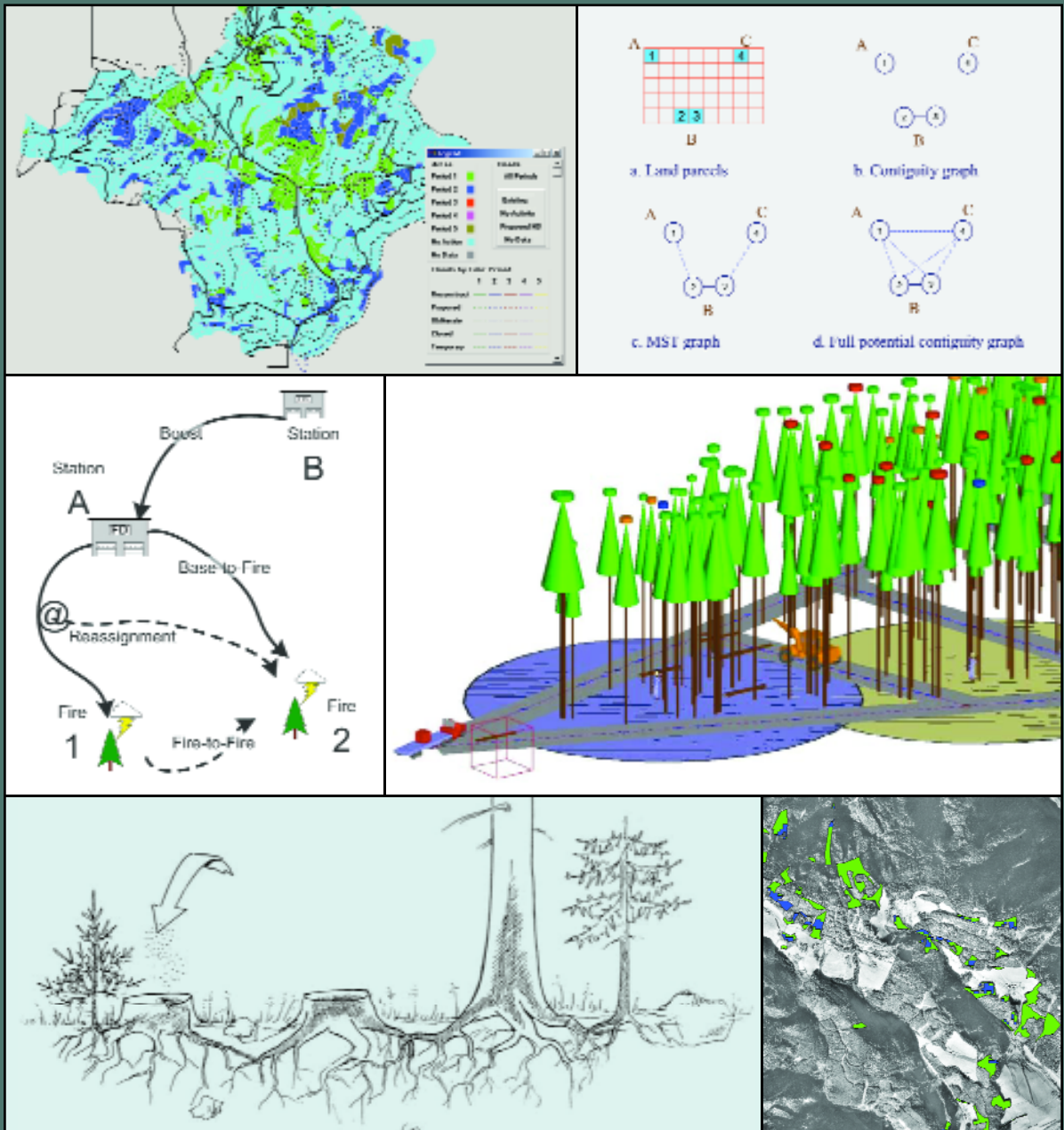




Systems Analysis in Forest Resources: Proceedings of the 2003 Symposium



COMPILED BY

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**Systems Analysis in
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Compiled by
Michael Bevers and
Tara M. Barrett

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ABSTRACT

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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 Rönqvist, 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 Rönqvist, 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

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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

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

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SUSTAINABLE FOREST MANAGEMENT: CONTROL, ADAPTIVE MANAGEMENT, HIERARCHICAL PLANNING

Eldon A. Gunn¹

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

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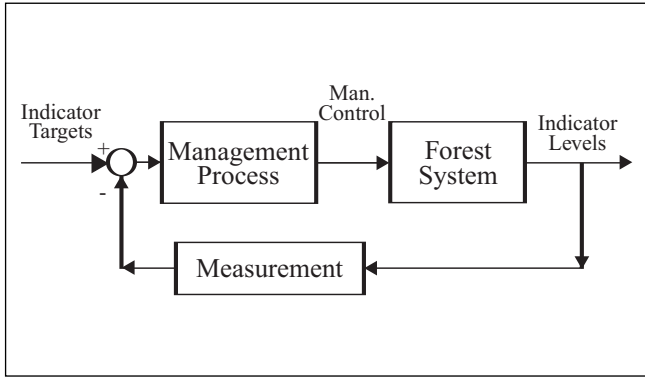


Figure 1—The Automatic Control (“Thermostat”) View of SFM.

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

Table 1—Number of criteria, elements and indicators

Criteria	Main elements	Indicators
1 – Biodiversity	3	8
2 – Ecosystem Health and Productivity	3	12
3 – Soil and Water	2	8
4 – Global Cycles	5	20
5 – Multiple Benefits	4	16
6 – Accepting Society’s Responsibility	5	19
Total	22	83

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:

$$\frac{d\mathbf{x}(t)}{dt} = A\mathbf{x}(t) + B\mathbf{u}(t) + C \quad \mathbf{x}(t) \in R^n, \mathbf{u}(t) \in R^m,$$

where $\mathbf{x}(t)$ is the state of the system and $\mathbf{u}(t)$ 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 ($\frac{d\mathbf{x}(t)}{dt} = \mathbf{v}(t)$). The control system designer attempts to find a matrix \mathbf{G} that gives a feedback control $\mathbf{u}(t) = \mathbf{G}(\bar{\mathbf{x}} - \bar{\mathbf{x}}(t))$ in tracking a target input $\bar{\mathbf{x}}$.

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

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 \mathbf{G} are not chosen properly, then a small perturbation in the system state away from the desired $\bar{\mathbf{x}}$ can result in large oscillations in system response. For a given control matrix \mathbf{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 $\bar{\mathbf{x}}$, and that this equilibrium is stable. The design problem is to try to find a \mathbf{G} that causes the system to have a stable equilibrium at $\bar{\mathbf{x}}$ 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 time 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 \mathbf{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 $\bar{\mathbf{x}}$ (or at least a target trajectory $\bar{\mathbf{x}}(t)$) and a fixed gain matrix \mathbf{G} . As discussed, it is unclear how one might set an $\bar{\mathbf{x}}(t)$. It is also hard to imagine public processes that can resist fiddling with the $\bar{\mathbf{x}}(t)$ and \mathbf{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 $J_t(\mathbf{x})$, the optimal expected return of the system over the future (possibly infinite) given that the system is in state \mathbf{x} at the present time t . $J_t(\mathbf{x})$ is referred to as the cost-to-go function in dynamic programming. The fundamental equation is :

$$J_t(\mathbf{x}_t) = \text{Max}_{u \in U(\mathbf{x})} \{ E_{\xi} [g_t(\mathbf{x}_t, u, \xi) + J_{t+1}(\mathbf{x}_{t+1}(\mathbf{x}_t, u, \xi))] \}$$

where $u \in U_t(\mathbf{x}_t)$ is the set of allowable control actions in state \mathbf{x}_t , ξ is the random realization, $g_t(\mathbf{x}_t, u, \xi)$ is the reward and $\mathbf{x}_{t+1}(\mathbf{x}_t, u, \xi)$ is the state that results from action u this period. Fundamental to dynamic programming is the notion of tradeoff of expected present returns $E[g_t(\mathbf{x}_t, u, \xi)]$

versus expected future returns $E[J_t(\mathbf{x}_{t+1}(u, \xi))]$. 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 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

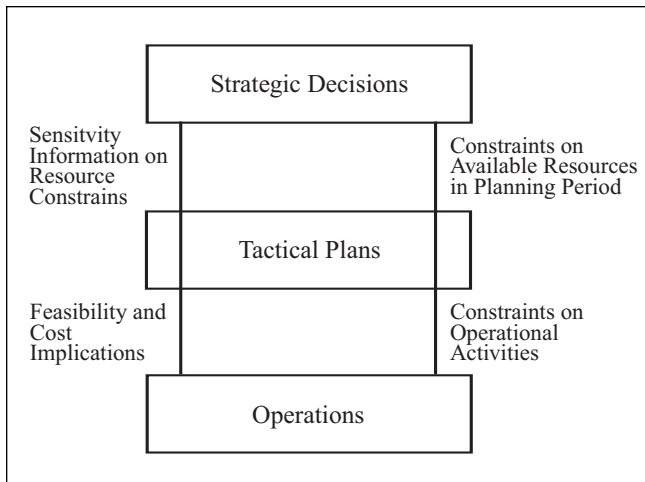


Figure 2—Feedback process of Decision Hierarchy.

Table 2—Characteristics of hierarchical processes

	Strategic analysis	Tactical planning	Operational control
Objective	Resource Acquisition	Resource Use	Execution
Time Horizon	Long	Middle	Short
Management	Top	Middle	Low
Scope	Broad	Medium	Narrow
Information	External/internal	External/internal	Internal
Level of Detail	Highly Aggregated	Mod. Aggregated	Very detailed
Uncertainty	High	Moderate	Low
Risk	High	Moderate	Low

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

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.

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

Ralph J. Alig¹

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

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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 countries. 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, ecological, and economic aspects, testing linkages among modeling components is critical. Sensitivity analyses can reveal critical linkages and information gaps and need for feedback 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 modules 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 plantations 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 respective regions might change in the future. For example, public 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 assessment, 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 activities 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

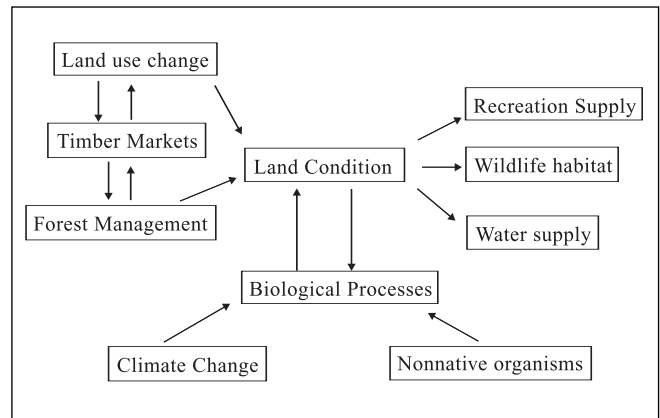


Figure 1—Schematic depicting conceptual framework for land condition projection system.

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 represents 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, modelers 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 information needs. An example of a possible case study in the

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

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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

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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).

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 $x = [x_1, x_2, \dots, x_k]^T$ be the vector of quantitative parameter values for a stand, where each $x_j, j = 1, 2, \dots, k$, 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 $x_i, i = 1, 2, \dots, N$. 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 α – 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

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

where $c \in [0, \max f(x)]$ 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 $y \notin T_{1-p}$, 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_{crit} from the central value x^c for a specified $(1 - p) \times 100\%$ acceptance level needs to be determined.

The critical distance d_{crit} , then, determines whether a parameter vector y is indistinguishable from the distance based target $T_{1-p}^d = \{d \mid \Pr(d, d_{crit}) = 1 - p\}$. The superscript 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, $d_y < d_{crit}$, 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 $X = \{x_1, x_2, \dots, x_M\}$ represent a set of parameter vectors $x_i = [x_{i1}, x_{i2}, \dots, x_{ik}]^T$ 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 $Y = \{y_1, y_2, \dots, y_N\}$ represent a set of N observed parameter vectors $y_j = \{y_{j1}, y_{j2}, \dots, y_{jk}\}$ 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

$$d(x, x^c) = (x - x^c)^T S_{x^c}^{-1} (x - x^c),$$

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

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

for $i, j = 1, 2, \dots, k$ 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_{x^c} 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,

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

was computed, and $d_{\text{crit}} = x_{(i_{\text{crit}})}^d$, where $\lfloor x \rfloor$ is the floor function, returning the largest integer less than or equal to x , and $x_{(i)}^d$ denotes the i th order statistic, $x_{(1)}^d \leq x_{(2)}^d \leq \dots \leq x_{(M)}^d$, 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 $y_j^d < d_{\text{crit}}$, 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; Ehler 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 area 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 $s = 1, 2, 3$, or 4 be the assessment scenario number, define $A^s = \{a_1, a_2, \dots, a_N\}$ to be a set of N available parameter vectors a_i from a sample of mature riparian forest stands. Identify a subset A_{target}^s of A^s , $A_{\text{target}}^s \subset A^s$, containing M of the available parameter vectors as the target data set for each assessment scenario. The sets $X = A_{\text{target}}^s$ 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 $(N_{\text{accept}}^s / N) \times 100\%$, where N_{accept}^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,

Table 1—Parameter vector descriptions for the four target definition and assessment scenarios.

Scenario (s)	Parameter vector dimension (k)	Parameter(s)
1	1	BA
2	1	CBA
3	2	TPA, QMD
4	3	TPA, QMD, H

and contain forest inventory data collected from all ownerships 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 analysis 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 established 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 parameters (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 motivated 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 contained 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 subplots distributed over an area of approximately 6.67 acres. Using the subplots directly for an analysis seemed reasonable and this is what was done. In doing so a subplot to plot scale factor of five was used when computing area-based values from the subplot data. Using the subplot data

directly simply increases the observed variability in computed 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 interest were computed using standard formulas and relationships. 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 $A^{s_{target}}$, 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 observation 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 percentages for the four assessment scenarios and the four acceptance levels are presented in table 4. A strong correspondence between the acceptance level and the computed acceptance percentages clearly exists. The acceptance percentages decrease as the acceptance levels decrease in all cases for all of the target definition and assessment scenarios. 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 2—Stand summary for the 127 riparian subplots defining the observation data sets in the four assessment scenarios.

Variable	Mean	Std. Dev.	Minimum	Median	Maximum
BA (ft ² ac ⁻¹)	252.1	121.1	30.5	241.5	673.8
CBA (ft ² ac ⁻¹)	215.1	136.6	0.0	201.2	673.8
H (ft)	97.6	32.5	33.1	99.5	191.2
QMD (in)	19.9	8.9	6.0	17.8	62.3
TPA	180.5	170.1	10.6	135.0	1095.6

Table 3—Stand summary for the 42 riparian subplots defining the target data sets in the four assessment scenarios.

Variable	Mean	Std. Dev.	Minimum	Median	Maximum
BA (ft ² ac ⁻¹)	247.7	107.8	30.5	239.9	507.6
CBA (ft ² ac ⁻¹)	206.9	126.6	0.0	187.8	507.6
H (ft)	99.1	33.0	33.1	96.7	162.3
QMD (in)	18.7	6.9	7.7	16.8	37.2
TPA	190.0	166.6	10.6	141.1	753.5

Table 4—Acceptance percentages (relative acceptance percentages) for the four target definition and assessment scenarios.

Parameter(s)	Acceptance level			
	95%	90%	80%	50%
BA	93.7 (98.6)	86.6 (96.2)	76.4 (95.5)	37.8 (75.6)
CBA	94.5 (99.5)	88.2 (98.0)	66.9 (83.7)	47.2 (94.5)
TPA, QMD	92.9 (97.8)	84.3 (93.6)	75.6 (94.5)	53.5 (107.1)
TPA, QMD, H	90.6 (95.3)	81.1 (90.1)	71.7 (89.6)	43.3 (86.6)

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

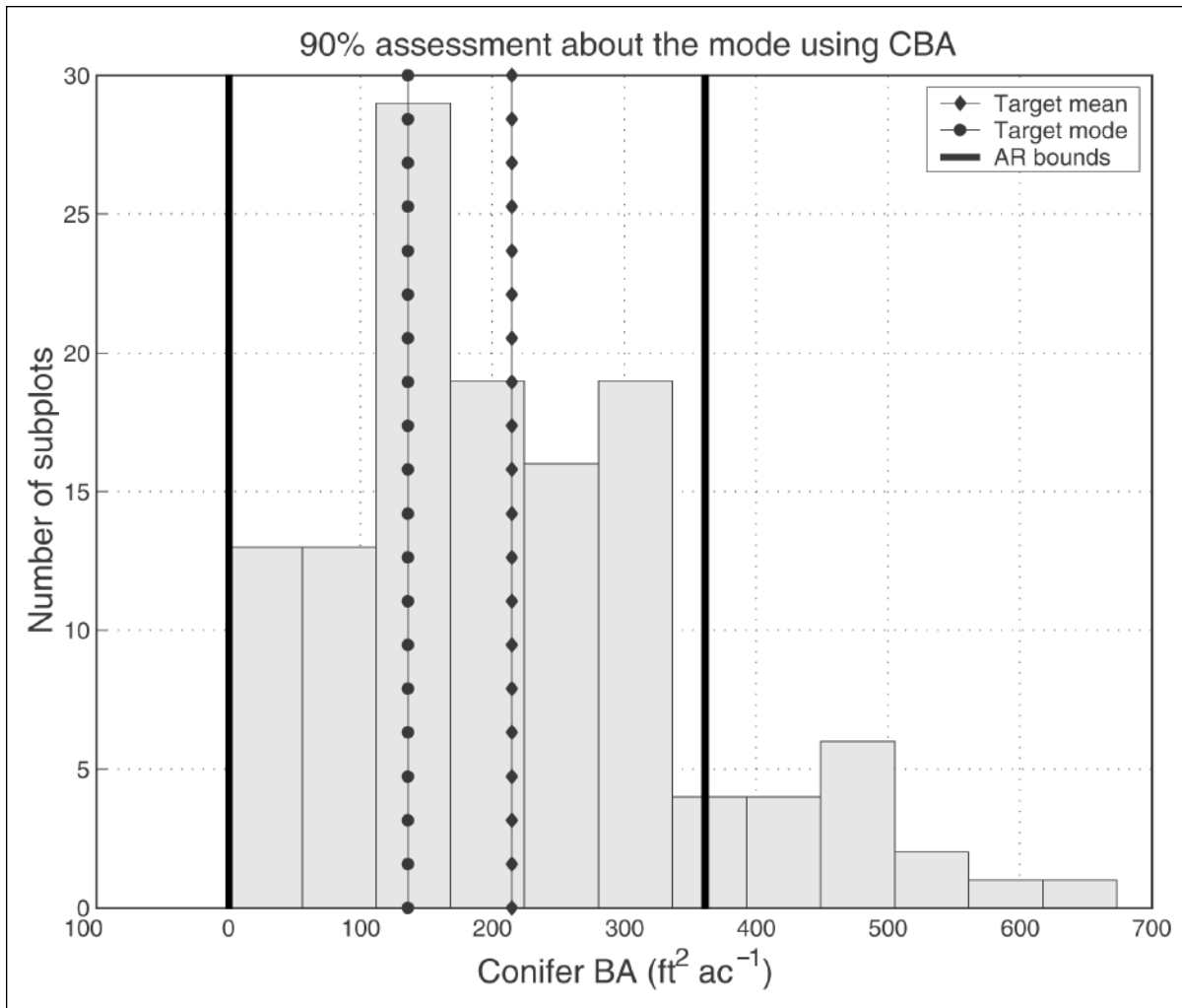


Figure 1—Histogram of CBA showing the 90% acceptance region (AR). The target mean and mode are also shown.

acceptance region boundaries and the mean and mode for the target CBA values, $215.1 \text{ ft}^2\text{ac}^{-1}$ and $136.3 \text{ ft}^2\text{ac}^{-1}$ 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.

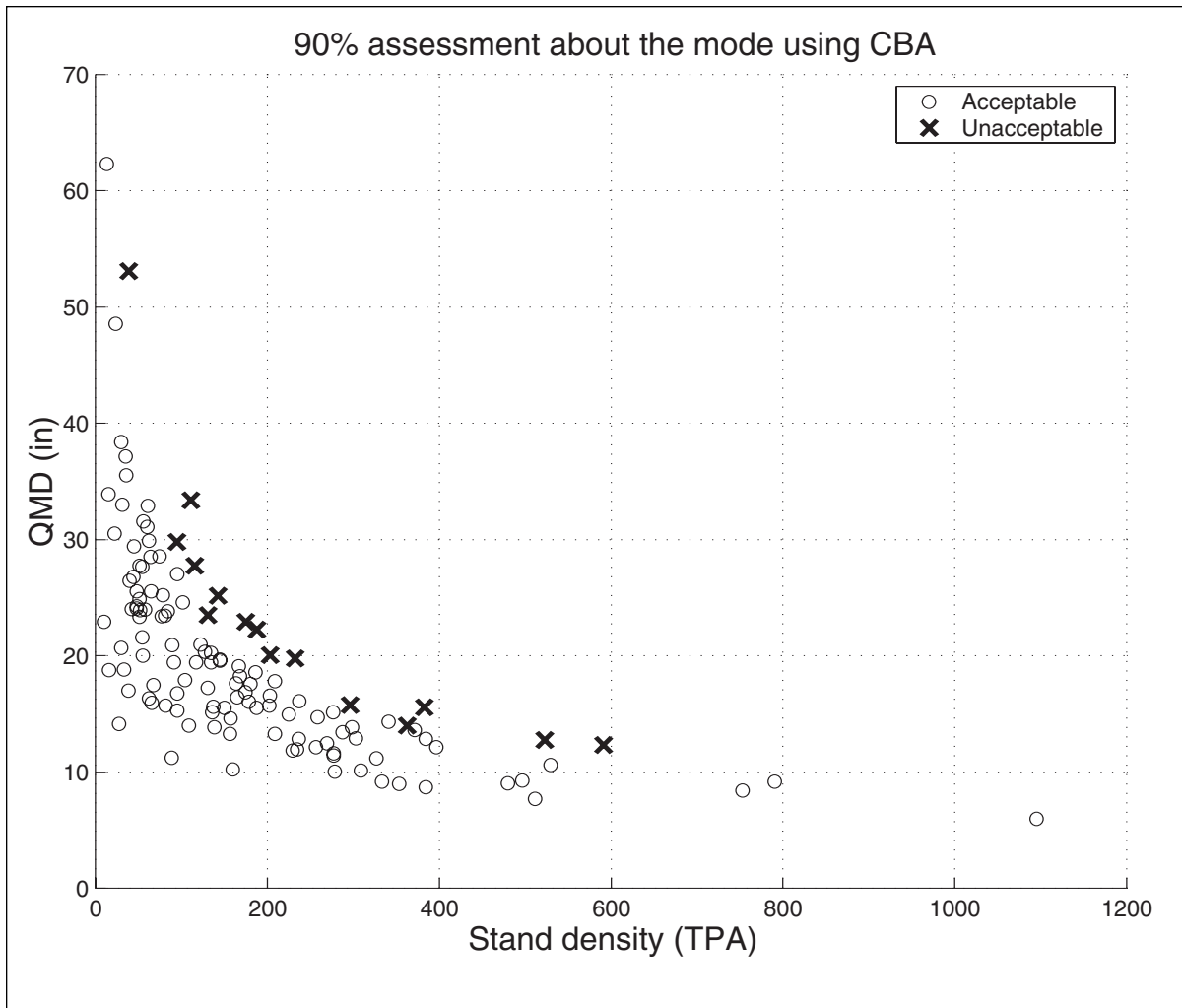


Figure 2—Plot of acceptable and unacceptable TPA and QMD values based on the CBA assessment and a 90% acceptance level.

The TPA and QMD assessment, therefore, succeeded in identifying stands meeting the desired conditions.

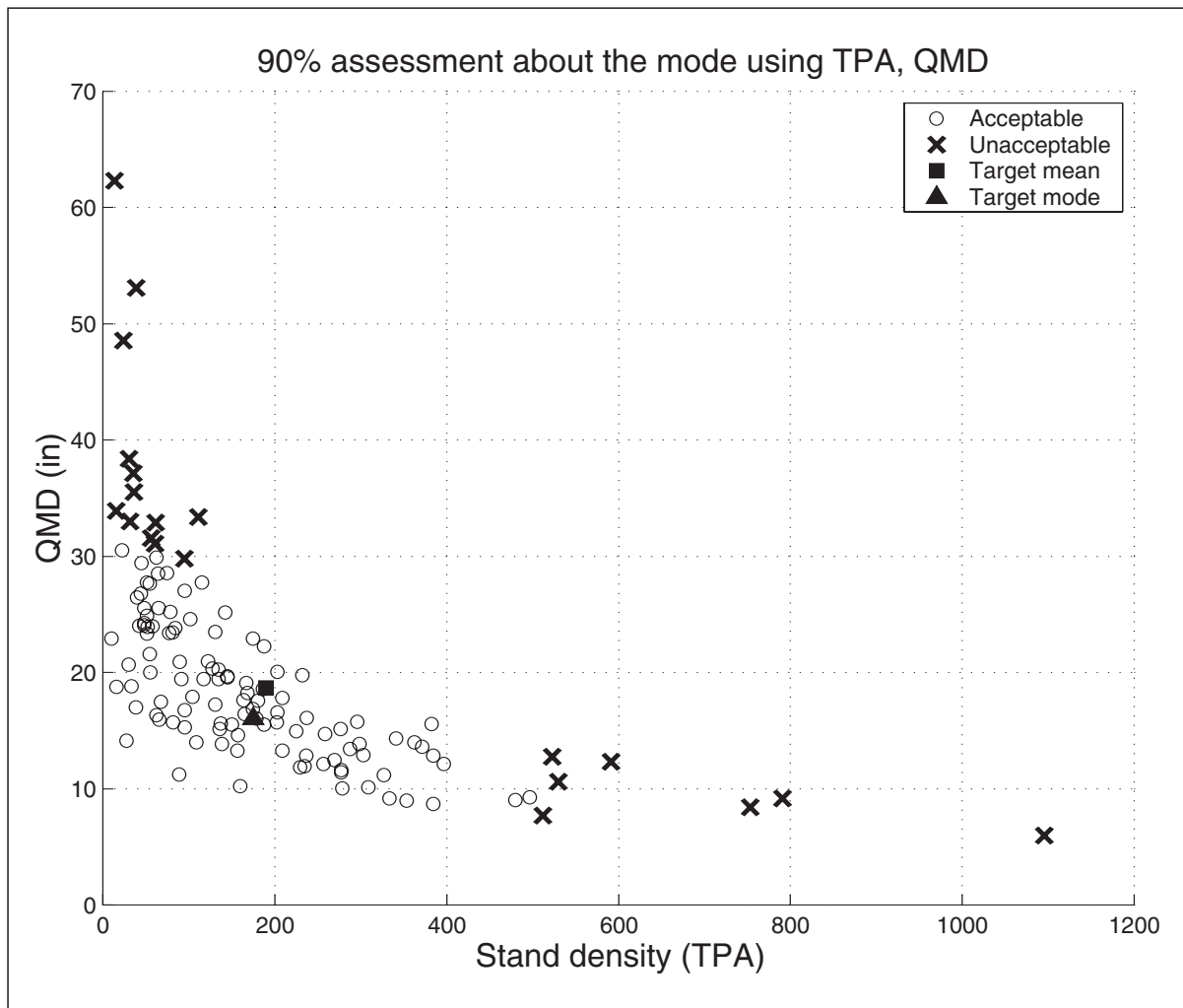
The TPA, QMD and H based assessment had an acceptance percentage of 81.1%. The assessment results appear in figure 4, with the mean and mode vectors for the target TPA, QMD, and H being 190.0 TPA, 18.7 inches, and 99.1 ft and 1750.1 TPA, 15.3 inches, and 78.3 ft respectively. As with the TPA and QMD 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



Figure—3 Plot of acceptable and unacceptable TPA and QMD values for a 90% acceptance level. The target mean and mode are also shown.

management, are likely to increase in the future. Target definition and assessment methods must allow for the variability inherent in natural systems and provide for flexibility in the attainment of the desired conditions. Further, effective target definition and assessment methods must be biologically and statistically consistent. Biological consistency is necessary to ensure that the defined targets are relevant, representative of actual conditions, and achievable. Statistical consistency is necessary to ensure the correct interpretation of inferences derived from the target definition and assessment procedures.

The nonparametric target definition and assessment procedures described automatically take into account the inherent variability of a desired forest structure, as identified 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 presented here provide an effective conceptual framework that may enable scientists and policy makers to focus on identifying the relevant biological issues, rather than setting potentially arbitrary targets for management.

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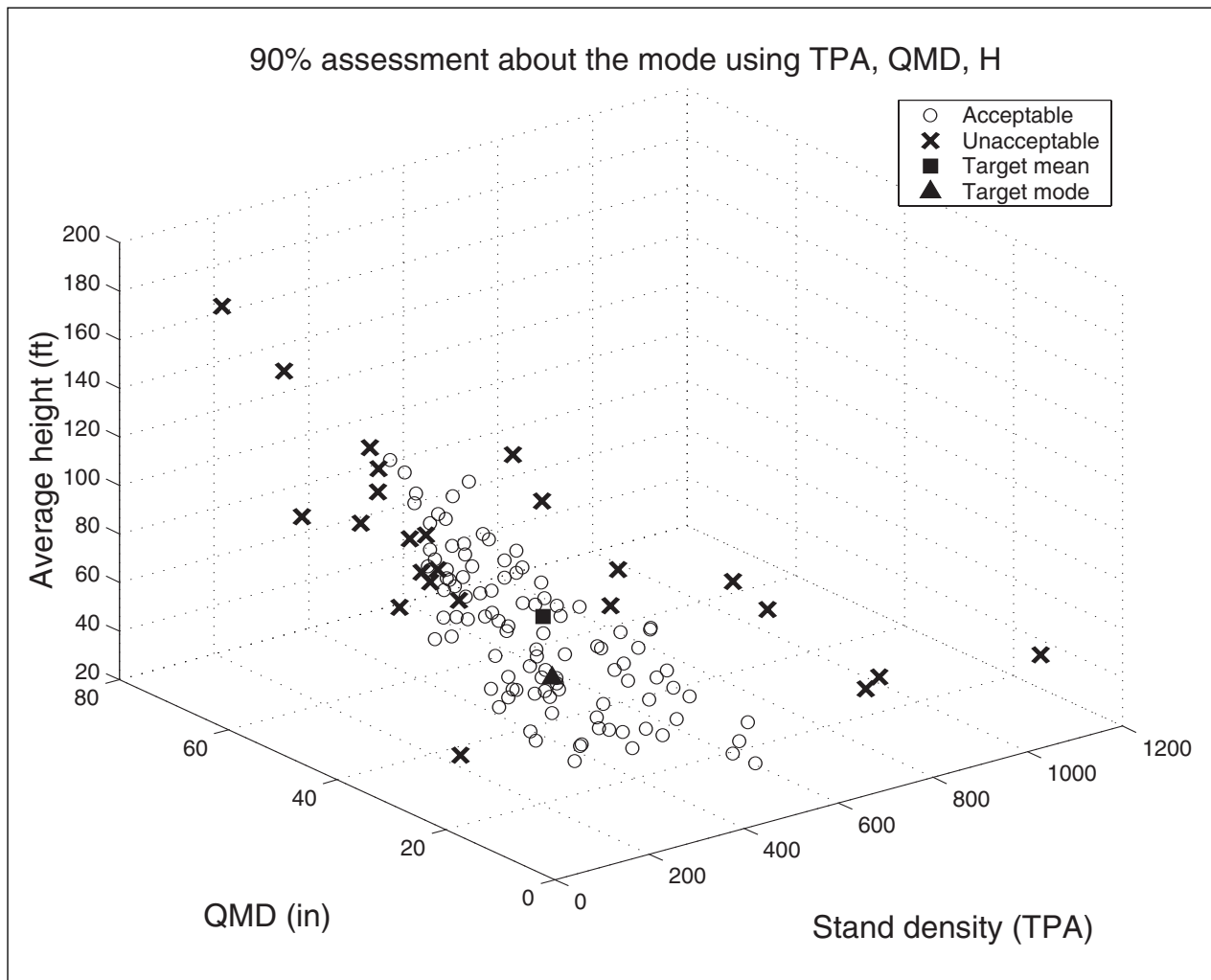


Figure 4—Plot of acceptable and unacceptable TPA, QMD, and H values for a 90% acceptance level. The target mean and mode, obscured by observations appearing in front of it, are also shown.

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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 Farrell¹

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. In the past, the AAC has been determined by the Provincial Chief Forester through a timber supply analysis that is conducted every 5 years. 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

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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 (m³). The long term sustainable cut level is projected to decline to 426,880 m³ 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

(1986), Eng and others (1986), and Maness and Adams (1991). We use the Sawmill Production Control Model (SPCM) developed by Maness and Norton (2002).

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 Jammick and Robak (1996) and Ogwen (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. *latifolia*) – 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).

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

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

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

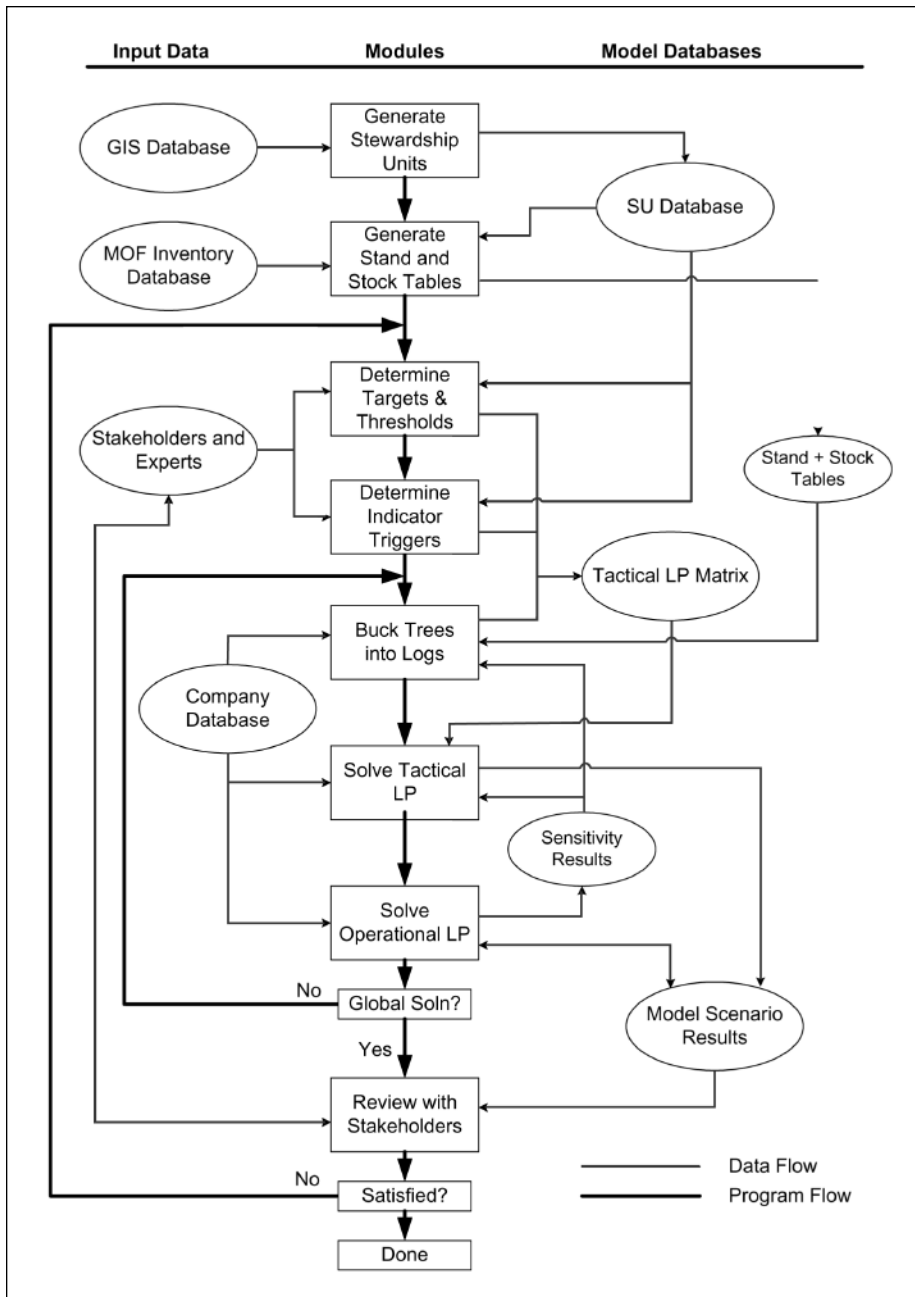


Figure 1—Flowchart of the overall solution process. The process continues iteratively in two domains: a) temporal domain, b) stakeholder domain. From Maness and Farrell (2004).

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.

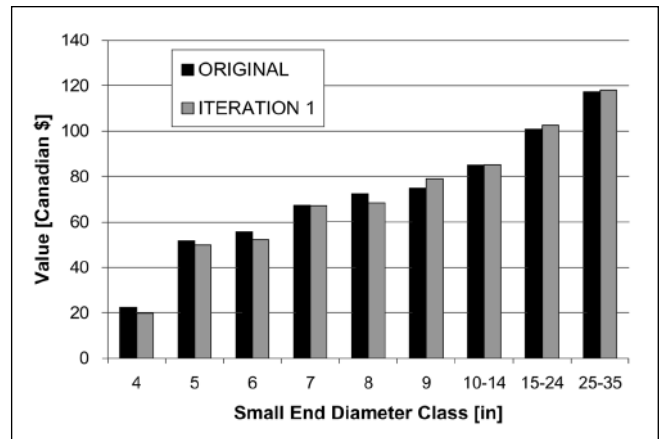


Figure 2—Return-To-Log (RTL) values for SPF by Small End Diameter (SED) for each iteration of the operational LP. From Maness and Farrell (2004).

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.

Table 2—Management prescriptions considered by the DSS, and the amount of each prescription selected in the base case.

Prescription ID	Method	Hectares treated	Harvest intensity	Net harvest volume	LU 27%	LU 29%
1	Clear-cut	3%	100%	3%	0.00%	0.03%
2	Clear-cut	10%	100%	10%	0.00%	0.00%
3	Clear-cut	20%	100%	20%	13.64%	0.32%
4	Clear-cut	32.50%	100%	32.50%	0.00%	0.00%
5	Clear-cut	100%	100%	100%	0.00%	1.01%
6	Selection-cut	25%	50%	12.50%	0.00%	0.12%
7	Selection-cut	67.50%	50%	33.75%	0.00%	0.00%
8	Selection-cut	95%	50%	47.50%	0.00%	0.15%
9	Selection-cut	97.50%	50%	48.75%	0.00%	0.00%
10	Preserve	100%	0%	0%	86.36%	98.37%

Table 3—Threshold percentages, attainment levels and attainment percentages for indicators used in the model.

Indicator	Indicator code	Threshold percent	Attainment level	Attainment percent
2. Ungulate winter range	UWR	90%	0.95	95%
5. Net profitability	PFT	75%	0.34	84%
6. Employment in forest sectors	EMPL	90%	1	100%
7. Benefits to governments	BNFT	90%	1	100%
8. Availability of recreation (Fishing)	FISH	90%	1	100%
9. Availability of recreation (Camping)	CAMP	90%	0.34	93%
10. Availability of recreation (Hiking)	HIKE	90%	1	100%

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,

Table 4—Indicator attainment levels determined by sensitivity analysis. From Maness and Farrell (2004).

Indicator	ECO	UWR	OLD	PFT	EMPL	BNFT	FISH	HIKE	CAMP	CWAT	VIS	MINIMUM
1. ECO	1.00	0.98	0.94	0.94	1.00	1.00	1.00	0.94	1.00	0.94	0.98	0.94
2. UWR	1.00	1.00	0.94	0.94	1.00	1.00	1.00	0.94	1.00	0.94	0.96	0.94
3. OLD	0.97	0.98	1.00	0.90	1.00	1.00	1.00	0.90	1.00	0.93	0.95	0.90
5. PFT	0.97	0.98	0.91	1.00	1.00	1.00	1.00	0.51	1.00	0.94	0.95	0.51
6. EMPL	0.98	0.98	0.95	0.95	1.00	1.00	1.00	0.95	1.00	0.95	0.96	0.95
7. BNFT	0.98	0.98	0.95	0.95	1.00	1.00	1.00	0.95	1.00	0.95	0.96	0.95
8. FISH	0.95	1.00	1.00	0.98	0.98	0.95	1.00	0.95	1.00	0.95	0.96	0.95
9. HIKE	0.95	1.00	1.00	0.98	0.98	0.95	1.00	1.00	1.00	0.95	0.96	0.95
10. CAMP	0.95	1.00	1.00	0.98	0.98	0.95	1.00	0.95	1.00	0.95	0.96	0.95
11. CWAT	0.72	1.00	1.00	0.97	0.98	0.98	1.00	0.72	1.00	1.00	0.97	0.72
12. VIS	0.90	1.00	1.00	0.97	0.90	0.90	1.00	0.90	1.00	0.90	1.00	0.90

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).

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.

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

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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

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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 Co-VIEW (<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,

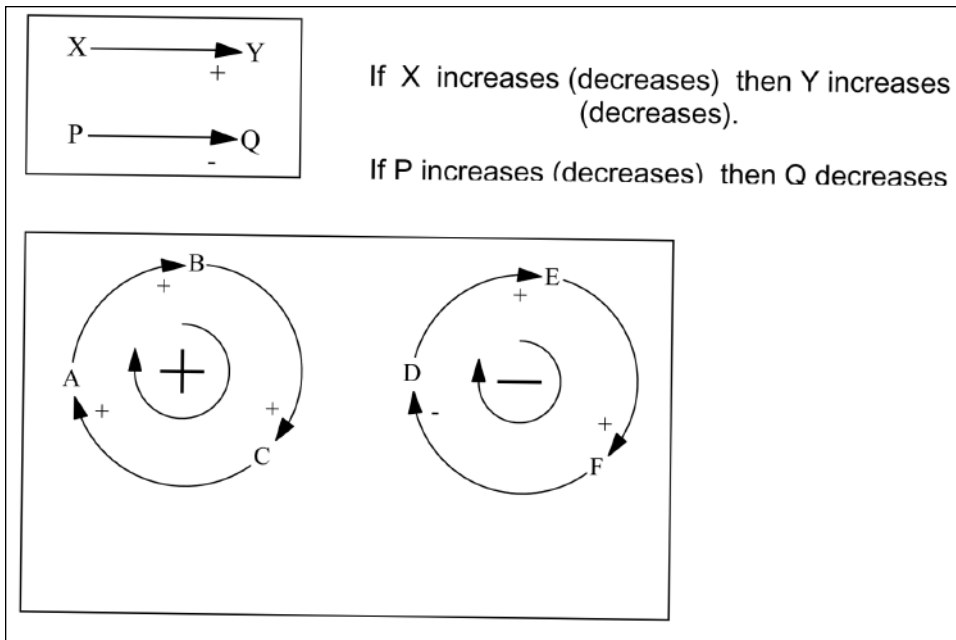


Figure 1—Components of causal loop diagram (Source: Purnomo et al. 2004).

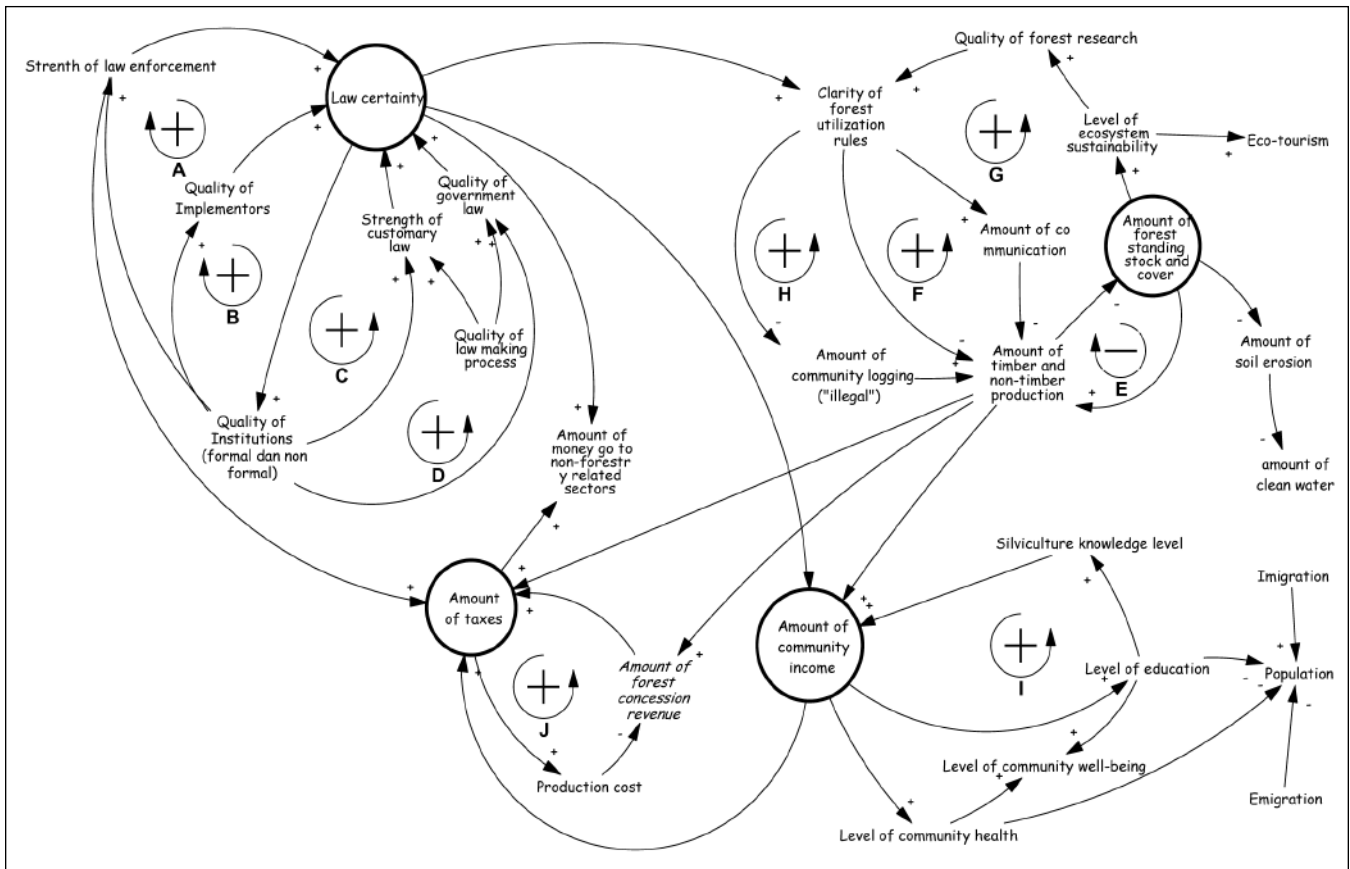


Figure 2—Causal loop diagram of management of forest as perceived by its stakeholders (Source: Purnomo et al. 2004).

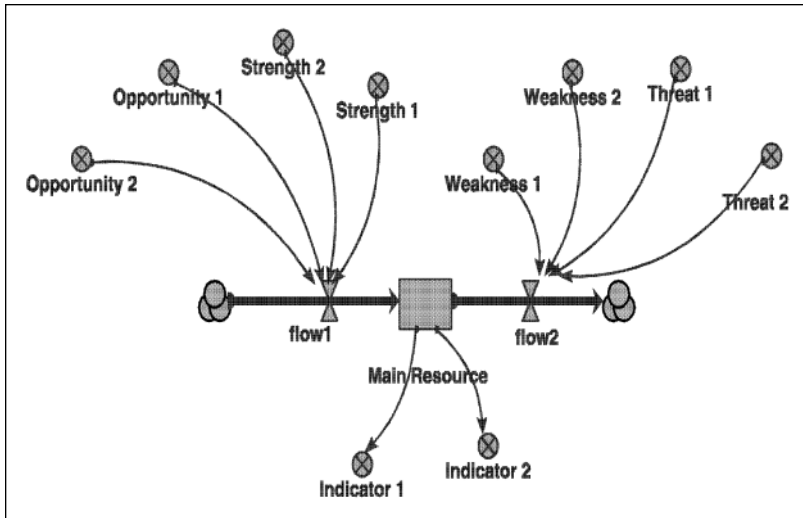


Figure 3—SWOT Elements Structured in a System Dynamics Framework.

