other business processes (Figure 4). It will produce a 30/36 year-plan that complies with PSF financial, self-supply and eucalyptus area expansion objectives. Tactical planning will produce a 3-year plan to comply with both long-term and other spatially detailed objectives. Strategic and tactical plans will be compared within the IFPS to check whether tactical objectives constrain substantially long-term objectives (Figure 5). If that is the case, the planning process will be restarted and a new long-term scenario will be generated. If not, the first year of the tactical plan will be used as input to operational planning (Figure 4). PSG regional divisions will validate the proposed operational plan. If not, the operational plan will be accepted and will provide the basis for the forest planning budgeting. The budget approval will determine the final acceptance of strategic, tactical and operational plans. Both work and budget monitoring will enable checking if proposed plans are being executed (Figure 5). If not, the overall planning process may be revised.

The results of IA included documentation identifying the informational entities needed to support the IFPS business processes and their relationships and an IFPS data dictionary. The results of AA included documentation defining the IS within the IFPS, the way they interface with each other and with other PSG systems. At a macro level, applications to include in the IFPS were strategic, tactical and operational decision systems, project and budget monitoring systems, silviculture and growth and yield model-base management systems and a planning control system. The latter coordinates the overall IFPS functionality. The results of the AA further included the detailed description of the modular structure of each IS. For example, the structure of the strategic planning application encompasses a module to extract the data needed for strategic planning that is stored in IS outside the IFPS, a module to generate strategic scenarios formulations and to search their optimal solutions and a module to compare and analyze solutions from each scenario (Figure 6).

The recommendations of TA to support the IFPS included technological solutions to each relevant technological area. The implementation/migration plan identified the impact

Figure 6—Description of the modular structure of the strategic planning application and of its interfaces with other IFPS applications.
of the IFPS on current IS in the organization. It presented business-oriented and technical-oriented implementation sequences. The former took into account on-going organizational system changes. It further listed expected benefits of the development of the IFPS and its critical success factors.

In summary, the EA process was crucial to an accurate understanding of how this vertically integrated forest industry works, enabling business changes. They further provided information needed to align business and IS management strategies.

SUMMARY

This paper presented results from a project to define an Integrated Forest Planning System for a vertically integrated forest industry. The focus was on the development of an approach to architecture of an IFPS that might best adapt both to the organizational system and to the strategy of a major European forest industry group. This approach encompassed the application of an Enterprise Architecture Planning methodology to evolve an effective forest industry data-to-information strategy. Business modeling and data, applications and technological architectures were deemed critical to a sustained and successful development and use of the IFPS. Rather than developing applications to address the needs of individual business processes in a fragmented way, the proposed approach emphasizes the need to frame this development by an overarching organizational ICT plan.

Results from an application of this approach to Portucel Soporcel Group, a vertically integrated forest industry that manages over $1 \times 10^5$ ha of eucalyptus forests in Portugal, suggest that it contributed to define an IFPS that may adequately support its management planning processes and objectives. Actually, the implementation/migration plan of this architecture project was accepted by PSG. At this moment implementation has already completed the development of the strategic and tactical planning applications. An interesting extension to this IFPS architecture is the architecture of the whole forest industry supply chain.

ACKNOWLEDGMENTS

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LITERATURE CITED


ESTIMATION OF FOREST PARAMETERS BY USING REMOTE SENSING SINGLE-TREE DETECTION AND FIELD PLOTS WITH TREE POSITIONS

Kenneth Olofsson¹, Jonas Bohlin², Tomas Lämås³ and Håkan Olsson⁴

ABSTRACT

Template matching, originally developed in Canada by Richard Pollock, is a method for single tree detection in high resolution (pixel size 0.3 m – 1 m) aerial digital imagery. The method was tested for Scandinavian conditions and further developed. It is a potential method to be included in a concept for estimating forest parameters from aerial imagery, such as stem number, stem volume, and tree biomass. Template matching gives estimates of position, crown diameter and crown shape for most trees in a stand. The concept proposed in this article includes a quick field method for measuring tree positions on field plots, which currently is under development at SLU. Another vital part is a method for rendering templates of whole field plots (with radius about 10 m), whereby the field plots can be exactly located in the aerial image. Then the vector of field-surveyed forest parameters can be related to the vector of image derived features for the same plot. If the image is divided into a grid, with approximately the same area as the field plots, the relations between image derived tree features and field plot data could be used for estimating forest variables for all grid cells, or as correlated information in a sampling scheme. In addition, maps of all trees visible from above can be created.

KEYWORDS: Forest inventory, image processing, template matching.