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 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). The

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

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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 volume₁, potential volume₂, potential volume₃

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

$$\sum_{t=1}^T \left(TV_t - \sum_{i=1}^n (a_i v_{i,t} x_{i,t}) \right)^2 \quad [1]$$

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

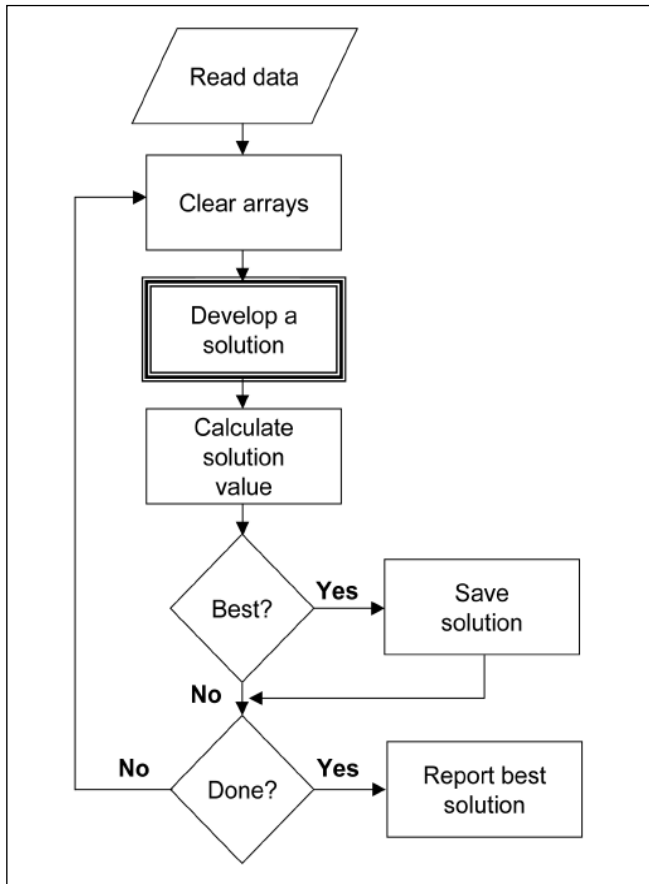


Figure 1—The basic Monte Carlo simulation process within HATT.

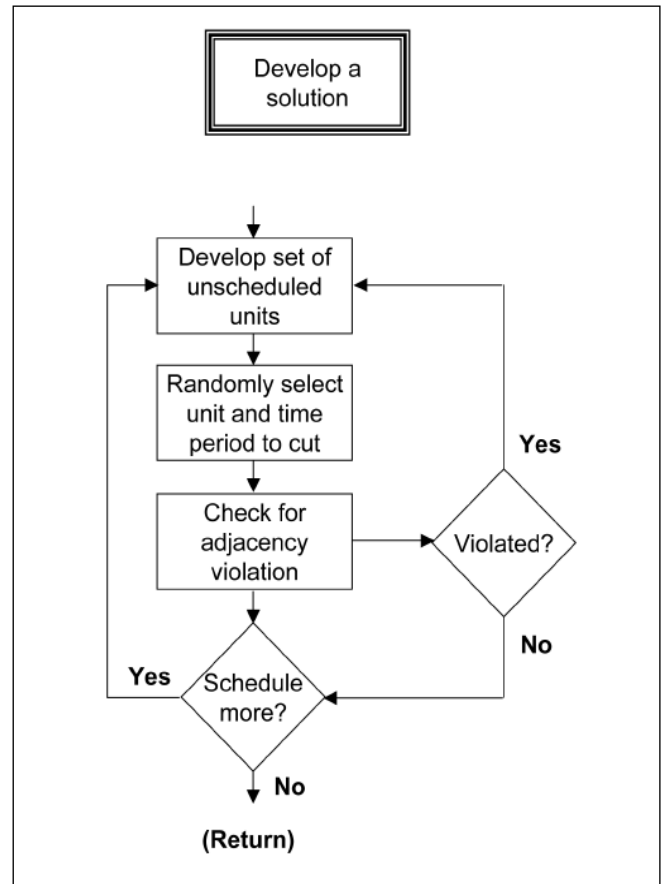


Figure 2—A more detailed examination of the “develop a solution” process within the Monte Carlo simulation process of HATT.

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.

$$\sum_{t=1}^T x_{i,t} \leq 1 \quad \forall i \quad [2]$$

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.

$$x_{i,t} + x_{j,t} \leq 1 \quad \forall i, t, j \in N_i \quad [3]$$

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

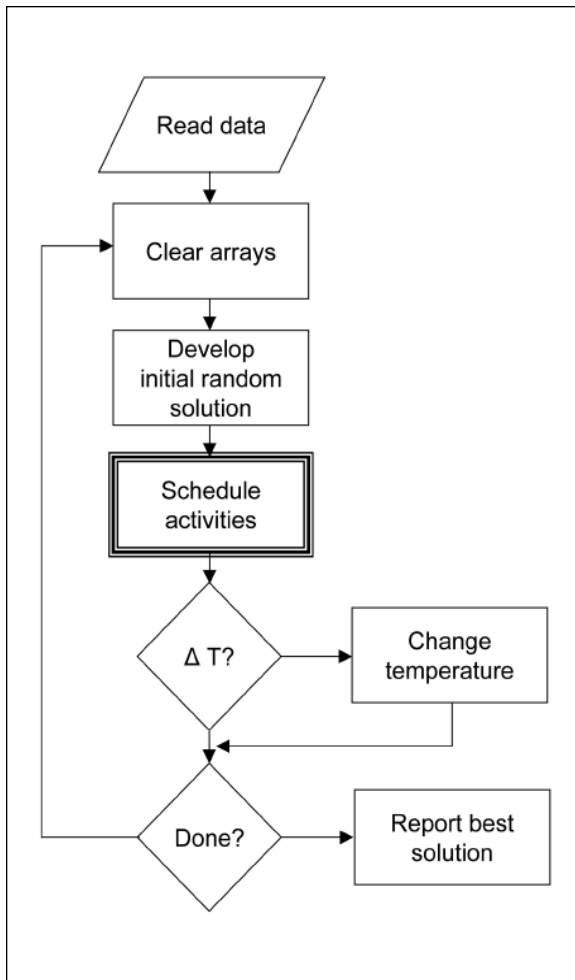


Figure 3—The basic simulated annealing simulation process within HATT.

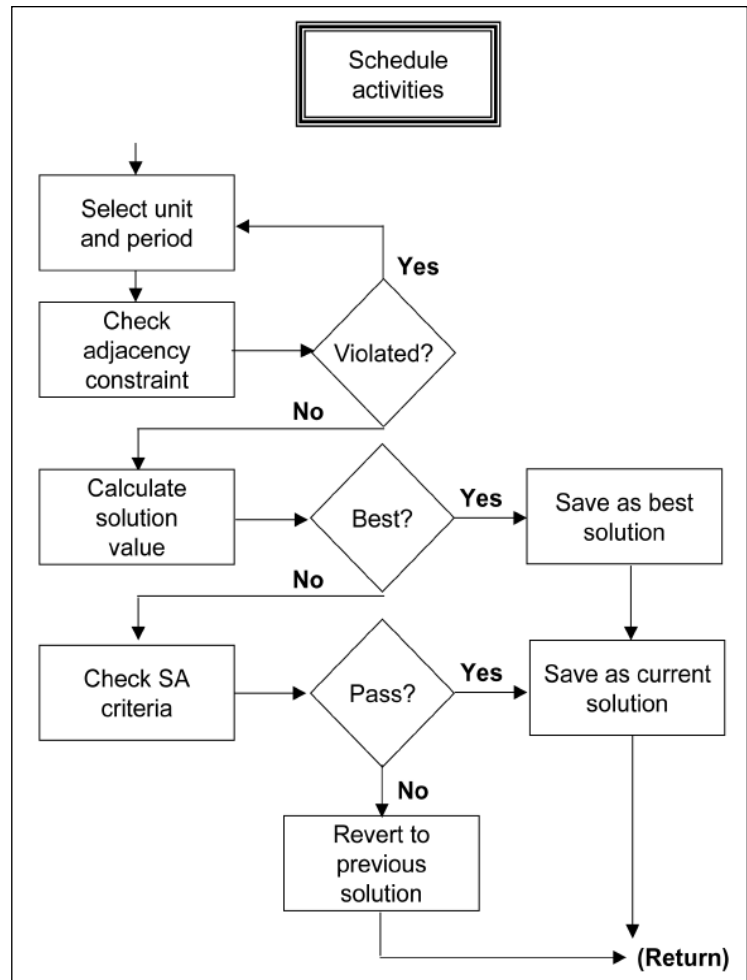


Figure 4—A more detailed examination of the “schedule activities” process within the simulated annealing process of HATT.

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 (Dowland 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

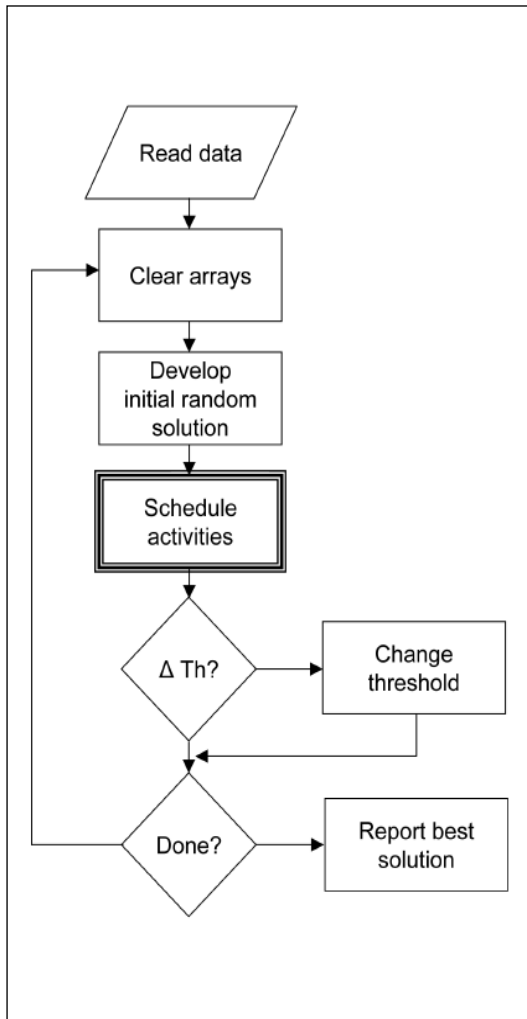


Figure 5—The basic threshold accepting process within HATT.

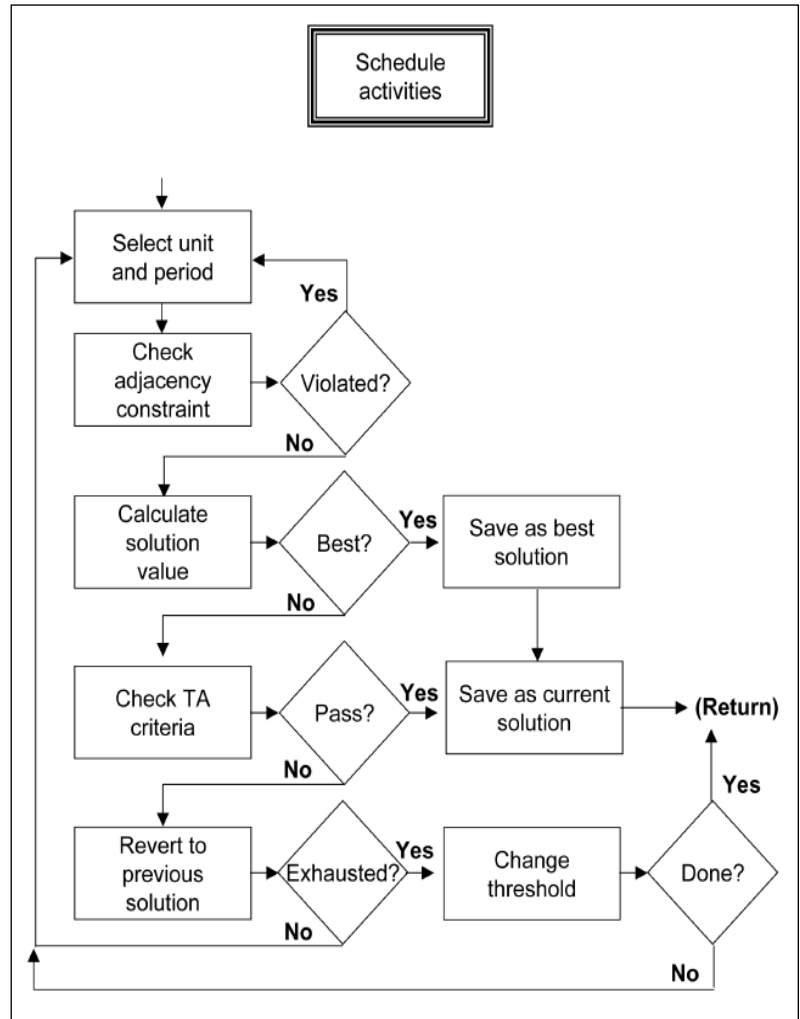


Figure 6—A more detailed examination of the “schedule activities” process within the threshold accepting process of HATT.

is assessed, and if needed, the simulated annealing criteria assessed. As in other SA applications, if a randomly drawn number is smaller than

$$EXP(-(proposed\ solution\ value - best\ solution\ value) / temperature) \quad [4]$$

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

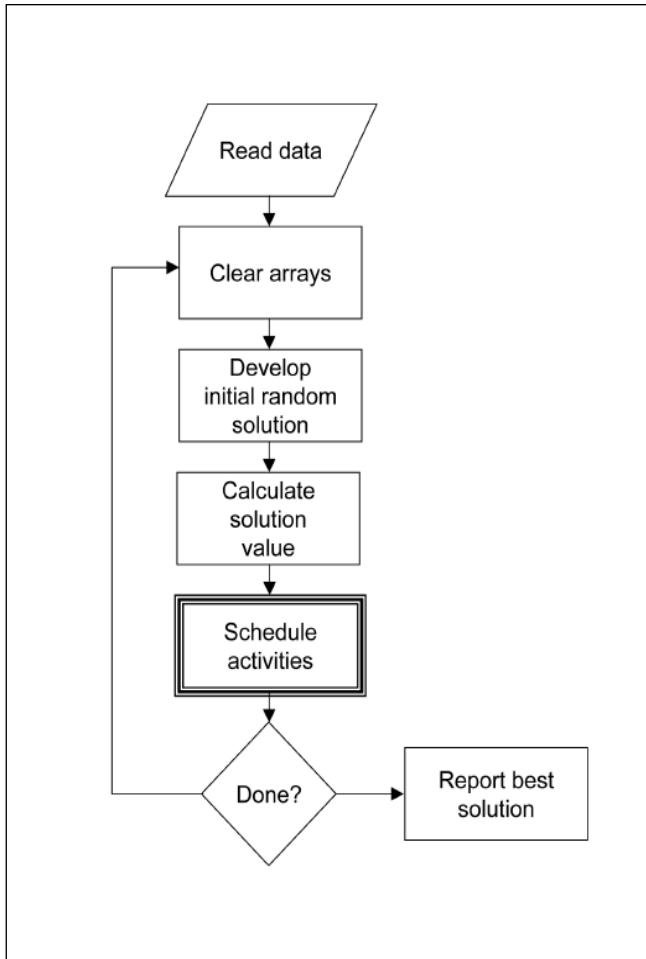


Figure 7—The basic tabu search process within HATT.

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

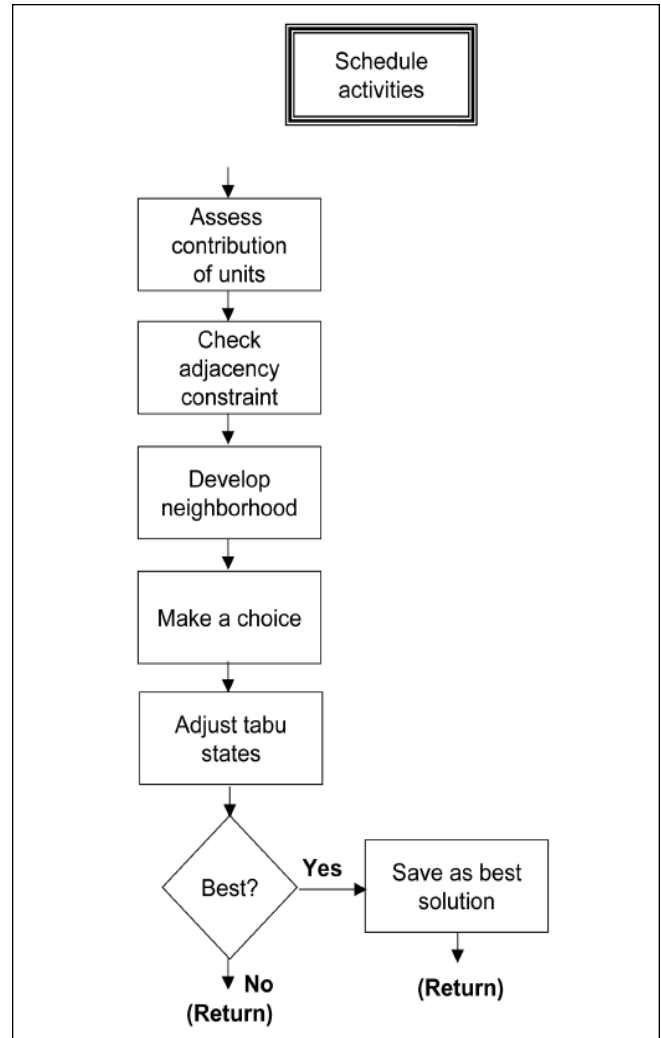


Figure 8—A more detailed examination of the “schedule activities” process within the tabu search process of HATT.

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.

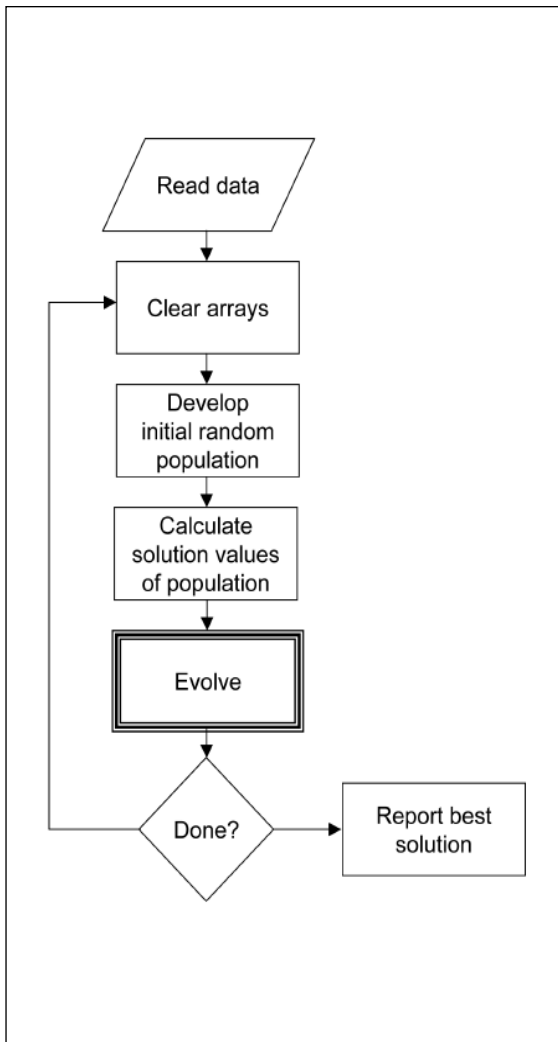


Figure 9—The basic genetic algorithm process within HATT.

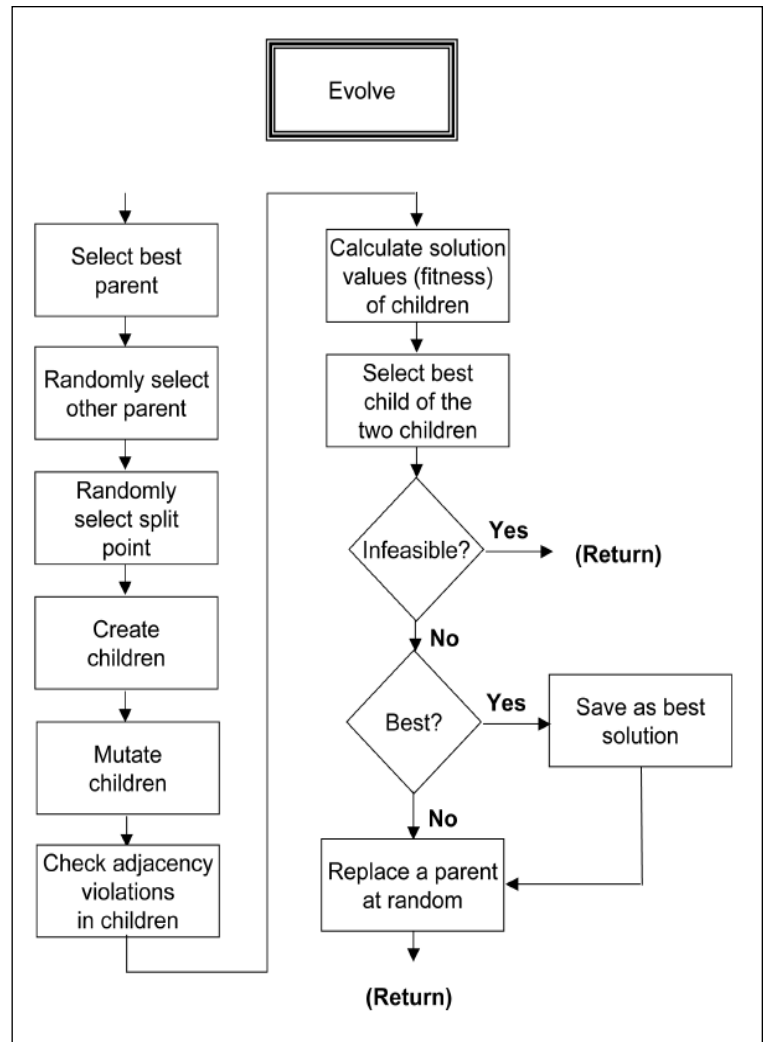


Figure 10—A more detailed examination of the “evolve” process within the genetic algorithm process of HATT.

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

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'XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
'XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
' Step 5. Check potential green-up constraints
'XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
'XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
Public Sub TS_assess_constraints()
' This code is used to determine whether any adjacency constraints
' exist
' First, clear an array
For i = 1 To TS_max_stand
  For tp = 1 To 3
    TS_constrained(i, tp) = 0
  Next tp
Next i
' Then, for each time period,
For tp = 1 To 3
  ' for each unit,
  For i = 1 To TS_max_stand
    ' If the unit is scheduled this time period,
    If TS_period_scheduled(i) = tp Then
      ' and for all adjacent units,
      For k = TS_pointers(i, 1) To TS_pointers(i, 2)
        ' indicate that they are constrained from being harvested this
        ' time period
        TS_constrained(TS_adj_list(k, 2), tp) = 1
      Next k
    End If
  Next i
Next tp
End Sub
'XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
'XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

```

Figure 11—An example of the programming code documentation available within HATT.

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](http://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

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

Value	Algorithm				
	MC ^a	TS ^b	TA ^c	SA ^d	GA ^e
Period 1 harvest	31,180.48	31,002.44	30,995.33	30,686.27	31,045.56
Period 2 harvest	31,532.88	31,002.31	30,991.07	30,734.55	30,596.48
Period 3 harvest	30,457.25	31,002.39	31,015.06	30,969.47	30,655.65
Obj. func. value	611,112	17	328	169,823	283,482

^a Monte Carlo simulation: Iterations = 10,000.

^b Tabu search: Tabu state = 150; Iterations = 10,000.

^c Threshold accepting: Initial threshold = 10,000,000; Iterations per threshold = 1; threshold change = 1,000; Unsuccessful iterations per threshold = 1,000.

^d Simulated annealing: Initial temperature = 11,000,000; iterations per temperature = 20; cooling rate = 0.98.

^e Genetic algorithm: Population size = 1000; Iterations = 10,000; mutation rate = 0.01.

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 algorithm has with this problem is that the vector of harvest timings for management units is arranged 1-n, yet the adjacency relationships are not as orderly. Management unit 1, in fact, is adjacent to management unit 48. Thus this algorithm 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 desirable substitute for actually developing an algorithm from scratch, but will hopefully engage those who are hesitant to learn and use computer programming techniques. In addition, 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).

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

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

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.

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

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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 m²). 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-harvest 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.

Buffer width (feet)	Forest features		
	Openings only	Openings and roads	Openings, roads, and water
98.4	47	89	98
196.8	90	168	185
295.2	132	240	263

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.

Buffer width (feet)	Forest features		
	Openings only	Openings and roads	Openings, roads, and water
98.4	23	76	85
196.8	45	146	163
295.2	68	212	225 ^a

^a Base case.

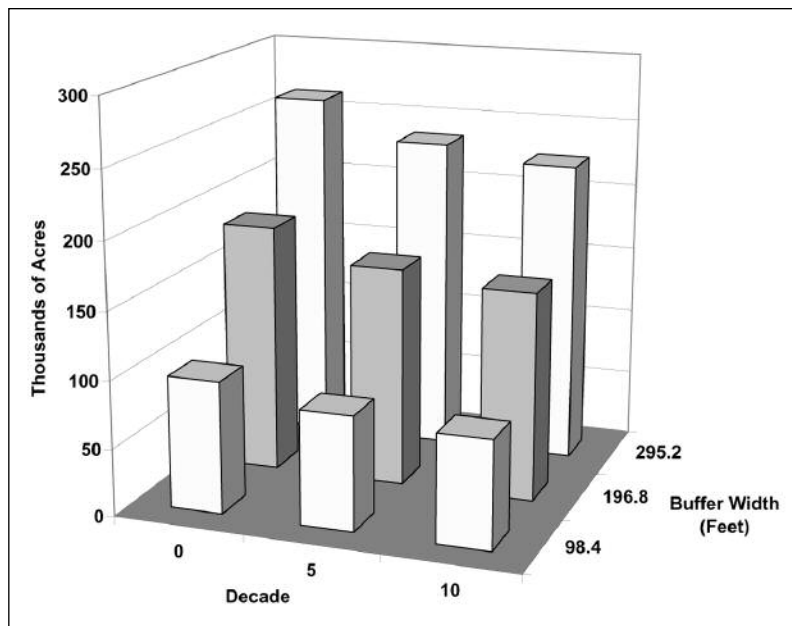


Figure 1—Area of edge habitat over time on the Nicolet National Forest based on openings, roads, and water features and buffer width.

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.^a

Buffer Width (feet)	Dispersion method		
	Oldest first	Dispersed	Clustered
295.2	225 ^b	243	242
590.4	407	436	432

^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.^a

No-harvest width (feet)	Habitat ^b	
	Edge	Forest interior
0 ^c	225	651
98.4	246	618
196.8	249	617
393.6	249	622

^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.

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.

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.

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MAGIS EXPRESS: SPATIAL MODELING FOR TIMBER AND ACCESS PLANNING

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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.

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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 assignment 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 state in particular ways. For example, a selective harvest treatment could reduce both the density and dominant 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.

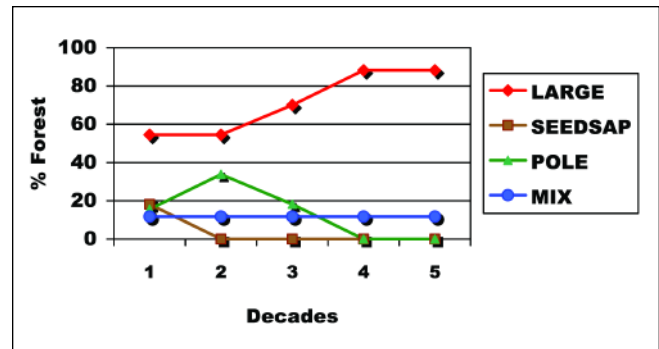


Figure 1—Relative distribution of vegetation size classes for the No Action scenario.

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 SIMPPLE (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 SIMPPLE 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.

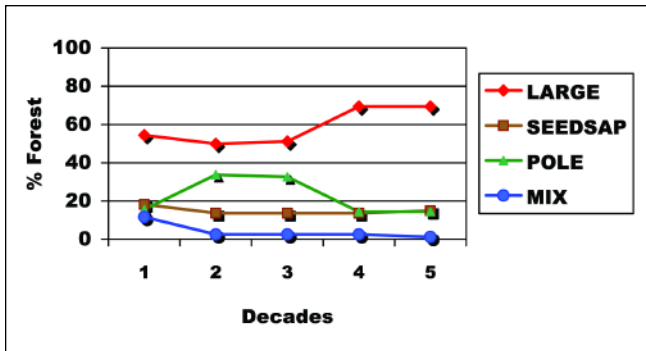


Figure 2—Relative distribution of vegetation size classes for Scenario 1.

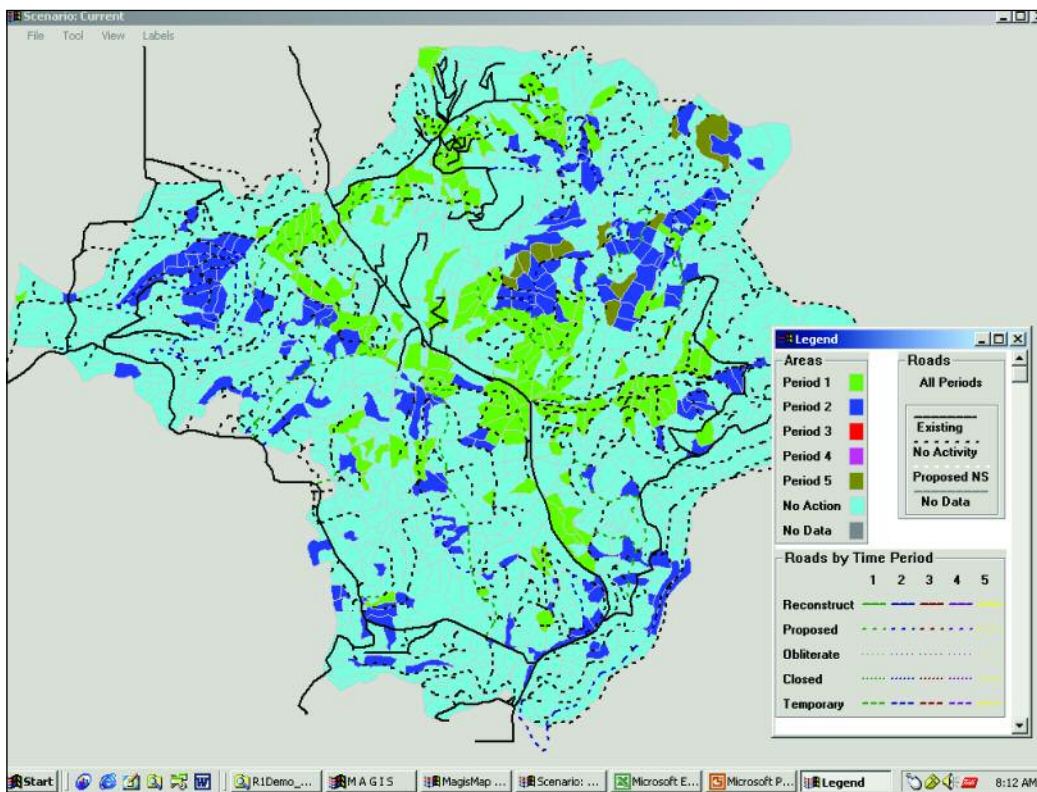


Figure 3—Scenario 1 Schedule of Treatments.

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

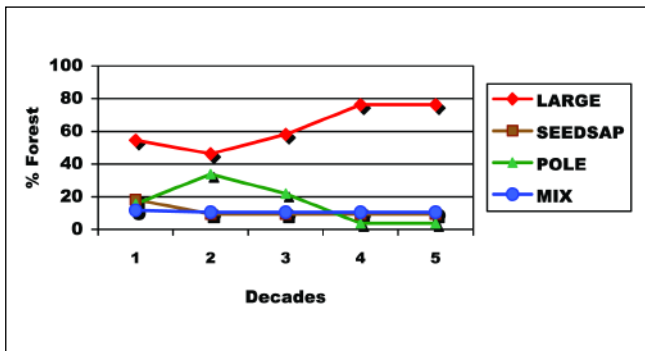


Figure 4—Scenario 2 Relative Distribution of Size Classes.

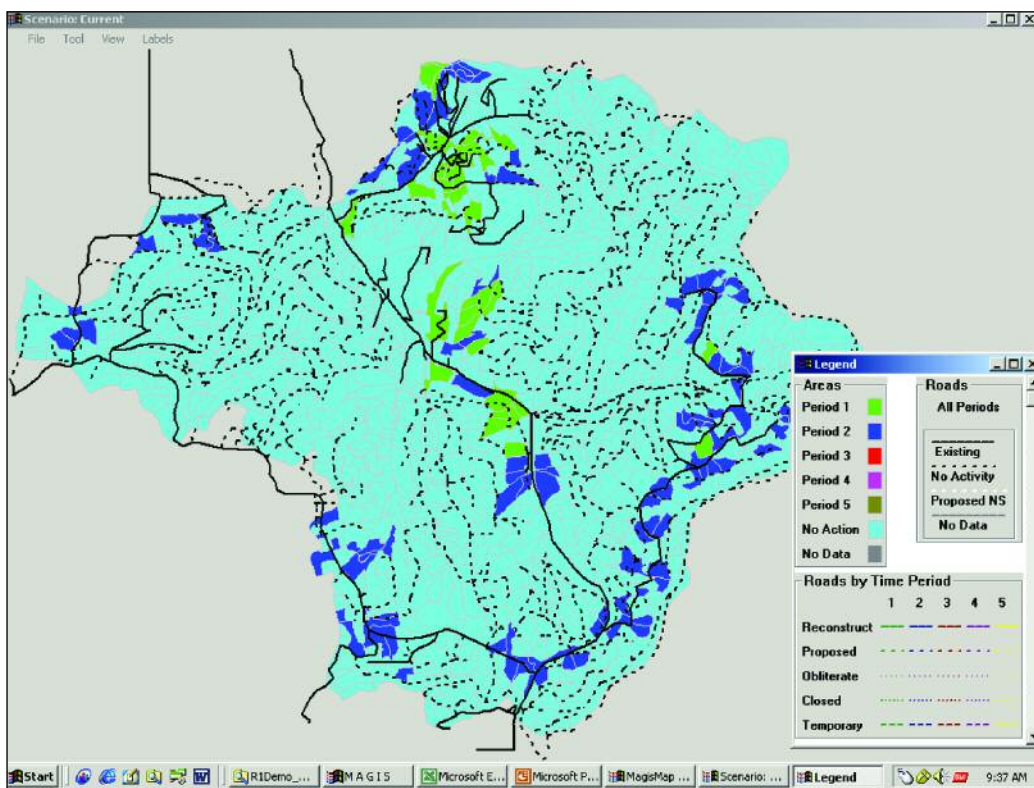


Figure 5—Scenario 2 Schedule of Treatments.

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.

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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

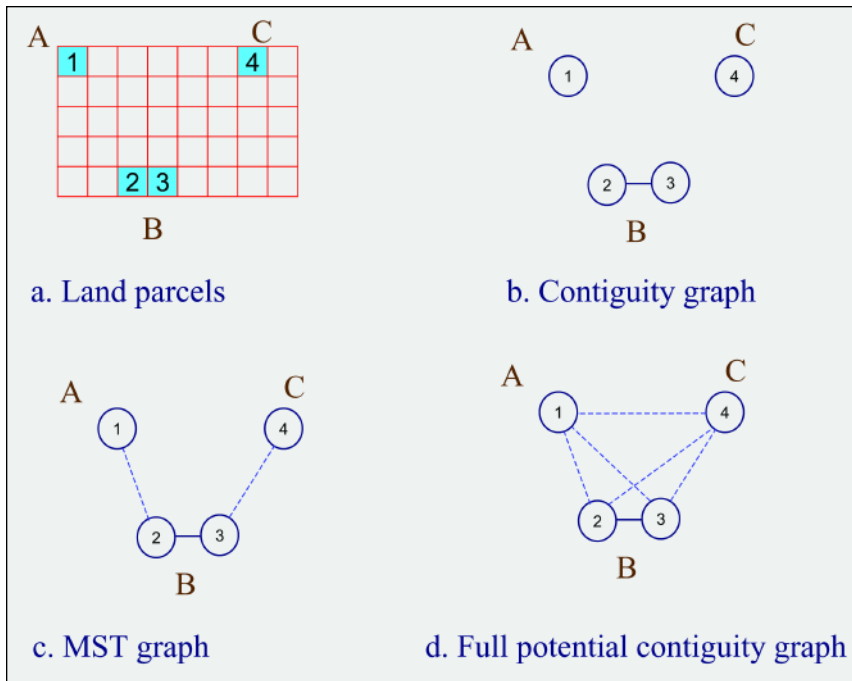


Figure 1—Graphic representation of selected land parcels.

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 Ω);
- 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:

$$C = \frac{\sum_{i \in \Omega} \frac{n_i(n_i - 1)}{2} + \frac{1}{2} \sum_{i \in \Omega} \sum_{\substack{j \in \Omega \\ i \neq j}} n_i n_j (d_{ij})^r}{\sum_{i \in \Omega} n_i (\sum_{i \in \Omega} n_i - 1)} \cdot \frac{1}{2}$$

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 were 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.

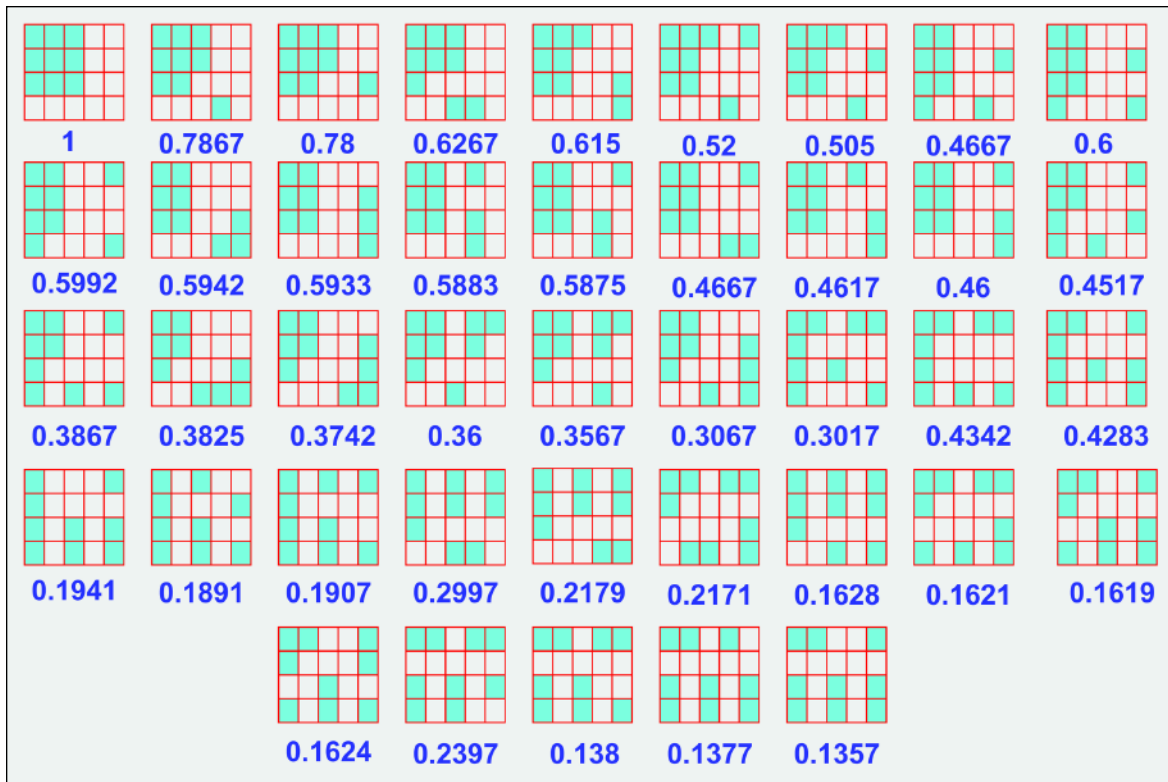


Figure 2—
Relative
contiguity of
various land use
configurations.

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

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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 Jammick 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

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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 1×10^6 tonnes of paper and 1.2×10^6 tonnes of pulp and has an annual turnover of $1,000 \times 10^6$ 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 138×10^3 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.portucel-soporcel.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 $30 \text{ m}^3/\text{ha}/\text{year}$ 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 $8 \text{ m}^3/\text{ha}/\text{year}$. 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

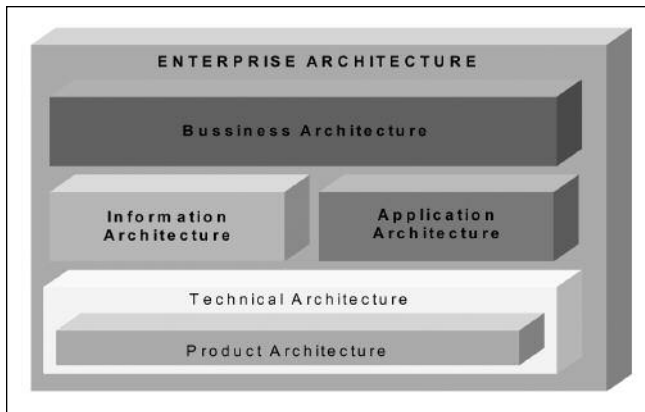


Figure 1—Enterprise Architecture Components. Source: <http://www.eacommunity.com>.

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

Activity (A) vs Entity (E)	E20 - Wood demand	E21 - Wood park capacity	E22 - Strategic information	E16 - Strategic parameters	E18 - Strategic plan	E23 - Tactical information	E17 - Tactical parameters	E25 - Tactical plan	E19 - Proposed tactical plan
A1 - Agregate strategic information	CR		C						
A2 - Organize strategic constraints				CRUD					
A6 - Reorganize strategic constraints				CRUD					
A3 - Strategic planning			R	R	C				
A4 - Strategic simulation validation					R				
A5 - Strategic simulation analysis					R				
A7 - Analise strategic information					R				
A8 - Organize strategic scenarios					RU				
A9 - Agregate tactical information	CR	CR				C			
A10 - Organize tactical constraints					R		CRUD		
A14 - Reorganize tactical constraints							CRUD		
A11 - Tactical planning						R	R		C
A12 - Tactical simulation validation									R
A13 - Tactical simulation analysis									R
A16 - Analise tactical information									R
A15 - Organize tactical scenarios									RU

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).

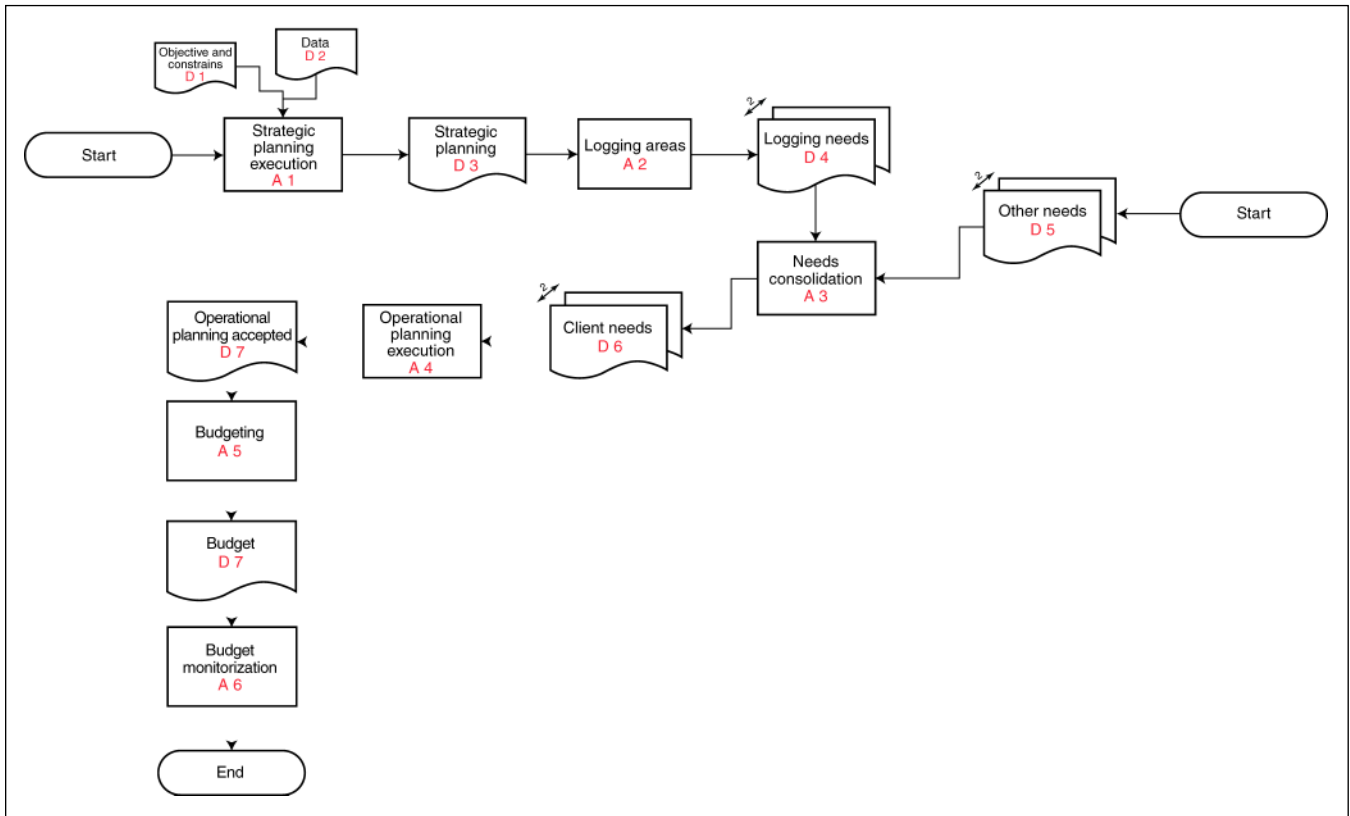


Figure 3—Current business processes. The symbol D identifies an information source. The symbol A identifies a business process activity.

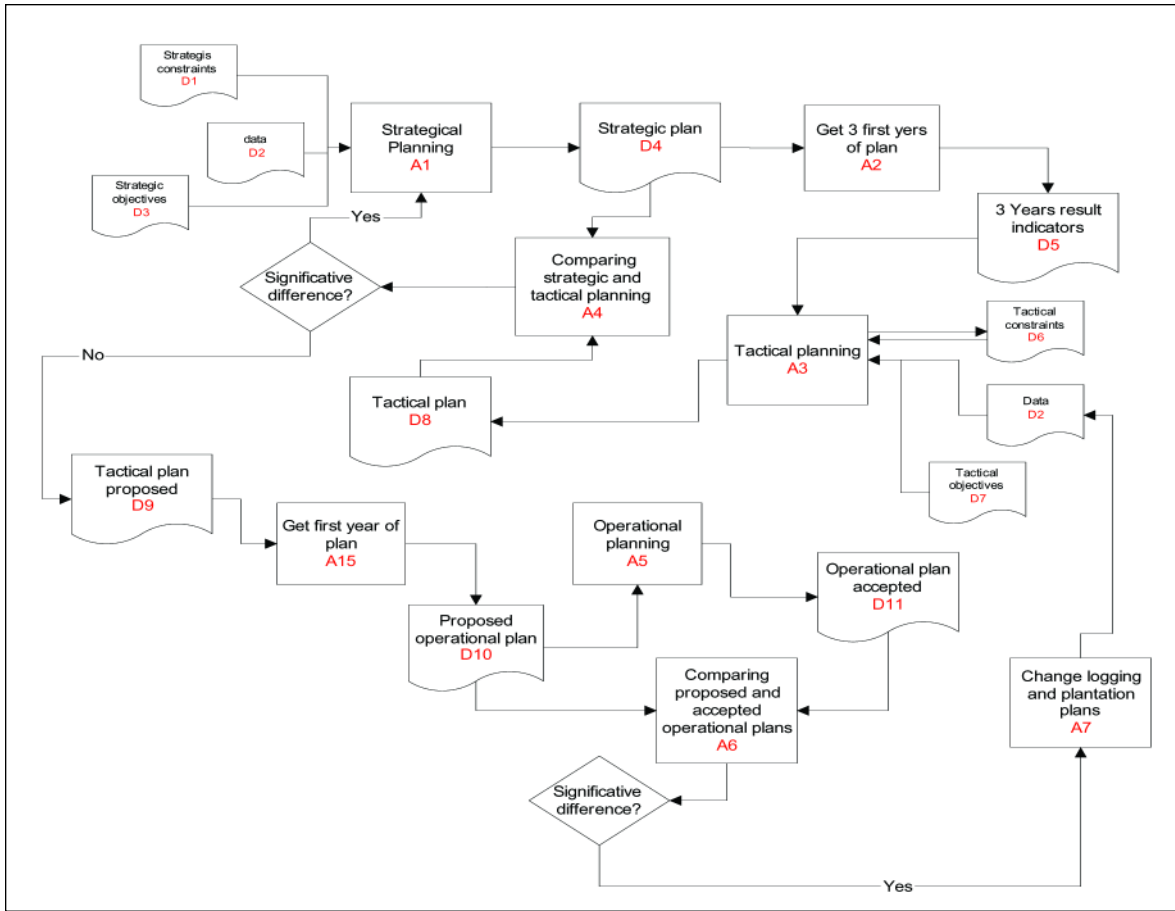


Figure 4—Fragment of future business model detailing strategic, tactical and operational planning. The symbol D identifies an information source. The symbol A identifies a business process activity.

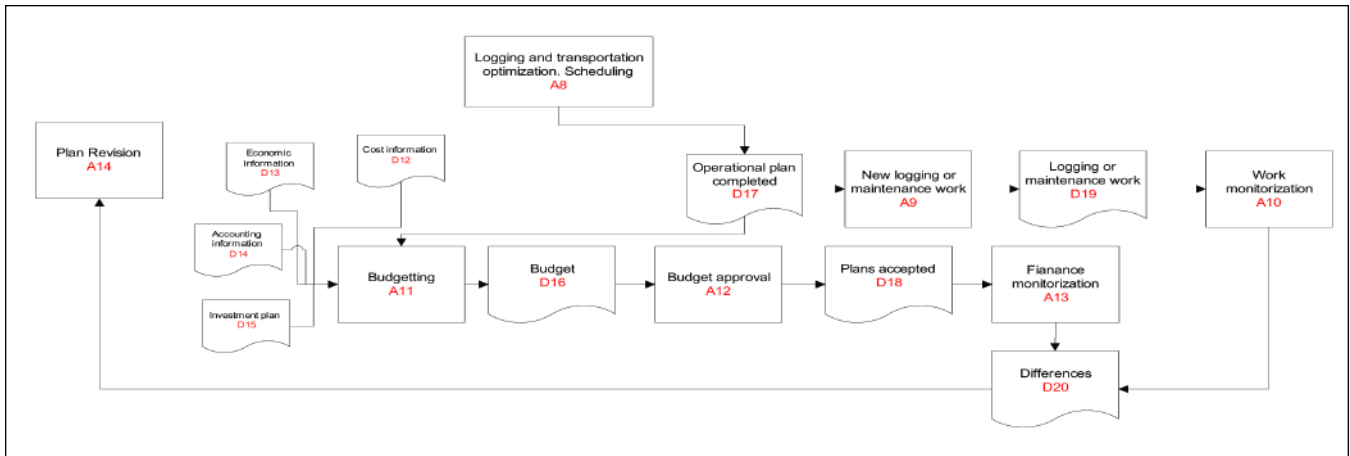


Figure 5—Fragment of future business model detailing work and budget monitoring. The symbol D identifies an information source. The symbol A identifies a business process activity.

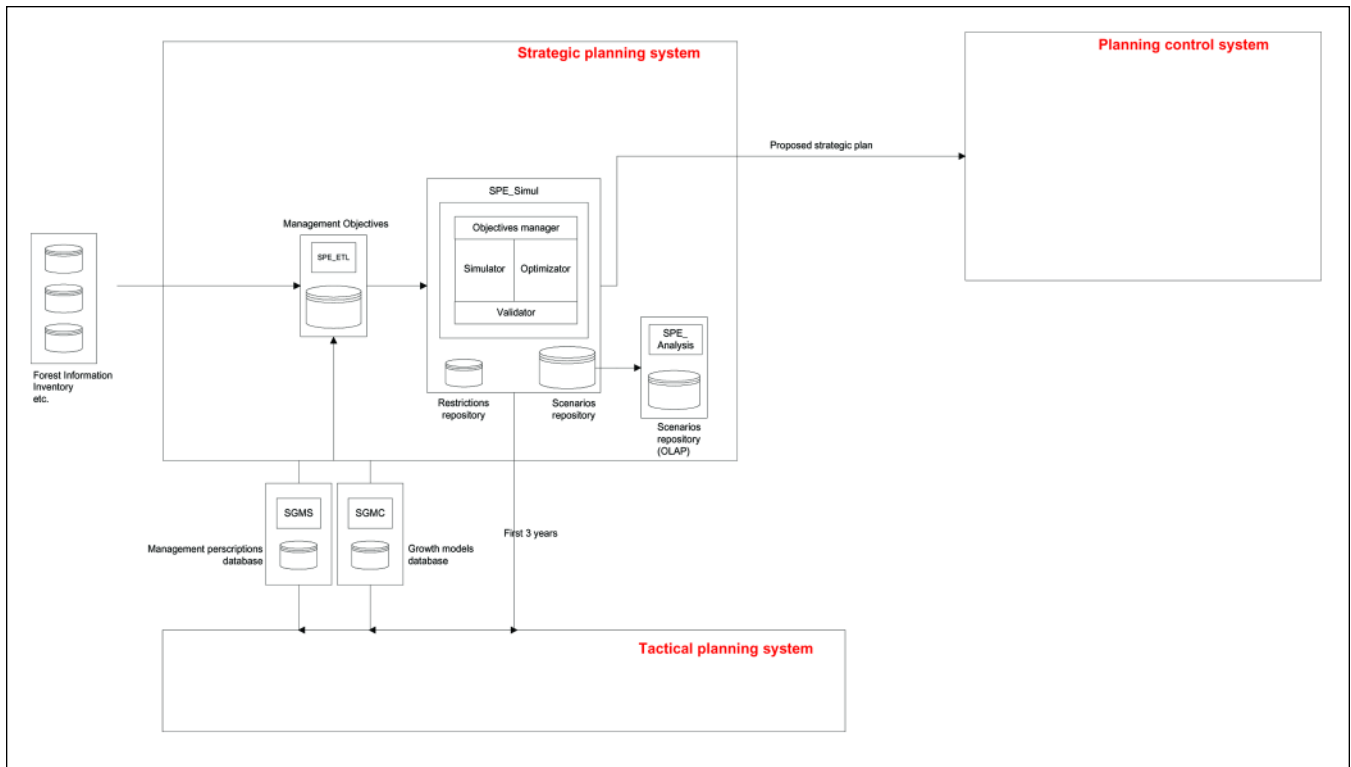


Figure 6—Description of the modular structure of the strategic planning application and of its interfaces with other IFPS applications.

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 operational conditions as evaluated by regional offices constrain substantially tactical objectives, tactical planning will have to be redone. 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

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 1×10^5 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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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.

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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.

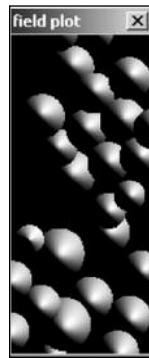


Figure 1—Synthetic image of a field plot generated from ground sampled data. The position, size and type of each tree in the ground survey, is used as input when generating the ellipsoidal synthetic trees.

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

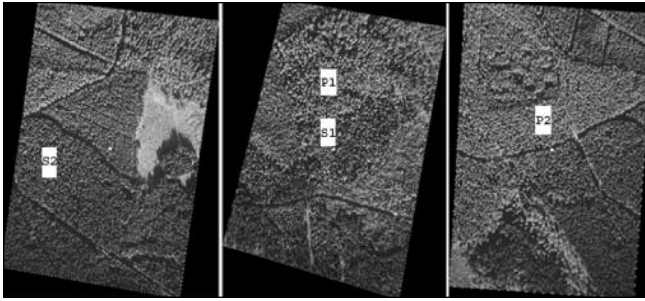


Figure 2—Aerial images used in the study. Left image 143, middle image 160 and right image 175. The positions of the stands P1, P2, S1 and S2 are marked in the figure.

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

Evaluation images	Stands	Width [pixels]	Height [pixels]	Resolution [meter / pixel]	Sun altitude angle[°]	Sun azimuth angle[°]	Time
Image 143	S2	3073	4149	0.147	29.19	18.40	11:53
Image 160	P1 and S1	3073	4054	0.154	29.67	14.71	12:06
Image 175	P2	3073	4375	0.136	29.77	13.85	12:09

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.

Stand	X [m]	Y [m]
P1	-10.0	131.9
P2	-21.4	59.0
S1	-10.2	30.9
S2	-120.2	-22.3

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

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:

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

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).

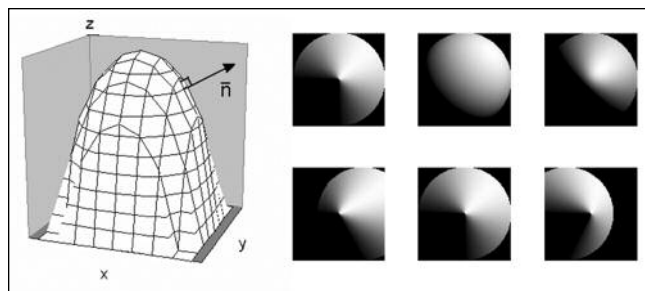


Figure 3—Generalized ellipsoids of revolution rendered with different parameters and in different viewing angles. Camera distance is 1000 pixels, X is the distance off centre when rendering the image, for parameters a , b and n , see equation 1. From the top left ($a=50$, $b=50$, $n=1$) ($a=50$, $b=50$, $n=2$) ($a=200$, $b=50$, $n=2$), units (pixels, pixels, 1). Down left ($a=50$, $b=50$, $n=1$, $X = -500$) ($a=50$, $b=50$, $n=1$, $X=0$) ($a=50$, $b=50$, $n=1$, $X=500$), units (pixels, pixels, 1, pixels).

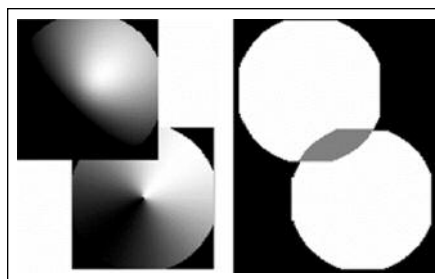


Figure 4—To the left, two templates which partly cover each other. To the right, the template masks. The intersection of the template masks is marked with grey. If the grey area ratio is larger than 70 % the templates are considered to be candidates to the same tree.

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

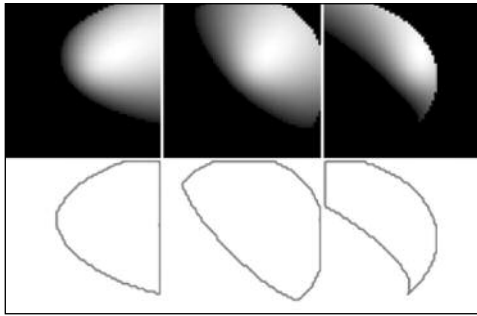


Figure 5—Templates (top) and the corresponding polygons of the sunlit area (bottom).

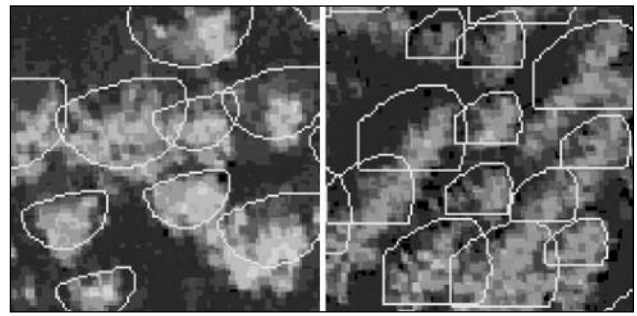


Figure 6—Aerial images with template hits shown as polygons. Left: near nadir viewing angle. Right: oblique viewing angle.

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

Name	Crown shape, n [1]	Crown radius, b [m]	Crown height, a [m]	Crown elevation [m]
Tree1	1.3	1.5	10.0	2.0
Tree2	1.3	2.5	10.0	2.0
Tree3	2	1.5	10.0	2.0
Tree4	2	2.5	10.0	2.0
Tree5	5	1.5	10.0	2.0
Tree6	5	2.5	10.0	2.0
Tree7	2	3.5	10.0	2.0

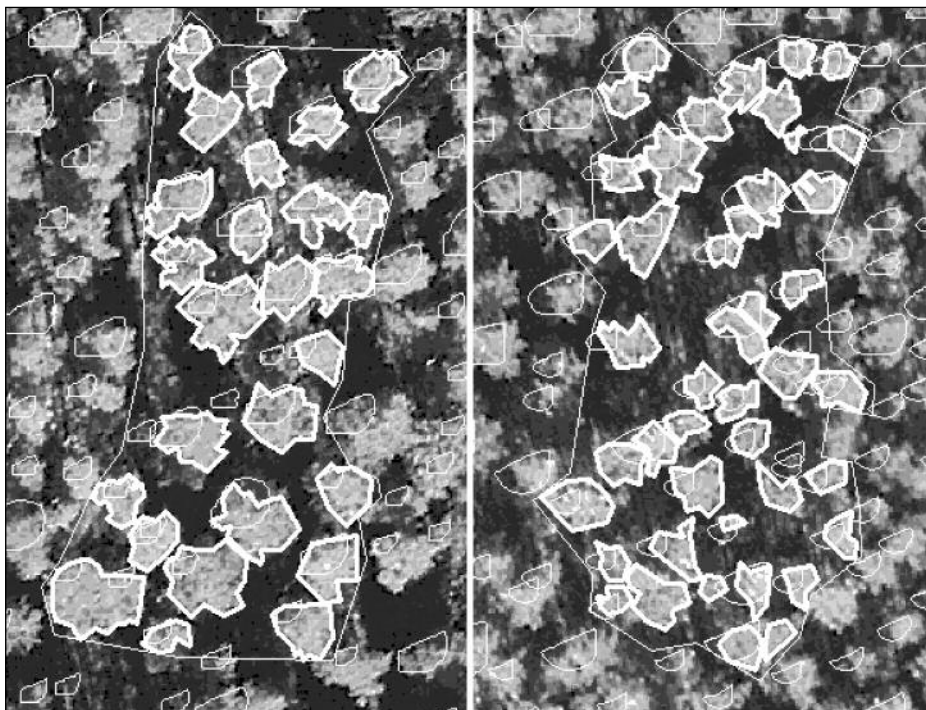


Figure 7—Template matching results for the pine stands. Left, stand P1, and right, stand P2. Test area delineation as a thin white lined polygon. Evaluation trees as thick white lined polygons. Template matching trees as thin white lined polygons.

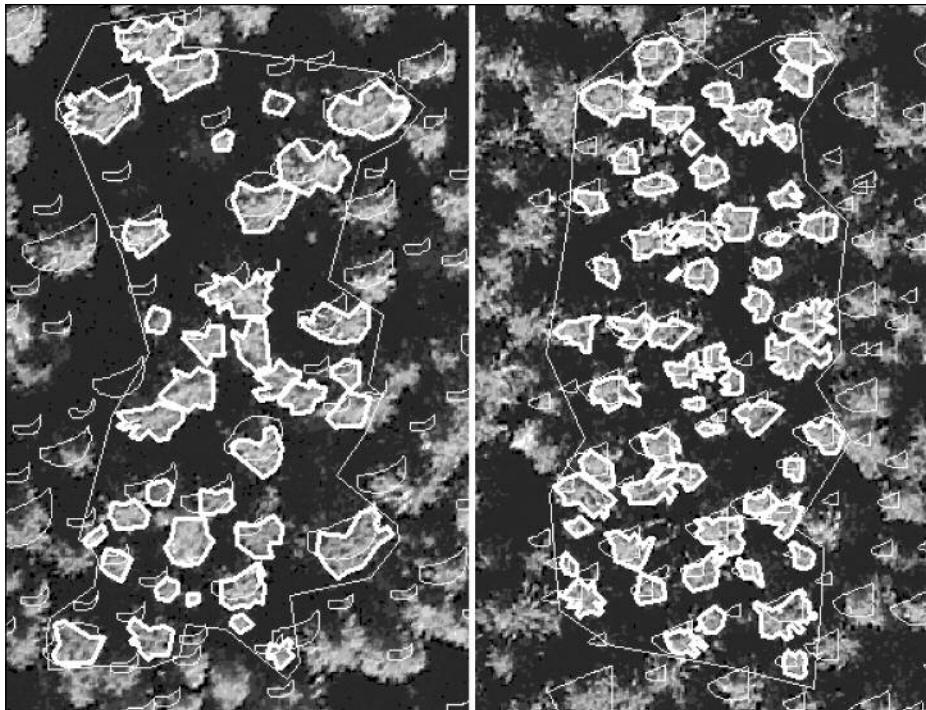


Figure 8—Template matching results for the spruce stands. Left stand S1. Right stand S2. Test area delineation as a thin white lined polygon. Evaluation trees as thick white lined polygons. Template matching trees as thin white lined polygons.

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

Plot	Ground survey		Template matching results			Results in percentage of visible trees			Results in percentage of all trees		
	Visible trees	All trees	Found visible trees	False hits	All hits	Found trees [%]	False hits [%]	All hits [%]	Found trees [%]	False hits [%]	All hits [%]
P1	26	28	26	7	33	100.0	26.9	126.9	92.9	25.0	117.9
P2	44	64	32	5	37	72.7	11.4	84.1	50.0	7.8	57.8
S1	36	48	23	9	32	63.9	25.0	88.9	47.9	18.8	66.7
S2	58	62	49	9	58	84.5	15.5	100.0	79.0	14.5	93.5
All plots	164	202	130	30	160	79.3	18.3	97.6	64.4	14.9	79.2

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

$(64 - 44)/64 \approx 31\%$. 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.

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MODELING INFECTION AND SPREAD OF *HETEROBASIDION ANNOSUM* IN CONIFEROUS FORESTS IN EUROPE

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ABSTRACT

The pathogenic fungus *Heterobasidion annosum* causes severe problems for forestry throughout the northern temperate zone, infecting mainly coniferous trees. Annual losses in the European Union are estimated at €790 million. The infection biology of the fungus is well described, although variation is considerable. This paper describes two modeling projects in Europe. The first, MOHIEF (Modeling of *Heterobasidion* infection in European forests), is a project within the European Union aiming to produce a decision-support tool for forest managers, as well as a tool for scientists throughout Europe. MOHIEF models infection and spread of the pathogen for various tree species over a range of forest conditions. The other project, Heureka, aims to produce a system for forest planning on strategic, tactical and operative levels in Sweden. Although national in scope, the model can be applied at regional and local levels. In Heureka the impact of *H. annosum* is one factor amongst other components that include growth and yield, wood properties, biodiversity, biomass-carbon relationships and forest-owner behavior. In this paper simulations of infection by *Heterobasidion* are demonstrated together with examples of how the models can be exploited, from a forest manager's and a scientist's perspective.

INTRODUCTION

The pathogenic fungus *Heterobasidion annosum* (Fr.) Bref. causes severe problems for forestry throughout the northern temperate zone, infecting mainly coniferous trees. Annual losses in the European Union are estimated at €790 million. In Sweden annual revenue losses attributed to decay and impacts on growth reach approximately €60 million. Apart from affecting income for the forest owner, *H. annosum* impacts the industry: pulp and paper manufacturers and sawmills experience log quality problems because of the fungus.

The extent of decay is difficult to estimate in standing trees; even so, some deduction for the risk of decay gener-

ally is built into stumpage prices. The likelihood of infection can be minimized by active means such as selection of the right season for cutting, stump treatment, or stump removal. These measures have a cost, however, and thus must be integrated into forest planning to fit the "right" operations to the "right" stands.

THE PATHOGEN

H. annosum forms perennial fruiting bodies that produce vast numbers of spores under suitable environmental conditions. In Sweden, spore dispersal takes place during the whole growing season (April to September) with a peak

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in the summer months, whereas in warmer climates, the fall and winter periods appear more favorable for spore production. Spores germinate on fresh woody tissue, favoring newly cut stumps (Rishbeth, 1951a). The mycelium grows into the stump and its roots, and infects neighboring trees via root contacts and grafts. Damage occurs as decayed wood on standing spruce and fir, and death of young pines. Fungal mycelium may remain viable in old stumps for decades, providing inoculum for the next generation of trees. In summary, *H. annosum* enters a stand primarily via stump surfaces and injuries, spreads from fresh stumps to trees, from tree to tree and/or from old stumps to standing trees (fig. 1).

The incidence of *H. annosum* disease can be higher under certain conditions; for example, high soil pH (Rishbeth 1951b), in first rotation stands (Rennerfelt, 1946), a high number of stems per hectare (Venn & Solheim, 1994) and on mineral soils with fluctuating water table (von Euler & Johansson, 1983). On the other hand, the risks of infection and spread appear to be lower on peat soil (Redfern, 1998), during rainfall (for example, Sinclair, 1964) and in stands with mixed tree species (Huse, 1983; Piri and others, 1990).

An active way to control *H. annosum* is to prevent stump infection by logging during a safe period when few spores are present, or by treating stumps with an agent that inhibits spore germination. In Europe protective stump treatment, with biological or chemical agents, is carried out on more than 200,000 hectares annually at an average cost of €1.2 per m³ (Thor, 2002). A remedial method of control is to remove old stumps prior to the establishment of a new stand. This expensive action is carried out on especially sensitive sites in the United Kingdom (UK) (Pratt, 1998). Silvicultural measures such as planting of less susceptible tree species, admixture of species, shortening the rotation period, or minimizing stand entries are other options that actively reduce spread of *H. annosum*. All in all, there is ample scope and complexity to apply a modeling approach to resolve this forest management problem. Models are useful for forest managers as well as scientists in order to understand the mechanisms of infection development and impact of *H. annosum*.

MODELING

An empirical model of *H. annosum* infection in Norway spruce exists for southern Sweden and Denmark (Vollbrecht & Agestam 1995, Vollbrecht & Jorgensen, 1995). Mechanistic models have been developed for *H. annosum* on Sitka spruce (*Picea sitchensis* Bong Carr.) in the UK (Pratt and others, 1989) and for *H. annosum* on Norway spruce in Finland

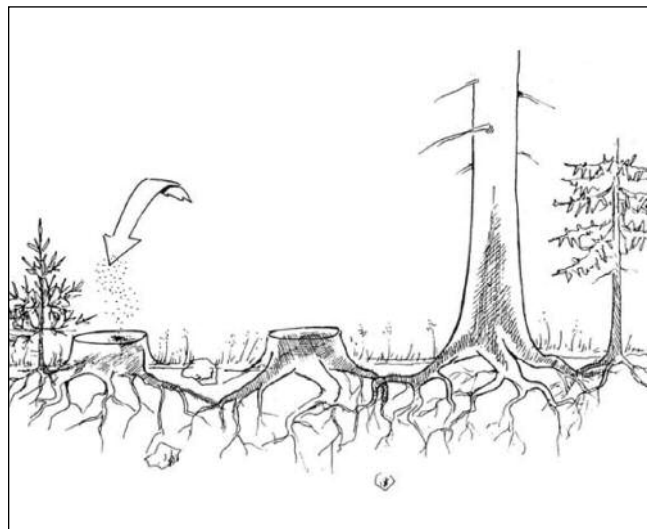


Figure 1—Spores of *H. annosum* germinate on fresh woody tissue, for example, stumps. Subsequently, fungal mycelium can spread to adjacent root systems and stems, which are decayed. Illustration from Swedjemark (1995).

(for example Möykkynen, Miina & Pukkala, 2000). Other root diseases that have been modeled include *Phellinus weirii* on Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) (Bloomberg, 1988). See also Pratt and others (1998) for further details about modeling disease development in forest stands.

The most comprehensive modeling effort to date, however, is the western root disease (WRD) model describing the dynamics of *H. annosum*, *Armillaria* spp. and *Phellinus weirii* in, for example, stands of fir (*Abies* spp.) and Ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) in western North America (Frankel, 1998). The WRD model was developed by American and Canadian forest pathologists over a period of more than ten years. In addition to the pathogens, the effect of windthrow and bark beetles can be simulated in the model which is linked to growth and yield models that respond to management actions.

The WRD model has inspired a European Concerted Action, MOHIEF (Woodward and others, 2003), in which a set of mechanistic models of *H. annosum* is to be developed for European conditions covering the range of, for example, soil, climate, geography and hosts.

In MOHIEF (Modeling of *Heterobasidion* infection in European forests) forest pathologists, forest managers and modelers are preparing a prototype decision-support tool to estimate potential losses from *Heterobasidion* attack. The work is divided into three subtasks; 1) establish the output

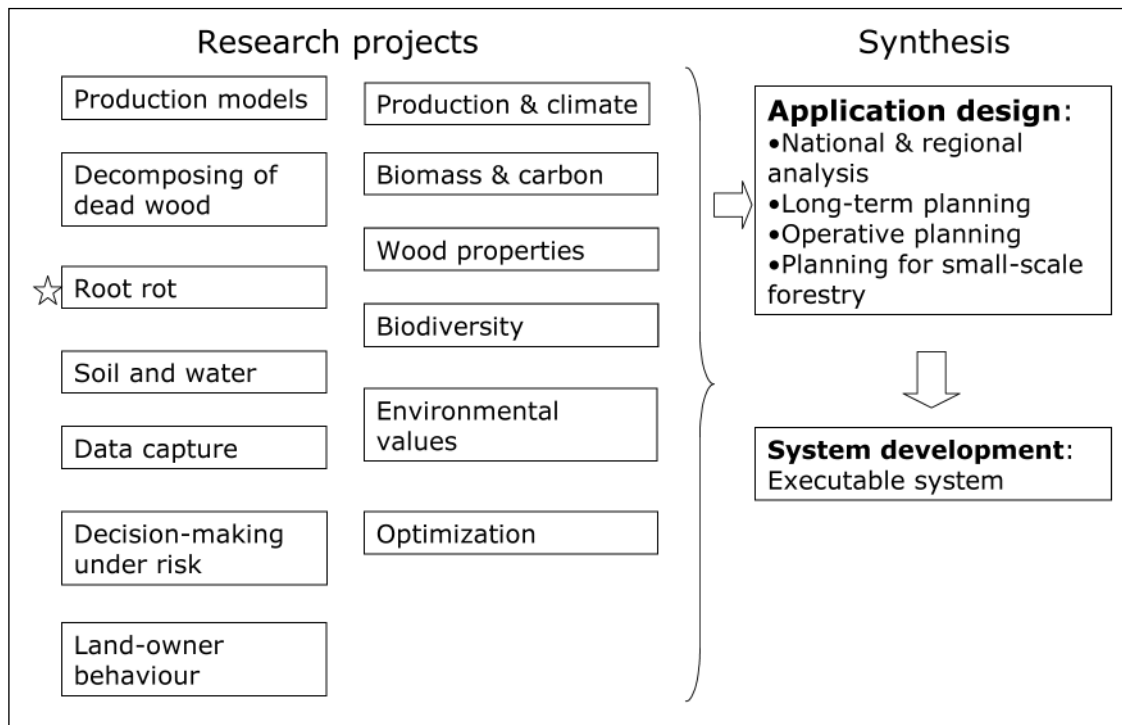


Figure 2—The principle of inter-disciplinary subprojects and syntheses in the multi-disciplinary Heureka project.

requirements needed by the end-users of such a tool, 2) clarify and collate the biological and management inputs required, and 3) construct a simulation prototype model. The project has been ongoing for 24 out of 36 months. Draft models and an interface have been produced, and are being tested. The range of conditions in the participating countries – as regards climate, forestry conditions, soils etc. – is challenging to the model. Also the basic growth and yield models differ significantly across the participating countries. Nevertheless, significant progress has been made: it is likely that the goals set for the project will be achieved within the 3-year time frame.

Heureka (Lämås & Eriksson, 2002) is a research programme developing computer based tools for forest analysis and planning in Sweden. Heureka uses a multi-disciplinary approach that includes 13 subprojects (fig. 2). Modeling of *Heterobasidion* is one of the 13 Heureka projects, with disease dynamics handled as in MOHIEF. Integrated applications will be designed from the projects, and associated systems will be developed. The project aims at four applications to serve different user groups.

1. National and Regional Analysis

This analyses modeling outcomes in terms of the state of the forest ecosystem, and supply and demand for various utilities. Basic data for this application could be the National

forest inventory, remote sensing data or information from estate data bases. Possible users include the Board of Forestry, the Environmental Protection Agency, forest owners' associations and organizations for forest fuels.

2. Strategic Planning in Large Forest Enterprises

The main focus is on wood production, but other values are also considered. Large forest areas can be handled. Optimizing methods are used to generate a strategic plan for the business. The application can generate future levels of cutting, net revenues etc., and also a list of stands proposed for harvest over the next 6 months to 3 years.

3. Operational Planning

The basis for operational planning in the short term (1 to 6 months) is the list of stands available for harvest created in the strategic planning application. The application will optimize the net revenues from timber and forest fuels, and allocate operations and transport.

4. Planning for Small-Scale Forestry

This application is aimed at smaller estates, and can also handle multi-purpose forestry and environmental issues. A problem area linked to this application is methods for data capture that keep costs low. The users are private forest owners, forest owners' associations, consultants and producers of forest management plans.

MODELING INITIAL CONDITIONS

Before modeling of disease dynamics, initiating data on the incidence of root rot are needed. At present, such information in stand records is limited. Consequently, the normal situation would be to model the root rot incidence in a stand. Current work (Thor and others 2005) uses a number of stand and site variables to model the probability of decay affecting a single tree. Data from the national forest inventory in Sweden were used to build the model. Records from over 45,000 Norway spruce trees were evaluated. These were analyzed for correlation between root rot incidence and environmental conditions. In a stepwise logistic regression, sets of functions were developed to show significance for the variables: stand age, site class index, temperature sum, elevation above sea level, tree diameter at breast height, soil moisture and texture, proportion of spruce in the stand, the occurrence of peat, and longitude. These parameters are commonly noted in most stand records in larger forest enterprises.

So far, the model only estimates the incidence of decay at breast height. A calibrating function is being developed to transform this to provide an estimate of rot frequency at stump level.

MODELING DISEASE DYNAMICS

For Fennoscandian conditions a model will be published within the MOHIEF structure (Pukkala and others, 2005). Dynamics of the disease are modeled on the basis of the development of the stand and by the changes in fungal dynamics over time. These sub-models are, however, not independent of each other.

To simulate tree growth, distance-dependent or distance-independent growth models for individual trees can be used. For cases in which there are no individual tree measurements available, a rectangular plot is generated from stand-level variables. Tree growth is calculated in 5 year time steps. The timing for thinning and clear-fell operations is triggered by basal area.

Modeling of the disease is based on the biology of *H. annosum* (Woodward and others 2003, Pratt and others 1998). The probability of spore infection is estimated for Scots pine and Norway spruce, depending on time of the year and the use of any stump treatment. Not all stumps that are spore infected transmit disease to adjacent trees. Growth and infectivity of the root system depends on its size, age and vitality. The growth rate of *H. annosum* is

much higher in dying roots of a stump than in a living tree. Once colonized, the root system is assigned a probability for transferring the pathogen to adjacent root systems. This process depends on soil conditions. When the fungus has reached a neighboring tree, the growth rate in the root system is simulated, as well as the spread of decay into the stem.

In cases of advanced decay in Norway spruce, tree growth is reduced. Young Scots-pine trees die more frequently after attack by *H. annosum* than do spruce trees.

MODELING ECONOMIC OUTCOMES

The effect of disease on the economic performance of a stand depends on growth reduction of infected trees, reallocation of produce assortments and their change in price, the costs of prophylactic treatment, interest rate, etc.

Once the models of the initial conditions and the dynamics of the disease are in place, the economic outcome for a number of feasible management schemes can be estimated. One tool for modeling the outcome of assortments is TimAn, developed at Skogforsk. TimAn is a software package for advanced analysis of bucking-to-order, and it covers stand inventory, construction of price lists, analysis and follow-up of the actual outcome. TimAn uses stem profiles for individual trees, which will be useful in these analyses.

APPLICATIONS OF THE MODELS

One of the main objectives of the disease model is to incorporate knowledge of root rot problems into forest planning by means of functions built into the planning systems of various forest enterprises. Stand-alone applications could be useful teaching tools, but will not help foresters or forest production researchers appreciate the significance of root rot problems.

Forester's point-of-view

When making strategic decisions it is crucial to include the impact of root rot in the analysis. For example, actions by large forest enterprises will definitely affect and may exacerbate future disease development. Issues to consider include altering the length of the rotation, modifying thinning schedules, exercising choice of tree species and use of protective treatments on stumps.

In turn, these factors will affect the potential harvest volumes and the assortment mix. One approach could be

scenario-handling, where different conceivable scenarios are hypothesized and the consequences are subsequently analyzed with the models. The models should predict average outcomes for large areas of forest: the high endemic variation requires caution when interpreting estimates on relatively small units, such as single stands or forests. Strategic decisions and policies based on this type of analysis are a practical way to use the models.

In the short term, down to a planning horizon of one year, the root rot situation should be considered as part of the ordering priority in which stands will be harvested. What are the consequences – for customers, for the supply organization, for the forest – of harvesting a Norway-spruce stand during the low-risk period instead of the high-risk period? What is the cost/benefit of applying stump treatment in thinning and clear-fell operations?

Supply organizations are likely to apply the models differently than companies with large forest holdings. Nevertheless, the basic need to incorporate root rot modeling into the planning process remains important for both groups.

Researcher's Point of View

A good model will describe the disease impact and improve understanding of the mechanisms involved in disease development. A sensitivity analysis can identify parameters critical to the outcome, and thus help to identify needs for research. Current work suggests that some issues are crucial, and need to be further investigated. They include the rate of expansion of disease centers and the probability of disease transfer in various soil types.

The type of modeling described above enables us to have a more complete understanding of the dynamics of *H. annosum*. In the typical sequence a primary descriptive model is developed (which has already been completed in several countries for root disease). After a period of research, data become available that allow for development of a more complex mechanistic model. Ideally this model improves our understanding so that critical processes can be described in further detail, enabling an iterative mechanistic approach to the process of modeling to be adopted. Used in this manner, modeling is a powerful means to achieve a more complete understanding of the processes involved in complex systems, such as the interactions between pathogen, host, soil, climate and human activity.

PRESENT CONDITIONS AND TIME-TABLE

With regard to modeling of *H. annosum*, there is a well-developed mechanistic model for Western North America (WRD model). In Europe a number of mechanistic models for *H. annosum* dynamics in a stand are under development. These models could be available, at least as prototypes, before the end of 2004.

Models to describe initial conditions in Sweden will be ready for practical use in 2004.

Models and simulation tools for detailed analyses of assortments and cost/revenue calculations exist, but they need to be modified to accommodate root disease dynamics.

COSTS AND REVENUES

In Sweden the primary problem with *H. annosum* occurs in Norway-spruce trees. However, the variation in conditions (rotation periods, management schemes, time of thinning and clear-felling) suggests a clear need for reliable quantification of the benefits of varying management schemes and measures taken in order to minimize the impact of root rot. Intuitively, stump treatment appears profitable in stands growing on productive soils with short rotations. The economic benefit is not equally obvious in stands growing on poorer sites with longer rotation periods. To handle this problem, tools are required; tools that the current projects could help to develop.

In Sweden, the difference between conifer pulpwood (in which decay is allowed to occupy 50 percent of the cross-section of a single log) and saw timber (in which no decay allowed) is about US\$ 19 (150 SEK) per cubic meter (Brunberg, 2003). With severe decay, a fuel assortment must be prepared, which doubles the value difference. Degradation due to decay has a significantly higher economic impact than a change from a higher timber class to a lower. Because large timber volumes are involved, even a small improvement in decay reduction results in large savings. A simple example from Sweden suffices: The annual saw-timber volume derived from Norway spruce is about 16 million cubic meters. Every one-percent of timber which could be reallocated from decayed to sound wood is worth US\$ 3 to 6 million (25-50 million SEK) to forest owners.

A typical stand with average Fennoscandian conditions would produce model outputs similar to those presented in

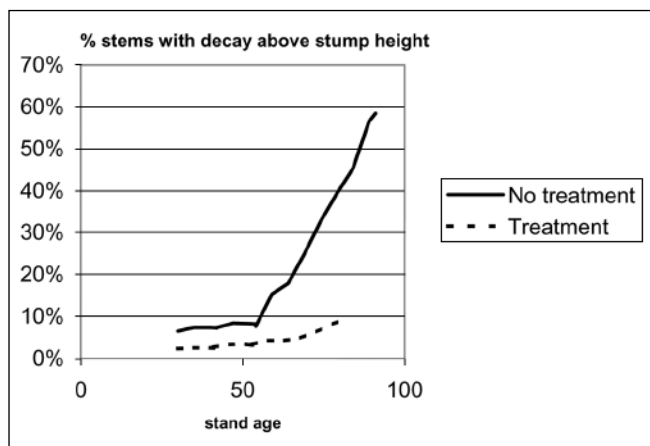


Figure 3—Example of results from a simulation of an average Fennoscandian Norway-spruce stand with two thinnings (at stand age 42 and 54). Estimated percentage of trees expressing some decay for two alternatives: Management with stump treatment in previous clear fell and both thinnings (“Treatment”), and management with logging during high-risk season and no stump treatment (“No treatment”).

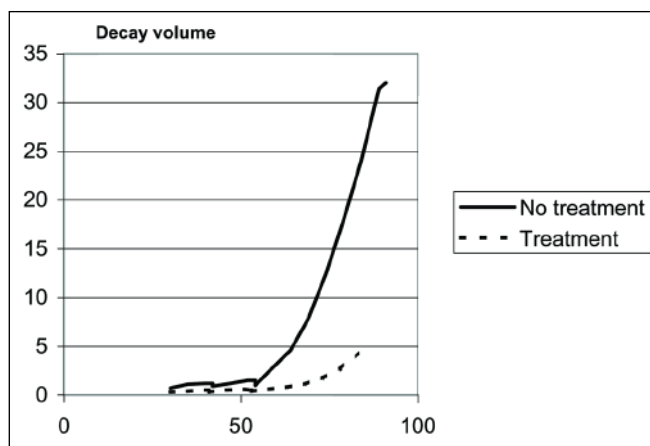


Figure 4—Example of results from a simulation of an average Fennoscandian Norway-spruce stand with two thinnings (at stand age 42 and 54). Estimated decay-affected volume for two alternatives: Management with stump treatment in previous clear fell and both thinnings (“Treatment”), and management with logging during high-risk season and no stump treatment (“No treatment”).

Figures 3 and 4. Note that the models used are somewhat preliminary. The output should therefore be regarded as illustrating the magnitude of the differences, rather than providing exact value differences.

CONCLUSIONS

Decay caused by *H. annosum* costs money for European forestry, but there are means of minimizing the effects.

It is possible to include dynamics of *H. annosum* in forestry planning, on strategic, tactical and operational levels.

Functions, models and tools for modeling *H. annosum* exist in part, and further models are under construction.

Integrating functions and models of *H. annosum* dynamics into existing forest growth and yield models are likely to result in more accurate and useful results than stand-alone applications.

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**FOREST
ASSESSMENT AND
PLANNING CASE
STUDIES**

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INTEGRATING SPATIAL OBJECTIVES INTO FOREST PLANS FOR MINNESOTA'S NATIONAL FORESTS

Howard M. Hoganson¹, Yu Wei², and Rickard H. Hokans³

ABSTRACT

National Forests in Minnesota are currently developing new management plans. Analyses for the plans are integrating the Dualplan forest management-scheduling model with DPspace, a dynamic programming model to schedule core area of mature forest over time. Applications have been successful in addressing a wide-range of forest-wide constraints involving 60,000 to 100,000 analysis areas, each with potentially thousands of treatment options. A key aspect for practical application has been trimming the list of possible treatment options for each analysis area without impacting optimality characteristics of the model formulations. Draft and deliberative results for the Chippewa National Forest suggest that the core area of mature forest can be increased substantially with little reduction in sustainable timber production levels. This is somewhat contrary to results from an aspatial model. Results also indicate that core area concerns are more of an immediate nature because past plans have not addressed spatial objectives. Careful planning is needed because existing core area of mature forest cannot be replaced rapidly once it is harvested. Given more lead-time, planning can increase core area over time.

INTRODUCTION

The Chippewa and Superior National Forests in Minnesota released their draft forest plans in April 2003. Analyses for the draft plans used the University of Minnesota's Dualplan forest management-scheduling model. Additional modeling work is refining schedules using DPspace, a spatial model based on dynamic programming. DPspace addresses explicitly the core area of mature forest produced over time in each major landscape ecosystem. Integrating the spatial model with the Dualplan model has been a critical step in the analysis process.

First, this paper describes the two models and an approach to link them. Then, the Minnesota situation is described and test results are presented for the Chippewa National Forest. Results presented are draft and deliberative test runs for the National Forests. They are not linked directly

with a specific forest-wide alternative presented in the draft environmental impact statement (USDA Forest Service 2003).

DUALPLAN

Dualplan is a forest management-scheduling model similar to linear programming (LP) models like the USDA Forest Service Spectrum model. Key differences with Dualplan are that it focuses on the dual formulation of the LP problem rather than the primal formulation (Hoganson and Rose 1984), and it subdivides the dual problem into many small subproblems that are each easy to analyze. Each subproblem of the dual is a simple stand-level optimization problem for one analysis area (stand). Estimates of the marginal costs of achieving the forest-wide constraints of the LP primal formulation are key to tying the subproblem analyses together. These estimates are used

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like market prices in the dual to value the effects of each stand-level treatment option on each forest-wide constraint. Initially the user estimates these marginal costs for Dualplan. Dualplan iteratively re-estimates them after using them to develop a forest-wide schedule. This initial schedule is optimal mathematically, but likely infeasible because of errors in the estimates of the marginal costs. Dualplan then uses information about the infeasibilities of the forest-wide constraints to re-estimate the marginal costs of the forest-wide constraints. For example, if the harvest volume for a specific time period is constrained to meet a minimum level and the resulting management schedule falls short of that level, then the estimate of the marginal cost for that constraint is likely too low, so the estimate is increased for the next iteration in Dualplan. In early applications of Dualplan, like those for the Minnesota Generic Impact Statement on Timber Harvesting in Minnesota (Jaakko Pöyry Consulting 1994), emphasis was on satisfying forest-wide constraints associated with timber production. Recently, many options have been added to track and constrain forest ecological conditions over time. Currently the USDA Forest Service is using Dualplan to analyze a range of forest-wide alternatives for the two National Forests in Minnesota. Besides constraints on timber production levels, these applications have recognized constraints that help describe desired future ecological conditions for the forest. Constraints have addressed: (1) the age distribution of the forest in each landscape ecosystem, (2) area targets for selected forest cover types over time in each landscape ecosystem, and (3) biodiversity values associated with having a mix of forest cover types and ages. This last set of constraints is similar to the concept of downward sloping demand curves for timber where less of a forest condition in a given time period implies a higher value for that condition in that period.

Dualplan can use either a model I or model II type of formulation for addressing the stand level problems (Johnson and Scheurman 1977). A model II formulation is usually more efficient because it eliminates the need to enumerate many combinations of first-rotation treatment types and rotation lengths with similar options for future rotations. Dynamic programming can be used to solve the stand level decision trees. An example decision tree (fig. 1) helps show how the size of such trees depends more on the number of options considered for future rotations than on the number of options considered for the current rotation. Options to convert to other forest cover types at the end of the first rotation can increase substantially the size of the decision trees for individual stands.

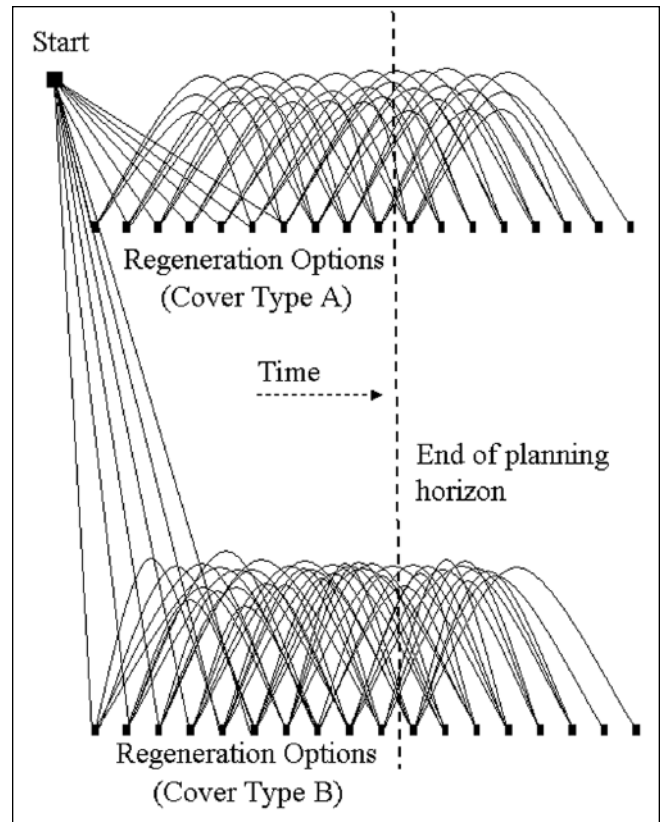


Figure 1—A stand-level decision tree linking first rotation options with regeneration options.

DPSPACE

DPspace is a forest management-scheduling model designed to address the spatial arrangement of the forest. Specifically, it can track and value the amount of core area produced. It uses a dynamic programming (DP) formulation of the problem similar to the formulation used by Hoganson and Borges (1998) to address adjacency constraints. Also similar to Hoganson and Borges (1998), a series of overlapping subproblems are used to address large problems. These overlapping subproblems are similar to moving windows used in geographic information systems where a separate DP formulation of the problem is solved for each window. For each window in the moving windows process only a portion of the solution will be accepted. The portion accepted is the portion of the window not to be included in the next window. It is the portion farthest from the remainder of the forest yet to be analyzed in the moving windows.

Core area is assumed to be area of the forest that meets specific age requirements and is surrounded by a protective

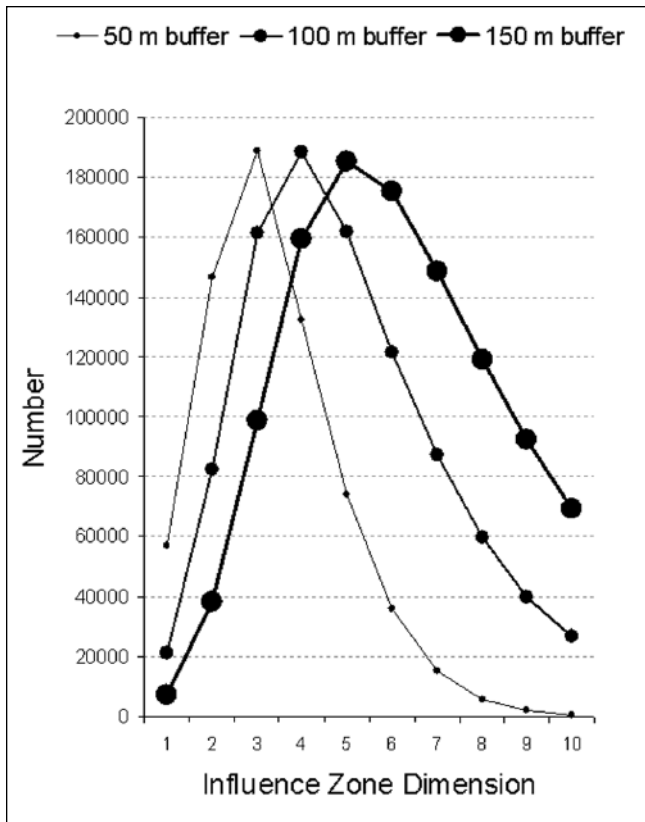


Figure 2—Breakdown of the Minnesota National Forests in terms of the number of influence zones by influence zone dimension.

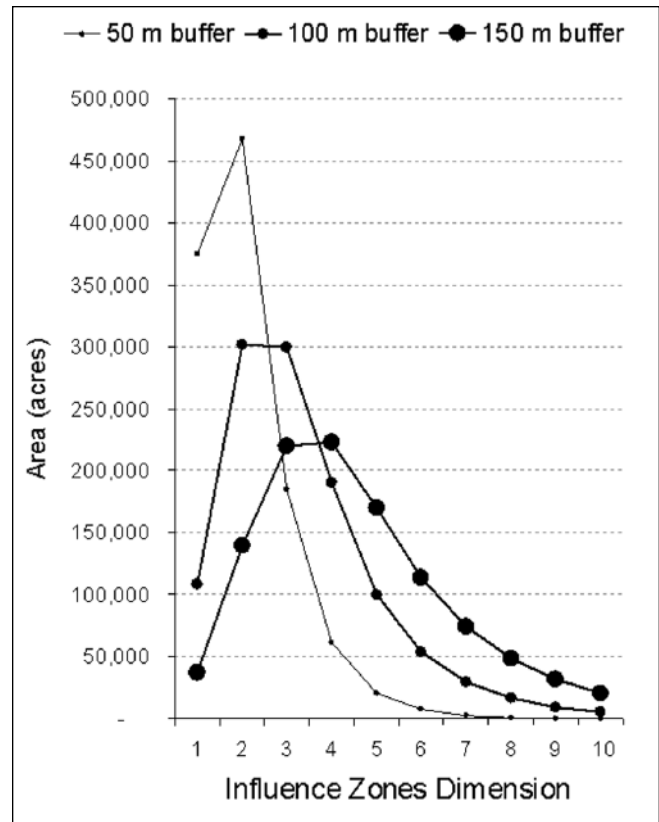


Figure 3—Breakdown of the Minnesota National Forests in terms of the area of influence zones by influence zone dimension.

buffer. Öhman and Eriksson (1998) recognized core area as an important spatial factor to address in forest management scheduling models. Core area of mature forest was identified as an important spatial measure to address in planning in Minnesota by the interdisciplinary planning team for Minnesota’s National Forest (USDA Forest Service 2003). For DPspace applications for both the Chippewa and Superior National Forests in Minnesota focus has been on the production of core area of mature forest. A 328-foot (100-meter) protective buffer distance has been assumed with minimum ages for core area varying by forest cover type and approximately equal to the age of financial maturity for each forest cover type. Minimum age for protective buffer also vary by forest cover type and are approximately 20 years younger than the age requirement for the core area.

DPspace uses “influence zones” to define the spatial interrelationships that impact the production of core area. The set of influence zones for a forest can be thought of as simply a map of the forest that indicates, for each point in the forest, those stands that influence that point in terms of its potential to produce core area. Each influence zone is a region of the forest that is influenced by the same set of

stands. Each influence zone may not be contiguous. In most existing large stands there will be a center core area that is influenced only by that stand itself. Other areas in the same stand are influenced by additional stands if they are within the core area buffer distance of the stand boundary. Generally for a forest as a whole there are many more influence zones than stands. Each influence zone can be labeled by the stands that influence it, and the number of stands influencing it can be considered the influence zone’s dimension. For example an influence zone ABC is influenced by stand A, stand B, and stand C because all of that influence zone is within the core area buffer distance from each of those stands. It has a dimension of three because it is influenced by three stands. A frequency distribution of influence zone numbers by influence zone dimension for the Minnesota’s National Forests (fig. 2) shows that the dimensions can be large and that the distribution is quite sensitive to the assumed core area buffer distance. Many influence zones involve three or more stands. Comparing the frequency distributions (fig. 2) with corresponding distributions of influence zone area (fig. 3) shows that the lower dimensioned influence zones are substantially larger in area on average. They contain a much larger portion of the forest

than the frequency distributions might suggest. With a 328-foot core area buffer distance, relatively little area is in influence zones involving more than six stands. As one would expect, with larger buffer widths, more of the forest involves more area in higher-dimensioned influence zones (fig. 3).

Each stage in the DP formulation used for solving each subproblem (moving window) corresponds with a stand-level decision. The decision addressed at each stage in the network is the choice of the management treatment option to assign to the corresponding stand. Treatment options are defined using a model I format (Johnson and Scheurman 1977) with a separate arc for each option. State variables for each stage describe the treatment options selected for some stands addressed in earlier stages of the network (much like a simple decision tree). Each stand remains as a state dimension of the DP tree in later stages of the network until all other stands it “influences” have also been represented by a stage decision. A stand influences another stand if there exists an influence zone that both stands influence. Each influence zone is incorporated into the decision tree at the last stage in tree that corresponds with one of the stands that makes up its influence zone dimension. For example, assuming influence zone ABC is influenced by stand A, stand B and stand C, and stand C is the last of the three stands addressed in the DP network, then the condition of the influence zone can be evaluated for all arcs associated with stage C nodes. This condition is based on: (1) the treatment option for the corresponding stand C arc and (2) the corresponding conditions for stand A and stand B as defined by the stand A and stand B state variables for the corresponding node at the start of stage C.