INTRODUCTION

The forest ecosystem is providing a wide set of goods and services such as timber, forest fuel and recreation opportunities. Other objectives concerning forest functions are, for example, the role of forests as a carbon sink, maintained biodiversity, and fire hazard reduction. Forest management is thereby a complex and intricate task. To provide decision makers with appropriate information on the outcome of different management options, complex decision support systems are being developed; see for example CLAMS (http://www.fsl.orst.edu/clams; Ohmann and Gregory 2002; Spies and others 2002) and Heureka (http://heureka.slu.se; Lämås and Eriksson 2003). In such systems, models forecasting the forest ecosystem state and models predicting the outcome of different goods and services are integrated.

Quite naturally, the tree cover forms the base for timber production but also for forest biodiversity, recreation, and other phenomena. Consequently, the models describing the tree cover and its development make up the core in forest decision support systems. Detailed information of the initial state of the tree cover is thereby crucial not only for timber production but also for forest management in a wider setting.

The objective of the Heureka Research Program is to build computerized decision support systems for multi-purpose forestry. The models included depend on accurate and large quantities of forest data. Therefore, development of efficient data acquisition methods (Lämås and Eriksson 2003) is a vital part of the research program. The present study is a part of that effort.
Most digital automated remote sensing methods have been developed for satellite remote sensing imagery with pixel sizes in the order of 10x10 m up to 30x30 m, for example Landsat TM. Such imagery is created by averaging reflectances from sunlit canopy and ground, and shadowed canopy and ground, for several trees per pixel. In addition, relative to airborne sensors, the view angle differences within the imagery are small because of the altitude of the satellite sensor. These factors makes “Landsat-type-imagery” a relative simple case for computer based analysis, where pixel values are used in combination with field plot data. However, the information content in reflectance mean values from a group of trees is limited, and it is for example difficult to tell if it is differences in tree size or in stem numbers that makes one pixel darker than another.

Air photos do potentially contain more information than satellite imagery. They are also often used as a visual background in GIS systems and are therefore often already available at forest companies, without any extra costs. Automated analysis of aerial photos is however a complicated task, with a “many pixels per tree” viewing situation, and large variations in view angle within the imagery. Kleman (1987).

There are several approaches for detecting single trees in digital aerial photos, such as segmentation (Gougeon, 1999; Erikson 2001), finding local maxima (Dralle 1997; Rudemo 1999), edge detection techniques (Brandtberg and Walter 1999) or template matching (Larsen 1999; Pollock 1996). The template matching approach was pioneered by Richard James Pollock (1996), University of British Columbia, and compared to several other methods; it has the advantage that view angle differences are handled in an integrated way.

Here, we present a framework for estimation of forest information, based on the template matching approach. The framework is based on (i) sample plot survey (ground truth), (ii) detection of single trees in digital aerial ortho-photos, and (iii) estimation of forest parameters for all trees, such as stem number and stem volume. That is, the estimations include also non-detected trees. A case study concerning the second step of this approach is presented. The template matching method is applied on four stands in a conifer dominated forest in southern Sweden. It is shown that most of the dominating trees can be detected using this method.

**A FRAMEWORK FOR ESTIMATION OF FOREST INFORMATION USING SINGLE TREE DETECTION**

For estimation of forest variables on stand level or larger areas, using single tree detection we propose the following framework. The primary forest variables to be assessed, such as stem height, stem diameter, age, and species, are measured on sample plots in the field. The plot centers are determined with an accuracy of a few meters, using GPS. Using the true field measured tree positions in a local coordinate system, the estimated visual appearance of the field plot in the digital image is rendered (fig. 1). The rendered plot template is matched against the digital image, to obtain the likely global position of the field plot in the image data. If this procedure is to be applied in practice there is a need for an instrument for quick field measurement of tree positions (in a local coordinate system) on sample plots. The Dept of Forest Resource Management and Geomatics at SLU are developing a system for such field measurements on circular plots with a maximum radius of approximately 10 m.

Single-tree detection is performed for the image data over the whole forest area to be assessed, such as a stand or a real estate. The image is analyzed as grid cells, for example of size 20 x 20 m. Based on the relative position, size and shape of the detected trees in a grid cell, a number of image derived features are computed. For the grid cells where sample plot field data is present, the image derived features are paired with the field measured forest data. This paired information could be extrapolated to all the image derived grid cells in a number of ways, for example, imputation using the kNN method (a non parametric imputation method much used for forestry satellite remote sensing Tomppo 1993), or estimation by regression or neural networks. The paired information could also be used in a sampling scheme, for example for post stratification of the field.
sample. According to the framework outlined, it is possible to obtain estimated parameters for all trees, such as stem number and stem volume. That is, these include trees that are not visible from above. In addition, the single tree detection method also provides the basis for drawing tree maps and 3D-visualizations of all trees that are visible from above.