Addressing the production of core area in the DP network is complicated somewhat by the assumption that the buffer area surrounding core area need not meet the required age of core area itself. In effect, each subcomponent of each influence zone (subcomponents defined in terms of the stand in which the it resides) must be examined separately. For all stands making up the influence zone, its portion of the influence zone will produce core area if the stand meets the age requirements of core area and all other stands in the influence zone meet the minimum buffer age requirements for core area. When addressing each influence zone in the DP network, these checks must be made for all subcomponents of the influence zone. It is not simply an all or none answer as to whether an influence zone produces core area during each period.

INTEGRATING COMPONENTS

A shortcoming of the DPspace model is its inability to address forest-wide constraints directly. Its focus is on integrating spatial and aspatial considerations assuming that the aspatial value of each stand-level treatment option is known. Net present value (NPV) estimates for the aspatial aspects of each treatment option for each stand is a key input to the model. These input values need not be based strictly on timber returns. They provide an opportunity for a direct linkage with the Dualplan model to consider forest-wide constraints. In the Dualplan solution process, stand-level treatment options are valued taking into account forest-wide constraints. Rather than view the Dualplan process as selecting one option for each stand, one can use the same approach to estimate the aspatial value of various treatment options to be recognized in DPspace.

The linkage described above is straightforward. But several factors make the problem challenging. First, the DPspace model will be impractical to use for large problems if most stands require a large number of treatment options to be considered in the spatial model. DPspace uses a model I format. Converting stand-level decision trees, like those shown in figure 1, to a model I format results in many treatment options per stand. Second, if spatial values addressed in DPspace are large, then the aspatial solution may be impacted substantially causing some violations of the forest-wide constraints in the aspatial model. In other words, the shadow price estimates from Dualplan alone are not likely accurate estimates of the marginal costs of the modeled, aspatial forest-wide constraints if they don't take also into account the spatial aspects of the problem.

To help keep the number of treatment options small for the spatial model without eliminating potentially optimal treatment options, a treatment trimming model was developed that uses both the results from Dualplan and a detailed analysis of the influence zones that define the potential for each stand to contribute to the production of core area. Two basic factors are considered for dropping a treatment option in the trimming process. First, treatments are dropped if crediting the treatment option for spatial benefits from all stands it influences spatially cannot raise its total value above the maximum aspatial value of the stand based on its best aspatial treatment option. Second, a treatment option can be dropped if there exists another treatment option that has a greater aspatial net present value and that other option spatially dominates the treatment option to be dropped. A treatment option spatially dominates another if it meets core area condition requirements in all time periods that the other treatment option meets core area condition requirements.

To recognize the impact of spatial considerations on achieving aspatial forest-wide constraints, Dualplan and DPspace were linked such that the DPspace solution becomes an intermediate solution in the Dualplan iterative process. Essentially the subproblems of the Dualplan model are no longer independent, single stand-level problems. Instead, the overlapping subproblems from DPspace are the Dualplan subproblems. Dualplan uses a summary of the DPspace solutions in terms of the measures of the forest-wide constraints to re-estimate the shadow prices for the forest-wide constraints. The process is repeated until schedules are found that are “near-feasible” in terms of the forest wide constraints. For each repetition (iteration), stand-level treatment options are re-evaluated and trimmed for use in DPspace based on the updated forest-wide shadow price estimates from Dualplan.

Multiple runs of the entire system can be done to examine a range of assumptions about the value for core area. Management schedules are easy to link with GIS systems for further analysis because schedules produced are spatially explicit.

MINNESOTA APPLICATIONS

Dualplan has been used to analyze seven forest-wide alternatives for each National Forest in Minnesota. These alternatives have focused on sustaining timber harvest levels over time while moving the forest closer to desired future conditions. Desired future conditions are defined specifically for each of seven landscape ecosystems in the Chippewa National Forest and each of eight landscape ecosystems in the Superior National Forest. Forest-wide alternatives differ in terms of assumptions defining desired future conditions and the rate at which the forest is moved towards the assumed desired future conditions.

For both forests the planning horizon consists of ten ten-year periods. Analysis areas (AA's) are spatially explicit with over 67,000 AA's for the 549,000 acres modeled for the Chippewa National Forest. Over 101,000 AA's are used for the 1,212,000 acres modeled for the Superior National Forest. Many of the AA's are substands representing riparian areas along lakes and streams. Seventeen silvicultural treatment types were recognized, representing various types of even-aged and uneven-aged management. For each treatment type, a range of harvest timings was considered. Twenty forest cover types were recognized for each forest with five timber-productivity site-quality classes for most all types. Desired future conditions for each landscape ecosystem were defined in terms of a desired mix of forest cover types and a desired stand age distribution. Natural succession was modeled recognizing that some stands change forest cover

type over time without treatment. Estimates of pre-settlement age distributions and stand replacement fire intervals served as a benchmark for defining desired future conditions and the rate at which harvesting is applied to mimic stand replacement fires.

Forest cover type conversion (restoration) options were an important consideration for stand-level decisions because desired future forest-wide conditions were defined in terms of a desired forest cover type mix. This added substantially to the number of treatment options modeled for most stands. Five key map layers influenced the set of treatment options considered for each stand. Besides the landscape ecosystem and riparian map layers described earlier, other layers included a map of management areas, a map of scenic classes and a map identifying sensitive areas for a number of plant and animal species. The map of management areas included 18 classifications used by the Forest Service to help define the theme of each alternative. For some forest-wide alternatives that emphasize older forest conditions, management area classifications limited treatment options substantially.

Tests of the spatial model for the National Forest applications focused on a forest-wide alternative somewhat similar to the alternative with the highest timber harvest level in the draft forest plan. That alternative was identified in the draft environmental impact statement (USDA Forest Service 2003) as the forest-wide alternative with the most fragmentation of mature forest over time. That alternative would also likely be the most complicated alternative to model simply because, on average, it is the least restrictive and thus involves more possible treatment options for each analysis area. Multiple model runs of the integrated modeling system were applied, varying the value of mature forest core area between applications. For each application, multiple iterations of the integrated model were needed to account for the impact of valuing core area on the marginal cost estimates for the many aspatial constraints. These aspatial constraints defined desired future conditions for each landscape ecosystem and sustained timber harvest levels over time. For all the values of mature forest core area examined, the aspatial constraints were satisfied after multiple iterations of the integrated modeling system. The resulting management schedules are potentially improved schedules in that they are near-feasible in terms of the aspatial constraints and produce more core area of mature forest.

Core area is valued in terms of dollars per acre per decade with values assumed to occur at the end of each decade. Assuming a four percent annual discount rate, a price of \$100 per acre per decade for core area, and that the midpoint of the first decade is used as the base year for

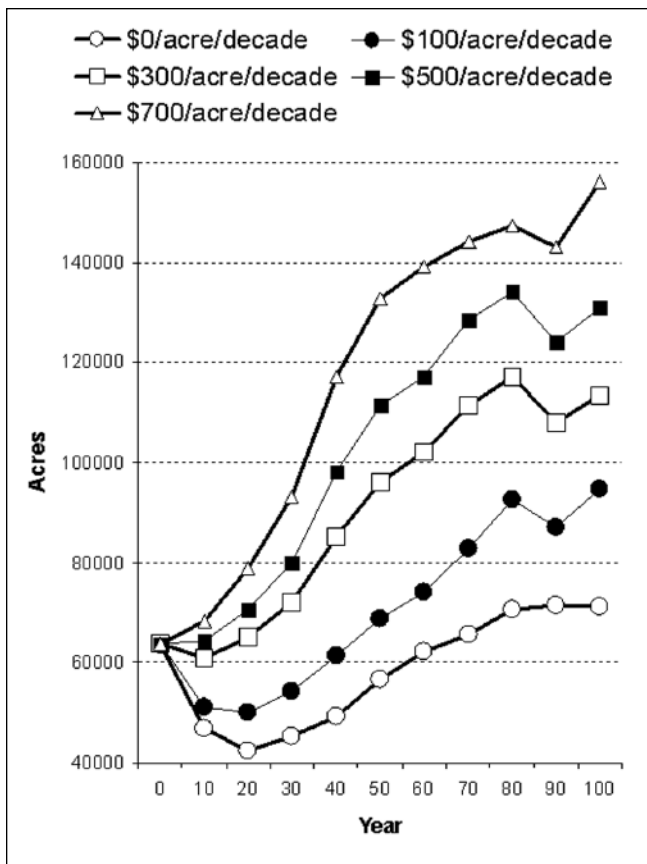


Figure 4—Impact of core area values on upland core area production for five model runs for the Chippewa National Forest.

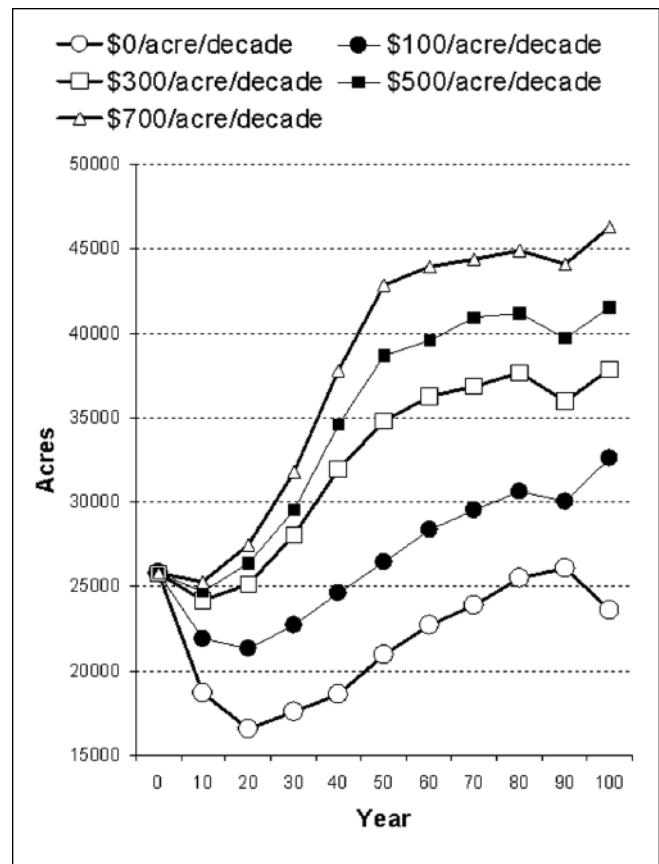


Figure 5—Impact of core area values on lowland core area production for five model runs for the Chippewa National Forest.

NPV calculations, then an acre that produces core area in every decade over an infinite horizon has a NPV of approximately \$253 per acre.

Results of the test applications were similar for both National Forests. Here, results are presented only for Chippewa National Forest. Two types of core area were valued and tracked for both forests: upland forest core area and lowland forest core area. Both types had core area minimum stand age requirements that varied by forest cover types with a minimum age of at least 40 years for all forest cover types. Core area value assumptions impacted core area production levels quite similarly for both uplands (fig. 4) and lowlands (fig. 5). Results for the \$0 per acre per decade value are equivalent to the Dualplan results where core area was not valued. Without valuing core area, core area levels decline substantially over the first two decades (fig. 4 and fig. 5). It should not be surprising that the draft environmental impact statement for the Minnesota Forest Plan (USDA Forest Service 2003) raises concern

about potential declines in core area of mature forest. Raising the core area values to \$100 per acre per decade raises the amount of mature area for both uplands (fig. 4) and lowlands (fig. 5) in the later decades, but there is still a decline in the early decades from the starting condition. A core area price of approximately \$300 per acre per decade is needed before such a drop is not present in the early decades. For the core area values modeled, higher values for core area led to higher core area output levels for both uplands and lowlands, with levels substantially higher in the long-term than in the short-term. Increases are less in the short-term because of the time required to produce larger blocks of mature forest that are relatively well suited for producing core area. In past planning efforts producing core area of mature forest was not a primary objective, so it is not surprising that the intermediate-aged stands are not arranged spatially such that they can produce large quantities of core area when they soon reach the minimum age requirements for core area of mature forest. With more lead-time and planning, substantially more core area can be produced in the longer-term (fig. 4 and fig. 5).

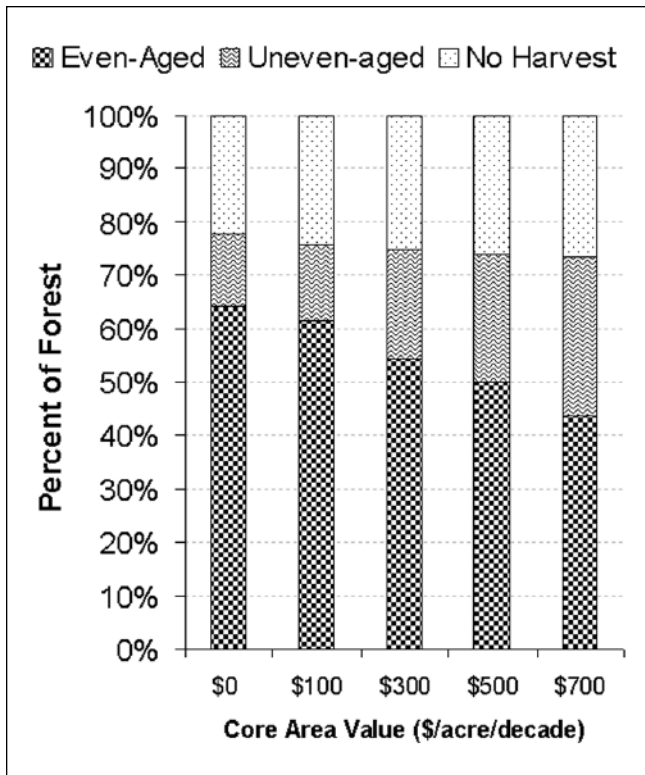


Figure 6—Impact of core area values on the type of stand-level management options selected for five model runs for the Chippewa National Forest.

Recognizing higher core area values tended to shift optimal management strategies from even-aged management to uneven-aged management (fig. 6). However, even-aged management was still predominant even at the highest core area values examined. Higher core area values also tended to lengthen rotation ages. As one might expect, higher values for core area resulted in larger patches of mature forest.

Results did not suggest that current harvest blocks should be large so as to later produce more core area. With levels of core area more difficult to increase in the short-term, designing harvests to focus more on what remains on the landscape in the short-term seems of more importance than the size and shape of harvests. Focus is more on what remains on the landscape rather than on what is harvested.

Model applications were performed using a Dell workstation with two 1.8 GHz processors and 512 MB of memory. Each iteration of DPspace took approximately one hour for the Chippewa National Forest and two hours for the Superior National Forest. Several heuristics have been used to help reduce the number of iterations needed for DPspace model. In effect, more iterations of the much faster Dualplan model are applied with heuristics incorporated to

tie solutions to the DPspace results. These heuristics are not applied in the last iteration of the process so as not to impact optimality characteristics of the final solution. Solutions that are close to satisfying all of the aspatial constraints have generally been found in approximately 10 to 20 iterations of DPspace. Publications to describe and test the specific details of the modeling process are in progress. The overall process for integrating the models shows enormous potential for improvement as intermediate iterations of the DPspace model unlikely need to use all stands or all influence zones. Early and intermediate iterations of the process can also likely use smaller subproblems (moving windows). The ability to use current shadow price estimates to screen and trim stand level alternatives is a key component of the modeling system. Like with Dualplan, intermediate iterations of the integrated model are done simply to help find better estimates of the shadow prices associated with the forest-wide aspatial constraints. Once good estimates are found, the DPspace model seems quite effective at finding near-optimal spatial solutions for the problem as it is formulated mathematically

Future work is needed to better automate system details for use by others. Improvements in the system can likely be achieved by better understanding how heuristics might be best used to help speed the solution process. Clearly, a key in application is having the ability to apply many model runs to learn about key model assumptions and trade-offs. In future research it seems desirable to consider options for recognizing multiple types of core area and other spatial measures. Linkages to forest plan implementation are also important, as issues are complex without simple guides for managers. The ability to decompose large problems into parts makes the system especially appealing. It suggests opportunities for large-scale collaborative planning involving multiple ownerships and model expansion opportunities to consider additional facets of the problem.

CONCLUSIONS

A modeling system closely tied to optimization techniques has been developed to better integrate timber harvest scheduling with ecological objectives of moving forests closer to desired future conditions. Desired future conditions are complex conditions that are difficult to define, varying by ecological land classes and involving species and age composition of the forest as well as its spatial arrangement. Core area of mature forest has been the spatial measure of focus in modeling applications by the National Forests in Minnesota. Test applications have found that relatively high timber harvest levels can be sustained while increasing the amount of core area of mature forest over

time. Spatial arrangement of the forest has not received attention in past planning efforts so it is not surprising that considerable time is needed to improve spatial conditions over time. Without recognizing spatial detail in planning, timber harvesting can reduce the existing core area of mature forest quite rapidly.

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LANDSCAPE CHANGES FROM MANAGING YOUNG STANDS A Fall Creek LSR Modeling Study

Brian McGinley¹, Allison Reger², Gary Marsh¹, and Kirk Lunstrum³

ABSTRACT

Public land agencies continually seek a better understanding of spatial and temporal changes in forested landscapes to guide successive management decisions. The 1994 Northwest Forest Plan developed a network of Late-Successional Reserves (LSR) with the primary goal of protecting and improving late-successional habitat. Improving LSR habitat can involve silviculture treatments in stands less than 80 years old, which would improve stem growth, canopy height complexity and understory community development. The Fall Creek Modeling Study, using TELSA (Tool for Exploratory Landscape Scenario Analysis), explores connections among young stand management strategies and resulting landscape habitat patterns. TELSA is a spatially explicit planning tool that simulates succession, natural disturbances, and management actions on a landscape over time. The Fall Creek LSR is a typical mosaic of young stands, fragmented late successional habitat, and high road densities created by intense forest management. The impetus for this project was insufficient funding to promote late-successional habitat by the thinning of all available hectares over the next 50 years. This modeling study evaluated a number of resource-driven scenarios for selecting prescriptions and prioritizing stands for treatment. The team used spatial mapping and stand simulation tools to assess the effects of these thinning scenarios on LSR habitat patterns over a 200 year period. For specific landscape objectives, such as interior habitat or mimicking natural fire patterns, location of habitat improvements from thinning are shown to be more valuable than total hectares of improved habitat.

INTRODUCTION

Public land agencies continually seek a better understanding of spatial and temporal changes to forested landscapes and to use this understanding in successive management decisions. Recent focus has moved toward complex assessments of forest habitat changes across large landscapes. This shift has been partially prompted in the Pacific Northwest by desires to protect old growth forests and its dependent species.

The 1994 Northwest Forest Plan, with a network of Late-Successional Reserves (LSRs), is an example of this focus on managing forest habitat changes across large-scale landscapes. One option in the LSR network strategy is

using silviculture treatments to improve late-successional habitat conditions within young stands less than 80 years old.

Thinning is accepted as a useful tool for accelerating vegetative development toward late seral conditions (USDA,USDI 1994; USDA,USDI 1998). Although much debate still remains on the best treatments or stand-level designs to apply, thinnings can effectively influence species composition, stem growth, canopy complexity, and understory communities in residual stands.

With most thinning in LSRs occurring in established plantations, managers should anticipate the temporal and spatial influence these plantations can have in shaping the

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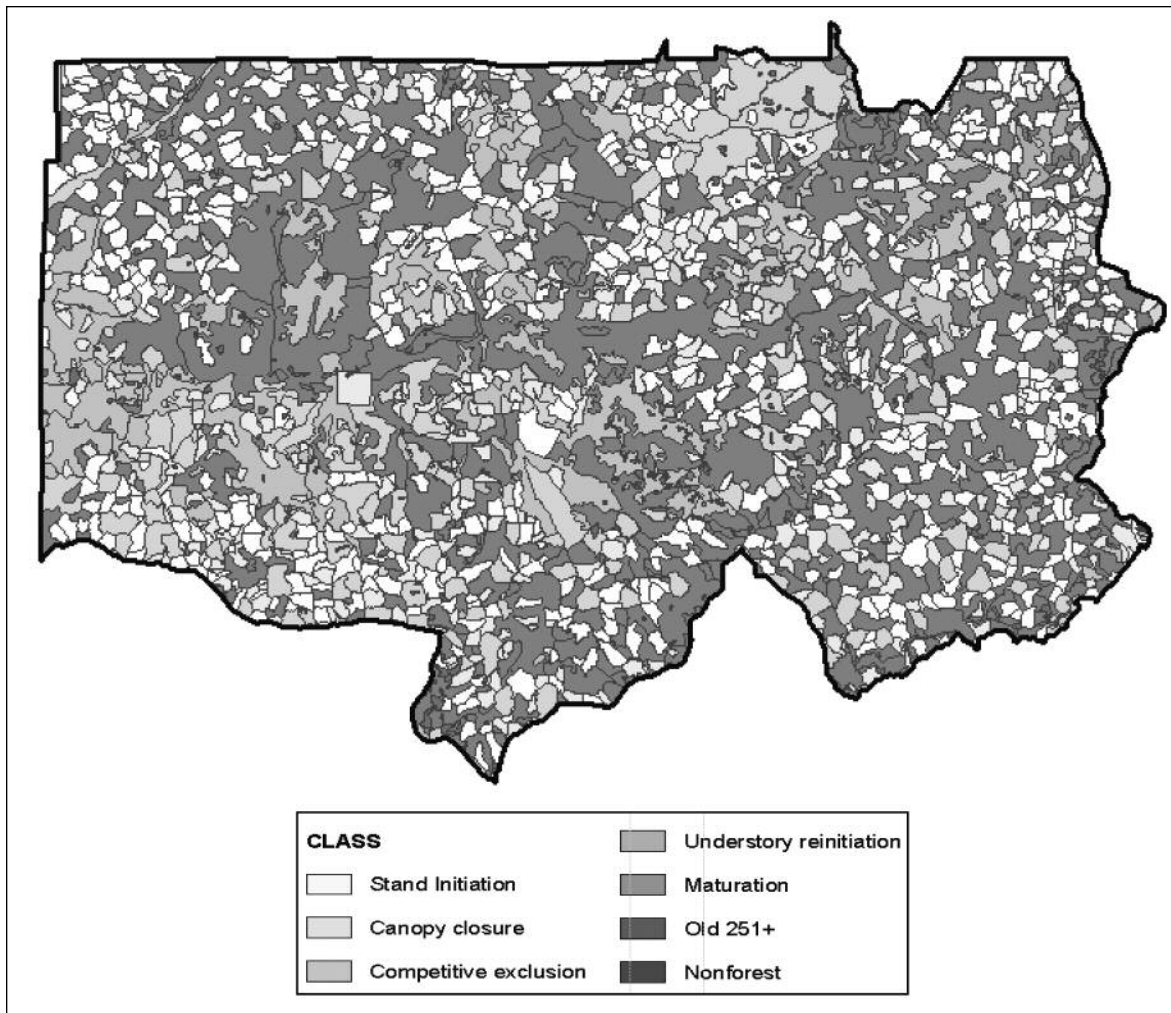


Figure 1—Existing Stand Conditions within the Fall Creek LSR.

landscape patterns of late-successional habitat. Plantations comprise around 25 to 35 percent of most large LSRs in the Mid-Willamette network, making their landscape role significant.

The Fall Creek Modeling Study explores the connections among young stand management strategies and resulting landscape habitat patterns.

STUDY AREA

The Fall Creek watershed and LSR were combined to create a 36,338 hectares analysis area on the Willamette National Forest (fig. 1). While 20 percent of the area is classified in the Forest Plan as outside the LSR boundary, this analysis was simplified to focus only on LSR objectives.

The Fall Creek analysis area is well fragmented with about 45 percent (16,498 hectares) occurring in plantations. Only one-third of plantation hectares have been thinned prior to age 20, with another one-third beyond the optimal age range for precommercial thinning.

Over the next 50 years, roughly 22,719 hectares will potentially be available for thinning, assuming multiple entries are prescribed in many candidate stands. This includes 2,328 hectares of 40 to 80 year old stands currently available for thinning in the next 10 years.

The Fall Creek LSR is well roaded with some of the highest road densities in the Mid-Willamette LSR network. About 89 percent of Fall Creek hectares have a road density of greater than 1.2 km/sq. km. A minimum

road network for this LSR includes only 23 percent (226 kilometers) of its total road system.

MANAGEMENT SITUATION

The Forest Plan identifies two principal goals for thinning stands less than 80 years old in LSR's: 1) to develop old growth forest characteristics, and 2) to reduce the risk of large-scale disturbance events like wildfire (USDA, USDI 1994, pp. B-5-6).

The Mid-Willamette LSR Assessment identifies more interior habitat and lower road densities as key management objectives for the Fall Creek LSR (USDA, USDI 1998). Enhancing late seral connective corridors along its eastern boundary is another focus for the Fall Creek LSR. While plenty of thinning opportunities exist in the analysis area, the Willamette National Forest does not expect to have sufficient funding or staffing to thin all available hectares over the next 50 years.

Current thinning efforts are using the same oldest/largest/closest-first priority strategy used in placing clearcuts on the landscape. A thinning strategy built from resource objectives for prioritizing stands is likely to create greater landscape habitat benefits.

MANAGEMENT SCENARIOS

This analysis evaluated a number of resource-driven management scenarios for selecting thinning prescriptions and prioritizing young stands for treatment. The following briefly describes the scenarios examined.

Management Scenarios

Scenarios are comprised of management constraints, a stand priority strategy, and thinning prescriptions. Commercial thinning prescriptions could potentially occur at one or more of three stand ages (40, 60 and 80 years) and at one of three treatment intensities (light, medium, heavy). There were six scenarios studied, each meeting a single resource objective or providing a benchmark for comparison.

1) The **No Action** scenario was modeled to provide a point of comparison. In this scenario no action was taken on any stands permitting the managed stands to now follow natural succession.

2) The **Owl Sites scenario** focuses on young stands within 2.0 kilometers of nesting activity centers and uses nesting success to prioritize activity centers. The objective of this scenario was to improve habitat near northern spotted owl nest sites.

3) The **Roads scenario** focuses thinning on habitat improvement and reducing road densities in land blocks (roadsheds) possessing high aquatic risk ratings (USDA, 1999). Thinning entries into roadsheds were spaced at least 20 years apart to allow for road closures and decommissioning. The objective of this scenario was to reduce aquatic risks through habitat improvement and lower road densities.

4) The **Natural Fire scenario** uses thinning to create habitat conditions predicted from defined natural fire regimes. Fire frequency, fire intensity and slope position were used to define resulting habitat conditions and assign treatments. This scenario was developed to mimic vegetative patterns created by natural fire regimes.

5) The **Interior Habitat scenario** focuses on young stands surrounded by or next to large interior habitat blocks. Thinning intensity was reduced to minimize edge effects on existing late-successional habitat and to expand large interior habitat blocks.

6) Finally, a **Two-Thin Benchmark** was applied to all young stands to provide an upper limit of thinning for comparing with other scenarios. This scenario was the most aggressive thinning strategy.

Several iterations of each scenario were tested to look at a range of possibilities.

Analysis Tools

The analysis team used spatial mapping and stand simulation modeling tools to assess the effects of thinning treatments on LSR habitat patterns. TELSA (Tool for Exploratory Landscape Scenario Analysis) is a strategic, landscape-level planning tool that can project planning strategies onto a landscape and assess long-term spatial and temporal effects using a range of performance indicators (ESSA, 1999).

PNW_GAP (originally ZELIG-PNW) is a stand growth simulator used to track stand attributes along development curves in response to thinning treatments (Garman, 1999). Garman (1999) tested a variety of thinning prescriptions for accelerating the development of late-successional stand attributes. These tools were used to apply thinning schedules for each scenario to the landscape and project late-successional attribute development over a 200-year time period.

Late-Successional Stand Attributes with Minimum Thresholds

Garman (1999) simulated a wide range of thinning

treatments on a 40-year old Douglas-fir stand that had been precommercially thinned at age 12 years. He tracked thinning effects on five late-successional attributes and the time needed to reach threshold values. (See attributes with minimum thresholds below).

Garman also used a composite Late-Successional Index (LSI) for tracking when stands meet all three live stand attribute thresholds. The Fall Creek analysis team focused only on the three live stand attributes and LSI to evaluate scenario influences on late-successional habitat and other management goals. The snag and downed wood attributes were not used in this study, because they could be readily created (topping or felling) once minimum large bole densities were achieved.

Thinning prescriptions selected from Garman's simulations for this analysis quickly met thresholds for the live stand attributes and matched other scenario objectives.

Late-successional Criterion

1. Density of large boles >100 cm
 - 10 boles per hectare
2. Canopy Height Diversity Index
 - Index = 8.0
3. Density of shade tolerant boles >40 cm
 - 10 boles per hectare
4. Density of snags >50 cm
 - 10 boles per hectare
5. Mass of logs >10 cm at large end
 - 30 Mg/ha

The TELSA spatial model was used to map stand attributes across the landscape at different time points for each scenario. Other key landscape attributes were used to evaluate scenarios (see below).

BUILDING RESOURCE SCENARIOS

TELSA, a spatially explicit model, requires data in a vector-based format. Several GIS layers used in this analysis included vegetation and planning area boundaries.

Using GIS technology the landscape was stratified into planning zones. Planning zones signify areas with discrete management goals or areas requiring separate reporting of results. Planning zones common to all scenarios were the project area boundary and transportation routes.

Transportation routes entered into TELSA tracked which roads were used during thinning operations and how long each road was left inactive (unused by thinning activities).

A combination of unique planning zones and thinning prescriptions customized each scenario to achieve key resource objectives highlighted by the scenario. In response to limited budget assumptions, the Fall Creek analysis team also created priority management goals for thinning within planning zones. These unique planning zones defined the key difference between resource scenarios. Each scenario had 1 to 2 additional planning zones added for stratifying the landscape based on differing management goals. Planning zones specific to each scenario are discussed below.

1) **No Action Scenario:** This scenario used no unique planning zones and no management was applied to the landscape. The scenario provided a point from which to measure the effects of thinning stands.

2) **Owl Scenario:** This scenario focuses habitat improvement in young stands near known spotted owl (*Strix occidentalis caurina*) activity centers. Based on monitoring data on the nest site occupancy and reproductive success, owl habitat centers were ranked into three site categories. A 1.1-km buffer around nest sites and the sites corresponding ranking became planning zones in the TELSA model. A two-thin prescription (a moderate thin at age 60 years, light thin at 80 years) was selected for all stands.

This prescription was selected by the analysis team to maintain forest cover and canopy closure for potential owl dispersal and foraging opportunities, while attaining threshold values of late-successional attributes quickly.

Owl scenario iterations differed in which owl circles were treated and which were left to natural succession.

3) **Roads Scenario:** This scenario divides the landscape into management blocks called "roadsheds"—lands that would feasibly log to a local road system. Roadsheds varied in size from 1,500 to 4,000 hectares. Two criteria were used to prioritize roadsheds for thinning and resulting road closures:

- a. Aquatic risk rating
- b. Plantation hectares available for thinning

The roadsheds and priority ranking were integrated into the TELSA model as a planning zone.

4) **Natural Fire Scenario:** Fire regimes defined in the Integrated Natural Fuels Management Strategy (USDA, USDI 2000) served as a template for the Natural Fire scenario. These fire regimes as identified for the study area became a key planning zone map in the model. These three regimes can be briefly described as:

1. moderate frequency/mixed severity;
2. low frequency/mixed severity; and
3. low frequency/high severity.

Slope position (lower 50 percent of the slope and the upper 50 percent of the slope) was a second planning zone added to include the variation of fire effects due to slope position. Thinning prescriptions were selected to match the stand conditions likely to result from representative fire events under these regimes. Moderate frequency areas received a two thin prescription (upper slopes – heavy at age 40 years, moderate at 80 years; and lower slopes – moderate at 40 years, light at 80 years). Low frequency areas received one heavy thin at age 60 years in the upper slopes only.

5) **Interior Habitat Scenario:** Old growth dependent species thrive best in late successional interior habitat, which provides higher relative humidity, moderated temperatures, and desirable physical structure. Interior habitat (IH) is also generally free of invasive and competing non-native species. As a rule, interior habitat conditions in late-successional stands improve as you move further from edges with early seral conditions.

This scenario was designed to focus thinning in young stands that help expand existing interior habitat (IH) blocks. Four landscape blocks were identified for prioritizing treatments and are listed by priority:

1. Stands within largest IH blocks
2. Stands creating sinuosity on the edge of the largest IH block
3. Stands connecting large IH blocks
4. All other stands

Because thinning may increase the risk of edge effects (edaphic changes and blowdown) on adjacent late-successional habitat, prescriptions were varied based on distance from late-successional edge:

- Within 120 meters of habitat edges—Moderate thin at 60 years, and light thin at 80 years.
- Beyond 120 meters from habitat edges—Heavy thin at 60 years, and moderate thin at 80 years.

Landscape blocks and distance from edge both became key planning zones in the TELSA model.

6) The **Two Thin scenario** prescribed a two-thin prescription (heavy thin at age 40 years, medium thin at 60 years) to all candidate stands with a constraint that reentry into any roadshed should not occur for at least 20 years. This constraint reduced open road densities by increasing opportunities for road decommissioning work.

Comparing Resource Scenarios

The following management goals were selected to compare resource scenarios:

- Total hectares of late-successional habitat (an LSI rating above 75 percent)
- Total hectares of interior late-successional habitat
- Total hectares of late-successional habitat within owl nesting circles.
- Total hectares of late-successional habitat within moderate fire intensity areas.
- Total kilometers of roads remaining inactive for 10 and 20 years.

Management goals were also expressed as relative measures of total hectares thinned. Resource scenarios were also evaluated and compared visually, as seen in figures 2 and 3, to generally understand how landscape habitat patterns change under each scenario. Finally the flow of thinning hectares across the analysis timeline was considered for operational reasonability.

ANALYSIS RESULTS

After 70 years, resource scenarios had thinned between 8,600 and 13,000 hectares. By contrast, the Two-Thin Benchmark thinned 31,000 hectares in just 50 years and the No Action scenario 0 hectares. Harvest levels by decade varied noticeably between scenarios. The Roads scenario created a tri-modal harvest pattern due to the 20-year harvest constraint for roadsheds, while other scenarios more equitably spaced harvest over time.

By analysis year 80, scenarios had increased late-successional habitat (hectares with an LSI rating above 75 percent) by 2 to 17 percent above the No Action scenario. Scenarios had increased LS habitat within owl circles by 3 to 13 percent above the No Action scenario.



Figure 2—Description of Habitat using LSI values by Scenario at Year 80.

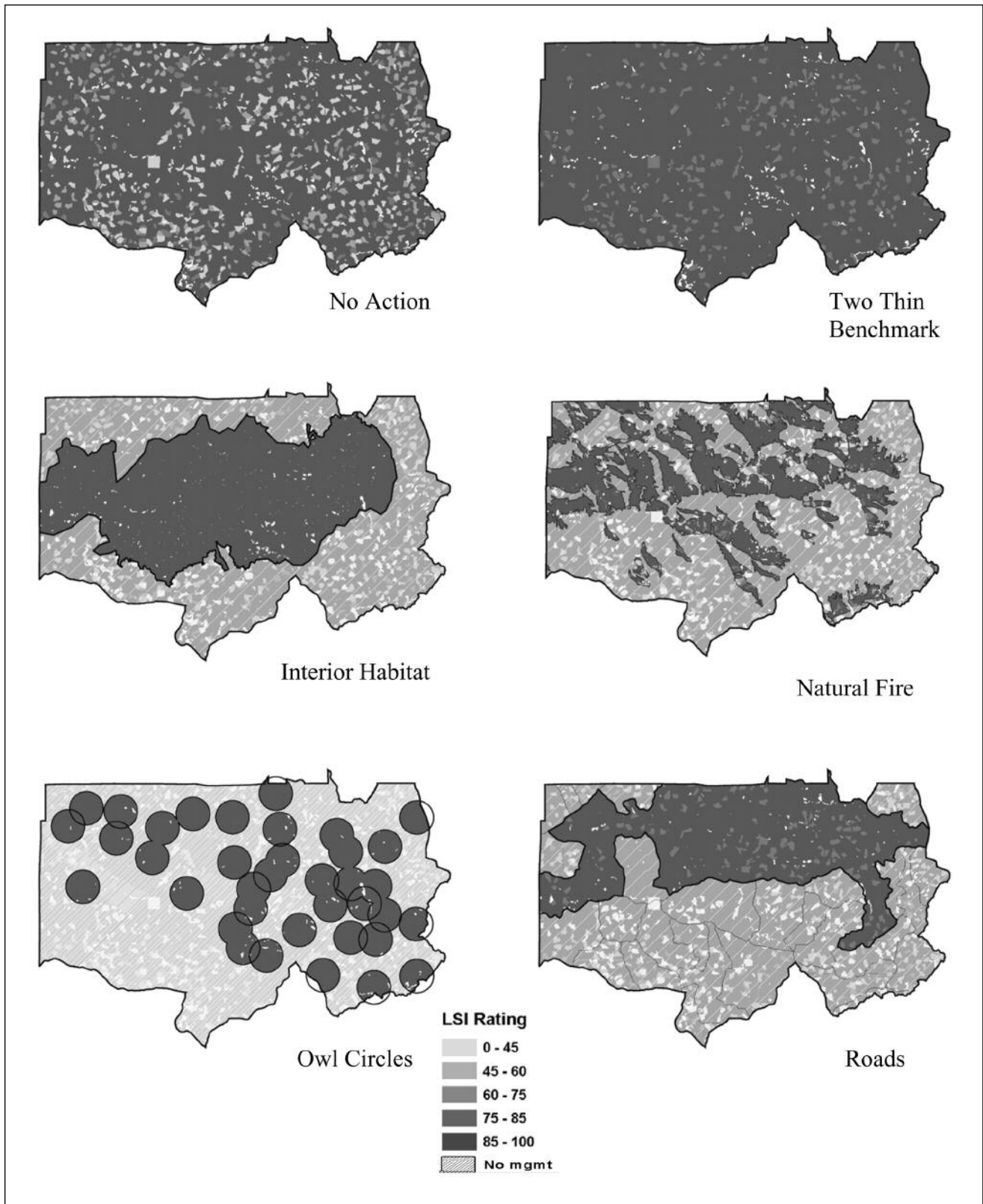


Figure 3—Description of Habitat using LSI values by Scenario at Year 120.

By analysis year 80, scenarios had increased interior habitat by 2 to 40 percent above the No Action scenario. The Roads and Interior Habitat scenarios achieved highest gains in interior habitat.

By analysis year 40, scenarios were able to keep 327 to 395 km of roads inactive (or unused) for more than 20 years. These roads are considered good candidates for closure. The Roads scenario created the most kilometers of inactive roads, largely due to the 20-year re-entry scheduling constraint and its narrow focus on only high-risk road-sheds.

Habitat patterns varied notably between scenarios, though total late-successional habitat differences were not great (figures 2 and 3). The Owl Site scenario concentrates habitat improvement efforts around only 37 nest sites spread across the landscape. The Natural Fire scenario also tended to spread thinning treatments across the landscape, in high fire frequency areas.

By contrast, the Roads scenario focused thinnings on the north side of the landscape, where aquatic risk ratings were highest. Similarly, the Interior Habitat scenario concentrated treatments within the core of the landscape along Fall Creek.

Efforts to include precommercial thinning options in the analysis were stymied by incompatible data sets of stand development curves, and were eventually abandoned.

CONCLUSIONS

Modeling helps to visualize the cumulative benefits/impacts of thinning strategies on LSR landscapes and compare management strategies. The Fall Creek analysis should provide useful reference points for future project analysis or creation of a 5-year action plan of thinning projects.

Results should prove useful for building public and agency confidence in using thinning to improve habitat conditions within LSR landscapes. For interior habitat values, location of habitat improvements on the landscape can be more important than total hectares of habitat improved. Landscape objectives help drive this placement of thinning efforts. Landscape attributes or habitat indices used to compare management scenarios are more useful when made relative to total treatment hectares.

NEXT STEPS IN THIS INVESTIGATION

- Model other resource scenarios of interest to managers.
 - Connectivity (travel corridors) between LSRs.
 - Combine several resource objectives into one scenario.
 - Allocate resource scenarios to different sections of the LSR and pursue simultaneously.
- Strengthen the simulations by testing complicated prescriptions involving precommercial thinning.
- Introduce implementation constraints (planning, budget, resource issues) into the scenarios.
- Use modeling results to create a five-year action plan of thinnings.

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EXAMINATION OF TRADEOFFS BETWEEN TIMBER PRODUCTION AND SPOTTED OWL HABITAT IN COASTAL OREGON

Pete Bettinger¹, and Jason Drake²

ABSTRACT

A forest planning model was developed to assess the trade-offs among timber production and spotted owl (*Strix occidentalis caurina*) habitat in coastal Oregon. The model utilized a threshold accepting heuristic technique to schedule, via 1-opt moves, timber harvests subject to spotted owl, adjacency, and green-up goals. The forest planning model was designed as a Model I problem, and only clearcut harvest decisions were made. The trade-offs among timber production and habitat goals are presented as a set of production possibility frontiers. With this preliminary analysis, it seems that there is a linear relationship between even-flow timber harvest levels and an allowable decrease in habitat levels (from projections of habitat under a “grow-only” scenario), up to a point. When habitat levels were allowed to decrease beyond 20% of the “grow-only” levels, no effect on timber harvest levels was noted. While this model helps managers and policy makers understand the trade-offs among timber production and spotted owl habitat levels, results may be limited to the landscape examined and the range of constraints tested.

INTRODUCTION

As forest and wildlife sciences evolve, researchers and practitioners become increasingly exposed to new hypotheses concerning the link between management (and hence landscape condition) and ecological and social values. The development of new hypotheses also provides opportunities for their integration with management models and subsequent evaluations of impact, effect, and association. Advances in wildlife habitat relationships research have provided forest planning the opportunity to more closely incorporate habitat goals into forest planning processes. The type of mathematical programming approach used to accomplish this integration will depend on the wildlife species under consideration and type of relationships used to evaluate the capability of a landscape to provide habitat. One example of new research on wildlife-habitat relationships is that provided by McComb and others (2002), who developed a wildlife capability model for the northern spotted owl (*Strix occidentalis caurina*).

The McComb and others (2002) owl habitat capability index (HCI) model includes both a within-stand nesting component and a home-range analysis, and thus requires measuring the characteristics of forest vegetation up to 2,400 m from each area of interest. Since a management activity scheduled to a management unit can affect the habitat quality of other management units up to 2,400 m away, this suggests the need for integer decision variables. A number of mixed integer and integer formulations of forest planning problems have been addressed in the forestry literature, from the pioneering work of Hof and Joyce (1992), Hof and Raphael (1993), and Hof and others (1994) using the exact techniques, to approaches provided by Bettinger and others (1997, 2002) and Calkin and others (2002) using heuristic techniques. This paper presents a process that integrates McComb and others (2002) HCI model with commodity production goals in a heuristic forest planning model.

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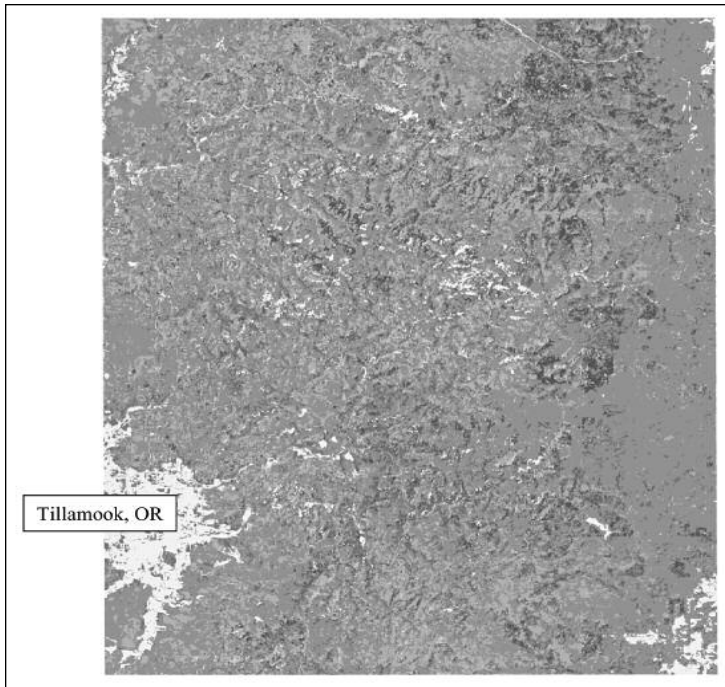


Figure 1—A 235,000 ha landscape in the Coast Range of Oregon.

METHODS

We selected a large landscape in western Oregon to use in modeling the integration of spotted owl *HCI* and commodity production goals in a forest planning context. The landscape (fig. 1) represents approximately 235,000 ha of land, mostly forested, and mainly managed by state and industrial land managers. Pixels in figure 1 are colored based on their vegetation class, and while not completely informative of the vegetative structure across the landscape, the figure allows one to locate the agricultural, urban, and cleared areas (the light colors), and to discern changes in topography based on the variations in the gray scale. The vegetation database was acquired from the CLAMS project (CLAMS 2002), and consists of a raster GIS database containing 3,752,714 pixels with a spatial resolution of 25 m. Each pixel in the vegetation GIS database has associated with it a tree list, as the database was created using a gradient nearest neighbor approach to classification that facilitates this association (see Ohmann and Gregory 2002). A tree list is simply a list of trees used to represent the forested conditions within each pixel. The lists used were derived from the U.S. Forest Service's Forest Inventory and Analysis program, the U.S. Forest Service's Continuous Vegetation Survey program, and research plots. Ohmann and Gregory (2002) provide more detailed information regarding the classification approach and assignment of tree lists to pixels in the GIS database.

The vegetation data associated with each pixel includes standing timber volume, average tree age, quadratic mean diameter, and several measures of coarse woody debris. This data facilitates measuring the impact of activities on both commodity production and habitat goals. The age class distribution of this area (fig. 2) shows that most of the forest vegetation is between 20 and 50 years old. A GIS database describing management units was acquired from the CLAMS project. Management units average 6-8 ha in size. The spatial relationship of each management unit in relation to others of which it shares a side was also developed, to facilitate the modeling of adjacency and green-up restrictions. Pixel data within management units are aggregated to arrive at average stand ages, volumes, and so on, for each management unit.

Objective function

The forest planning problem we solved attempts to maximize even-flow of timber harvest volume subject to adjacency, green-up, minimum harvest age, and spotted owl habitat constraints. The objective function was designed to measure and minimize the deviations of actual scheduled harvest volume from some target harvest volume.

$$\text{minimize } \sum_{t=1}^T \left[\left(\sum_{i=1}^N (x_{it} v_{it}) \right) - TV \right]^2$$

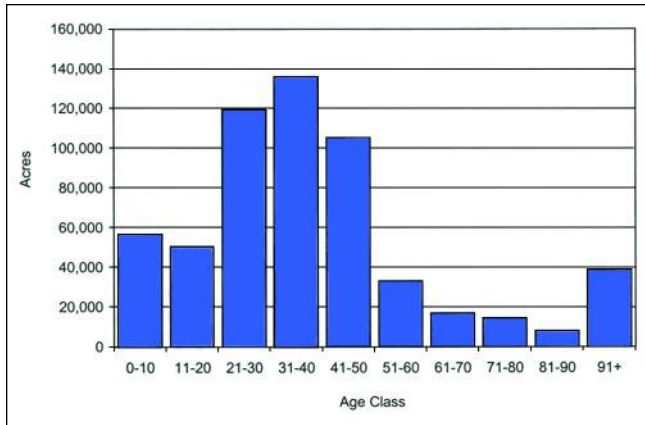


Figure 2—Age class distribution of forest land in a 235,000 ha landscape in the Coast Range of Oregon.

Where:

t = a time period

T = total number of time periods

i = a management unit

N = total number of management units

TV = target timber harvest volume per time period
(a constant)

x_{it} = a binary (0,1) variable indicating whether or not management unit i is clearcut during time period t

v_{it} = the volume available in management unit i during time period t

In this research, the time horizon was assumed to be 40 years, and consisted of eight 5-year time periods. There were 39,500 management units in the study area, each containing approximately 100 pixels. It is possible that not all of the pixels in a management unit could be harvested in each time period. A number of factors may prevent harvest of a pixel, including the following: it is represented as having a non-forest vegetation condition, its age is below the minimum harvest age, it is located within a riparian area, it is reserved as a leave-tree clump. Therefore, v_{it} for each management unit only represents the available volume during that time period.

Constraints

There are five main constraints contained within this planning process. First, we assume that each management unit could only be scheduled for harvest once during the time horizon.

$$\sum_{t=1}^T x_{it} \leq 1 \quad \forall i$$

Second, each management unit, based on the average age of its forested pixels, had to be above a minimum harvest age before a clearcutting activity could be scheduled. Thus the average harvest age of each management unit during each time period was computed, then the set of potential choices for each management unit was determined.

$$\left[\frac{\sum_{j=1}^{J_i} (a_j \text{Age}_{jt})}{\sum_{j=1}^{J_i} (a_j)} \right] = AHA_{it} \quad \forall i, t$$

$$\begin{aligned} \text{If } AHA_{it} \geq MHA \text{ Then } x_{it} &\in \{0,1\} \\ \text{Else } x_{it} &= 0 \end{aligned}$$

Where:

j = a pixel within a management unit

J_i = the set of forested pixels contained within management unit i

a_j = area of a pixel

Age_{jt} = age of trees contained within pixel j during time period t

AHA_{it} = average potential harvest age of management unit i during time period t

MHA = the minimum harvest age for a set of trees within a management unit

The third constraint indicates that clearcut sizes are limited to a maximum of 48.6 ha (120 acres). The scheduling process used a recursive function to determine the actual size of all proposed clearcuts by sensing the size of potential clearcuts from neighbors of proposed sales, and their neighbors, and so on.

$$x_{it} CA_{it} + \sum_{z \in Ni \cup Si} x_{zt} CA_{zt} \leq MCA \quad \forall i, t$$

Where:

CA_{it} = potential clearcut area of management unit i during time period t

z = an adjacent management unit

Ni = the set of all management units adjacent to management unit i

Si = the set of all management units adjacent to those management units adjacent to management unit i

MCA = the maximum clearcut area assumed (48.6 ha)

This definition is very similar to that proposed by Murray (1999) for area restriction problems. Si is essentially the set of clearcut units that contain all units adjacent to the neighbors of unit i , and all units adjacent to the neighbors of neighbors, etc. It is referred to as a recursive function

because of the potentially sprawling cluster group that must be assessed depending on the direct or indirect contiguity (of other clearcut units) with management unit i (Murray 1999).

The fourth constraint is related to the heterogeneity of vegetation contained in the initial raster vegetation GIS database. Given the salt and pepper nature of resulting classifications of satellite images, we wanted to ensure that a significant proportion of the forested area of each management unit was actually available for clearcut harvest prior to allowing a clearcut to be scheduled. While this constraint may seem redundant, given the minimum harvest age constraint noted above, it does prevent the scheduling of small (and very old) portions of management units. Here, the percentage of forest pixels that are available for clearcut harvest are summed each time period, and if this percentage is higher than a minimum percentage, the management unit may be available for clearcut harvest. A minimum harvest area of 65% was chosen based on numerous evaluations conducted within the CLAMS project. Higher minimum percentages significantly constrain harvest levels, while lower percentages allow small parts of management units to be harvested.

If $\gamma_{it} \geq MHP$ Then $x_{it} \in \{0,1\}$
Else $x_{it} = 0$

Where:

γ_{it} = the percentage of management unit i available for clearcut harvest during time period t

MHP = the minimum harvest percent (minimum percentage area available for clearcut harvest within each management unit)

Finally, the fifth constraint allows the scheduling model to constrain activities to those that are possible without reducing the “grow only” spotted owl HCI levels “too much.” Here, the spotted owl HCI levels were first computed for the landscape under the assumption that no harvests will occur over the 40 year time frame. Then, a maximum allowable decrease was determined for each time period.

$$LHCI_t \geq w \text{ (“grow only” } LHCI_t) \quad \forall t$$

Where:

$LHCI_t$ = the potential spotted owl HCI level for the entire landscape during time period t

w = the maximum percentage decrease ($0 \leq w \leq 1$)

The landscape HCI levels are computed from individual management unit HCI estimates

$$\left[\frac{\sum_{i=1}^N (A_{it} HCI_{it})}{\sum_{j=1}^N A_{it}} \right] = LHCI_{it} \quad \forall t$$

Where:

A_{it} = forested area of management unit i during time period t

HCI_{it} = the HCI estimate for management unit i during time period t

We utilized the “model 2” spotted owl HCI model developed by McComb and others (2002) to make the HCI evaluations across the landscape. The spotted owl HCI model was developed to measure the capability of a patch and its surrounding neighbors to provide conditions important to survival and reproduction of spotted owls. HCI levels were estimated by computing a nest stand capability index and a landscape capability index:

$$HCI_{it} = (NCI_{it}^2 LCI_{it})^{(1/3)}$$

Where:

NCI_{it} = the nest stand capability index component of the HCI for management unit i during time period t

LCI_{it} = the landscape capability index component of the HCI for management unit i during time period t

NCI_{it} is a function of the density of trees 10-25 cm dbh, trees 25-50 cm dbh, and trees 75+ cm dbh, as well as a diameter diversity index. LCI_{it} is a function of the percentage of large and medium sized trees within three zones around each management unit: 28 ha, 202 ha, and 1,810 ha. These spatial zones were translated to radii around each management unit: 300 m, 800 m, and 2,400 m. The centroid of each management unit was used as the base point of each evaluation, and if any other management unit’s centroid was within these search distances, they contributed to LCI_{it} . This represents a simplification of the process described in McComb and others (2002), where LCI was computed as a moving window around each pixel, more precisely measuring the zonal areas. Here, we computed management unit HCI levels, and by basing the LCI computations on this, gain significant processing speed during the scheduling process. The disadvantage of this approach is that the difference in the evaluation of owl

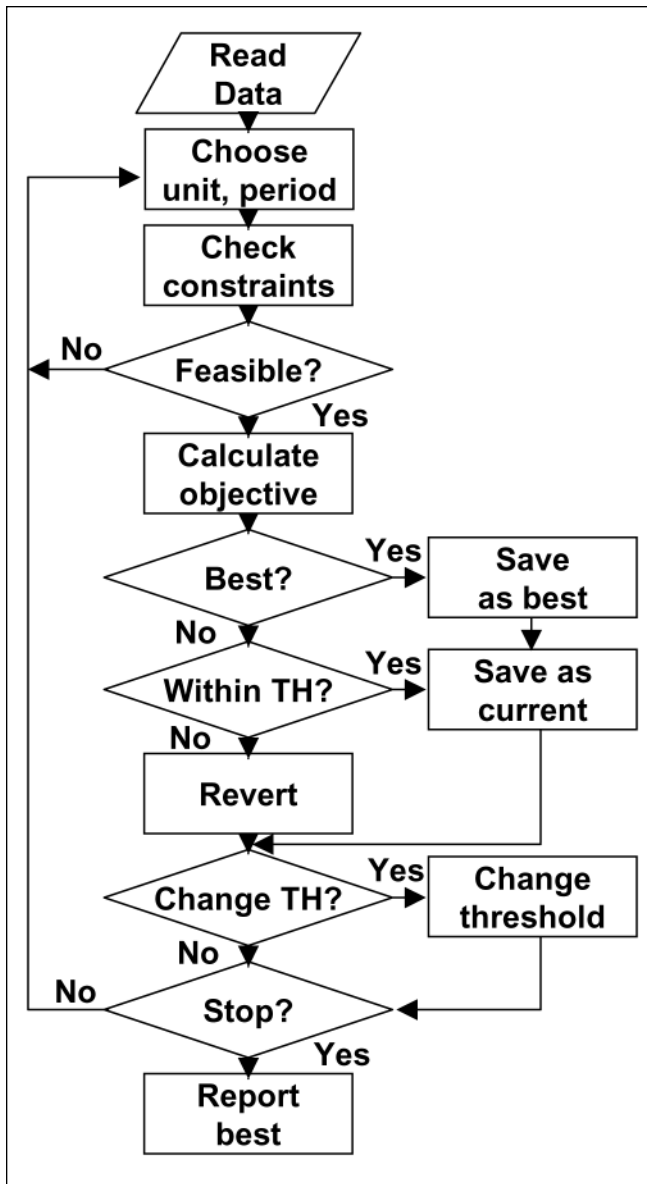


Figure 3—A flow chart of the threshold accepting scheduling process.

habitat (by pixel or by management unit) reduces the heterogeneity possible in habitat values from 3,752,714 possible distinct values to 39,500. In addition, the spatial zone evaluated using the original approach would resemble a smooth circular radii evaluated around each pixel, while the approach implemented here results in a rough approximation of the radii around each management unit. The impact of these deviations from the original model, in terms of the quality of habitat evaluations, is uncertain, however, maps of the initial habitat condition values were compared to those provided by McComb and others (2002), and through visual inspection we determined that

the difference in the spatial distribution of habitat (within the ranges mapped) was negligible even though it was not entirely clear whether McComb and others (2002) used the same data as used here.

Heuristic scheduling process

A threshold accepting heuristic technique called Habitat Optimization for Owls (HOO) was developed and utilized to schedule management units for clearcut harvest over the 40-year time horizon. Threshold accepting was introduced by Deuck and Scheuer (1990), and has been applied to forestry problems in Bettinger and others (2002, 2003). Our implementation of threshold accepting to this problem used a Model I (Johnson and Scheurmann 1977) problem formulation, and 1-opt moves (i.e., a change to the timing of harvest of a single management unit) to arrange efficient harvest schedules for the landscape of interest. Given a feasible solution, a management unit and a harvest time period were chosen at random, as shown in the flow chart describing the search process (fig. 3). This “potential” change to the solution was then evaluated with respect to the constraints. If a constraint is violated, the process reverted to the previous feasible solution, and a new potential choice of management unit and harvest time period was made. If no constraints are violated, the objective function was evaluated. If the proposed solution results in the overall best solution found, the proposed solution became both the best and the current solutions. If the proposed solution is not the best solution, yet was within a certain range of the overall best (as defined by the best solution value - the threshold value), the proposed solution was retained as the current solution, and the process continued. If the proposed solution was not within a certain range of the overall best solution, the process reverted to the previous feasible solution. The solution process was run a number of times with several target even-flow harvest volumes. The preliminary results provided here illustrate the potential trade-offs among even-flow harvest volume and spotted owl habitat capability index levels.

RESULTS

When average harvest volumes for the eight planning periods are plotted against the average spotted owl habitat capability index levels, one can begin to visualize the trade-offs among timber production and habitat levels for this landscape (fig. 4). In this case, the spotted owl *HCI* levels were unconstrained. If we were to constrain spotted owl *HCI* levels to so that they may decrease x% from the grow-only projections of *HCI* levels (for the entire landscape), a clearer picture of the interaction between the commodity production and ecological goals arises (fig. 5). Here, we see that allowable decreases in *HCI* of 20% or

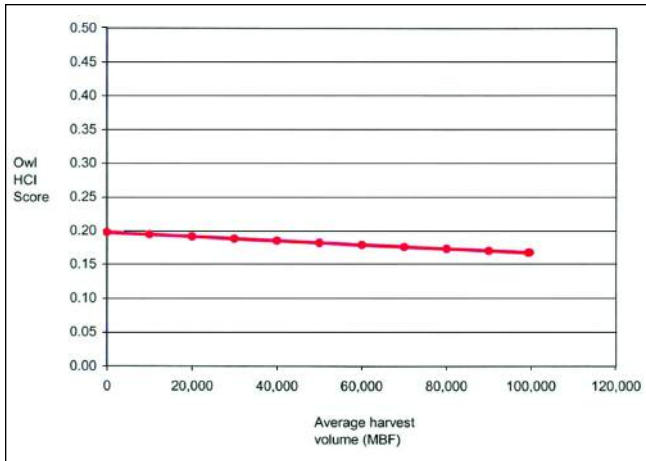


Figure 4—Production possibility frontier relating average *HCI* level to average even-flow timber harvest level, when *HCI* levels are unconstrained.

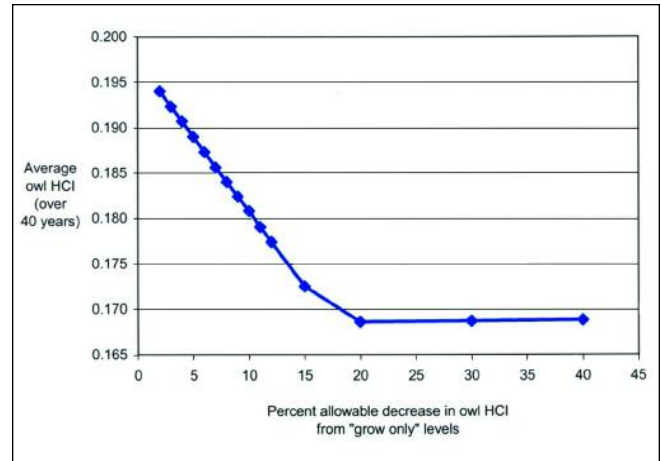


Figure 6—Average *HCI* levels when *HCI* is allowed to decrease from 1 to 40 percent from grow-only projections of the landscape.

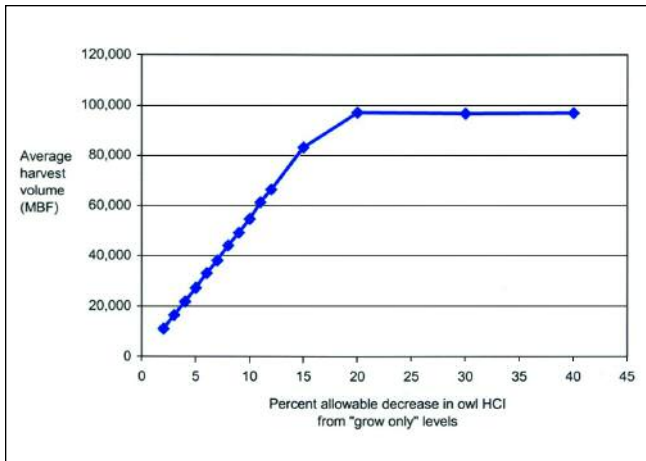


Figure 5—Even-flow harvest levels when *HCI* is allowed to decrease from 1 to 40 percent from grow-only projections of the landscape.

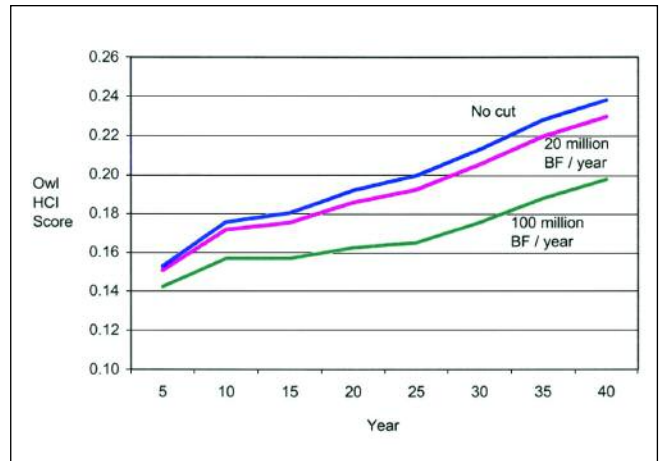


Figure 7—Actual *HCI* levels over the planning horizon under three different policies regarding the desired even-flow timber harvest levels (i.e., the target harvest levels).

more had no effect on timber harvest levels. When *HCI* was constrained to an allowable decrease of less than 20%, there was almost a linear relationship between the allowable decrease and the resulting even-flow timber harvest levels. Similarly, average *HCI* levels decreased in a nearly linear fashion as the allowable decrease in *HCI* from the grow-only condition increased, up to 20% (fig. 6). Allowable decreases in *HCI* beyond 20% seemed to have no effect on average *HCI* levels on this landscape. The *HCI* level at this point (0.168) represents the level most likely under full utilization of the landscape under economic objectives. Allowing small deviations in owl habitat levels from the “grow only” case constrains the achievement of economic objectives to a point (up to a 20% allowable decrease), but beyond this point this constraint has no impact on solution

values - *HCI* levels are at their lowest given the age class distribution of the landscape, the management direction, and the other constraints recognized (e.g., adjacency). Figures 5 and 6 contribute to this insight.

While we have been relating timber harvest levels to average *HCI* levels over the 40-year planning horizon, *HCI* levels were not static, and generally increased over time (fig. 7). The trend in the increase of *HCI* levels over time seemed to be consistent no matter what target even-flow harvest level was specified in the HOO model. The ‘no-cut’ *HCI* levels in figure 7 were the levels obtained when the landscape was projected under a grow-only policy. It is from these levels that the allowable decrease in *HCI* was measured when *HCI* is constrained.

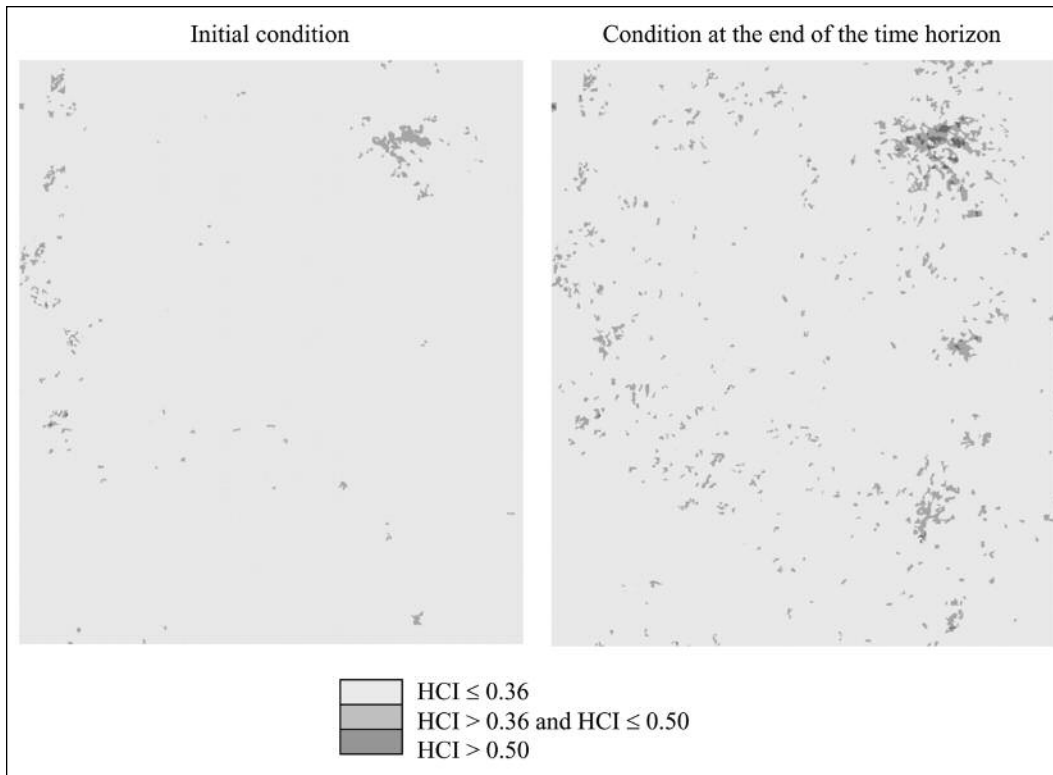


Figure 8—Spatial representation of the *HCI* levels for the initial condition of the landscape, and the ending condition (after the 40-year planning horizon) when the target

Spotted owl *HCI* levels can also be mapped, as the *HCI* for each management unit is reported by HOO. It is our intent to perform some spatial analyses of these maps to investigate the spatial effects of various timber harvest level goals, although those analyses are not provided here. Figure 8 illustrates the change in *HCI* levels from the initial condition of the landscape to the end of the time horizon, when the target even-flow harvest level was 20 million board feet per year.

DISCUSSION

The HOO model can be viewed as an optimization model that allows the evaluation of different policies containing both economic and ecological goals, and one that can be applied across a broad area and over a long time frame. This ability, however, is not unique, as other heuristic models have also been described in the literature where complex habitat relationships are incorporated into a mathematical programming context. HOO merges strategic and tactical planning considerations, so that processes at a variety of temporal and spatial scales can be represented. We have shown here the use of the area restriction model for

handling adjacency relationships of almost 40,000 management units (resulting potentially 320,000 integer variables), which may be intractable in other mathematical optimization processes.

The quality of solutions generated by a model such as HOO can be assessed in three general ways. First, one could compare the results provided here to solutions generated by formulating and solving the problems with linear programming (LP) techniques. These LP results would necessarily should be viewed as “relaxed” results, as one or more constraints (i.e., adjacency and owl habitat) would need to be ignored to allow the LP model to solve the problem. However, if produced, the LP results could be viewed as an upper bound on potential solutions to the problem. Second, the problems could be formulated and solved with integer programming (IP) techniques, resulting in direct comparisons with the heuristic solutions, since the constraints may be formulated in such a way that they can all be recognized. Given the number of potential integer variables, however, this seems an unreasonable goal. Finally, one could generate an estimated global optimum solution from a set of heuristic solutions, as proposed by Bettinger

et al. (1998) and Boston and Bettinger (1999). This latter approach has its drawbacks, including the time required to generate a sufficient set of solutions, the assumptions required to confidently use extreme value theory, and the fact that a bad heuristic can produce a misleading estimate of the global optimum solution to a problem. For these reasons, we leave this work for the future.

Other capabilities are being integrated into the HOO model beyond those described here. For example, since vegetation is represented at the pixel level, the ability to restrict management within certain distances of the stream system is possible. In addition, the ability to model leaving "leave tree clumps" in clearcut areas is possible. We plan to, given a desired level of retention specified by a user of HOO, randomly leave x% of potential clearcut pixels uncut in harvest units. This would facilitate analyses of potential legacy policies as well as voluntary ecological-oriented contributions of landowners. HOO also facilitates an examination of a variety of green-up and adjacency policies, as the length of the green-up period and the size of the maximum clearcut is not fixed, but variable, and adjustable by users of the model.

Other management activities have been suggested as ways to accelerate the development of spotted owl habitat in the Pacific Northwest. Thinnings, in particular, may result in faster growth rates of residual trees, thus accelerated development of spotted owl habitat. However, given the short tenure of the planning horizon (40 years), it remains to be seen whether the potential gains through thinning can be realized via this modeling process. Thinnings could, however, have an effect on total timber harvest volume produced, thus could potentially increase the maximum even-flow harvest levels. Thinnings are, however, less widely used in steep terrain, as the cost of logging may exceed the revenues generated, so it remains to be seen whether the impact of thinnings is significant on timber harvest levels (i.e., more than 10 percent, which is a common assumption about how much thinning volume contributes to overall harvest levels in the Pacific Northwest).

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ASSESSING SHORT- AND LONG-TERM THINNING OPPORTUNITIES ON THE WILLAMETTE NATIONAL FOREST

Bruce Meneghin¹, Allison Reger², and Neal Forrester²

ABSTRACT

The Willamette National Forest conducted an analytical exercise to examine thinning treatments in the short and long term. Objectives of the analysis were to verify short-term thinning estimates; to gain an understanding of long-term implications and capabilities of commercial thinning on the forest; to develop a model to be used for analyzing vegetation management proposals and policies in the future; and to provide useful information about thinning that could be linked with short, mid and long-term management strategies. A linear programming model was constructed, and scenarios with varying mixes of operational and allocation constraints were examined. Where practical, multiple entry prescriptions offered the best prospect of achieving a sustained flow of forest products. Limiting thinning to Late Seral Reserve (LSR) lands or stands previously managed greatly reduces available harvest volumes in the short term. Issues that need further investigation are fuels treatments and management objectives on lands outside of LSRs.

INTRODUCTION

The Willamette National Forest is comprised of 1.6 million acres of land on the western side of the Cascade mountains in western Oregon, USA. From the 1960's through the early 1990's the Willamette was a significant timber producing forest, harvesting between 500 and 800 million board feet of timber annually. Since that time, management objectives of the forest have shifted dramatically. The current management direction, established by the Willamette Forest Plan (USDA Forest Service 1990) and the Northwest Forest Plan (USDA Forest Service 1994), emphasizes the establishment and maintenance of a system of Late Seral Reserves (LSRs), and implementing an aquatic conservation strategy for protecting riparian habitat and native fish stocks. This management direction has divided the Forest into three broad land allocation classes, shown in figure 1. One third of the forest is allocated to LSRs while another 14 percent is designated as riparian areas critical to the implementation of the aquatic conservation strategy. The remainder of the lands are referred to as

matrix lands – a mix of vegetation types and land allocations that surround the LSRs and riparian areas.

Under the current management direction the harvest levels are projected to be 116 million board feet annually. However, timber harvests in mature and old-growth forests using clearcutting are very controversial on the Willamette. Therefore, the most promising opportunity for achieving the planned harvest levels is to conduct thinnings in the 350,000 acres of young forest that were created during the last forty years.

STUDY OBJECTIVES

This analysis was driven by four key questions from managers:

- What would the maximum harvest level be if thinning was the only harvest activity?
- What would the maximum harvest level be if thinnings were limited to lands that had been previously managed?

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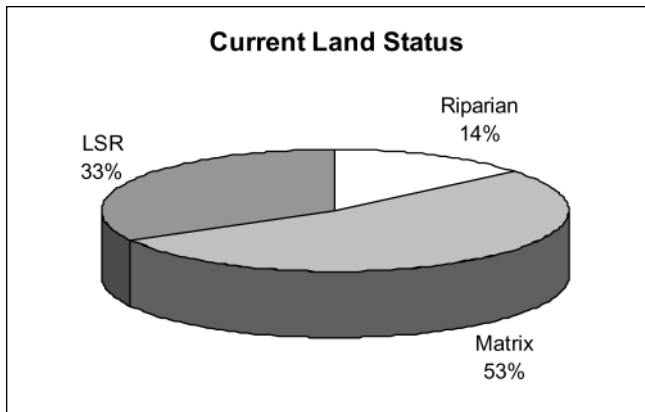


Figure 1—Proportions of the Willamette National Forest by major land status groups.

- How long could a “thinning only” program be sustained?
- What would be the long-term implications of limiting harvest activity to thinning?

In order to answer these questions an analysis project was designed with these analytical objectives:

- Verify thinning estimates made by District offices. Crude estimates based on acreages had been developed at the field level. We wanted to improve the accuracy of these estimates.
- Determine the long-term implications of a commercial thinning program. We needed to be able to quickly and consistently estimate future forest age class distributions under different management scenarios.
- Provide information useful to short-term and long-term thinning strategies.
- Develop a model for future analyses. We wanted to develop a model that could be easily adapted to analyze questions posed by future administrative and political proposals.

MODEL DEVELOPMENT

To meet these analysis objectives we decided to construct a fairly traditional linear programming harvest schedule model with a Model 1 structure as presented by Johnson and Scheurman (1977). The model was formulated using Spectrum, the LP based planning model supported by the USDA Forest Service (1998) and commonly used in forest plan revisions (Rupe 1995). The contents and structure of the model are described briefly below.

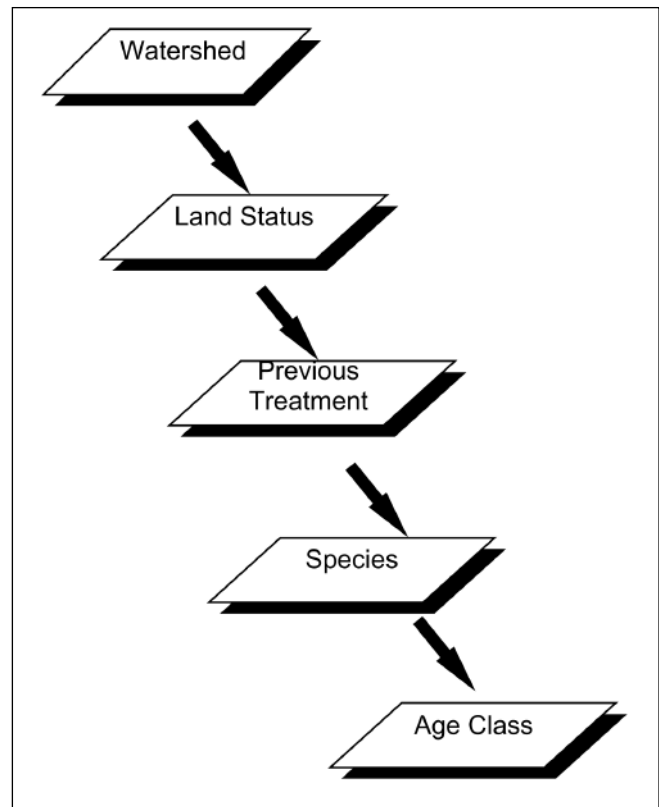


Figure 2—Analysis units were created by overlaying five layers of information. A total of 3900 unique analysis units were used in the analysis.

Time Frame

The planning horizon was delineated by thirty, five-year planning periods. Five-year periods was chosen to synchronize with the yield simulator, and a 150 year planning horizon was chosen to observe long term implications of management strategies.

Land Stratification

Land attributes used for stratification, illustrated in figure 2, were chosen to differentiate current timber inventory, growth rates and response to management, and to allow expression of current and potential management objectives in the model. Watersheds were included to provide geographic specificity and to control activities within watersheds. The land status layer was a reclassification of management designations that identified suitability for thinning prescriptions. The previous management layer was used to assign appropriate thinning prescriptions from a silvicultural point of view. Finally, species and age class stratifications were carried to differentiate inventory, growth and response to treatment. The combination of these layers resulted in 3900 analysis units with unique attributes. In many cases, analysis units were comprised of non-contiguous land units.

Management options

A variety of thinning treatment options were developed for each analysis unit. Within LSR areas, these treatments are intended to encourage the development of key old-growth characteristics desired in LSRs (Spies 1991; Willamette National Forest 1998). These included regimes with and without pre-commercial thinning, and regimes that had one, two or three commercial thinnings during the planning horizon.

Outputs and Effects

To keep the model simple, a small number of outputs and effects were modeled. Timber growth and yield projections were developed using the Forest Vegetation Simulator (FVS). These simulations provided estimates of inventory and harvest amounts as well as estimates of fuels produced from thinning operations. The per-acre cost of thinning operations was also estimated. These costs varied by combinations of land status, species group and thinning intensity.

Management Objectives

Management objectives that were likely to intersect with harvesting objectives were represented in the model. These objectives and their representation in the model are listed by resource area.

Fish and Watershed—

- Limit potential ground disturbance and possible sedimentation or impacts to streamside vegetation, amphibians, and arthropod populations.
- Ensure not all closed canopy dispersal corridors in a given watershed are impacted at the same time and limit potential adverse cumulative effects within desired levels.
- Maintain or minimize disruption of microclimates in riparian reserves and minimize edge impact on streamside stands.
- Minimize stream course impacts during peak flow events.

These objectives were represented in two sets of constraints in the model. The first controlled the number of acres within riparian areas that could be harvested in a period. Willamette biologists felt that limiting the harvesting to less than seven percent of the riparian acres per period would keep cumulative impacts to an acceptable level (equation 6, below). The second set of constraints aimed at protecting the fish resource was the enforcement of standards established in the Northwest Forest Plan (USDA Forest Service 1994). This standard limits the acres harvested in selected watersheds to less than fifteen percent of the acres in that watershed per period (equation 8).

Wildlife—

- Conduct silvicultural treatments in young stands within LSRs to promote recruitment into suitable old-growth habitat.
- Provide dispersal habitat for spotted owls as well as maintaining some level of landscape continuity and dispersal habitat for other species.

These objectives were modeled with decision variables representing management choices designed to produce desired habitat and with constraints that limited the number of acres treated within LSRs. Specialists felt that limiting the treatments to less than twenty five percent of an LSR in a ten-year period would ensure that habitat requirements could be met (equation 7).

SCENARIO DESIGN

In order to meet the analysis objectives, three broad level scenarios were studied. Scenario 1, designed as a benchmark, sought to maximize harvest levels with few constraints. Scenario 2 was designed to represent the management objectives for fish, wildlife and watershed that might interact with timber production objectives. Finally, Scenario 3 was similar to Scenario 2 but harvest activities were limited to stands that had been previously managed. The mathematical formulation for Scenario 2, stated as in Clutter et al. (1983), is shown below.

Maximize:

$$(1) Z = \sum_{i=1}^{30} \sum_{j=1}^R \sum_{k \in LSR} V_{ijk} X_{jk}$$

$$(2) Z' = \sum_{i=1}^2 \sum_{j=1}^R \sum_{k=1}^N V_{ijk} X_{jk}$$

$$(3) Z'' = \sum_{i=1}^{30} \sum_{j=1}^R \sum_{k=1}^N V_{ijk} X_{jk}$$

Subject to:

$$(4) \sum_{j=1}^R \sum_{k=1}^N V_{i+1,jk} X_{jk} \leq \sum_{i=1}^R \sum_{k=1}^N 1.25 V_{ijk} X_{jk} \quad (i = 1,2...29)$$

$$(5) \sum_{j=1}^R \sum_{k=1}^N V_{i+1,jk} X_{jk} \geq \sum_{j=1}^R \sum_{k=1}^N 0.75 V_{ijk} X_{jk} \quad (i = 1,2...29)$$

$$(6) \sum_{j=1}^R \sum_{k=1}^N H_{ijk} X_{jk} \leq \sum_{j=1}^R \sum_{k \in RZ} 0.05 X_{jk} \quad (i = 1,2...30)$$

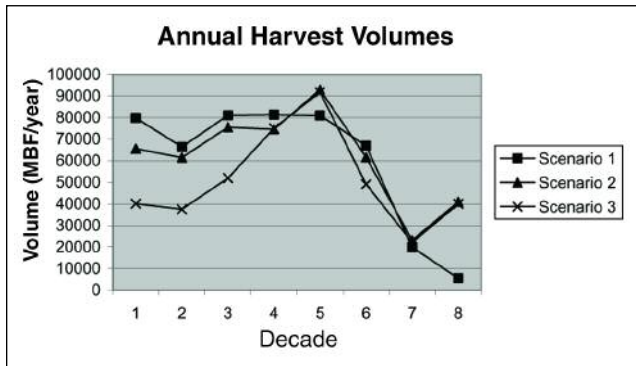


Figure 3—Annual harvest volumes through time for the three scenarios.

$$(7) \sum_{j=1}^R \sum_{k \in LSR} H_{ijk} X_{jk} \leq \sum_{j=1}^R \sum_{k \in LSR} 0.25 X_{jk} \quad (i = 1, 2, \dots, 30)$$

$$(8) \sum_{j=1}^R \sum_{k \in WR} H_{ijk} X_{jk} \leq \sum_{j=1}^R \sum_{k \in WR} 0.15 X_{jk} \quad (i = 1, 2, \dots, 30)$$

where,

- R = number of management regimes
- N = number of analysis units
- V_{ijk} = volume per acre harvested from analysis unit k under regime j in period i
- X_{jk} = acres of analysis unit k allocated to management regime j
- LSR = set of analysis units residing in LSRs
- $H_{ijk} = 1$ if harvest occurs in period i on analysis unit k under regime j , 0 otherwise
- RZ = set of analysis units residing in riparian zone
- WR = set of analysis units residing in watersheds with special restrictions

The model was solved using a lexicographic goal programming approach described by Mendoza (1987) and commonly used in Forest Service planning models (Rupe 1995). The objective functions (1), (2) and (3) were solved iteratively. Objective function (1) seeks to maximize harvest volumes produced in designated LSRs. After maximizing using equation (1), the model was solved to maximize the volume harvested in the first two periods, (equation (2)) subject to (4) through (8) and equation (1) reformulated as a constraint:

$$(9) \sum_{i=1}^{30} \sum_{j=1}^R \sum_{k \in LSR} V_{ijk} X_{jk} >= 0.99Z$$

where Z is the objective function value achieved during the first solution.

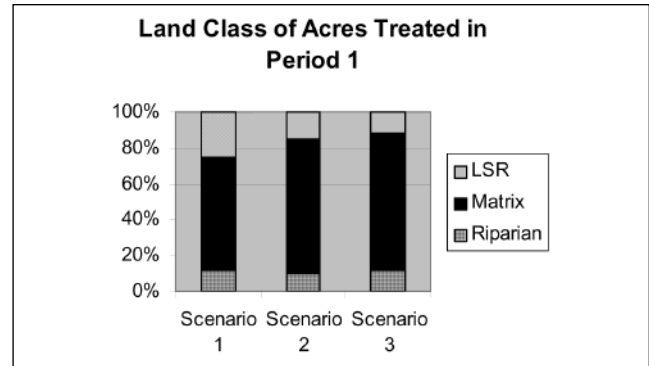


Figure 4—Proportion of thinned acres from different land classes in the three scenarios.

This process was repeated for objective function (3) which maximizes volume produced over the entire planning horizon.

Equations (4) and (5) represent the maximum periodic increase and decrease allowed for timber volumes. Equation (6) meets management objectives for fish by limiting harvests in riparian areas, while equation (7) enforces wildlife objectives by limiting harvests within LSRs. A series of equations represented by (8) limited harvesting in select watersheds.

RESULTS

All three scenarios showed similar trends in harvest volume through time as shown in figure 3. All scenarios were characterized by steady or increasing harvest volume for the first five decades followed by a steady decrease after decade five. The lower volumes in the early periods of scenario 2 were due to the increased restrictions on percentage of acres harvested in riparian and LSR areas in a given period. These restrictions were compounded by a smaller available land base in scenario 3 which resulted in an even lower harvest in the early periods.

Scenarios 2 and 3 were able to match the volume production of the benchmark in decade five because of two factors. First, the solutions for these scenarios chose regimes that called for two and three entries on many acres. Secondly, these solutions harvested more acres from matrix lands than did the benchmark, as shown in figure 4. Matrix lands allow greater use of the multiple entry regimes and thus play an important role in maintaining harvest levels while meeting other resource objectives. The slight increase in harvest volume in decade eight for scenarios 2 and 3 comes from a third thinning on matrix lands.

All three scenarios show a transition in the long term to a forest that is greater than 95% late successional stands. For all scenarios, the decline in acres available for thinning begins in decade five and continues. Natural disturbance, not accounted for in the model, will be the only means for regenerating the forest.

CONCLUSIONS

This analysis shows a potential for the Willamette National Forest to sustain a “thinning only” harvest program for seventy to eighty years. During that time harvest levels climb from 65 mmbf on 4500 acres to 91 mmbf on 6200 acres annually for scenario 2. If harvests are limited to managed stands, then early harvest levels fall to 40 mmbf on 3200 acres annually. If LSR lands are maintained and the aquatic conservation strategy objectives are met, the greatest opportunities for harvest come from multiple-entry thinning regimes on matrix lands.

In addition to answering the questions outlined at the beginning of the study, this analysis also raised new questions. The large proportion of thinning from matrix lands called for by scenarios 2 and 3 will require that clear silvicultural objectives be established for these treatments. Some mid-level analysis may also be needed to determine thinning priorities and entry schedules in sensitive watersheds. Finally, additional analysis will surely be needed to examine the potential fire risks associated with fuels generated from thinning operations.

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GENERATING A FOREST PARCELIZATION MAP FOR MADISON COUNTY, NY

Susan L. King¹ and Brett J. Butler²

ABSTRACT

It is well documented that the size of forested landholdings directly affects the management of forest resources. Traditionally, this information has been presented in tabular format. A spatial format will provide a more useful mechanism for summarizing and utilizing this important information and can provide new insight into the causes, or at least correlates, with differences in sizes of forest landholdings. The objective of this study was to investigate techniques for modeling forest parcel size in order to facilitate future efforts to generate a national map depicting the distribution of forest parcel sizes. County tax records and land-cover data for Madison County, New York, were used to generate a dataset containing forest parcel size by owner. This area was selected because, unlike most of the country, the land ownership parcel data are readily available in a format conducive to spatial analysis. Ancillary data included both social and biophysical predictor variables. Multiple linear regression, neural network, and decision trees were used to model these data. The models were tested using validation datasets and accuracy was assessed with enhanced kappa statistics. A decision tree was selected as the final method because it provided superior validation results, fewer parameters to adjust, and ease of explanation and visualization to non-experts.

KEYWORDS: Parcelization, decision trees, simple kriging with a varying local mean, neural networks.

INTRODUCTION

A parcel is a contiguous polygon of land owned by a single ownership. An ownership is an individual, group of individuals, business, or public agency that has legal title to the polygon of land. Between 1994 and 2002, the number of private landowners in the United States increased by 7 percent (Butler 2004). At the same time, the area of forest land collectively owned by these families, individuals, companies, and other groups increased by less than 3 percent (www.fs.fed.us/woodlandowners). This continuing trend of forest land ownership increasing faster than forest land is resulting in the fragmentation of forest ownerships or forest parcelization. An alternative way to define parcelization is a decrease in the average landowner's landholdings.

The consequences of parcelization are not fully understood, but they have important implications for the preservation of working forest land (Sampson 2000). A basic limitation imposed by parcelization is related to economies of scale (Row 1978). For working forest land to be sustained, it is necessary for the land to be profitable, and timber is the most profitable market commodity from such tracts. The profitability of a timber harvest is a function of the realized stumpage value and fixed and variable costs. While the variable costs can be adjusted, at least partially, to reflect the size of the parcel being treated, the fixed costs (e.g., transportation of equipment) by definition are invariant to treatment area.

Forest parcelization, itself is not detrimental to ecosystem functions, though it often is a catalyst for change.

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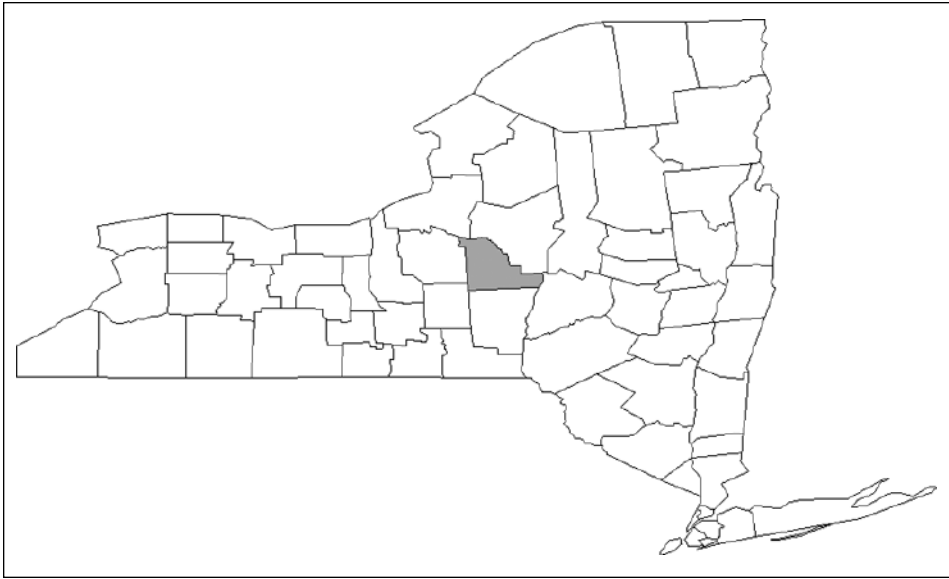


Figure 1—Madison County, located in central New York, is bordered to the north by Oneida Lake. The Lake Plains physiographic region surrounds Oneida Lake; the southern portion of the county is part of the Appalachian Uplands physiographic region. Numerous lakes are interspersed among the rolling hills.

Specifically, parcelization often precedes the conversion of forest land to other land uses, e.g., residential development, which, in turn, leads to fragmentation of the physical forest resource. Forest fragmentation has been shown to be detrimental to ecosystem functions ranging from water quality to the availability of nesting habitat (Rochelle et al. 1999; Saunders et al. 1991).

Likewise, parcelization may not directly affect the resources available to people desiring access (e.g., hunters), but access will be hampered by the need to contact an increasing number of land owners. This access also affects programs designed to educate or influence landowners. As the number of owners increases, the cost of implementing cost sharing or extension programs will be affected.

The characteristics of the owners also are correlated with the size of landholdings (Butler 2004; Birch 1996). Landowners of smaller forested tracts are more likely to have objectives related to home ownership and aesthetics, whereas owners of larger forested tracts are likely to actively manage their forests for timber production.

To accurately predict forest parcelization patterns, the processes or patterns of the underlying forces must be understood. To date, most of the information on forest parcelization has been obtained from coarse-scale ownership surveys that allow only tabular summaries, limited spatial resolution, and limited ability to combine with other data sources. Mehmood and Zhang (2001) built a multiple linear regression model to describe parcelization for the United States. Their dependent variable, a measure of

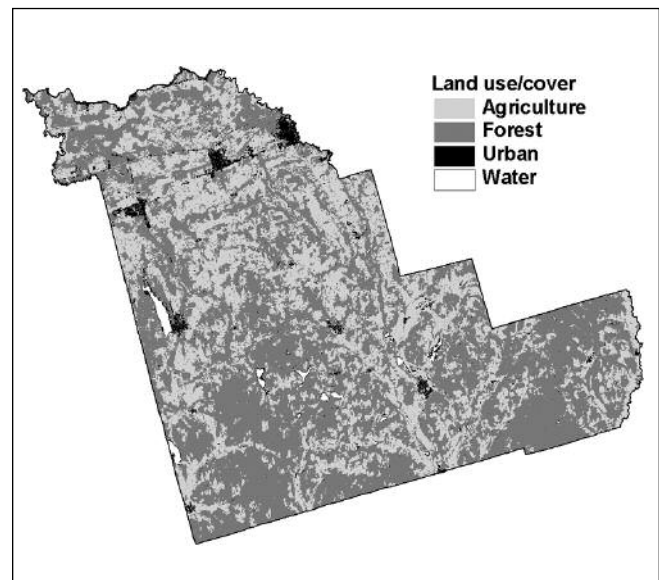


Figure 2—Agricultural and forest land are the predominate land uses. An urban corridor exists along Interstate 90 at the edge of the Lake plains physiographic region. Syracuse is a major population center to the west.

parcelization, is the change in average nonindustrial private forest size between 1978 and 1994 on a per-state basis. Their independent variables are suited for a state-level model and reflect changes over time. Our model is a geographical approach; that is, we investigated methods that model forest parcelization both on a continuous and categorical scale. The purpose of this case study was to gain experience using different modeling techniques and independent variables which will enable us to build a national map that depicts the size of forest parcels. This map will

Table 1—Dependent and independent variables used in the study.

Variable	Abbreviation	Description
Forest parcel	<i>ForParc</i>	Area (acres) of forest in a parcel
Percent forest	<i>PerFor</i>	Percent forest within (1, 5, 25, or 100) acres of the parcel centroid
Percent agriculture	<i>PerAg</i>	Percent agriculture within (1, 5, 25, or 100) acres of the parcel centroid
Percent urban	<i>PerUrb</i>	Percent urban within (1, 5, 25, or 100) acres of the parcel centroid
Population density	<i>PopDen</i>	People per square mile within a census block
Dwelling density	<i>DwDen</i>	Dwellings or houses per square mile within a census block
Family density	<i>FamDen</i>	Families or households per square mile within a census block
Public ownership	<i>PubOwn</i>	Dummy variable indicating parcel centroid is within a public ownership
Distance to roads	<i>DistRoad</i>	Distance (mi) of parcel centroid to nearest improved road
Distance to water	<i>DistWater</i>	Distance (mi) of parcel centroid to nearest census water
Slope	<i>Slope</i>	Average slope within (5 or 100) acres of parcel centroid
Elevation	<i>Elev</i>	Average elevation within (5 or 100) acres of parcel centroid
Income	<i>Inc</i>	Average annual income (US\$) within a block group
Education	<i>Ed</i>	Percent of population with a college degree within a census block group
Gravity Index	<i>Grav</i>	Weighted distance of the census block centroid to population centers

allow us to increase our understanding of the processes underlying forest parcelization and its consequences.

METHODS

Study Area

The study area was Madison County in the center of New York State (fig. 1). The county contains numerous lakes interspersed among the flat plains and rolling hills of the Lake Plains and Appalachian Uplands physiographic regions. Agricultural and forest lands are the major land uses (fig. 2), but, as in many parts of the county, these industries have been superseded by service and retail sectors in the local economies. Currently, 69,000 people live in Madison County (U.S. Census Bureau 2001). The county covers 661 mi² giving it an average population density of 104 people per mi².

This area was selected because it is one of relatively few counties in the United States where tax records have been digitized in a format that is amenable to further analyses and are publicly available for a nominal fee (www.madisoncounty.org). All legal property boundaries for this county have been digitized with polygon topology and information about the ownership of each parcel is available.

Variables

The dependent variable, size of forest parcel, was derived by combining county's tax records and remotely sensed imagery. The (total landholdings) parcel map was created by assigning every ownership in the county a

unique numerical identifier and then combining adjacent parcels to remove "artificial" boundaries. A forest/nonforest map was created by reclassifying the 30m pixels in a 1992 National Land Cover Data (Vogelmann 2001) image for Madison County as 1 for forest or 0 for all other land-cover categories. The total number of forest pixels within a parcel (based on pixel centroid) were calculated and multiplied by 0.2 ac to obtain the total forest area per parcel.

The independent variables for this analysis (table 1) were limited to data that were publicly available and have national coverage. Thus, the results can be used to create a product that covers a larger geographic area. The physical variables originated from remotely sensed imagery, digital elevation models (DEM), and census data. Percent forest, agriculture, and urban were derived from the 1992 National Land Cover Data. Slope and elevation were estimated from the DEM (Defense Mapping Agency 1997).

The Census Bureau (U.S. Census Bureau 2001) was the source of the socioeconomic variables available at the census block or block group level. Data for the finest spatial resolution available were incorporated. Variables related to the number of people across the landscape included population, dwelling, and family density. These variables are all highly correlated, but not completely redundant. The average income and education of the people within a census block group were tested. A dummy variable indicating public ownership was derived from county tax records, though this variable can also be derived from regional or national data sources (McGhie 1996).

A gravity index (Kline 2001; Haynes 1984) was included to represent the relative influence of population centers. Parcels closer to an urban area are more likely to be subject to urban land-use influences. It is hypothesized that this will result in smaller parcels. The index was calculated as:

$$\text{Gravity index}_i = \sum_{k=i}^3 \frac{(\text{Population}_k)^{0.5}}{\text{Distance}_{ik}}$$

where

i = U.S. Census block group centroid

k = a city having a large urban influence

The selection of three nearest cities was based on the work of Kline and Alig (2001). Cities within an 50 mi buffer of the county were included. The city with the largest population (163,860 people) was Syracuse, located west of the county. The remaining urban centers ranged in population from 166 to 68,637.

MODELS

Several procedures for mapping parcelization were investigated. Both simple kriging with a varying local mean and decision trees were investigated. In simple kriging with a varying local mean, the large-scale variability is modeled using a nonspatial approach such as multiple linear regression, neural networks, or generalized additive models. A linear model, multiple linear regression, and a nonlinear approach (neural networks) were investigated. Forest parcelization is predicted on a continuous scale with simple kriging and on a categorical scale with decision trees.

Multiple Linear Regression vs. Neural Networks

In multiple linear regression, the relationship between independent and dependent variables is assumed to be linear in the unknown parameters and interactions between the independent variables must be specified a priori by the user. The parameters are estimated by least squares. In neural networks, there is no assumed relationship between the independent and dependent variables. The relationship between independent and dependent variables is learned through an iterative process.

A neural network requires no assumptions about the distributions, mean, or correlation of the errors. Neural networks may provide a superior solution over a traditional statistical procedure when the distributions are unknown and possibly nonlinear, outliers may exist, and noise is present in the data (Burke 1991). In this research, a feed-forward neural network with backpropagation, the most widely used learning algorithm, is implemented. Briefly, a backpropagation network consists of processing elements

analogous to the brain's neuron. The backpropagation network is hierarchical, consisting of at least three layers. The first layer is an input layer with the same number of processing elements as independent variables, which are thought to relate to the output classification signal. This layer typically operates as a simple input buffer and uses a linear transfer function to distribute each of the input attributes to the second layer processing units. The second layer is the hidden layer. There can be multiple hidden layers, but usually only one is used. The number of processing units in the hidden layer is undeterminable a priori. Each of the hidden layers uses some form of a nonlinear sigmoidal transfer function, which usually has the same number of weights as the number of input attributes. The third and usually final layer, the output layer, typically has the same number of processing units as classification categories. The output signals from each of the hidden layer's transfer functions feed into another sigmoidal function at the output layer. The difference between the observed and estimated values of the dependent variable is formulated as a function of weights. This is an unconstrained minimized problem and there are numerous solution techniques available (King 1999). Selection of initial weights can influence the convergence to an optimum solution and ultimately the final set of weights which are used on new data.

Simple Kriging with a Varying Local Mean

Because each datum has a geographical reference, geostatistical procedures are feasible. One geostatistical approach for incorporating secondary information is simple kriging with a varying local mean. Large-scale variability is modeled using multiple linear regression or neural networks; small-scale variability is modeled using simple kriging (Majure et al. 1996; Metzger 1997; Hunner et al. 1998; Goovaerts 2000; Lister et al. 2000). The two surfaces are then added to produce the final map. If there is no small-scale variability, the large-scale map may stand alone.

Decision Tree

Decision trees partition the decision space into smaller segments defined in terms of the input variables. These partitions define the predictive relationship between the inputs and the dependent variable. This partitioning continues until the subsets cannot be partitioned further using user-defined stopping criteria. The homogenous groups allow for greater accuracy in predicting the dependent variable from the independent variables. Chi-Square Automatic Interaction Detector (CHAID), the decision-tree algorithm used in this study, selects the most significant predictor with the lowest adjusted probability at each level based on the Bonferroni adjusted Chi-Square statistics (KASS 1980). A small p-value indicates that the observed association

between the predictor and dependent variable is unlikely to have occurred solely due to sampling variability. If a predictor has more than two categories, there may be many ways to partition the data set based on the categories. A combinatorial search algorithm finds a partition that has the smallest p-value. CHAID partitions the data into multiway splits, which result in more interpretable trees than binary splits. The root of the tree is the entire data set. The subsets and subsets form branches of the tree. Subsets that meet a stopping criterion and cannot be further partitioned are leaves. As with neural networks, over and underfitting are modeling concerns in decision trees. A tree with too many branches overfits the data and a tree with too few branches underfits the data.

Statistical Tests