Below a case study is presented in which the template matching method is applied to detect single trees on four stands in a conifer dominated forest in southern Sweden. Estimation of totals for all trees (including non-detected trees) using the approach outlined above will be presented in forthcoming studies.

CASE STUDY

Materials and Methods

The forest areas in the experiment are two pine stands, labeled P1 and P2, and two spruce stands, labeled S1 and S2, located at the Remningstorp estate in the south west of Sweden (lat. 58° 30' N, long. 13° 40’ E), table 1, table 2 and figure 2.

Field Survey—The field survey was carried out in November 2000. Stem diameters of all trees (≥ 0.05 m stem diameter at 1.3 m above ground) within the areas were measured and the tree species were registered. The position of the centre of these tree stems was measured (1.3 m above ground) relative to two reference points in the nearest open area using a theodolite/EDM total station (SOKKISHA SET 4). The positions of the reference points were measured using kinematic GPS equipment. According to the specifications for the GPS equipment, accuracies of 5 to 10 cm were possible to achieve.

Aerial images—The aerial photos were acquired 25 September 2001 around 12:00. The flight height was 600 m. The camera used was a Hasselblad SWCE 61085, lens Biogon 38 mm f/4.5, with a digital back. The images received were True color (24 bit, tiff) RGB files, see table

### Table 1—The rectified aerial images used in the study and corresponding field stands.

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Image 143</td>
<td>S2</td>
<td>3073</td>
<td>4149</td>
<td>0.147</td>
<td>29.19</td>
<td>18.40</td>
<td>11:53</td>
</tr>
<tr>
<td>Image 160</td>
<td>P1 and S1</td>
<td>3073</td>
<td>4054</td>
<td>0.154</td>
<td>29.67</td>
<td>14.71</td>
<td>12:06</td>
</tr>
<tr>
<td>Image 175</td>
<td>P2</td>
<td>3073</td>
<td>4375</td>
<td>0.136</td>
<td>29.77</td>
<td>13.85</td>
<td>12:09</td>
</tr>
</tbody>
</table>

### Table 2—The relative positioning of the stands compared to the aerial images center. The X-axis is pointing to the east and the Y-axis is pointing to the north.

<table>
<thead>
<tr>
<th>Stand</th>
<th>X [m]</th>
<th>Y [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>-10.0</td>
<td>131.9</td>
</tr>
<tr>
<td>P2</td>
<td>-21.4</td>
<td>59.0</td>
</tr>
<tr>
<td>S1</td>
<td>-10.2</td>
<td>30.9</td>
</tr>
<tr>
<td>S2</td>
<td>-120.2</td>
<td>-22.3</td>
</tr>
</tbody>
</table>
1 and figure 2. The images were rectified to a geo-referenced system RT90, using objects in the photo with known coordinates.

**Evaluation key**—Visible tree crowns in the aerial images were for validation purpose delineated manually using the positions from the field survey. Small hidden and shaded trees were not digitized. Polygons of the test areas were chosen so that no visible trees outside the test areas would interfere with the evaluation.

**Template Matching**—Template matching is an image processing technique where a library of 3-dimensional model trees are cross correlated against any potential tree position in the digital image (Pollock 1996). The tree positions and tree templates with the highest correlations are considered as likely trees. A three dimensional model accounts for the viewing angle and the sun angle variations of aerial images. The library trees are rendered with a different view depending on where in the image the cross correlation is performed. This makes it possible to detect trees in images where the viewing angle difference from the nadir to the image edge is large. The library trees are generated from generalized ellipsoids of revolution:

\[
\frac{z^n}{a^n} + \frac{(x^2 + y^2)^{n/2}}{b^n} = 1
\] (1)

where \(x\), \(y\) and \(z\) are the coordinates describing the surface and \(a\), \(b\) and \(n\) are the height, radius and shape parameters of the ellipsoid. By changing the parameter \(n\) in equation 1 it is possible to create trees with different crown shapes. The shape is conical if \(n = 1\), corresponding to spruces, and elliptical with \(n = 2\), corresponding more to pine trees. When \(n = \infty\) the shape is cylindrical. The parameters \(a\) and \(b\) influences the height and radius of the ellipsoid. Figure 3 shows ellipsoids with different parameters and viewing angles.

By matching each template with the aerial image using the correlation coefficient (Gonzalez and Wintz 1987), a correlation map is produced. The local maxima in this correlation image correspond to a possible tree. If the correlation coefficients of these possible trees are above a chosen threshold the item is considered to be a hit. If two or more hits are close to each other the templates will cover each other. To remove multiple hits that possibly originate from the same tree the amount of coverage is measured, as suggested by Olofsson (2002), and compared to the first and the second template area. If the coverage ratio is larger than 70 % for at least one of the templates the trees are considered to be candidates to the same position (fig. 4).