The level of agreement between truth and the model classification were evaluated using Cohen's kappa (κ) (Congalton and Green 1999). Some agreement between truth and the model classification would be expected by chance. The κ analysis gives the representation of the proportion of agreement beyond that expected by chance. A κ score of 1 indicates perfect agreement and a score of 0 indicates no more agreement than would be expected by chance. A negative score indicates less agreement than would be expected by chance, that is, disagreement. The κ statistic is based on an equal weighting of the classes, which assumes that all of the errors are of equal importance. Weighting the cells closer to the diagonal more heavily than those cells farther away takes into account near disagreements. The Fleiss-Cohen weighting scheme was used. Pontius (2000, 2002) has argued that the standard κ index of agreement is inappropriate for map comparisons. The standard κ was developed for studies when the marginal distributions are unknown. The goal of a map is to obtain similar marginal distributions as the population. Hence, Pontius believes that the standard method to compute the expected proportion correct classification by chance usually is inappropriate for classification schemes that specify both quantity and location. Two maps are best compared by tabulating the cross classifications between truth and prediction in a $j \times j$ contingency table, where j is the number of categories in each map. Quantification error occurs when the quantity of cells in a category in one map differs from the quantity of cells in the other map. Even if there is no quantification error, location error can occur where the location of a category in one map differs from the location of that category in the other map. The criteria of Landis and Koch (1977) were used to interpret the κ scores.

Model and Validation Data Sets

Madison County has 35,370 land parcels of which 19,903 are forested. The dependent variable, forest parcelization, was divided into four classes (table. 2) based on work by Birch (1996). The overwhelming number of small parcels and the scarcity of large parcels pose a modeling challenge. Equal number of observations in each class does not represent all possible dependent and independent variable combinations, especially in the small parcel class. We used different dependent variable class percentages. The final model included 2 percent of the first class, (smallest parcels), 10 percent of the second class, and 70 percent of the third and fourth classes. Many trials were conducted with randomly generated data sets with these percentages. The final model and validation data sets had 791 and 19,112 observations, respectively.

Results and Discussion

Models with a continuous dependent forest-parcelization variable were built using both multiple linear regression and neural networks. Variogram analysis showed that there was a significant spatial dependence. The small-scale structure was modeled using simple kriging. For both multiple linear regression and neural networks, adding the small-scale variability improves the R^2 , 0.462 for multiple linear regression and 0.892 for neural networks. The multiple linear regression model included percent forest within 100 acres, ownership, gravity, distance to roads, and distance to water, while neural networks substituted dwelling density and slope within 100 acres for gravity. Unfortunately, both models fail to generalize on new data. For the validation data set, multiple linear regression underpredicts parcel size and neural networks overpredicts parcel size, particularly small parcels. After adding the small-scale spatial variability to the validation data sets, both procedures predict numerous parcel values as negative. A neural network has many parameters that require adjustment (initial weights, number of hidden layers and the number of hidden nodes within each hidden layer, type of sigmoidal transfer function at the nodes in the hidden layers and output nodes, and optimization techniques). Additional adjustments could have been made, and possibly a better solution obtained. However, it is not easy to interpret the output from a neural network because it is not apparent which input variables contribute heavily to the outcome. Also, many parameters require adjusting in producing a variogram and in simple kriging. Because the ultimate objective is a national map, these procedures were abandoned in favor of a decision tree, which is highly interpretable has fewer parameters to adjust, and is easily implemented on a production scale.

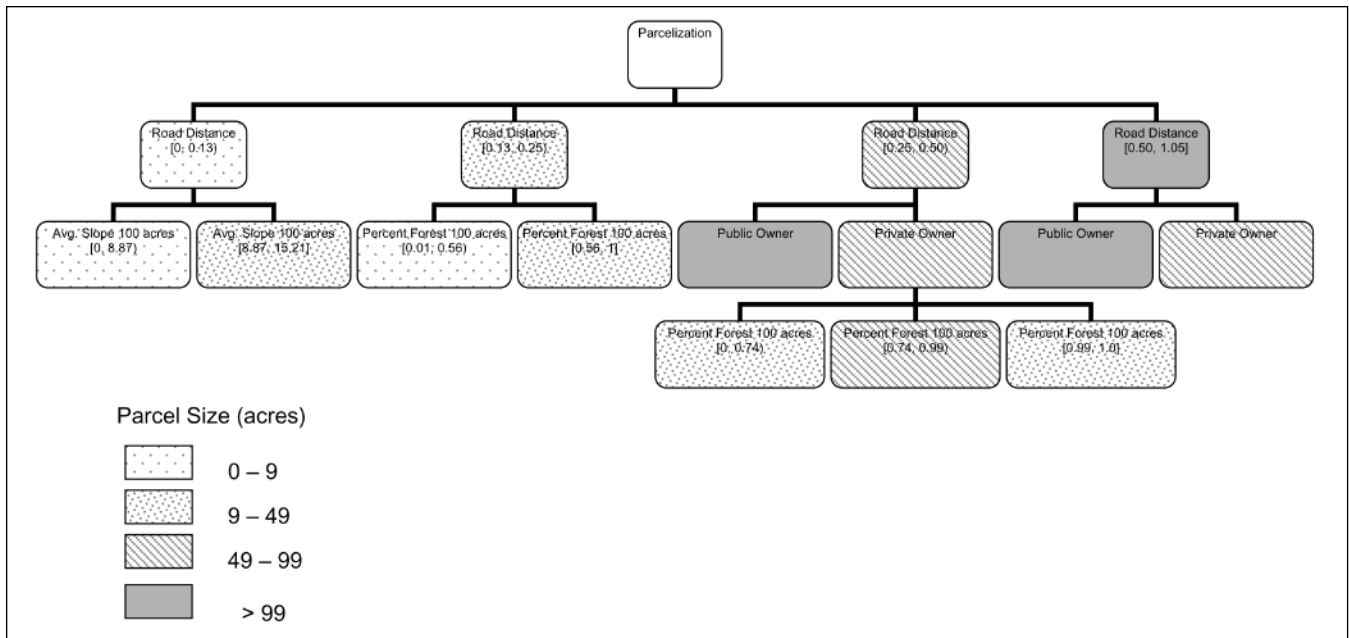


Figure 3—Final decision tree for classifying forest parcelization. Distance to roads is important in classifying parcel sizes. The larger parcels are farther from the road than smaller parcels. Ownership is important in classifying large parcels. Slope and percent forest are important in classifying small parcels.



Figure 4—Map of a) observed and b) predicted parcel classes. The large parcel sizes are on the public land in the higher elevations in the southern part of Madison County and on private land in the plains near Lake Oneida in the northern part of the county. The decision tree misses the higher parcels on private land. Most of the misclassifications are classified as an adjacent parcel size.

Table 2—Distribution of forest parcels by size class.

Parcel size (acres)	Frequency	Percent
0 - 9	17,088	85.86
9- 49	2,563	12.88
49 – 99	201	1.01
> 99	51	0.26

Table 3—Agreement between observed and predicted forest parcels for the model and validation data sets.

Predicted parcel class	Model				Total
	Observed parcel class				
	0 – 9	9 – 49	49 – 99	> 99	
0 – 9	311	42	9	0	362
9 - 49	31	160	58	2	251
49 – 99	11	41	83	6	141
> 99	0	11	11	15	37
Total	353	254	161	23	791

Predicted parcel class	Validation				Total
	Observed parcel class				
	0 – 9	9 – 49	49 - 99	> 99	
0 – 9	13,832	2,336	550	8	16,726
9 - 49	379	1,324	595	14	2,312
49 – 99	5	20	31	4	60
> 99	2	3	6	3	14
Total	14,218	3,683	1,1822	29	19,112

The final decision tree is presented in figure 3. Good generalization is achieved by limiting the depth of the tree and selecting a lower bound on the number of observations required for a leaf. The final model was based on both the κ statistics and expert interpretation. In all trials, the most significant predictor and the first to enter the model was distance to roads, the most highly correlated variable with forest parcelization ($\rho = 0.34$). The smaller distance to roads, the more likely the forest parcel will be small. Slope and percent forest within 100 acres further predict smaller parcels. Public versus private ownership is the most significant predictor of large parcels. Dwelling density could be a replacement for percent forest within 100 acres of the parcel in the fourth level of the tree. The final model completely misclassifies parcels over 99 acres on private land. Figure 4 presents both the observed and predicted maps.

The over 99 acre parcels in the northern part of the county are on private land and are misclassified in the lower class. The confusion matrices for the model and validation data sets are given in table 3. The percentage of perfectly matched cells or overall accuracy is larger for the validation than the model data set (79.48 versus 71.94 percent) due to the large number of small parcels. The κ statistic decreases from 0.57 with a 95-percent confidence interval of (0.53, 0.62) for the model to 0.37 with a 95-percent confidence interval of (0.36, 0.38) for the validation data set. This indicates fair to moderate agreement according to Landis and Koch (1977). Similarly, the weighted κ statistic is 0.73 with a 95 percent confidence interval of (0.70, 0.77) for the model, indicating substantial agreement, and 0.41 with a 95 percent confidence interval (0.40, 0.43) for the validation data set, indicating moderate agreement. Pontius'

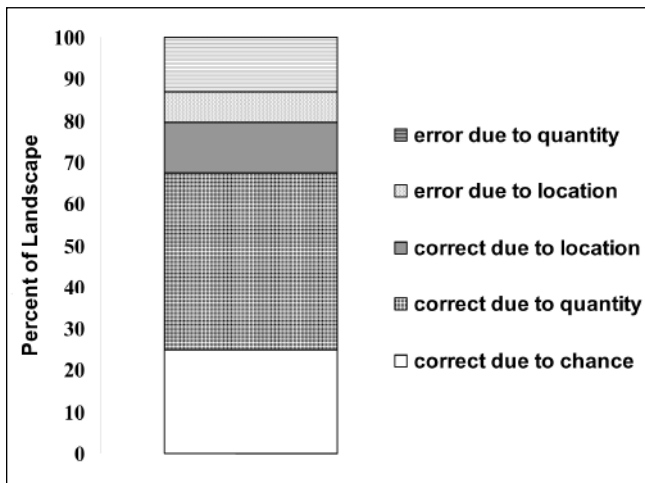


Figure 5—Of the 19,112 parcels in the validation data set, 79 percent are classified correctly. Because there are four classes, 25 percent are classified correctly due to chance, 42 percent classified correctly due to quantity, and 12 percent are classified correctly due to location. The location error is 7 percent and the error due to quantity is 13 percent.

distribution of correct classification and errors percentages is shown in figure 5. The validation data set is 79 percent accurate.

CONCLUSION

It is difficult to build a model that captures both dominant and rare events. Of the methods tried, decision trees gave the best results. There are fewer parameters to adjust, it is easy for an expert to tweak the model, and it is visually explainable. Neural networks are superior to multiple linear regression for this problem and newer neural network software might have more options to prevent overfitting. Ownership is the predominate variable in differentiating large parcels. Distance to roads, slope, and percent forest best partition smaller parcels.

Currently, many of the consequences of forest parcelization are only hypotheses. Although, these hypotheses are built on a plethora of antidotal evidence, more work is needed to quantify the connections. The generation of forest-parcelization maps across broad geographic areas will allow these questions to be better explored. The methods developed in this study are an initial step in this process and will be expanded to cover a larger geographic area. Future efforts will focus on using point-based estimates of forest parcel sizes to generate a map depicting forest parcel size. These estimates will come from the National Woodland Owner Survey (www.fs.fed.us/woodlandowners). Due to

the sampling technique (probability proportional to size), the inverse problem will be experienced: large parcels will outnumber smaller parcels. The techniques explored in this pilot study will still be applicable. From the map we will be able to graphically display the distribution of forest parcel sizes across broad geographic areas and explore the causes and consequences of observed patterns.

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PROJECTING LANDSCAPE CONDITIONS IN SOUTHERN UTAH BY USING VDDT

James Merzenich¹ and Leonardo Frid²

ABSTRACT

The Vegetation Dynamics Development Tool (VDDT) is a state-transition modeling system that integrates the effects of succession and natural disturbances such as wildfire with management treatments. VDDT is used to evaluate the response of non-spatial indicators to management actions. This study used VDDT to project changes in vegetation in response to different management scenarios for a mixed forest and range watershed in southwest Utah. The vegetative composition of this landscape has been significantly altered because of the effects of fire suppression and grazing. Pinyon-juniper acreage has increased from historic levels while aspen, sage, and oak habitats have declined. Key environmental factors projected by VDDT include the percent of area dominated by open shrubs, pinyon-juniper, and aspen, and the percent of dry-site conifer acres at high risk of uncharacteristically severe wildfire. The analysis shows that an aggressive vegetation treatment schedule is needed to reverse current trends and restore ecological conditions and processes in this area.

KEYWORDS: Landscape modeling, natural disturbance, simulation, forest dynamics, vegetative succession.

INTRODUCTION

The Vegetation Dynamic Development Tool (VDDT) is a simulation model used to project landscape-scale vegetative conditions over long time frames (Beukema and others 2003; Merzenich and others 1999). VDDT models the effects of alternative levels of management treatments on vegetation as influenced by stochastic disturbances such as wildfire.

Discrete states are defined in VDDT on the basis of a vegetative cover type and structure class. In each model run VDDT uses up to fifty thousand simulation units to project change. Simulation units are initially assigned to states based on the proportion of area contained in those states. These simulation units then progress along time-dependent successional pathways or change states in response to probabilistically applied disturbances or management treatments. VDDT projects the proportion of units

(or area) contained in each state and the levels of disturbances that may be expected.

The U.S. Forest Service, Pacific Southwest Station, is conducting a study comparing landscape-scale fuel treatment models at seven major locations in the United States (Weise and others 2001). Two reports describing the use of VDDT in conjunction with this study are available. In a retrospective analysis, VDDT models were used to predict stand replacement fires between 1937 and 1996 in Yosemite national park (Arbaugh and others, 2001). In the Bitterroot front of western Montana VDDT was used to estimate the level of fuel treatments needed to restore ecological conditions and reduce the risk of uncharacteristic stand-replacement wildfires (Merzenich and others, 2001). This paper presents the results of applying VDDT to the Beaver River drainage, an area of mixed range and forest, in southwest Utah.

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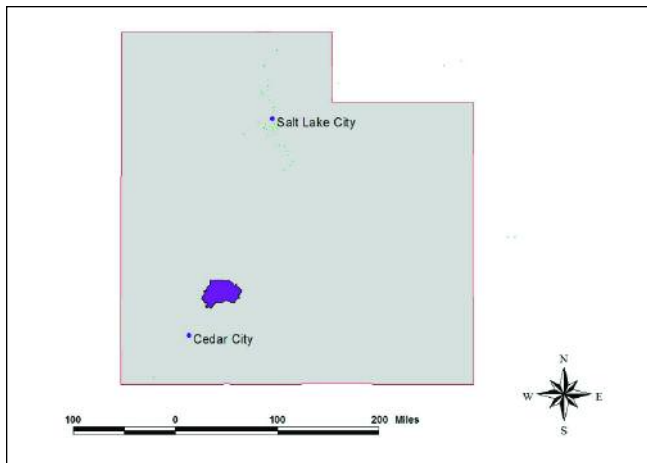


Figure 1—Map of Utah. Shaded area represents Beaver River drainage.

The study area contains 350,000 acres (142,000 ha.) located primarily on the Fishlake National Forest and adjoining Bureau of Land Management land (fig. 1). Elevations vary from approximately five to twelve thousand feet (1500 to 3700 meters). The study area contains acreage associated with nineteen of twenty-four VDDT models developed for potential vegetation types in southern Utah (Long and Merzenich, 2004). The major vegetation types represented by these models are Wyoming big sage (*Artemisia tridentata* var. *wyomingensis*), mountain big sage (*Artemisia tri-dentata* var. *vaseyana*), Gambel oak (*Quercus gambelii*), ponderosa pine (*Pinus ponderosa*), montane fir (mix of *Pseudotsuga menziesii* and *Abies concolor*), and Spruce/fir/aspens (*Picea engelmannii*, *Abies lasiocarpa*, and *Populus tremuloides*).

A combination of wildfire suppression and livestock grazing has significantly altered the vegetative composition of the study area over the past 150 to 200 years (Campbell and others, 2003). At lower elevations, a mosaic of grass and shrublands has been replaced by vast areas of dense shrubs and non-native annuals such as cheat grass and red brome (*Bromus tectorum*; *Bromus rubra*). On more mesic sites pinyon pine (*Pinus edulis*) and juniper (*Juniperus* spp.) are replacing sage and perennial grasses. Mid-elevation mixed pine and fir forests, once maintained by frequent ground fires, now have unnaturally high levels of easily combustible fuel and are at high risk of catastrophic wildfire (Bradley and others 1992). Quaking aspen stands, dependent upon fire disturbance for regeneration and detrimentally affected by livestock browsing, are being replaced by shade tolerant spruce and subalpine fir (Bartos and Campbell, 1998).

The objectives of this study were to track the response of key indicators, such as aspen, ponderosa pine and pinyon-juniper acres, to management scenarios that represent: 1) no management; 2) management at levels commensurate with current funding; and 3) management at a higher level believed necessary to restore ecological conditions.

METHODS

Historically fires were common within most vegetative types in the Beaver River drainage with estimated fire frequencies ranging from every 5-25 years for ponderosa pine stands to 50-80 years for spruce/subalpine fir stands (Campbell and others, 2003).

Data on the acreage burned by individual wildfires for the modern period are available for this drainage for the years 1970 to 2002. Because of active fire suppression and the reduction of fine fuels due to grazing, there has been a decrease in the acres burned during this modern period, as compared to historic. The average area burned per year in wildfires was about two hundred acres for the period 1970 to 1991 and two thousand acres for the period 1992 to 2002. The burn data for this latter period (1992-2002) are believed to be more reflective of current fuel and climatic conditions and were used to estimate annual wildfire probabilities for VDDT. Based on these data, the average fire return interval is now 175 years with 0.57 percent of the area burned per year.

The wildfire acreage burned per year varies based on ignitions, climatic conditions, and resources available to suppress fires. Options available in VDDT to vary wildfire disturbance probabilities temporally, by type of fire year, were not used in this analysis.

Most wildfires in the last decade have occurred in the grass/shrub and woodland classes. In this analysis average fire return intervals are estimated to be 150 years (0.0067 annual probability) for grass/shrub and woodland, 200 years for dry forest, and 300 years for high elevation spruce/fir and aspen areas. These fire return intervals and annual probabilities correspond to an expected acreage burned per year for the entire study area of about 2,000 acres. This is consistent with the burn data for the period 1992 to 2002.

Wildfire probabilities also vary according to the succession class. For example, on areas dominated by annual grasses or high-risk conifer stands wildfire probabilities are increased, while on low-risk stands they are decreased. For each vegetative class both stand-replacement and low intensity (underburns and mixed severity) fires are modeled.

Table 1—Wildfire frequencies and treatment levels for Full_mgt scenario (Campbell and others, 2003)

Vegetation type	Fire freq. (historic)	Fire freq. (current)	Treatment	Trt freq Ann rate	Targeted classes
Wyo. Sage	40-60	150	Mech/Pres burn	50 (2%)	All stands with pj or closed shrub
Mtn. Sage	20-40	150	Mech/Pres burn	30 (3.3%)	All stands with pj or closed shrub
Oak woodland	20-50	150	Pres burn	50 (2%)	All but seedlings
Dry forest	5-25	200	Pres burn	30 (3.3%)	Pole and larger open
Sprucefir/aspens	50-80	300	Thin/burn	50 (2%)	Mature dense
			Pres burn	50 (2%)	All mature/old
			Regen harv	100 (1%)	Mature sprucefir/aspens

Three scenarios were developed to estimate the effect of alternative levels of management treatments over a 50-year time frame. This time frame was chosen to make this analysis consistent with other analyses comparing landscape-scale fuel treatment models (Weise and others 2001). The VDDT models for this area are actually designed to allow projections for 300 or more years.

The following assumptions apply to all scenarios: active wildfire suppression will continue; regeneration harvest is used to promote aspen; partial harvests are used to reduce fuels and promote early seral species; and livestock grazing will continue at current levels. The three scenarios are described as follows.

- 1) **No_mgt:** No management except fire suppression and grazing
- 2) **Full_mgt:** Management at a level designed to restore and maintain ecological function as quickly as practicable.
- 3) **Current_mgt:** Management at a level commensurate with current funding. The treatment level is assumed to be one-third that of the full-management scenario.

An explanation of the full-management scenario (scenario 2) as it applies to the major vegetation types follows. Table 1 shows projected treatment levels associated with this scenario along with the estimated historic and current fire return intervals.

Grass and Shrublands: Approximately 42 percent of the study area was historically dominated by perennial grass and sagebrush. Two major management issues in these vegetation types are the proportion of acres in which pinyon-juniper is dominant and the amount of open versus closed shrub. Pinyon pine and juniper develop slowly and are susceptible to mortality by wildfire. Historically pinyon-juniper stands were mostly confined to rocky outcrops

or other areas that frequently escaped wildfire (Bradley and others 1992). The area dominated by pinyon-juniper is presently at least three times higher than the historic level (O'Brien 1999). Pinyon-juniper stands reduce water yield and streamflow through evapo-transpiration, and retard the growth of grasses, forbs and shrubs. Pinyon-juniper stands are often fire resistant due to the lack of fine fuels in the understory.

Most sage stands are presently closed canopied. Natural sagebrush areas maintained by fire would have nearly equal acreage in perennial grass, open shrub, and closed shrub.

Few large wildfires presently occur in this landscape. An average fire return interval of 150 years was applied to areas dominated by perennial grass, shrubs and pinyon-juniper. On areas dominated by annual grasses (e.g. red brome or cheatgrass) the assumed fire return interval is 50 to 75 years. If large areas of contiguous annual grasses were to develop wildfire probabilities could dramatically increase. In cheatgrass dominated landscapes in southern Idaho average fire-return intervals are now less than 10 years (Paysen and others, 2000).

The primary prescription is to apply mechanical treatment (Dixie harrow, brush choppers, cut and burn) and prescribed fire to closed shrub classes and classes containing pinyon-juniper at a ratio of 75 percent mechanical treatment to 25 percent prescribed fire. This is done at a 50-year return interval for Wyoming sage and a 30-year interval for mountain sage areas. These treatments include seeding annual grass areas to perennial grass where appropriate with an assumed success rate of 50 percent. The purpose of these treatments is to remove pinyon-juniper and to lower the density of sage. The closed shrub and pinyon-juniper classes younger than 200 or 250 years are the target areas to be treated. Some non-target areas are burned with prescribed fire, however. When applying prescribed fire we assumed that perennial grass, annual grass, and open shrub areas

will be burned at a ratio that is approximately one-third that of the other classes. Thus, if targeted states were burned at a rate of 3 percent per year, these non-target states would be burned at a rate of 1 percent per year.

Woodlands: Oak and associated woodlands comprise about 29 percent of the Beaver River landscape. Historically fires occurred in these areas every 20 to 50 years (Campbell and others, 2003). Pinyon-juniper now dominates a majority of this acreage. The major issue is controlling the amount of pinyon-juniper and maintaining young oak stands commensurate with the historic fire return interval. The assumed current fire return interval for these areas is 150 years. The primary treatment is to prescribe burn these areas at a rate of 2 percent per year.

Dry Forest: Approximately 10 percent of the study area is comprised of dry forest comprised mostly of ponderosa pine, Douglas fir, and white fir. These stands often have an aspen associate. The historic fire return interval is 5 to 25 years (Campbell and others, 2003). Wildfires in dry forests are now uncharacteristically severe and most areas that were dominated by ponderosa pine and aspen are now overstocked with white fir and Douglas fir. Major issues are the decline of aspen and ponderosa pine. Fuel treatments are needed to restore the natural role of fire. The assumed current fire return interval for these areas is 200 years. The primary treatment is to apply a salvage treatment (partial harvest and burn) to the mature and old high-risk classes at a rate of 2 percent of these areas per year. This treatment should transform these stands to the low-risk class. Immature, mature, and old low-risk stands are then prescribed burned every 30 years to maintain them in an open-canopied low-risk state.

High Elevation SpruceFir/Aspen forests: Approximately 12 percent of the study area is comprised of higher elevation forests. Dominant cover types are subalpine fir, Engelmann spruce and aspen. Historically fires occurred in these areas every 50 to 80 years, maintaining about 80 percent of the area in aspen (Campbell and others, 2003). Presently most acres are dominated by spruce and fir. The major management issue is the decline in the acreage and vigor of aspen. The primary treatments are to prescribe burn the mature aspen and spruce/fir stands capable of supporting aspen at a rate of 2 percent per year and to apply regeneration harvest to mature spruce/fir stands still containing an aspen component at a rate of 1 percent per year. These treatments restore aspen and reduce the amount of overage spruce/fir. In southwest Utah all aspen reproduction is by vegetative sprouting usually triggered by disturbance (Bartos and Campbell 1998).

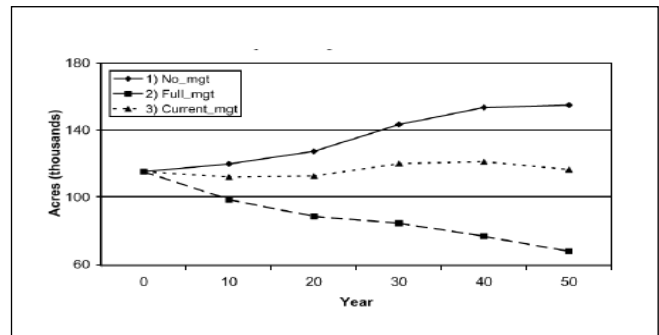


Figure 2—Scenario comparison: Pinyon-Juniper dominant acres

RESULTS

Four key environmental variables are used to compare the results of each scenario over the next 50 years.

- 1) **Acres dominated by pinyon-juniper** within both the grass/shrub and woodland models. Pinyon-juniper acreage has increased at least three fold from historic levels. The treatment objective is to reduce this acreage.
- 2) **The acres of open versus closed shrub** in grass/shrub areas. A relatively even proportion of open and closed shrub provides near optimal sage grouse habitat and is more reflective of historic conditions. Presently nearly 90 percent of sage stands are closed.
- 3) **Acres dominated by aspen** in forested areas. The intent of the treatments is to increase the aspen acreage at the expense of montane fir and spruce/fir.
- 4) **Acres of low-risk stands** in dry forest areas. These are the poletimber and larger stands historically maintained by frequent surface fires. Most dry forest stands are presently at high-risk for a stand replacement wildfire due to missed fire cycles and the associated fuel buildup.

Figure 2 shows the projected acreages dominated by pinyon-juniper for the three scenarios. In the full-management scenario pinyon-juniper dominated acres decrease 41 percent from 115 to 68 thousand acres over the next 50 years. With no treatment this acreage would increase 35 percent to 155 thousand acres over this same period. At current treatment levels pinyon-juniper acres are relatively constant.

The ratio of open to closed shrub area is graphed in figure 3. This ratio increases substantially with the full-management scenario and slightly when no treatments are applied. Changes in the no-treatment option are in response to projected wildfire acreage. If wildfires continue at the

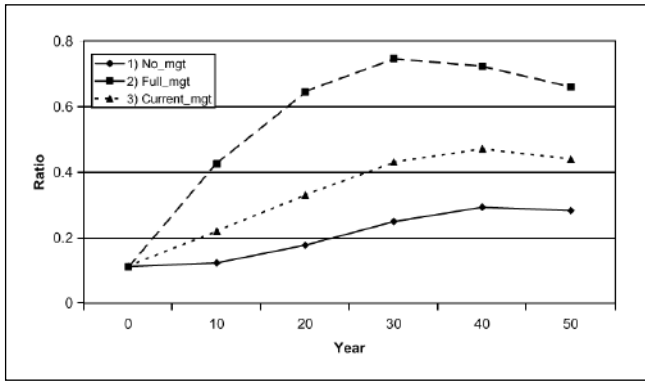


Figure 3—Scenario comparison: Ratio of open/closed shrub

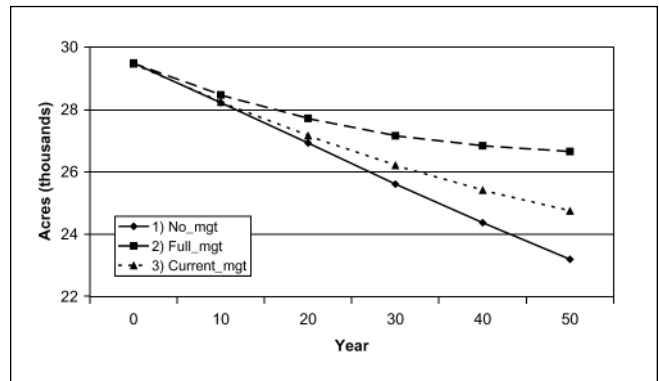


Figure 5—Scenario comparison: Acres with aspen present

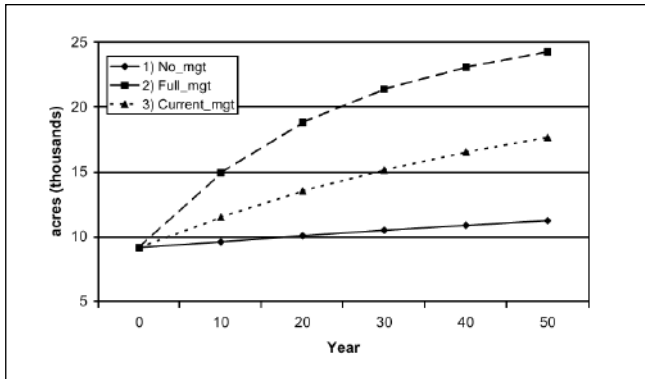


Figure 4—Scenario comparison: Dominant aspen acres

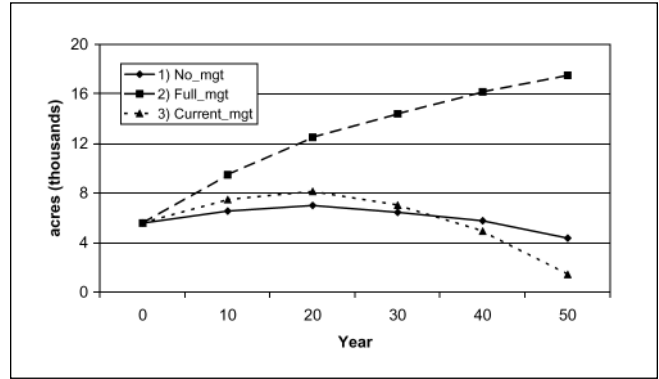


Figure 6—Scenario comparison: Dry Forest, low risk acres

rate of the past 10 years, there may be an increase in open shrub areas, regardless of whether management treatments are applied.

Acres dominated by aspen over the 50-year period are graphed in figure 4. Dominant aspen acreage increases from 9 to 24 thousand acres with full management and from 9 to 17 thousand acres at current treatment levels.

The increase in dominant aspen acreage associated with the no-treatment scenario (from 9 to 11 thousand acres) results from projecting the wildfire rates from the past decade for the next 50 years. Presently there are approximately 17 thousand acres of spruce/fir forests that contain aspen. Aspen is presently dominant on only 3 percent of this area (500 acres). Since wildfires in sprucefir/aspen stands normally result in an aspen dominated stand, the acres of dominant aspen acreage increases over the next 50 years even at a burn rate of 0.33 percent per year. Prior to European settlement, aspen was dominant on about 35 thousand acres in the Beaver River drainage (Campbell and others, 2003).

Aspen reproduces primarily by suckering from the parent root system. This suckering is normally in response to a disturbance such as wildfire. When aspen are lost from the landscape they will not reseed an area, as do conifers (Bartos and Campbell 1998). Overtopping by conifers, and reduced vigor caused by grazing, is gradually causing aspen to die out of many stands. Figure 5 shows the projected acreage in which aspen is present, but not necessarily dominant. Because all at-risk stands containing aspen cannot be immediately treated, the acres containing aspen declines with all three scenarios.

Figure 6 compares the projected acres of dry forest that are at a low risk for uncharacteristic stand-replacing fires. These are the open ponderosa pine and mixed ponderosa pine and Douglas fir stands. The acreage of low-risk stands steadily increases with the full-management scenario but ultimately decreases with the no-treatment and current-management scenarios.

Management treatments in this study area are generally designed to restore ecological conditions and reduce the

intensity of wildfire. In range areas within the Beaver River drainage these treatments result in a slight increase in potential wildfires. This is due to the increased acreage of annual and perennial grasslands, which are more prone to fire. In forested areas management results in a small decline in potential wildfire acres. The net result of these two factors is that the total wildfire acreage is projected to be nearly the same for the three scenarios.

DISCUSSION

VDDT is a non-spatial model intended mainly for broad scale analysis. VDDT projects changes in vegetative conditions in response to succession, disturbances, and management treatments. In the Beaver River drainage key indicators are used to estimate environmental conditions under different management scenarios, as projected by VDDT.

Major shifts in vegetative composition have occurred as a result of fire suppression and grazing. Historically fires burned vegetative types within the Beaver River area at frequencies ranging from every 5 to 80 years. In the past decade only 0.57 percent of this area burned per year for an average fire frequency of 175 years. In the previous two decades (1973 – 1992) virtually no acres burned. Current conditions in this drainage are reflective of conditions on the Fishlake National Forest as a whole. On the Fishlake National Forest spruce and fir acreage are estimated to have increased 238 percent from historic levels, while aspen has declined 259 percent. Pinyon-juniper acreage is believed to have increased 357 percent, while sage/grass/forb acreage has declined 295 percent (Campbell and others, 2003). These changes result in reduced streamflows caused by increased coverage of conifers including pinyon-juniper, reduced habitat for sage and aspen dependent wildlife species, and increased risk of uncharacteristically severe wildfires in dry forest areas.

This analysis suggests that if management treatments are maintained at current levels, vegetative conditions will most likely stabilize or decline further over the next fifty years. Active management, with treatment levels designed to mimic natural processes, would be necessary to restore this area and reverse current environmental trends.

The VDDT software, manual, and tutorial exercises can be downloaded from the website <http://www.essa.com>.

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**FIRE SUPPRESSION,
FIRE PLANNING, AND
FUEL MANAGEMENT**

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INTEGRATED TIMBER HARVEST AND FIRE MANAGEMENT PLANNING

Mauricio A. Acuña¹, Cristian D. Palma², Andrés Weintraub³, David L. Martell⁴, and Wenbin Cui⁵

ABSTRACT

Harvest planners often consider potential fire losses and timber production plans can influence fire management, but most timber harvest planning and fire management planning activities are carried out largely independently of each other. But road construction, timber harvesting and silvicultural activities can influence the flammability of a forest, so the procedure applied in this work considers an integrated fire and forest management planning methodology that accounts for and exploits such interactions using a fire spread model, a network model that identifies crucial stands that can influence the spread of fires across a landscape, and a spatially explicit timber harvest scheduling model. The model and how it is being applied to a forest management unit in the boreal forest region of Canada are described.

KEYWORDS: Mixed integer programming, heuristics, forest planning.

INTRODUCTION

Fire, a natural component of most forest ecosystems, has a significant impact on peoples' safety, public and private property, and economic activities based on forestry resources, such as wood production and recreation (Martell and Boychuk, 1997). Likewise, fire plays a significant role in innumerable functions of the ecosystem, such as biodiversity, the creation of habitat for animal life, etc.

Different studies have examined the effect of fire on wood supply (Reed and Errico, 1986; Van Wagner, 1979, 1983; Martell, 1994), applying linear programming approaches and stochastic losses. These studies all indicate that very small burn fractions translate into substantial reductions to long-term wood supply. Moreover, all these approximations have considered fire losses as variables exogenous to the problem of forest planning, without considering that forest

management decisions can have positive effects in terms of reducing fire spread. Thus, for example, Hirsch and Pengelly (1997) state that including certain forest management criteria, such as harvest planning and the design of cutting units, could reduce the probability of fires by considerable magnitudes. In other words, the strategic fragmentation of the forest that results from harvesting could have a firebreak effect, which would translate into a reduction of the burn area.

The forest management planning systems use the outputs from the fire management system (annual burn fraction) as an exogenous parameter. Forest management decisions, however, particularly the areas and timing of harvesting directly affect fuel continuity and therefore fire spread. This integration requires the design of decision-making support systems that can be used jointly by persons associated with both forest and fire management to develop,

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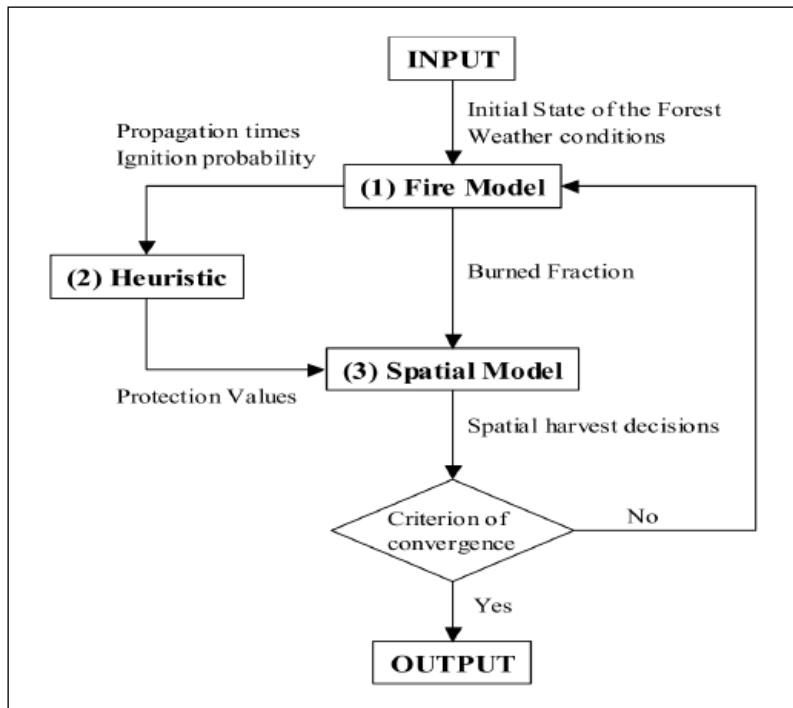


Figure 1—Iterative Planning Approach

evaluate and implement strategies and policies that contribute to sustainable forest management.

Our objective was to apply an integrated methodology that includes the use of forest planning spatial models, heuristic procedures and fire simulation models to evaluate the effect of fire spread on harvesting in a real case.

METHODOLOGY

Area of Study

The area of study selected to evaluate the integration of forest and fire management through spatial models is located in the centre-west region of the province of Alberta, Canada, and covers an area of more than 20,790 hectares (rectangular area of 16.5 km x 12.6 km) managed by the company Millar Western Industries. Of this total area, about 17,270 hectares correspond to forested areas used in this evaluation, with the remainder occupied by bodies of water, roads and towns.

General Approach

Given the close interaction between forest and fire management decisions, their integration is proposed using an iterative approach to planning as figure 1 indicates.

The proposed methodology includes the interaction of three systems: (1) a fire spread model, (2) a heuristic procedure for assigning a value to interrupting fire spread, and

(3) a spatial model for forest planning. Its main functions are described below and a detailed description of (2) and (3) is presented further along.

(1) Fire Spread Model: This model permits the simulation of burn occurrences over time, based on spatial information for the study area (type of vegetation, topographical conditions, etc.) and weather information such as wind direction and speed. The information provided by this model and relevant to our study is as follows:

- Fire spread times from each point (cell within the regular grid) to its neighboring points and the probability of a fire starting in each, to be used in (2).
- Statistics on burnt species to be able to estimate *annual burn fraction*, to be used in (3).

(2) Heuristic for assigning a value to interrupting fire spread: this heuristic procedure assigns a relative “value” to harvesting an area of the forest according to its positive impact on interrupting the fire’s advance. It is based on calculating the shortest routes for fire spread between two points, with the result used in spatial planning of forest harvesting. For implementation, the study area was divided into 231,000 cells, each measuring 30 x 30 m.

(3) Spatial forest planning model: This corresponds to a mixed integer programming model that maximizes the net present value (NPV) and whose decision variables include when and where to harvest the forest. The model

includes losses of wood that result from fires, expressed as the annual burn fraction, and considers the positive impact that harvesting can have on interrupting fire spread when it is associated with management decisions to achieve minimum “protection” levels.

This system proceeds as follows. Initial information about the state of the forest feeds the fire module. This generates (a) the information necessary (fire spread times, probable fire starts, etc.) for calculating a “protection value” using a heuristic procedure and (b) information on the fraction of the forest that burns given current conditions for determining management decisions within the spatial model. Meanwhile, protection values generated by heuristic procedures are included in the spatial model. Because the spatial harvesting decisions obtained modify the original conditions for fire spread and, as a result, its behavior and the fraction of forest burned, spatial model decisions are again fed into the fire module, generating new information for calculating protection values and for the spatial model. The process is stopped upon reaching a specific convergence criterion.

Procedure for Assigning a Value to Interrupting Fire Spread

This heuristic procedure assigns a value to each cell for interrupting the fire spread. As a fire starting in a cell should reach a destination cell along the route of least resistance to the fire it can be represented by the different shortest routes found for each pair of cells (Finney, 2002).

The importance of each route, $R(i,j)$, will vary according to the ignition probability in the cell of origin $I(i)$, the value to be protected in the destination cell $V(j)$, and the fire spread time between both cells i and j $T(i,j)$, and it is calculated as $R(i,j) = I(i) * V(j) / T(i,j)$. The higher the probability of a fire occurring at a point or the higher the value to be protected in the destination cell (which will burn if the fire reaches it), the more important it is to block this route. Similarly, if the fire takes too much time to reach the destination cell, blocking its spread by harvesting a cell will be less important, since it is more likely the fire will be suppressed through active measures. In our case, the value to protect in the destination cell corresponds to the volume of wood available, but it could also consider the presence of towns or critical infrastructure. The value of the different routes, $R(i,j)$, is added to cells that belong to the corresponding route, so the protection value assigned to each cell of forest will vary according to the quantity and importance of the fires that it can interrupt.

Finally, the procedure permits the creation of an index or ranking that represents the cells’ belonging to different

routes for possible fires. Thus, regions prone to fire spread will form part of many fire routes and their protection values will be higher.

Spatial Forest Planning Model

The model is for a mixed integer programming problem, implemented by using the modeling language GAMS/IDE v.19.6[®] and the solver CPLEX v.7.1[®]. The model establishes a spatial harvesting schedule that integrates fire protection. To do so, the model uses as its basis Model III by Reed and Errico (1986) and the variation proposed by Martell (1994), in order to maximize the NPV over an 80-year planning horizon, divided into eight 10-year periods. Model assumptions included:

- Completely accessed forest, so no road-building decisions were included.
- Harvest flows (volumes of wood) were accepted varying $\pm 30\%$ between periods.
- Harvested and burned areas regenerate naturally at no cost. The model does not include reforestation decisions, which means that once harvested the forest will always reforest with the same species.
- Transportation and harvesting (logging) costs per cutting unit were included, along with income per m^3 of wood harvested.
- There is an inventory of every age class when the planning horizon ends.
- Harvesting occurs at the mid-point of the period.
- If the decision is made to cut a stand during the period, it is completely harvested.
- No adjacency restrictions are included.
- It is assumed that the fire consumes some fixed proportion of the area not harvested in each age class and that this proportion does not vary over time. As indicated previously, this is referred to as the burn fraction.
- Fire protection values are included for each cutting unit. To do so, protection values for all the cells belonging to a cutting unit are added together to reach its final protection value.

As output, the spatial model determines a harvesting schedule for all cutting units over time and the supply of wood arising from the allowable annual cut.

Information the Model Requires—As input, this model receives the initial state of the forest, which consists mainly of cutting units, species, the commercial volume per species and age classes, all of which form part of Millar Western Industry’s inventory information for the study area.

Cutting unit: To define the cutting units we used the geographic information system ArcInfo[®], as our objective was

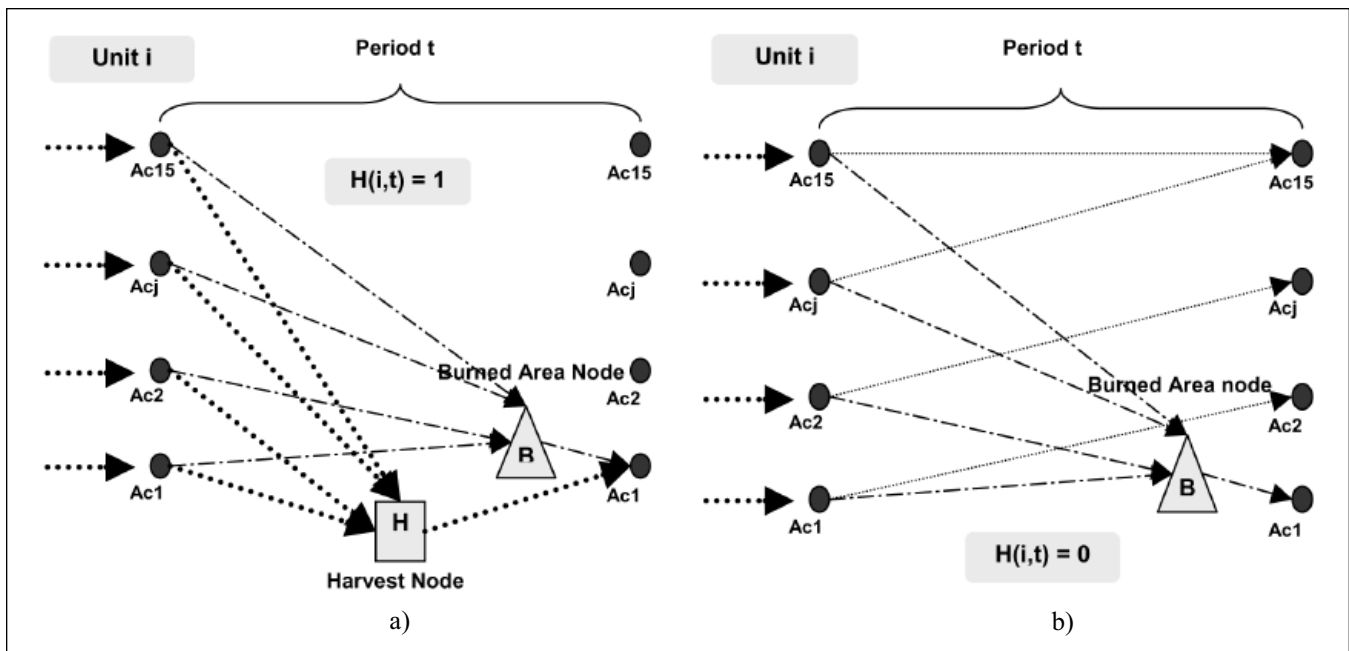


Figure 2—The network modeling approach. Cases in which the cutting unit is harvested (a) and not harvested (b).

to generate the largest number of units of a single species and age class, or a single species and different age classes. Moreover, unit area was restricted to the 15-45 hectare range, for a total of 628 cutting units averaging 27.5 hectares per unit.

Wood volumes, ages and species: Using the above definition of cutting units, a species and age class representing each cutting unit in the initial forest can be associated to run the spatial harvesting model. Likewise, to calculate commercial wood volumes, yield tables per species and age class were used, as taken from inventory reports by the company (Millar Western Forest Products Ltd., 2000).

Model Representation Using Networks—Our modeling focus at the forest level can be represented as networks, one for each cutting unit (figure 2), using the outline presented in Martell and Boychuk (1996).

Figure 2 depicts the area outcome over time. To do so, the area in each age class, that is, a strata-based approach, characterizes the forest at the beginning of each period. The nodes represent the existing surface area of each age class at the beginning of each period. The arcs represent the surface flow among nodes. Thus, if the decision is taken to harvest a cutting unit in a given period (figure 2a) the entire area harvested of each age class is brought together in a harvesting node, which will belong to the regeneration age class (age class 1) in the next period.

Similarly, if a cutting unit is not harvested (figure 2b), the whole area in each age class is transferred to the next age class for the following period. Logically, the area of some nodes and arcs in each period of the network may be zero.

For both situations within the same network a burn node is used, which brings together the whole area for each age class and each period that each cutting unit is affected by fire. As indicated previously, the burn is a fixed fraction that does not change over time or with each age class, so independently of whether a cutting unit is harvested or not, the area affected by fire is always discounted. This surface area, as with harvesting, moves to the next regeneration age class in the following period. With this formulation the spatial detail is maintained during the periods as the area harvested and burned as well as the area transferred to the next period are tracked and known.

RESULTS AND DISCUSSION

Information used by the model and dimensions of the problem to be optimized

For the base problem a total of 464 cutting units were considered. The burn fraction in each period was 5 percent, the interest rate was set to 5 percent and the maximum variation of volume between periods was set to 30 percent.

Table 1—Impact of different levels of burn fraction on volume harvested and NPV

Scenario	Burn fraction	Total area burned (ha)	Total volume harvested (MM m ³)	Objective function (MM \$)
0	0%	0.0	1.758	21.438
1	1%	129.6	1.714	20.907
2	3%	388.9	1.635	19.899
3	5%	648.2	1.554	19.068
4	10%	1296.4	1.341	16.312

Table 2—Effect of fire protection on the total timber volume harvested

Protection (%)	Burn fraction before protection (%)	Burn fraction after protection (%)	Volume before protection (MM m ³)	Volume after protection (MM m ³)	Difference (%)
10	5	4.85	1.554	1.554	0
10	5	4	1.554	1.590	2.2
10	5	3	1.554	1.625	4.6
10	5	2	1.554	1.668	7.3

Table 3—Effect of fire protection on the Net Present Value (NPV)

Protection (%)	Burn fraction before protection (%)	Burn fraction after protection (%)	NPV before protection (MM \$)	NPV after protection (MM \$)	Difference (%)
10	5	4.85	19.068	19.068	0
10	5	4	19.068	19.376	1.6
10	5	3	19.068	19.697	3.3
10	5	2	19.068	19.978	4.8

As for the problem to be optimized, this one had the following features:

- Total number of variables: 345,260
- Number of binary variables: 3,712
- Number of equations: 349,443
- Number of iterations: 53,557
- Resolution time: 801 seconds

Analysis

A number of scenarios were evaluated in order to investigate the variation of timber volume in each period and the economic effects of different strategies of fire protection.

Effect of different burn fractions on the harvest schedule—The model was run varying the annual burn fraction starting from a 0 percent level to a burn fraction

of 10 percent. Five different scenarios were evaluated whose burn fractions per period were 0, 1, 3, 5, and 10 percent, respectively.

The results obtained from these scenarios, their effects on the objective function as well as the area and the total volume harvested are shown in Table 1.

With an annual burn fraction of 10 percent the volume and the objective function decrease about 24 percent in a period of 80 years compared to the situation with no fire. This situation can be more negative if the results are projected over a longer-term horizon, in other words, 200 years or more, where the losses can be dramatically higher than the ones presented here (Martell, 1994).

In this work a burn fraction of 5 percent was used to run the models. With this relatively small amount of fire on the landscape, it is possible to observe losses of about 11 percent in volume and in NPV, corresponding to 204 million cubic meters and 2.37 million dollars respectively. Logically, these losses are considerably higher if the burn fraction is increased (e.g. 30 or 40 percent). As the losses associated to the presence of fire appear to increase exponentially, they can become an important risk for the company's wood supply.

Effect of different fire protection levels on the harvest schedule and their impact on the annual burn fractions—As described in the methodology, a number of different fire protection levels were used for running the model and evaluating its effects.

Being an ongoing research the results are preliminary and some of them are generated under assumptions (tables 2 and 3). Firstly the model was run with a 5 percent burn fraction which represented the base level and whose value was of 3.302E+7 units. Then we used two different protection levels, 10 and 20 percent, which were included into the model along with the benefit of a reduced area burn achieved with this higher protection. In this paper we only present the results for a 10 percent of protection.

We analyzed the case of timber volume and NPV. For the case with 10 percent of protection it is necessary to reduce the actual burn fraction 0.15 percent, to a level of 4.85 percent in order to have no additional benefits in volume or in NPV. With a higher fire protection the model becomes more constrained which means a decrease both in the objective function and the volume harvested. However, at the same time this negative effect in the objective function is neutralized with a reduced burn fraction as the protection increases.

If it is possible to reduce the burn fraction only from 5 percent to 4 percent, the total volume harvested increases a little more than 35,000 cubic meters, or a 2.2 percent. Likewise, reducing the burn fraction 1 percent with a protection of 10 percent increases the NPV 1.6 percent, or \$307,991.

Conversely, in an optimistic scenario with a protection level of 10 percent over the base level and a reduction of the burn fraction to 2 percent the volume increases in 7.3 percent or more than 114,166 cubic meters compared to the scenario with no protection. The positive effect in NPV is slightly lower than the benefit in volume. NPV increases

\$910,000 for the entire horizon or 4.8%. As we used logging costs generated by a uniform distribution and a fixed income for each cubic meter harvested, different results would be obtained by using real information.

CONCLUSIONS

From these results further research might be focused on studying the effect of having higher initial burn fractions in the landscape with no protection and the effects of greater reductions in burn fraction as more protection is applied. It is clear that the benefits are higher in landscapes strongly affected by fire and when the spatial harvest planning generated by this methodology is able to considerably reduce the annual burn fraction.

It is also necessary to study the effects of different forest structures and age class distributions and their impact on the timber volume to be harvested in each period. The forest information and data used for carrying out this study present much heterogeneity characterized by a considerable number of different species and ages. In a commercially managed forest the positive effect of applying this methodology both in volume and NPV can be higher than the results presented here. Therefore, this methodology should be tested in different kinds of forests with different structures and management in order to have more realistic results and conclusions.

Finally it is important to continue studying and evaluating the methodology presented in this paper, in particular the procedure for calculating the protection values as a measure to stop fire propagation. We have just considered the shortest paths between pairs of cells in order to know the different routes for the fires. It might be useful to evaluate the effect of other paths, perhaps the K-shortest paths that fires can take as alternatives routes. As this can be computationally challenging and may not provide better answers, other solution schemes such as using simulation in a probabilistic way, for example Monte Carlo simulation, might be studied in a further research.

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A SYSTEMS ANALYSIS MODEL FOR WILDLAND FIRE PREPAREDNESS PLANNING

Marc R. Wiitala¹ and Andrew E. Wilson²

ABSTRACT

Planning an effective and efficient initial attack wildfire suppression organization in preparation for an uncertain fire season is a challenging task for fire planners. This paper describes features of WIRAS, a discrete-event stochastic simulation model that can assist fire planners in wildfire preparedness planning and policy analysis. WIRAS simulates, according to user-defined rules, all phases of initial attack resource management and movement to meet the service needs in response to the ebb and flow of fire workload over the landscape and through time. In an operational setting WIRAS is used to test alternative preparedness programs against annual historical fire occurrence datasets to gauge performance with respect to spatially and temporally variable fire seasons. Planning capability at the national and regional scales is complemented by a unique ability of WIRAS to evaluate local preparedness programs within a larger geographic context to account for the impact of external competition for shared suppression resources, like airtankers, helitack, and smokejumpers.

INTRODUCTION

The initial attack system remains a critical component in the protection of the nation's resources at risk to wildland fire. Planning the appropriate amount and use of fire-fighting personnel and equipment to effectively deal with the fire fighting workload presented by impending fire seasons remains problematic for federal land management agencies (GAO 2002).

Operations research technologies are available to improve the quality of analytical tools for wildland fire planning. The method of system simulation is particularly suitable for application to the fire planning problem. Industry has often used simulation to model complex systems such as road transportation systems, emergency services delivery, mining operations, and supply systems. In Canada, the province of Ontario is successfully using system simulation for fire preparedness planning (Martell and others 1994; McAlpine and Hirsch 1999). System simulation offers a

great opportunity to capture the salient operating characteristics of the initial attack resource delivery system. An appropriately designed computer simulation model would provide fire managers a powerful analytical tool to evaluate the relative performance of initial attack program alternatives and resource deployment policies. Investments in other wildfire protection programs, like prevention, detection, and fuels treatment, would also lend themselves to examination by the model.

The need for a modern wildland fire planning and policy analysis tool is the target of a research and development project funded by the National Fire Plan (USDA and USDI 2001). The project has designed and built a new initial attack simulation model based on currently available simulation technologies. The model is currently undergoing testing and validation on the Umatilla National Forest in eastern Oregon and Washington. This paper describes the anatomy of this simulation model—the Wildfire Initial Response Assessment System (WIRAS). Before beginning, we briefly

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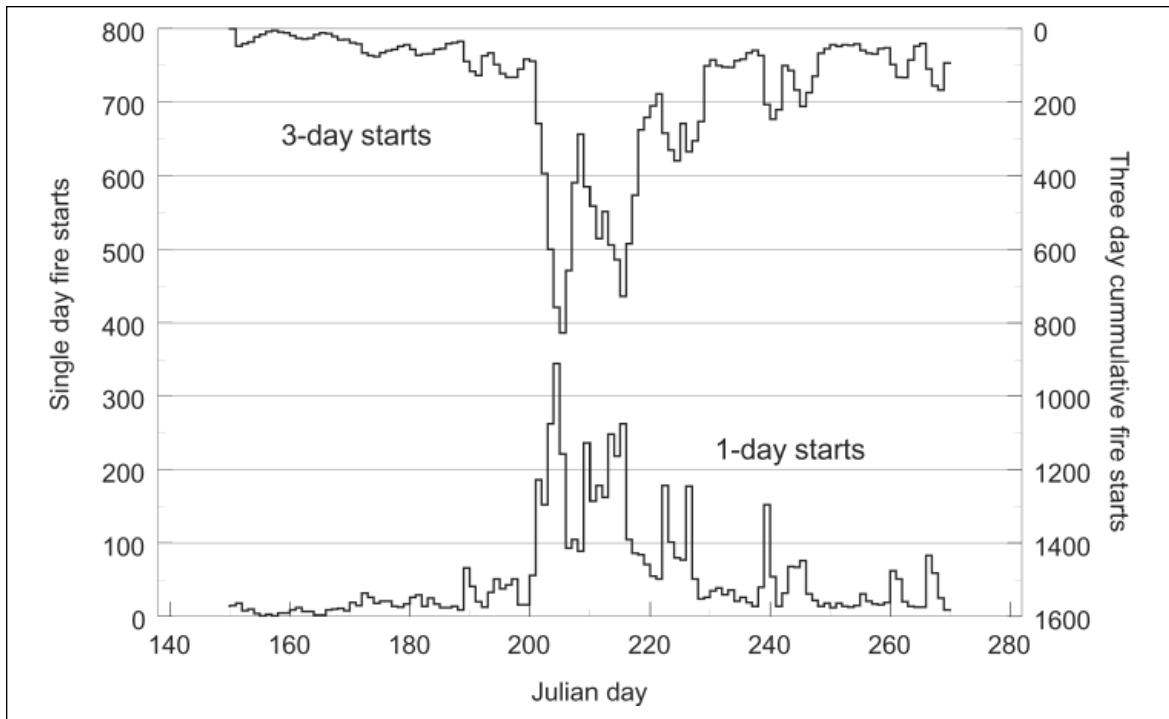


Figure 1—Comparing the temporal distribution of single and consecutive three-day fire starts in the northwestern United States in 1994.

look at the nature of fire planning problem and the initial attack environment.

PLANNING PROBLEM

In preparation for fire seasons, wildland fire managers choose the size, composition, and location of the fire suppression organization that best meets land management and protection objectives, usually with respect to alternative levels of fiscal constraint. Managers make this decision in the face of uncertainty, where fire seasons in many locations of North America vary greatly in intensity over time and across the landscape.

Choosing an appropriate presuppression organization more specifically involves selecting, for example, the number, size, location, and term of hand and engine crews to hire and long-term investments in capital equipment and facilities like fire engines and helicopter bases. Fire preparedness planning also develops dispatch policies for using not only locally controlled resources but also for those shared among jurisdictions, for example, airtankers and smoke-jumpers.

Initial Attack Environment

The initial attack setting has been aptly described by Martell and others (1984) and Wiitala (1998). We summarize the account given by the latter, but with reference to initial attack activity on federal lands in a region containing northern California, the Pacific Northwest, Idaho, and western Montana.

The initial attack process in this broad area consists of the collective action of many administrative units deploying wildland fire suppression forces in response to a seasonal flow of fires distributed temporally and geographically. The number of fires in this region can exceed 10,000 per summer season. Several hundred fires can occur on a given day and approach 1,000 on several consecutive days (figure 1).

Because thunderstorms are responsible for these peak periods of fire activity, fires tend to cluster spatially and temporally. This phenomenon creates localized heavy fire workloads that can tax the capabilities of local initial attack organizations and result in larger project fires. In a large geographic area, multiple thunderstorm cells often give rise to spatially dispersed fire clusters, creating competition for aerial initial attack resources shared over larger geographic scales.

As a general characterization of the local initial attack process, when fire activity commences, the resource dispatching process begins. Rules for resource dispatching vary between administrative units. The type and effort of response vary with uncertain conditions of the fire environment, land management objectives, and available resources. In general, dispatchers favor use of local ground resources with the shortest response times, provided the response times are reasonable for the conditions of the fire and protection objectives. Otherwise, dispatchers will deploy aerially delivered fire fighters, if available. Dispatchers may also request the support of airtankers to deliver retardant or water to the fire. Or, after delivery by helicopter, a crew may request a helicopter to support fireline construction with water drops.

Initial attack resources work a fire until it is contained or becomes unmanageable. In the latter instance, a large fire suppression organization assumes management of the fire. In either case, how quickly initial attack resources demobilize and return to a ready status depends on a variety of conditions including the time required for fire mop-up, the level of fire activity, time of day, and accessibility to transportation.

MODEL

WIRAS uses a process-oriented approach (Law and Kelton 1991) in its design of a discrete-event, stochastic computer simulation model representing the initial attack system. An enhanced variant of the discrete-event simulation language General Purpose Simulation System (Hendriksen and Crain 1989) originally developed by Gordon (1962), is the language used to build the simulation model. WIRAS shares many attributes and capabilities with the clock-driven, next-event simulation models of Fried and Gilless (1988), Martell et al. (1994), and Wiitala (1998), which address how the frequency and magnitude of multiple fire events and spatial interactions of initial attack affect program performance.

WIRAS distinguishes itself from its predecessors by featuring the ability to plan both local and national fire preparedness programs. It also pioneers the ability to conduct local planning within the context of the national fire environment and fire fighting activity. This embedded planning approach allows fire planners to design a local program while taking into account their success in competing for nationally shared aerial resources. To describe the structure of WIRAS, we present its major components.

Suppression Resources

WIRAS contains distinct subsystems to simulate the activities of various types of aerial and ground resources in the initial attack system. Each resource subsystem features a unique design to capture disparate operational features.

Airtanker, Smokejumper, and Helitack resources—The aerial subsystems deliver both water and retardant and crews to fires. The airtanker subsystem consists of single and multiple engine airtankers delivering retardant from a system of geographically fixed airtanker bases. Additionally, the single engine aircraft can operate from a mobile base. Not all bases can accommodate all airtanker types. For this reason, each airtanker and retardant base carries attributes within the model to permit imposing base use or capacity restrictions on some airtankers. Attributes affecting airtanker operations within the model include airspeed, retardant carrying capacity, loaded weight, refueling and reloading times, and a single engine airtanker identifier.

Major time-consuming operations modeled at an airtanker base include landing, taxiing, taking-off, refueling, and loading. The simulation model monitors daily airtanker flight hours to determine when to refuel an airtanker as well as when to limit use due to daily flight-hour restrictions. The number of loading bays, refueling trucks, and parking spaces specified for bases affects their ability to service airtankers and ultimately affects retardant delivery system performance.

The model's helitack subsystem is responsible for the delivery of crews, water, and retardant. After delivering a crew to a fire, the model may augment crew fireline building activity with helicopter water bucket support. In the model, bucket support continues until there is a need for the helicopter to refuel, deliver a crew, or return to base before nightfall. Helitack is modeled as a locally controlled resource operating from a system of bases with varying numbers of deliverable crew members. This subsystem permits sharing helicopters between bases but not crews.

The fixed-wing aircraft deliver smokejumpers primarily to fires that are remote or when the supply of local resources is exhausted. Smokejumpers are highly mobile at the national scale. Wiitala and Dammann (2003) provide a detailed description of the smokejumper subsystem as used in WIRAS. In summary, smokejumpers and their delivery aircraft attack fires from a system of bases dispersed across the western United States. The simulation model moves smokejumper assets between bases in response to demands created by the ebb and flow of fire activity across the national landscape.

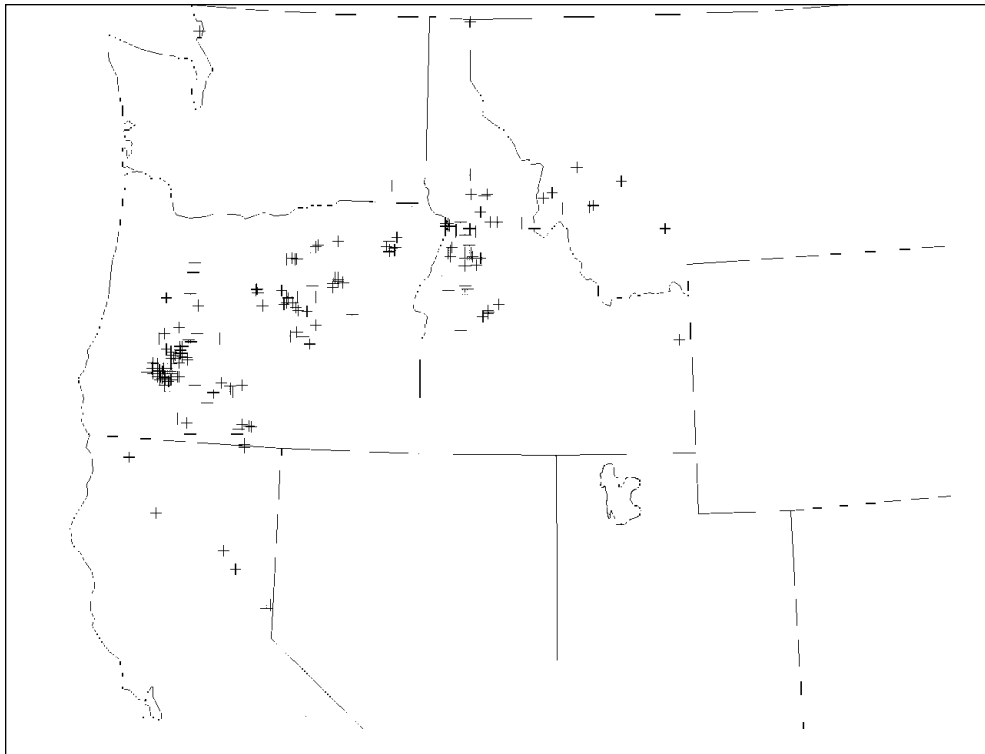


Figure 2—An example of the spatial distribution of fires on a day.

Ground resources—Because ground resources are very numerous, they not only make the greatest contribution to initial attack fire suppression, they also present the greatest obstacle to designing a computationally efficient simulation model. Initial attack ground resources in WIRAS currently consist of different sizes and types of hand crews, engines, water tenders, and dozers. The simulation model manages these resources in two different ways. The first way, used at the broad scale, gains computation speed at the expense of modeling accuracy. Here, ground resources lose their individual identity and specific locations as the model aggregates line-producing capabilities of disparate ground resources into a pool of generic capability called crew person equivalents. Aggregation takes place over user defined geographic areas. As fires occur during a simulation, the model dispatches crew person equivalents from the resource pool for the geographic area in which the fire occurs. As a pool of resources declines, the remaining resources are assumed to be more widely dispersed on an increasingly coarse grid and, thus, to have a higher mean response time to each new fire. To implement this approach, the model makes a random draw from a probability model describing distance to nearest grid point (resource location) to determine a distance for calculating the travel time of the first arriving resource. Not having to track within the model the

many individual ground resources populating the national landscape substantially increases the speed of simulation runs.

While the above scheme for capturing the suppression contribution of ground resources is sufficient when planning nationally shared resource programs like airtankers and smokejumpers, planning a local organization requires more detail for modeling local ground resources. In this second method, WIRAS resolves this problem by accepting a list of local ground resources containing specific resource attributes like location, line production capability, and travel speed. This detailed information allows the model to simulate more closely the deployment policies and travel dynamics for the local resources with only minor loss of computation efficiency. By simultaneously simulating fire and suppression resource activity both locally and nationally, WIRAS allows local planners to take into account the competition for nationally shared resources, like smokejumpers, while planning individual components of their local preparedness programs.

Fire Workload Generation

The number of ignitions, fire behavior, and resistance to fire control define fire workload. The combined effect of

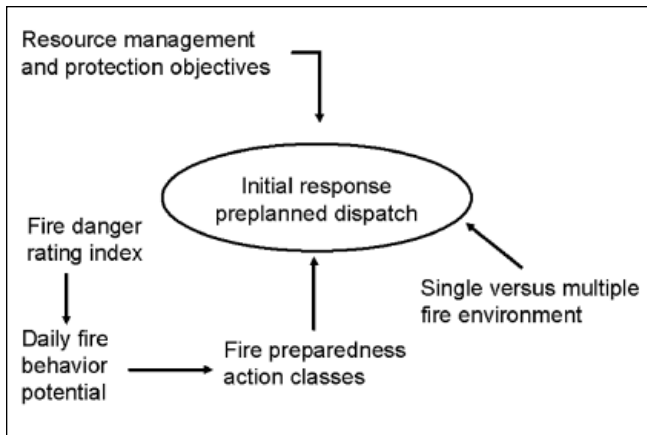


Figure 3—Factors determining the preplanned initial response to a fire.



Figure 4—Factors affecting reassessment of fire staffing needs upon first resource arrival.

temporal variation in fire occurrence (figure 1) and spatial variation in ignition pattern (figure 2) is an important determinant of initial attack program performance both locally and nationally. To preserve the impact of spatial and temporal autocorrelation on program performance, WIRAS simulates program performance for an entire set of fires from a season. Because fire workload varies significantly between years, WIRAS addresses the implications of fire workload variation on initial attack performance by testing a preparedness program against a range of fire seasons. Historical fire records currently provide WIRAS with the necessary time stream of geographically located fire ignitions.

Strength of Response

WIRAS mimics an administrative unit’s dispatch rules for determining the strength and priority of initial response

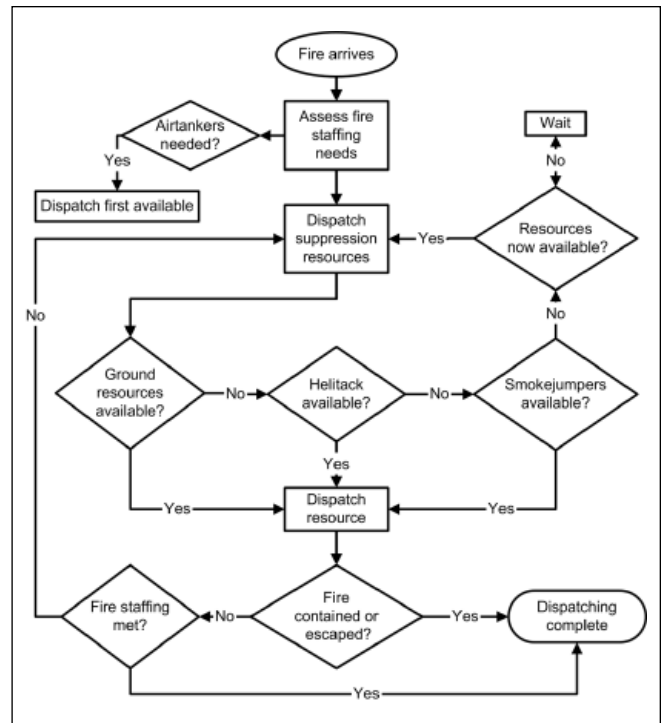


Figure 5—Resource dispatch decision process for staffing fires.

to a fire. Initial response policies revolve around dispatch blocks. Each dispatch block is a geographic area that reflects a difference in one or more of the following: management and protection objectives, fire behavior potential, and level of fire activity (figure 3).

As is true operationally, when the first resource arrives on a fire, the simulation model reassesses the needed staffing level based on actual fire conditions (figure 4). Depending on assessed needs and the strength of the initial response, the model may look for additional resources or halt the response of some resources in transit to the fire. In accordance with local practice, the model may also initiate airtanker support.

Resource Dispatching and Allocation

WIRAS controls resource dispatching through a system of Boolean variables that mimics the rules and priorities governing an administrative unit’s dispatch policies (figure 5). The model maintains and updates several state variables used by the Boolean variables to reflect the types of information typically available to dispatchers. This system of Boolean variables is sufficiently flexible to permit planners to set the conditions for the dispatching ground resources based on attack times, fire behavior potential, and protection objectives.

During a simulation, if the conditions for a ground resource response are not met, the model attempts to dispatch helitack crews. Failing this, WIRAS searches the smokejumper system for available suppression resources. The search for resources to dispatch to a fire continues until meeting fire staffing needs as determined by the initial response or by reassessment upon first resource arrival. If no initial attack resources are available, the model queues the staffing request. When a resource becomes available for dispatching, WIRAS selects from the service queue the highest priority fire serviceable by the resource. The model user can set the priority scheme based on protection objectives and fire behavior potential. However, WIRAS always attempts to complete unfulfilled fire staffing needs before staffing new fires.

Response Time Calculations

Accurate modeling of resource response times is critical to the successful modeling of the initial attack system. In WIRAS, components of response time include getaway, reloading, refueling, and travel time. Travel time is usually the largest component. For aircraft, distance between travel points and airspeed combine to calculate travel time. During periods of high fire activity, the response time of airtankers can lengthen if they have to wait for a retardant loading bay at congested airtanker bases.

For ground resources, WIRAS combines vehicle travel along a road network and off-road travel for ground resource travel time (Wilson and Wiitala, this proceedings). The simulation model integrates a computationally efficient least-cost-path algorithm to estimate ground resource travel times. To improve simulation time, many of the ground resource response times are computed prior to simulation based on known origins and destinations. During a simulation, a ground resource in transit to a fire may be diverted to another fire. At this point in the simulation, its location is calculated and the least-cost-path algorithm invoked to calculate response times to all fires to which the resource might respond.

Fire Growth and Containment

WIRAS implements a time-dependent accounting process operating on a five-minute time step to calculate fire perimeter growth, track resource arrivals, and compute fireline to determine when a fire is contained or escapes initial attack. The forward rate of fire growth is estimated at 2:00 PM from historical data for the fuel and environmental conditions at the location and on the day of fire occurrence. Fire growth is diurnally adjusted to account for wide differences in growth rates over a 24-hour period. A

double elliptical growth algorithm calculates perimeter expansion over time (Anderson 1983). Fire line construction occurs on the flanks of the fire from the point of ignition. WIRAS contains fires according to a model developed by Quintilio and Anderson (1976) that accounts for the effect of fireline production in moderating the growth of a fire's perimeter.

Fires are considered contained when fireline reaches a user specified percentage of fire perimeter. WIRAS escapes a fire (removes it from initial attack status) when fire perimeter exceeds constructed fireline by a user specified amount or fire area reaches a defined threshold.

Demobilization and Return to Service

Assumptions regarding how quickly initial attack resources become available for dispatching after fire containment or escape can greatly influence program performance. WIRAS encodes these assumptions into user changeable rules that provide the opportunity to evaluate how alternative demobilization and return to service policies affect system performance.

Under the existing default rules, when finished fighting a fire, WIRAS returns initial attack resources to service on the next day following fire containment and on the second following day if the fire escapes initial attack. The model makes two exceptions to this rule. First, if ground resources in roaded areas contain a fire sufficiently early in the day, the model may dispatch them to other fires awaiting service, response time permitting. Second, those crews simulated as walking deep in wilderness or unroaded areas will remain with the fire a full burning period after containment. This policy assures full fire control and minimizes the risk of a subsequent response to a reigniting fire in a remote area of high cost for aerial delivery or long response times for ground-based crews.

MODEL OUTPUTS

During a simulation, WIRAS collects a variety of operational statistics. These statistics help planners judge the physical and economic performance of alternative approaches to organizing a fire preparedness program for their administrative units. For example, information collected on resource utilization allows planners to identify underutilized resources and bases.

Planners can also combine a program's cost with suppression costs and projected natural resource losses estimated from model outputs to evaluate relative economic

efficiency of alternative preparedness programs. Program budgeting issues are also addressable. Other statistics include acres burned, escaped fire numbers, fire dispatches, aircraft flight hours, gallons of delivered retardant, and frequency distributions for contained fire sizes and resource attack times.

CONCLUSION

The purpose of this paper was to briefly describe the anatomy of WIRAS—a stochastic simulation model for fire preparedness planning. Stochastic simulation is proving to be a powerful operations research method for planning highly complex initial attack service delivery systems. Taking a system analysis perspective in the design of the WIRAS, the resulting initial attack simulation model can address a wide range of program and policy issues not previously addressable by other fire planning technologies. Not only can fire planners use WIRAS to determine the best program composition, they can also use it to improve their resource deployment and dispatch policies—locally, regionally, and nationally.

Opportunities for the application of WIRAS are now becoming apparent. In one recent application at the national level, WIRAS identified effective alternatives to the use of heavy airtankers in support of initial attack activities. Geographic area command centers are interested in the potential of WIRAS to examine and implement aerial resource prepositioning strategies during a fire season in response to fire severity forecasts. Also under consideration is the use of WIRAS to quantify improved initial attack program performance and consequent benefits of reduced suppression costs resulting from hazardous fuels treatment. Each new application of WIRAS generally necessitates creating a new variant of the core simulation model to address the unique characteristics of the new problem.

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OPTIMIZING INITIAL ATTACK EFFECTIVENESS BY USING PERFORMANCE MEASURES

Andrew G. Kirsch¹ and Douglas B. Rideout²

ABSTRACT

Increased scrutiny of federally funded programs combined with changes in fire management has created a demand for a new fire program analysis model. There is now a need for a model that displays tradeoffs between initial attack effectiveness and alternative funding levels. The model is formulated as an integer linear program that operates in a performance based, cost-effectiveness analysis (CEA) environment. Using the performance measure of weighted area protected (WAP), the model employs a non-monetized approach to interagency fire planning. The model optimizes the initial attack deployment for a user-defined set of fires that a manager would like to be prepared for across alternative budget levels. The paper shows how an integer programming formulation can use optimal deployment to address the annual fire program. It is also shown, for the first time how simultaneous ignitions can be incorporated into an optimization approach. This compact and robust model can provide the basis for a wider scale formulation with the potential to measure an organization's performance and promote a higher level of accountability and efficiency in fire programs.

INTRODUCTION

Estimating the preparedness organization for an upcoming wildfire season on public lands is a complex process. Federal land management agencies expend considerable effort to estimate the budget and to decide upon the resources that will be needed to protect public lands from wildfire each year. In preparedness planning, a fire manager's decisions often include the type and number of firefighting resources to have available. The difficulty of determining the number of resources is often compounded by the occurrence of simultaneous ignitions and having to plan for the possibility of receiving alternative appropriation levels. A suitable analysis of the tradeoffs of all of the possible combinations of appropriation levels, resources, and uses, requires a sound analytic system and a definitive measure of performance.

Many approaches have been suggested to assist decision makers in analyzing parts of the preparedness problem.

Approaches employing optimization have their roots in World War II and the birth of operations research. Much of the optimization literature extends Parks (1964) who designed a deterministic model to minimize the cost of suppression plus damages to find an optimal constant workforce. See Parlar and Vickson (1982), Parlar (1983), Aneja and Parlar (1984) for models that extend the Parks formulation. Boychuk and Martell (1988) also evaluated seasonal forest fire fighter requirements utilizing the least cost plus loss framework by using Markov chains. Recently, Donovan and Rideout (2003) used an integer linear programming model to optimize a firefighting resource allocation to a single fire using a cost plus net value change framework.

Despite the difference in optimization approaches, most previous models have relied heavily on derivatives of the cost plus loss theory first applied to wildfire in the early 20th century (Sparhawk 1925). The cost plus loss framework requires monetization of the damages caused by wildfires. As a fire advances across a landscape it can affect a

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myriad of natural resources, each posing its own challenge for accurate valuation. The valuation of fire damage continues to be an extremely difficult and costly task (Cleaves 1985; Pyne and others 1996).

Non-monetized approaches have also been used in a few fire management applications. For example, Kourtz and O'Regan (1968) used a cost effectiveness analysis (CEA) to assess fire detection systems, Nautiyal and Doan (1974) used iso-dissatisfaction curves to assess trading planned cut for wildfire protection expenditures, Omi and others (1981) used a damage reduction index to optimize fuel treatments, and Mees and Strauss (1992) used a utility measure of the relative importance of holding different constructed fireline segments to evaluate strategies for the tactical deployment of resources to a single large fire. Our research has been enriched by these previous studies as we have developed an optimization model in a non-monetized system.

Here we provide the first non-monetized application of an optimization model applied to preparedness planning. This approach shows how a strategic fire management planning effort can utilize integer linear programming to organize and optimize the initial attack response, in a CEA framework. The output of the model gives the planner an optimal list of resources to have available for an entire season across a range of possible budget appropriations. The model accounts for simultaneous ignitions, which are important planning elements that have not previously been considered in an optimization model.

DEVELOPING THE MODEL

Our approach demonstrates how a performance based optimization model can inform strategic planning decisions. For example, the model can provide information to aid with the development of a menu of initial attack firefighting resources that would be available for the fire season while considering both single and simultaneous fires. This strategic scope is in contrast to tactical or real-time decision-making such as the deployment of specific resources to a specific fire event. Because we optimize initial attack performance, as opposed to extended attack or large fires, only local resources affecting the planning unit's budget allocation are included in the model.

We use a deterministic integer linear programming (ILP) optimization approach to model the initial attack planning problem for several reasons. First, strategic planning involves decisions that are often integer or binary. These decisions include the number, location, and type of resources to have

available for deployment to a set of fires. Second, an ILP allows for the evaluation of thousands of decisions in a compact and flexible formulation. Our optimization model employs a performance-based CEA to display the tradeoffs between funding levels and initial attack performance. Cost effectiveness analysis helps decision makers allocate limited resources efficiently when performance measures are used in lieu of monetized benefit estimates (Robinson and others 1995; Osborne and Plastrik 2000). The results of a CEA are often displayed by forming a frontier as in figure 1, where costs are compared with effectiveness. While all points on the interior of the frontier are possible, they are technically inferior to points that comprise the frontier. For any interior point, there is at least one point on the frontier that can be shown to be preferable. Optimization enables the analyst to focus on solutions or points that define the frontier.

To compare the effectiveness of different initial attack organizations, we provide a performance measure defined as the weighted area protected (WAP). A WAP is a geographical area (for example, acre or hectare) assigned a proportional numerical weight representing the importance of protecting that area relative to another area from damaging wildfires. The WAP combines both qualitative and quantitative assessments of damage caused unwanted wildfires. Not all fires are created equal and the WAP captures the importance of protecting our natural treasures in a way that dollars values could not. Tradeoffs are clear to see and are directly related to performance on the ground. Defining WAP as a performance measure will allow the model to weigh the possibility of using scarce resources to contain more important fires while letting less important fires escape. Using a frontier estimated from the collection of a program's analyses, the overall effectiveness of the initial attack organizations can be displayed and analyzed as in figure 1.

The model requires an input set of fires that reflect the expected workload of a future fire season. Initially, the model needs predetermined initial response analysis period. This time can take on any value and each time step does not have to be constant allowing for a flexible analysis. Each fire is defined by an initial reporting size at time zero and its total cumulative perimeter and area burned for each time step in the analysis period. The fire's perimeter is directly related to cost through resource production rates and the fire's burned area is directly related to performance through WAP. Other fire behavior characteristics such as flame length and fire intensity can be reflected in the firefighting resources' ability to construct fireline. This allows managers to incorporate tactical firefighting standards, such as a fire with flame lengths of four to eight feet can



Figure 1—Generic cost-effectiveness frontier

be too intense for a direct attack with hand tools, but bulldozers, engines, and aerial drops can be effective (BLM Standards Chapter 9 2003). We use the free burning fire containment rule from previous deployment models (for example, USDA Forest Service 1991; Donovan and Rideout 2003) that states a fire is contained when the total fireline produced by firefighting resources is greater than the free burning fire perimeter. A fire is defined as having escaped initial suppression efforts if it cannot be contained in the initial attack time period because of either a lack of funds or inadequate fireline production.

The attributes of the firefighting resources constitute the main set of inputs to the optimization routine. The model requires a list of resources to choose from in order to maximize the WAP. This list includes all of the resources that are potentially affected by a planning unit's budget. Each resource is defined by a total fireline production and by its fixed and variable cost. Fireline production is input to the model as cumulative values for every time step of each fire. An advantage of this integer time step format is that the production rate does not have to be constant or linear and can reflect fatigue and other disruptions in the production such as water refills and refueling. Arrival and other travel times are also reflected in these production values. Resources produce zero chains of fireline during travel periods. The model uses the production information along with costs to solve for the optimal deployment.

The costs of initial response resources are important considerations in estimating the optimal deployment. While previous approaches included cost information, costs did not directly affect resource deployment. Our model relies upon fixed and variable costs that are directly input to aid with the management of optimal deployment (Donovan and Rideout 2003). The fixed cost is modeled as a one-time charge that is incurred only if the resource is deployed to any fire during the season. Each resource's variable cost is modeled as an hourly cost that reflects its operating costs on each fire, including maintenance, fuel, regular hourly wages, overtime and hazard pay.

Including simultaneous ignitions in the optimization model adds depth and advancement to the analysis. To model simultaneous ignitions we force certain resources to choose to fight a maximum of one of the simultaneous ignitions. We assume that once a resource is deployed to a fire, it is not released when containment is achieved for another deployment.

The following is the mathematical representation of the model:

Maximize WAP

$$WAP_o - \sum_{i=1}^I \sum_{d=0}^{D_e} (W_{id} * f_{id} * A_{id}) \quad (1)$$

Subject to:

$$\sum_{d=1}^D x_{ird} \leq u_r \quad \forall i, r \quad (2)$$

$$\sum_{d=0}^{D_e} f_{id} = 1 \quad \forall i \quad (3)$$

$$\sum_{r=1}^R \sum_{d=1}^D (x_{ird} * L_{ird}) \geq \sum_{d=0}^D f_{id} * P_{id} \quad \forall i \quad (4)$$

$$\sum_{d=0}^D d * f_{id} \geq \sum_{d=1}^D d * x_{ird} \quad \forall i, r \quad (5)$$

$$\sum_{i=1}^I \sum_{r=1}^R \sum_{d=1}^D (x_{ird} * H_{rd}) + \sum_{r=1}^R u_r * F_r \leq TC \quad (6)$$

$$\sum_{r \in S_n} \sum_{d=1}^D x_{ird} \leq u_r \quad \forall n, r \in R_S \quad (7)$$

Decision Variables

- x_{ird} = Binary(0,1) = 1 if resource (r) is used for (d) time periods on fire (i).
= 0 if resource (r) is not used on fire (i) for (d) time periods.
- f_{id} = Binary (0,1) = 1 if fire (i) burns for (d) time periods.
= 0 if fire (i) does not burn for (d) time periods.
- u_r = Binary(0,1) = 1 if resource (r) is deployed to any fire for any duration.
= 0 if resource (r) is never used.

Parameters

- I = set of all fires indexed by i.
R = set of all firefighting resources indexed by r.
D = resource deployment and contained fire duration indexed by d.
 D_e = escaped fire duration. D_e is defined as $D+1$.
 S_n = (n)th set of simultaneous ignitions.
 $S_n \subseteq I$.
- R_s = set of firefighting resources that are restricted to fight at most one of the fires that ignite simultaneously.
 $R_s \subseteq R$.
- F_r = fixed cost for resource (r).
 H_{rd} = total hourly cost accrued for resource (r) for (d) time periods.
 L_{ird} = total (cumulative) fireline produced by resource (r) for (d) time periods during fire (i).
 W_{id} = relative weight for the area burned by fire (i) after (d) time periods.
 P_{id} = total fire perimeter of the burned area for fire (i) after (d) time periods.
 A_{id} = total area burned by fire (i) after (d) time periods.
Calculated from P_{id} .
TC = total cost of initial attack input to the model.
 WAP_o = total weighted area of the fire planning unit.

The objective function (1) maximizes effectiveness defined as the weighted area protected for a given budget. Equation (2) limits a resource to at most one deployment per fire. For example, a firefighting resource cannot be deployed for two time periods and four time periods to the same fire. The equalities in (3) force each fire to have exactly one burn duration. Equations (4) are the containment constraints. For each contained fire, the total amount of fireline produced by all resources must be greater than or equal to the fire's burn perimeter. Equations (5) force each fire to burn at least as long as the longest duration of any resource deployed to that fire. For example, if on a given fire there were two resources used, one for three time periods and the other for six time periods, the fire would

burn for six time periods. Inequality (6) is the budget constraint. The total cost of all resources deployed to all fires, both hourly and fixed, must be less than or equal to the total cost denoted as TC. Equations (7) are used for fires that are modeled as simultaneous ignitions. Fires in these groups compete for firefighting resources. We assume that a resource can only be deployed to one fire in each group of simultaneous ignitions.

CONCLUSION

Our formulation provides an approach to performance based initial attack planning that incorporates the tenets of CEA in an optimization model. The performance measure of WAP shows how a non-monetized performance based system could be applied while addressing key elements of preparedness planning. While this model expanded previous work to optimize simultaneous ignitions, future efforts could continue to expand the scope of analysis. For example, one could change the deterministic model to incorporate stochastic elements, such as a range of likely fire occurrences. Other possible scope extensions could include linear or piecewise linear approaches to reduce the solution times.

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AN EMPIRICALLY BASED MODEL FOR ESTIMATING WILDFIRE SUPPRESSION RESOURCE RESPONSE TIMES

Andrew E. Wilson¹ and Marc R. Wiitala²

ABSTRACT

Suppression resource response times are an important component in planning models used to evaluate the effectiveness of wildfire preparedness organizations. Most fire planning models rely on subjective estimates of travel times between pre-determined points on the landscape. This paper describes a raster-based travel time model that provides greater accuracy, objectivity, and flexibility in estimating travel times between points on the landscape. The methodology used to create the travel time prediction model integrates existing GIS data with empirical travel data collected using GPS. Although the need to develop this rose from development of WIRAS (Wildland Initial Response Assessment System), it will be useful to many wildland fire pre-suppression planning efforts where there is a relationship between the time it takes fire suppression resources to respond and the final size and resultant costs of suppression.

INTRODUCTION

Planning for wildfire suppression is one of many ways to help increase the efficiency of a forest fire-fighting organization. Pre-suppression planning and analysis involves assessing how many resources to use, where to locate them, and how they will be dispatched. While there are several approaches to planning a pre-suppression organization, most account for and place great importance on the time it takes the suppression forces to move from their location to a fire incident. Mees (1986) found response time to be one of the most influential factors in his study of suppression resource base locations.

In that same study, Mees also describes suppression resource response time as having two major components: getaway time and travel time. For the initial response to a fire, the getaway time is the time between a dispatcher's request for a resource to respond and the beginning of transport to the fire. Travel time begins with the start of transport and ends with arrival at the fire.

Different types of fire fighting resources travel differently over the landscape. Travel time for aerial resources is easily determined by assuming flights are made in straight lines between locations. Accounting for terrain, transportation infrastructure, equipment capabilities, and other uncertainties complicates the computation of ground resource travel times.