All templates that are candidates to the same position are added to a list. Only one of the template members of this list is selected by the program. The program chooses the member with the largest correlation as the selected hit. When all multiple tree hits are removed, the template matching estimate of the tree positions and crown sizes and shapes in the aerial image remain. Pixel coordinates are transformed to a geo-referenced system.

The sunlit part of the canopy was delineated for the trees in the evaluation key. To compare the template matching hits with the evaluation key the sunlit part of the templates were therefore transformed into polygons (fig. 5). Two images are shown in figure 6, one with a near nadir viewing angle and the other with an oblique view. The template hits are shown as polygons in the aerial images.

Before the evaluation, the template matching system was trained on aerial images near the evaluation areas. The
Table 3—Tree library used by the template matching method in the evaluation.
Crown shape, radius and height correspond to parameters, $n$, $b$, and $a$ in equation 1. The crown elevation is the height from the ground to the base of the generalized ellipsoid.

<table>
<thead>
<tr>
<th>Name</th>
<th>Crown shape, $n$ [1]</th>
<th>Crown radius, $b$ [m]</th>
<th>Crown height, $a$ [m]</th>
<th>Crown elevation [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tree1</td>
<td>1.3</td>
<td>1.5</td>
<td>10.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Tree2</td>
<td>1.3</td>
<td>2.5</td>
<td>10.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Tree3</td>
<td>2</td>
<td>1.5</td>
<td>10.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Tree4</td>
<td>2</td>
<td>2.5</td>
<td>10.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Tree5</td>
<td>5</td>
<td>1.5</td>
<td>10.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Tree6</td>
<td>5</td>
<td>2.5</td>
<td>10.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Tree7</td>
<td>2</td>
<td>3.5</td>
<td>10.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Tree library with the best results from the training was chosen to be used in the template matching of the evaluation stands (Table 3). When evaluating the method the template polygons with more than 50% of its area inside the stand polygon was used in the evaluation. If one of these template polygons covered a visible-tree polygon, it was considered to be a hit. If one template was connected to several visible-tree polygons the one with the largest cover area was chosen, thus giving only one tree connection for each template. After this the tree polygons were searched for multiple template connections. If there were several templates for each tree the one with the largest cover area was chosen. This way there was only one template connection for each tree. These hits were considered to be true. All others were considered as false trees.

**RESULTS**

The results of the case study are shown in figure 7 and 8 and in Table 4. Around two thirds of the trees were detected. The optical method used detects most of the visible trees, around four fifths. As seen in Table 4, the amount of hidden trees are \((202 - 164)/202 \approx 19\%\) for all stands. Area P2 with the largest number of hidden trees have an amount of

### Table 4—The template matching results for the test areas, on average 79.3% of the visible trees were found

<table>
<thead>
<tr>
<th>Plot</th>
<th>Ground survey</th>
<th>Template matching results</th>
<th>Results in percentage of visible trees</th>
<th>Results in percentage of all trees</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Visible trees</td>
<td>All trees</td>
<td>Found visible trees</td>
<td>False hits</td>
</tr>
<tr>
<td>P1</td>
<td>26</td>
<td>28</td>
<td>26</td>
<td>7</td>
</tr>
<tr>
<td>P2</td>
<td>44</td>
<td>64</td>
<td>32</td>
<td>5</td>
</tr>
<tr>
<td>S1</td>
<td>36</td>
<td>48</td>
<td>23</td>
<td>9</td>
</tr>
<tr>
<td>S2</td>
<td>58</td>
<td>62</td>
<td>49</td>
<td>9</td>
</tr>
<tr>
<td>All plots</td>
<td>164</td>
<td>202</td>
<td>130</td>
<td>30</td>
</tr>
</tbody>
</table>

Figure 8—Template matching results for the spruce stands. Left stand S1. Right stand S2. Test area delineation as a thin white lined polygon. Evaluation trees as thick white lined polygons. Template matching trees as thin white lined polygons.
These trees cannot be detected by an optical method and have to be estimated in another way. That is, a method to estimate forest stand parameters needs additional ground truth information to increase the accuracy.

**DISCUSSION**

As the case study shows, the single tree detection software detects most of the visible trees in the spruce and pine stands in southern Sweden. It also shows that on average 20% or a maximum of 30% of the trees might be hidden or shaded. These trees cannot be detected by an optical method and have to be estimated in another way. Moreover, many primary forest variables, such as stem diameter, can never be assessed directly in image data only. The most immediate gains with the suggested method is that the estimates of parameters such as stem number and stem volume can be derived for all trees in the stand, in addition to tree maps for the dominating trees.

**ACKNOWLEDGEMENTS**

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**LITERATURE CITED**