The need for improved techniques for predicting travel times arose during the development of the Wildland Initial Response Assessment System; also known as WIRAS (Wiitala and others, this proceedings). WIRAS is a simulation system designed for use in planning and analyzing strategic pre-suppression decisions, such as quantities and locations of fire fighting resources and deployment rules. To properly assess the effectiveness of the system, the response times for aerial and ground resources are evaluated on an event-by-event basis as the scenario unfolds. WIRAS uses these response times in two primary ways: first, to select the quickest arriving fire fighting resources from a pool of

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available resources, and secondly to simulate the proper delay before individual resources start fireline production.

Within WIRAS, there are three possible location situations where a resource would be available to respond to a fire (fig. 1):

- at a base such as guard station or district office,
- at a fire, or
- at an intermediate location along a dispatch route.

This last situation arises when a resource in transit to a fire becomes available to respond to another fire. This could happen when the first resource arriving on the fire scene determines some of the resources en route to the fire are not needed for fire containment. The surplus resources are then available to respond to other incidents or, if not needed, return to their base.

WIRAS also simulates the demobilization of resources from fires back to bases. Travel times for these movements between bases and fires as well as those from fire to fire are computed prior to simulation. However, the travel times of in-transit resources becoming available for reassignment must be computed during the simulation from their calculated locations at the time of reassignment.

WIRAS provides the capability to address the variable nature of response times. These variations arise from the imperfect information on fire location that results in additional search time and other random time-consuming events related to getaway and travel times.

To meet the unique needs of WIRAS, a development effort was started to improve travel time prediction capability for the simulation model. This paper describes an on-going study to develop a model with greater accuracy, objectivity, and flexibility in estimating ground resource travel times between points on the landscape. The methodology used to create the travel time prediction model integrates existing GIS data with empirical travel data collected using GPS.

RELEVANT TRAVEL TIME STUDIES

A prominent study of vehicle travel time on forest roads is the Logging Road Handbook (Byrne and others 1960), verified by Moll and Copstead in 1996, which focused on log truck operations. To predict speeds, the study used engineering characteristics of the road (such as slippage due to surface type and curvature derived through surveying particular stretches of roads) and the physical

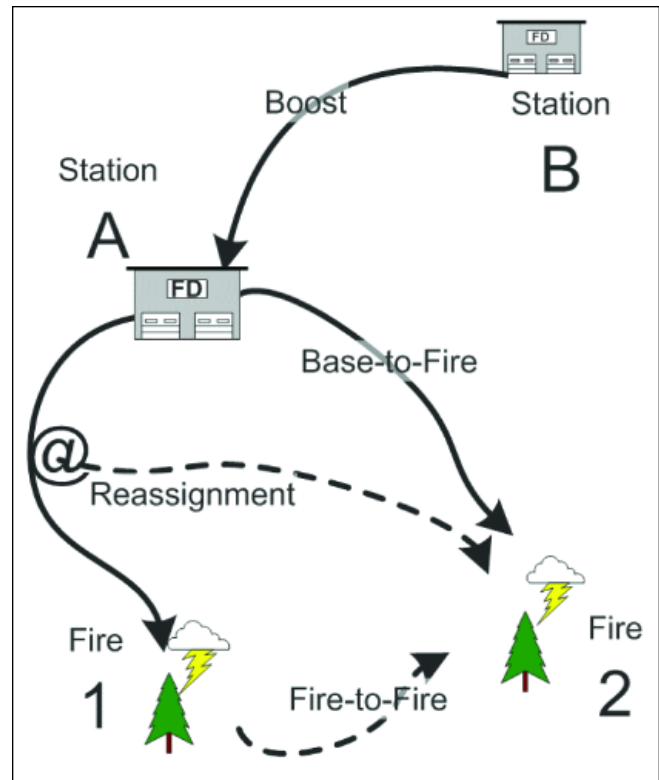


Figure 1—Potential origins when responding to fire 2 include a base (A), another fire (1) or an intermediate point (@) where the resource, initially responding to fire 1 is reassigned to fire 2.

characteristics of the vehicles (including gross vehicle weight, horsepower, tire pressure and weight of the load). This methodology required intensive attribution of equipment and travel routes, and in the context of forest road engineering, it was able to ignore the problem of off-road travel by foot.

Mees (1978) developed a model of firefighting resource allocation as a network problem (nodes connected by lines with travel times) using linear programming optimization to determine minimum travel time from an origin (a base) to destination (a fire). The network method works well when travel is restricted to linear features, like roads and trails. Mees resolved the problem of fires not falling on the transportation network by creating pseudo-nodes at the points on the inter-node connections closest to the incident and connecting these points to the incident with perpendicular segments using a fixed ground speed. There was not a discussion on how this heuristic worked in the face of terrain barriers and the methodology of determining inter-node times was not disclosed.

Travel speed by fire fighters on foot has been reported in relation to escaping from fires (Dakin 2002; and Butler and others 2000). While the former study focused on short (250 m) courses, the latter used historical records of fire fighter travel rates at two well-documented incidents to make estimates of sustainable travel rates over broad slope categories. Howley and Franks (1992), in the context of sports medicine, used human physiology to determine walking speeds over varying slopes based on a fixed rate of energy output. A comparison in figure 2 of the physiological walking model derived from this work and the sustained travel rates that Butler and others found shows the results are similar.

The intensive development of physical characteristics required for the engineering approach to this problem suggested by the *Logging Road Handbook* did provide insight into important factors in travel time, the time and costs of implementation were not compatible with the broad nature of fire pre-suppression planning across forest or landscape levels. The simple approach suggested by the linear programming approach forwarded by Mees did not adequately address the problems of access across varied terrain where the shortest distance is not necessarily the quickest distance.

STUDY AREA

The Umatilla National Forest was selected for the site of the study. The forest occupies about 1.4 million acres in an area 110 miles by 130 miles in the Blue Mountains of Northeast Oregon and Southwest Washington. It has four districts, two in the steeper, wetter north half of the forest and two in the drier, more rolling south half. Outside wilderness and inventoried roadless areas, fires are moderately accessible with 64 percent of the forest within ¼ mile of an open road, a distance within which fires can generally be attacked by an engine hose lay.

The Umatilla fire season has about 136 fires in a year with the majority of them spread across July, August and September. The forest directly employs about 20 engine and hand crews. Cooperators and contractors provide additional sources of dozers, tenders, engines and hand crews. A typical initial attack resource deployment at a district includes three engines and two or three hand crews. The Pendleton Interagency Communications Center, which dispatches fire suppression resources for the Umatilla National Forest and cooperatively protected lands, provided much of information on initial attack resource assignment required by this study.

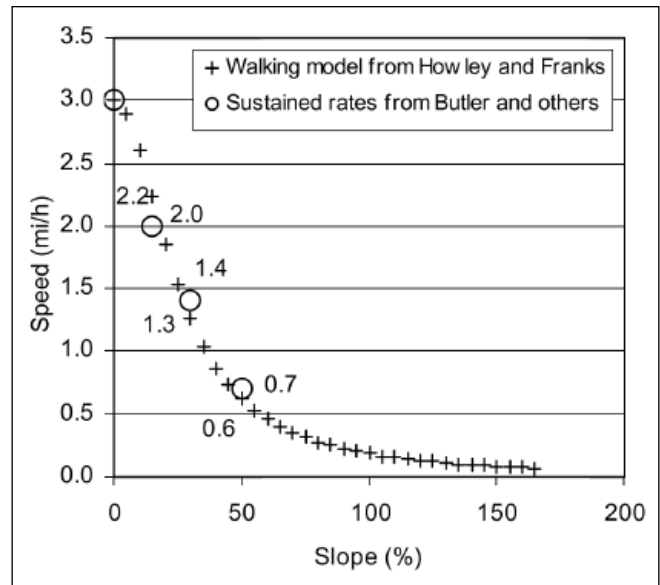


Figure 2—A comparison of walking model estimates of a firefighter's sustainable walking speed with sustainable walking speeds found in Butler and others (2000).

METHODOLOGY

The study's methods consist of two parts: the development of a raster-based model to calculate travel times and an empirical analysis of travel times. To predict travel times, a raster-based rather than network approach was selected to maximize computational speed and facilitate travel time calculations anywhere across the landscape. This model uses a travel resistance surface that incorporates both vehicle and foot travel. The travel time model incorporates a minimum cost path algorithm (Hatfield and others, this proceedings), which can calculate in a few seconds the responses of twenty or more resources spread across the forest to a single fire. Using the raster approach allows a better representation of the walk-in portion of the response time that can be affected significantly by terrain.

A major component of the travel time study is the empirical collection and analysis of travel time data. Empirical travel times provide a basis for testing accuracy of the minimum cost-path algorithm time calculations and adjusting the model for identified systematic bias. The deterministic predictions of the raster-based travel time model are expected to be different from actual travel times. As noted earlier, these statistical differences arise from variable search times due to imperfect initial fire reports and other delays experienced during an initial attack response. The empirical travel time data will be used to

quantify these underlying statistical processes for incorporation into the travel time prediction mode for use in WIRAS.

To acquire the necessary data to develop the travel time surface and support our verification and statistical analysis, we chose to collect empirical data on response speeds over the fire season. Three different data sets were collected: position-velocity logging, dispatch records, and radio transmission position logs.

Position-velocity logging units were installed in engine and crew vehicles and kept a record of the vehicles velocity based on time and position. The data (the time, the location of the vehicle and its speed) were determined within the unit with GPS and recorded at 15-second intervals as long as the vehicle was moving, regardless of whether the vehicle was responding to an initial attack incident or not. The data was stored on removable storage media and manually downloaded periodically.

To determine the data points where the vehicle was responding to a dispatch, we gathered the dispatch record information on resources ordered for each incident, including the unit identifier, when the dispatch order was sent and where the unit was, and when the unit arrived at the incident or was reassigned/released. The unit identifier and the dispatch start and stop times were used as key fields to filter the excess data from the logged velocity points. By examining the time series of logged position-velocity data points associated with each run, we could detect and quantify travel delays for resources responding to incidents. The magnitude of a delay is measured by the difference in expected response time and actual response time. This information is used to determine the nature of the variability of these delays.

There is always the possibility of confusion over which resources were involved in a dispatch and where they were located at the time of dispatch (especially in the reassignment case). We attempted to reduce the possibility of this confusion by augmenting the resource position information in the dispatch record with a resource position data set based on a radio-based real-time position tracking system. This position tracking system provided a GPS-derived coordinate/time pair for each radio transmission from the fire fighting resource that helped precisely determine unit initial attack response start and stop times and positions. Since the position information was displayed in real-time in the coordination center, it improved dispatch knowledge of resources and subsequent record keeping.

Once the velocity data was associated with initial attack incidents, the position information was used to determine the attributes of the predictors. Based on forest engineering studies like Byrne and others (1960) and discussions with engineering staff, we selected a set of available and fairly complete data elements from the Forest Service database (INFRA) that stores travel route information linked to a GIS route system. While the INFRA database had relatively fine attribute detail, it was sparse beyond the boundaries of forest Service administrative boundaries. We augmented the INFRA data these areas with information from the GTRN transportation database (BLM 2002) developed by the Bureau of Land Management. The other needed piece of spatial information was the terrain database. We resampled the 10-meter database from the national elevation dataset (USGS 2003) to 30-meter resolution, as we believed that this was the size of ground relevant to the movements at the forest scale. The specific road attributes examined included surface type (paved, gravel, improved native and native), operational maintenance level (closed, high clearance, suitable for passenger cars, moderate degree of user comfort and high degree of user comfort) and two derived attributes, Grade and Alignment. Deriving these two attributes required segmenting the linear road dataset to a finer resolution detail – rather than segments that connect intersections, the segments were split so that the maximum length was $\frac{1}{4}$ -mile. This length was chosen to approximate the average area of influence the attributes would have on a vehicle's speed and, given the rate of sampling, to ensure that pieces would not be missed in normal transit. To derive Grade, the elevation difference between each segment's endpoints was divided by the connecting road length segment. The Alignment measure was determined by dividing the straight-line distance between two points by the actual road distance depicted in the data. This resulted in a continuous measure of alignment, where the straighter the road was, the closer to unity the alignment value would be.

The other portion of the trip to the fire involves walking to the fire from where the vehicles are parked. Ideally, empirical data of the entire trip could be collected much like the velocity-position logging that was gathered on vehicles. Unfortunately, a cost-effective method to collect this type of data has not been discovered. Instead, the physiological-based model introduced above was applied and will be tested against the empirical data from the dispatch record and radio transmission logs. This model uses the assumption of constant energy expenditure based on energy requirements for walking (Howley and Franks 1992). The sum of vertical and horizontal net oxygen costs determines the change in speed as slope varies. This simplifies to a quadratic slope-speed relationship.

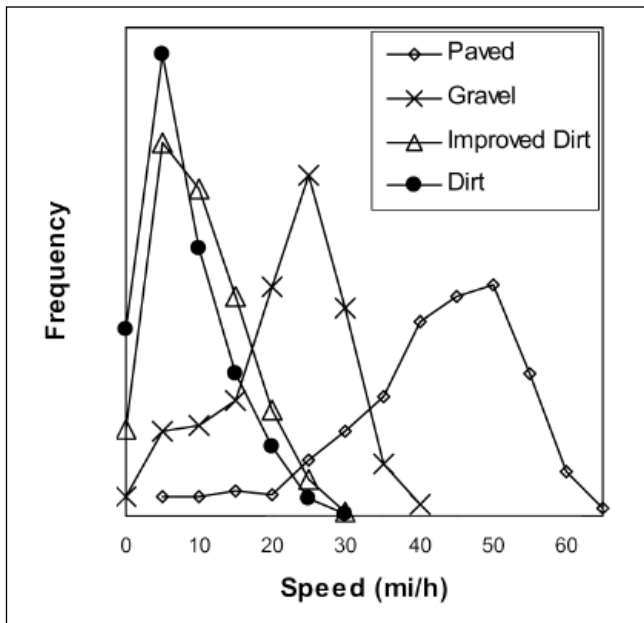


Figure 3—Frequency distribution of speeds observed on different road surface types.

We assume that travel by vehicle will be at least as fast as travel by foot, so the final model uses the vehicular travel model where the roads exist, and the walking time model elsewhere. The combined model, measured in minutes per unit measure, can then be summed to determine travel time across the landscape, the basis for determining the minimum duration path.

RESULTS

Position-velocity loggers were installed in initial attack vehicles in the south half of the forest in late-summer 2002 and the dispatch records associated with these vehicles were coded into the database. Difficulties in the engineering of the radio-based tracking system delayed implementation of those units until spring, 2003. All resources being examined had both position-velocity logging units and the radio position tracking hardware installed in them. The 2003 season will have the full complement of data for examination when it is complete in mid-November, allowing a full analysis of the data.

Even though there was limited data from the 2002 season, the procedures were tested to ensure that the data could be filtered and analyzed to allow preliminary examination of relationships. Given this preliminary nature of the data,

we saw that a primary factor in vehicle speed was the surface type (fig. 3) – most of the paved roads were highways with resultant high average observed speed of 44 mi/h with subsequent drops in speed as the vehicle moved to lower quality surfaces of gravel (24 mi/h) and improved and unimproved native materials (12 and 10 mi/h).

Examination of the data at the tails of the curves showed that there were errors induced by lack of coincident positioning between the observed GPS data and the GIS data. Many of these errors occurred at intersections between road classes. In the GIS, roads are lines without widths. Even a very accurate observation near an intersection would not fall precisely on either road in the GIS and would have some probability of being closer to the intersect road. As the accuracy of the position decreases, the probability of being closer to the intersecting road increases. While it is tempting to remove all points near intersections to remove this error, potentially there are factors affecting speed at these same intersections as well.

Other problems associated with the GPS measurements included occasional incorrect positions (usually not more than 300 yards from the actual location) when a poor set of satellites was chosen from the constellation by the GPS unit, causing one or more locations to be recorded incorrectly. Resolving these errors required a thorough manual examination of the time series of data points to catch these errors. An even rarer error (about one in 10,000) was the recording of an anomalous velocity attribute. These were always single incidents in the data stream and were identified through looking at a moving window of statistics in the time series. Another source of error was the dispatch record. It had to be thoroughly examined and compared to the observed data to ensure that it was correct. Many of the problems occurred during days when there were multiple fires and were caused by the combination of more resources to track and additional dispatchers that were not familiar with the area.

Although the data for the first year was from the south half of the forest and only included the last part of the fire season, we were able to observe some apparent relationships. Once the data was classed on surface type, it appears that alignment was significant in determining speeds on the paved roads, while it had little impact on the improved native roads. There was a high degree of correlation between surface type and maintenance level when looking at all categories, however, the closed road class in maintenance level was not as correlated and provided predictive power on the non-paved roads.

It should be noted that using the raster approach as described above might not be an appropriate tool for real-time routing of emergency response services. Individual routes determined optimal with the model may, in reality, be infeasible or may have longer durations than the model specifies. As well, complex traffic controls, such as one-way roads and restricted intersections are more difficult to address. However, the model works well within this strategic planning realm of wildfire suppression.

CONCLUSION

This paper describes development of a model to estimate the response time of initial attack resources for use in strategic planning. It discusses data collected and used in developing the model. Problems with the GPS-derived data are pointed out and methods to remove errors are posited. Finally, preliminary results are presented and indicate that this will be an effective improvement in the determination of response times in analysis of wildland fire pre-suppression planning.

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MODELING OPPORTUNITIES AND FEASIBILITY OF SITING WOOD-FIRED ELECTRICAL GENERATING FACILITIES TO FACILITATE LANDSCAPE-SCALE FUEL TREATMENT WITH FIA BIOSUM

Jeremy S. Fried¹, Glenn Christensen¹, Dale Weyermann¹, R. Jamie Barbour²,
Roger Fight³, Bruce Hiserote¹, and Guy Pinjuv³

ABSTRACT

Utilization of small diameter trees is viewed by many as the key to making landscape-scale fuel treatment financially feasible. But little capacity currently exists for utilizing such material and capacity of sufficient scale to have a significant impact on the economics of small diameter removals will only be added if predictable feedstocks can be assured. The FIA BioSum modeling framework that incorporates Forest Inventory and Analysis (FIA) plot data, a transportation cost model, a treatment cost accounting module, a log valuation model, and a crown fire hazard evaluator was applied to a 28 million acre study area containing 6200 FIA plots spanning the Eastern Cascades, Southern Cascades, Klamath Mountains and Modoc Plateau ecoregions of western Oregon and northern California. Up to nine fuel treatment prescriptions with a high likelihood of producing a substantial reduction in crown fire hazard were simulated for each plot, and 221 potential biomass processing sites were considered. With four 50 MW biomass-fueled power plants strategically distributed over the study area, up to 5.3 million acres could be effectively treated with net revenue of 2.6 billion dollars, a merchantable yield of 9.5 billion cubic feet, and a biomass yield of 79 million green tons, if net-revenue maximizing fuel treatments are selected. If merchantable volume minimizing treatments are selected instead for these 5.3 million acres, net revenue would be negative 2.6 billion dollars, merchantable yield would be 3.6 billion cubic feet and biomass yield would be 75 million green tons. With the constraint that every acre generate positive net revenue, only 2.6 million acres would be treated, even if the net revenue maximizing treatment is selected.

INTRODUCTION

As large, stand-replacing fires have become common over the past few years in the western United States, interest in assessing the potential for landscape-scale fuel treatment has intensified. Doubts have grown about the feasibility and/or wisdom of widespread use of prescribed fire due to concerns about air quality, liability, narrow windows of opportunity to implement treatments, and potentially undesirable fire effects. Fuel treatment has for most forestry professionals and most of the public come to be virtually synonymous with mechanical removal or thinning of the

forests to reduce fire severity and the likelihood of stand-replacing fire, especially since the advent and passage of the Healthy Forest Restoration Act of 2003.

The conventional wisdom has been that in order to be effective, such treatments would require the removal of large numbers of small stems, at considerable cost, but that this harvested material would have little or no value. In part to address this concern, but also with an eye towards promoting renewable energy options and increasing employment opportunities in rural forests, proposals have been and continue to be floated in many parts of the U.S. to

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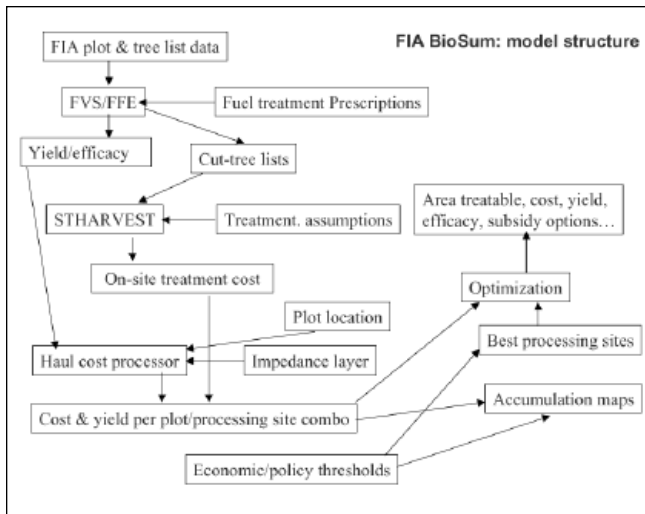


Figure 1—Flow diagram of the FIA BioSum modeling framework.

develop markets for submerchantable-sized trees by promoting the construction of biomass processing facilities of various capacities that would convert biomass to electrical energy via direct combustion or through various intermediate pathways (for example, gasification). However, such facilities require a sizable, up-front investment—one that is unlikely to be made by the private sector without some confidence that there will be an adequate source of supply over a long enough period for the investment to generate a positive financial return.

Fire and forest planners and managers, rural community economic development staff, and potential investors in biomass processing capacity believe they could benefit from knowledge of where the “hot spots” of potential biomass supply are to be found and the kinds of materials, both submerchantable and merchantable, that could be reasonably expected to flow from landscape-scale fuel treatments. This analysis was undertaken to identify such hot spots, but has evolved, thanks to wide-ranging discussions with diverse clients, to encompass a great deal more—including comparison of a number of fuel treatment prescriptions, assessment of the economic feasibility of fuel treatments with a complete accounting of harvest and haul costs, and a model-based characterization the fire risk reduction accomplishment of such a fuel treatment program. Questions we sought to address progressed from “how much biomass is out there” and “where is the best place to site a biomass processing facility” to “how much biomass is legally and economically accessible”, “how much will treatments cost”, and “will a subsidy help”.

We constructed a geographically explicit analytic framework for assessing and summarizing biomass production opportunities, dubbed FIA BioSum (fig. 1). We used publicly available, field-collected forest inventory plot data, publicly available road and ownership GIS layers, a suite of publicly available models, and sets of assumptions, parameters and decision rules developed in consultation with local fire, fuels, silviculture, and logging experts as well as biomass plant operators to address the feasibility issue for a 28 million acre, 4 ecosection study area in Oregon and California. These ecosections (Klamath, Modoc Plateau, southern Cascades, and eastern Cascades) were selected because current fire regime condition class maps of the U.S. show much of the area in these ecosections as in condition class 3—lands that have significantly altered vegetation composition, diversity, and structure due to altered fire return intervals so that they verge on the greatest risk of ecological collapse due to loss of key ecosystem components from fire and are thus likely to receive high priority for fuel treatment (USDA, USDI 2002).

METHODS

Forest inventory data for this analysis were drawn from six inventories undertaken at various times during the 1990s by the USDA Forest Service PNW Research Station’s Forest Inventory and Analysis Program, USDA Forest Service Region 5, USDA Forest Service Region 6, and the Bureau of Land Management. While there were numerous design differences among these inventories, each was a statistically representative sample of a portion of the total landscape and included measurements of tree attributes such as diameter, height and species with this information compiled to produce plot level estimates of volume, biomass, basal area and density, for example. A total of 6200 field plots representing 22.2 million acres of forested land fell within the study area boundary. This plot set was culled to remove from further analysis plots that were evaluated in the field as non-forest or located in designated wilderness, natural areas, parks, preserves, monuments, national recreation areas, national wildlife refuges, and inventoried roadless areas that had been under consideration for possible protection in the 1990s. We also omitted plots on steep (> 40 percent) slopes that were more than 2000 feet from the nearest mapped road on the grounds that current skyline harvesting systems cannot economically reach beyond this limit, and the cost of building new roads to bring such equipment closer to the plot would likely be prohibitive and is in any case beyond the scope of this analysis. Finally, we omitted plots containing no trees over 5 inches d.b.h.. Due to unforeseen data management problems, the 20 percent of the plots that contained

Table 1—Fuel treatment prescriptions applied in a test of the FIA BioSum analytic framework.

Prescription	Density reduction					Fuel reduction			
	A	B	C	D	E	F	G	H	J
Target residual basal area ft ²	125	125	90	90	90	80	60	60	60
Maximum d.b.h. (in.) allowed for harvested trees	21	none	21	16	none	21	21	none	10

more than one condition (in other words, the plot contained road or non-forest land in addition to forest or contained more than one type, size or density of forest) could not be processed in time for this analysis, so the results presented here cannot be considered comprehensive over all lands and surely underestimate costs, revenues, area treated and product flows by an unknown amount if considering the entire landscape; still, these results do apply to the 80 percent of the landscape represented by single condition plots. The net result of all these reductions is a set of plots that represents about 10.4 million acres of forest land—8.2 million acres of this federally administered and 2.2 million acres privately owned. We did not account for special use areas with harvesting restrictions such as riparian buffers or late successional reserves designated under the Northwest Forest Plan. Nor did we include restrictions such as those found in the Healthy Forest Restoration Act of 2003 that attempt to focus treatments within a fixed distance of communities. Either of these types of management restrictions could be accounted for in future analyses if they are accurately mapped.

The plots used in the analysis were loaded into the Forest Vegetation Simulator (FVS) (Stage 1973; Wykoff and others 1982) to simulate fuel treatment prescriptions and, via its Fire and Fuels Extension (FFE) (Reinhardt and Crookston 2003), the likely change in fire hazard these treatments would produce. The two FVS variants applicable to this study area, South-central Oregon and Northeastern California (SORNEC) and East Cascades (EC), were used for modeling and their FFEs were used to derive several fire-related stand attributes and ultimately compute indices of crown fire potential for each plot, specifically, torching index (TI) and crowning index (CI). TI represents the wind speed at which fire could be expected to move from surface fuels into crown fuels and is highly influenced by vertical stand structure (ladder fuels) and height to crown base

(derived from crown ratio); CI is the wind speed at which a crown fire could be expected to be sustained and is heavily influenced by crown bulk density. For the purposes of this study, increases in CI or TI brought about by fuels treatment were assumed to reduce fire hazard.

Nine fuel treatment prescriptions representing two treatment approaches were developed in consultation with fire and fuels specialists and applied to all plots for which they were valid (table 1). For example, a prescription calling for a post-treatment residual basal area of 125 ft²/ac could not be applied to a plot containing only 80 ft²/ac. Five of the treatments were designed for density reduction (personal communication with John Gerritsma on 3 May 2002), with a primary focus of reducing the propagation of a crown fire, and involved thinning proportionately across all diameter classes to a target residual basal area, with the proviso that 70 percent of the basal area cut be from trees that are 5.5-14.5" d.b.h. with the remainder from trees >14.5 inches. The other three were designed as ladder fuels reduction treatments (personal communication with John Szymoniak, 6 May 2002), with a primary focus of reducing the initiation of crown fire, that thinned from below (>5.5" d.b.h.) to a residual basal area target. The treatments had a range of residual basal area targets (60-125 ft²/ac) and maximum acceptable diameter for cut trees (10" to no limit). For both kinds of treatments, but mainly for ladder fuels reduction, if the maximum diameter limit was reached before the residual basal area target, then the latter was not achieved. For all prescriptions and on all plots, trees less than 3.5" d.b.h. were cut into pieces and scattered, and trees 3.5-5.5" were cut and scattered on steep slopes (>40 percent) and harvested and collected to the landing as biomass on gentle slopes. Because the most aggressive treatment had a residual basal area of 60 ft²/ac, plots with less basal area were excluded, leaving 6.9 million acres represented in the analysis.

These prescriptions were applied in FVS-generated “cut lists” for each plot and, with post-processing via various program scripts, numerous plot and tree attributes used at later stages in the analysis (for example, slope, number of stems harvested, average stem size harvested, and volume and biomass by species and size class) were computed and stored. Post-treatment estimates of TI and CI were computed with FFE for each prescription for each plot.

Data extracted from the FVS output was processed with STHARVEST (Fight and others 2003), a spreadsheet model composed of regressions and look-up tables for logging cost components derived from empirical data on small timber sales. STHARVEST requires specification of assumptions regarding logging system (for example, whole tree, cut-to-length, cable), range of tree diameters to be included, volume per acre, and disposition of residue. Miscellaneous costs (for example, “brush-cutting”, waterbars) were also accounted for. Whole tree logging systems were assumed for slopes ≤ 40 percent (except for trees too large to be handled without bucking); cable systems were used on slopes > 40 percent, with manual felling, bucking and limbing in the woods (in other words, limbs and tops not recovered for biomass utilization). For each plot and prescription, STHARVEST provided an estimated on-site cost of implementing the prescription (in other words, from stump to truck). Harvested material was allocated to one of two categories: Merchantable, which consisted of boles of trees > 7.0 ” d.b.h. to a 5” diameter top, and Biomass, which consisted of trees brought to the landing that were 3.5 – 7.0” d.b.h., the limbs and tops of merchantable trees, and all harvested hardwoods. Delivered biomass was valued at \$18 per green ton, the going rate circa 2003 in places like northern California where multiple biomass facilities compete for material, and merchantable material values were assigned from a look-up table based on species group and tree diameter. Plot-treatment combinations that generated less than 300 ft³/ac of total volume (biomass and merchantable combined) were deemed unrealistic and discarded; for some plots, no treatment cleared this hurdle and these plots were excluded, leaving a set of plots representing 5.7 million acres amenable to one or more of the fuel treatment prescriptions.

Because this analysis targets fuel treatments that reduce the risk of stand-replacement fire, only treatments that are effective in achieving this goal are included. Reaching a consensus among fire and fuel managers on which crown fire potential index is most critical and on how much an index must change for the effect to be significant proved elusive. Consequently, we developed, as a working criterion to demonstrate FIA BioSum’s analytic potential, an

arbitrary, minimum threshold of fuel treatment effectiveness: a 20 mph improvement (increase) in either TI or CI with no reduction in the other. Treatments that fell short of this threshold were deemed ineffective and discarded; this resulted in some plots being untreatable and reduced the area in the analysis to 5.4 million acres.

Because the problems we tackled are strongly associated with location (where can treatment be feasibly applied, where to site biomass processing facilities) and our plans to eventually integrate this analysis with maps of the wildland urban interface, we chose to pursue a spatially explicit analytical framework that would account for differences in haul costs and identify locations with a sufficient potential accumulation of biomass to justify investment in a processing facility. An approximately 20x20 km grid of 221 potential processing sites (psites) was established over the study area, approximate in the sense that we relocated psites that fell on public lands. GIS road layers obtained from BLM, USDA Forest Service Region 5, USGS and others were combined, edge-matched, cleaned of gross anomalies and massaged to produce a study area-wide, topologically imperfect vector GIS road coverage with each road segment attributed as to likely rated speed. This road coverage was then tessellated into 250 m grid cells, with each cell’s value set to the cost per ton-mile of traversing the cell on the fastest (lowest cost of transit) road in that cell, resulting in an impedance surface that formed the basis of haul cost calculations for FIA BioSum. Cells containing no roads were assigned infinite cost of transit, and plots occurring in such cells were “moved” to the nearest road for purposes of haul cost calculation, retaining the distance moved as an input to the yarding cost calculations used by STHARVEST. For each psite, a cost accumulation grid was generated in Arc/Info, and overlaid on the plot grid to provide haul cost in dollars per ton to that psite from every plot in the study area. The haul costs were combined with the outputs from FVS, FFE, and STHARVEST to create a database that stored the biomass and merchantable yields, harvest and haul costs, gross and net revenues, and change in TI and CI associated with every combination of plot, psite and prescription.

To test the simulation framework and develop preliminary estimates of biomass processing opportunities for this broad region, we evaluated seven fuel treatment policy scenarios under the assumption of the construction of 4 biomass processing facilities capable of generating 50MW each. The locations were selected from among the sites with the best accumulation potential – of biomass, merchantable volume, net revenue, and acres treated—with the additional requirement that they be geographically separated (in other

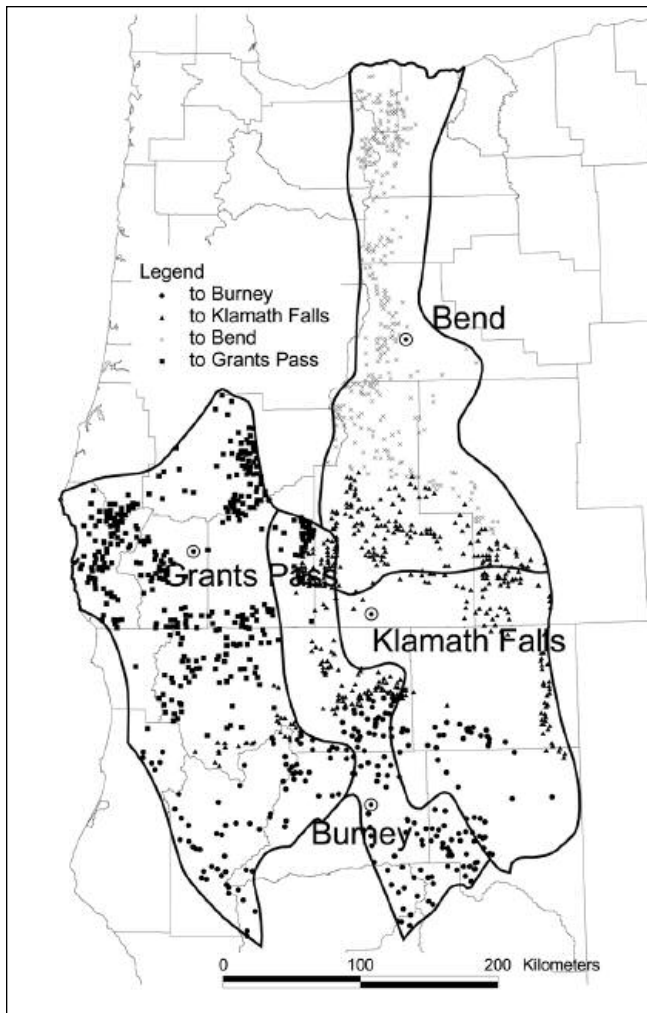


Figure 2—The Oregon-California study area with ecosections, accessible plots and the four potential processing sites considered in this analysis.

words, one per ecosection) so as to have little influence on one another's markets. Each of the 1556 plots (representing the 5.4 million acres that could be treated effectively) was allocated to the psite with the lowest haul cost: Grants Pass OR, Burney CA, Klamath Falls OR, or Bend OR, and the rest of the analysis proceeds with those allocations (fig. 2). Four of the treatment scenarios were: treat all treatable plots and select the prescription for each plot that 1) maximizes net revenue, or 2) maximizes improvement in TI, or 3) minimizes the merchantable material removed, or 4) maximizes improvement in CI. The other three scenarios 1A, 2A and 3A, corresponded to scenarios 1, 2 and 3, except that only plots with non-negative net revenue would be treated. Scenario 1 was designed to make as much profit as possible subject to the non-trivial constraint that all treatments were designed with an eye towards reducing crown fire potential, not maximizing economic return or even

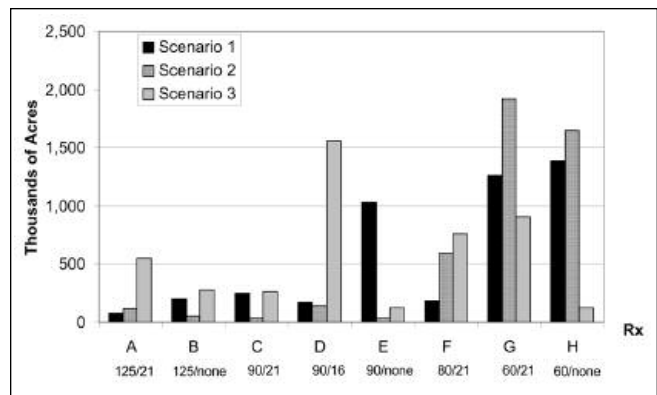


Figure 3—Number of acres for which each fuel treatment prescription was selected; numbers below prescription letters are target residual basal area in ft²/upper diameter limit in inches.

facilitating a positive cash flow. Scenarios 2 and 4 represent a no-holds-barred policy of reducing fire hazard as the paramount objective, while scenario 3 might be more appealing to groups or individuals who favor the achievement of some measure of fuel reduction but do not support the removal of sawtimber-sized trees and or the generation of profits from fuel treatment activity.

RESULTS

The fuel treatment policy scenarios 1-3 lead to quite different distributions of treatments. The most frequently selected treatments for scenario 1 were H, G, and J, for scenario 2 were G, H, and F, and for scenario 3 were J, G and F (fig. 3). Given the substantial differences in the treatments selected, we expected to see substantial differences in the aggregate results; however, the most substantial differences among scenarios were in net revenue, while the biomass yield was rather robust under this range of scenarios (table 2). Under scenario 1, net revenue was positive for every psite when all effectively treatable plots were treated. Even when selecting prescriptions that minimize merchantable yield (scenario 3), there would still be 3.6 billion ft³ of merchantable volume produced, though the aggregate net revenue under this scenario is extremely negative. Under every scenario, the acres feeding material to the psite at Grants Pass generated the greatest merchantable volume and the greatest biomass.

With the added constraint that, as proposed in the Healthy Forests Initiative, "every acre pays its own way", the area that could be treated would be reduced to no more than 12 percent of the forested landscape (table 3) in scenarios 1A, 2A and 3A. Of the four sites, Grants Pass again results in the greatest amount of net revenue, acres treated,

Table 2—Aggregate net revenue, area treated, and yields of merchantable volume and sub-merchantable biomass by potential processing site for three, fuel treatment policy scenarios in which all effectively treatable plots are treated.

Scenario 1: Maximize net revenue				
Processing site	Net revenue <i>(Millions of dollars)</i>	Acres treated <i>(Thousands)</i>	Merchantable volume <i>(Millions of cubic feet)</i>	Biomass <i>(Millions of tons)</i>
Burney	542	1,546	2,635	24
Klamath Falls	593	1,101	1,741	14
Bend	343	741	998	12
Grants Pass	1,162	1,962	4,153	30
Total	2,640	5,351	9,527	79
Scenario 2: Maximize torching index improvement				
Processing site	Net revenue <i>(Millions of dollars)</i>	Acres treated <i>(Thousands)</i>	Merchantable volume <i>(Millions of cubic feet)</i>	Biomass <i>(Millions of tons)</i>
Burney	-12	1,546	2,256	30
Klamath Falls	415	1,101	1,602	15
Bend	144	741	822	11
Grants Pass	376	1,962	3,940	37
Total	923	5,351	8,620	94
Scenario 3: Minimize merchantable yield				
Processing site	Net revenue <i>(Millions of dollars)</i>	Acres treated <i>(Thousands)</i>	Merchantable volume <i>(Millions of cubic feet)</i>	Biomass <i>(Millions of tons)</i>
Burney	-795	1,546	974	21
Klamath Falls	-157	1,101	773	12
Bend	-148	741	384	9
Grants Pass	-1,465	1,962	1,444	34
Total	-2,565	5,351	3,574	75

biomass yield, and merchantable yield under scenario 1A. Scenario 3A treats about the same area as scenarios 1A and 2A, but produces less than half the net revenue, largely because there is much less revenue from merchantable volume in the prescriptions selected for this scenario that could be used to offset treatment costs.

All scenarios produced quite different opportunities in terms of the potential longevity of a biomass plant (table 4). Under scenario 2, sufficient biomass could be collected to operate 50 MW generating stations at Grants Pass and Burney for about 50 years, and in all likelihood, much

longer given that this was a static analysis (that did not account for regeneration and continued growth of the residual trees and involved no harvest scheduling component), and preliminary analysis of post-treatment plots modeled forward with FVS indicates a need to re-treat as soon as 20 years after the initial treatment for fire hazard reduction to be maintained. Requiring every acre to pay its own way dramatically cuts the projected longevity of biomass supply, and scenario 3A (minimum merchantable yield and nonnegative net revenue) would appear to all but eliminate the opportunity to attract capital investment for the construction of new biomass generating capacity except at Grants Pass.

Table 3—Aggregate net revenue, area treated, and yields of merchantable volume and sub-merchantable biomass by potential processing site for three, alternate fuel treatment policy scenarios in which only the effectively treatable plots that generate positive net revenue are treated.

Scenario 1A: Maximize net revenue	NR+ Net revenue <i>(Millions of dollars)</i>	Acres treated <i>(Thousands)</i>	Merchantable volume <i>(Millions of cubic feet)</i>	Biomass <i>(Millions of tons)</i>
Processing site				
Burney	1,112	735	2,017	11
Klamath Falls	891	524	1,482	7
Bend	536	335	833	8
Grants Pass	2,382	1,023	3,478	16
Total	4,921	2,616	7,809	42
Scenario 2A: Maximize torching index change, NR+				
Processing site	Net revenue <i>(Millions of dollars)</i>	Acres treated <i>(Thousands)</i>	Merchantable volume <i>(Millions of cubic feet)</i>	Biomass <i>(Millions of tons)</i>
Burney	944	711	1,873	12
Klamath Falls	798	516	1,407	7
Bend	486	329	780	8
Grants Pass	2,184	1,014	3,295	17
Total	4,413	2,569	7,355	44
Scenario 3A: Minimize merchantable yield				
Processing site	Net revenue <i>(Millions of dollars)</i>	Acres treated <i>(Thousands)</i>	Merchantable volume <i>(Millions of cubic feet)</i>	Biomass <i>(Millions of tons)</i>
Burney	442	735	1,320	12
Klamath Falls	357	524	898	7
Bend	238	335	539	8
Grants Pass	942	1,023	2,182	21
Total	1,978	2,616	4,939	47

Not surprisingly, average effectiveness of fuel treatments in terms of both TI and CI was usually greatest under scenario 2, as shown in figure 4 for CI. What was surprising was that the average improvement in both indices was comparable between with scenario 1, in which the fuel treatment with the greatest net revenue was selected. Scenario 3 was substantially less effective on the plots feeding every psite, with an average CI improvement of 20 to 40 mph, most likely because prescriptions that remove less merchantable material also leave stands with higher canopy bulk-density.

Table 5 summarizes the aggregate results for scenarios 1, 2 and 3 plus scenario 4 (maximize improvement in crowning index). Scenario 4 has greater yields of both biomass and merchantable material, most likely because it favors treatments that reduce canopy bulk density (by removing more of the medium-sized trees greater than 7” d.b.h. and generally less than 21” d.b.h.). It is the additional merchantable component that accounts for the boost in net revenue as compared with scenario 2. The pre-treatment TI and CI averaged 7 and 23, respectively, so on average, all of the scenarios lead to substantial improvements in these indices.

Table 4—Years of feedstock for a 50 MW biomass-based electrical generating plant consuming 1750 green tons per day of biomass in an operation 24/7.

Scenario	Burney	Klamath Falls	Bend	Grants Pass
1. Maximize net revenue	38	22	18	47
1A. Maximize net revenue, treat only stands with nonnegative NR	18	11	12	25
2. Maximize improvement in TI	47	24	18	58
2A. Maximize improvement in TI, treat only stands with nonnegative NR	19	11	12	27
3. Minimize merchantable yield	33	18	14	53
3A. Minimize merchantable yield, treat only stands with nonnegative NR	19	10	12	33

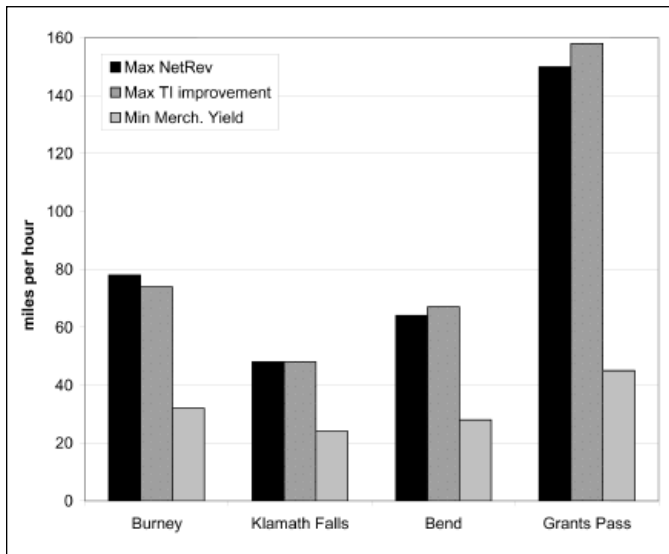


Figure 4—Average improvement in FFE-predicted crowing index, by proposed processing site to which recovered material would be hauled, by scenario for scenarios 1, 2 and 3.

Table 5—Aggregate yield, net revenue, and improvement in crown fire potential (from a pre-treatment mean CI of 22 and TI of 7) for the four ecoregion study area for four fuel treatment policy scenarios, when all effectively treatable acres are treated.

Scenario	Biomass (millions of tons)	Merchantable volume (millions of ft ³)	Net revenue (millions of dollars)	Mean change in CI (miles per hour)	Mean change in TI (miles per hour)
1. Max. net rev.	79	9,527	2,639	63	96
2. Max Δ TI	94	8,620	922	83	98
3. Min Merch. Vol.	75	3,574	-2,566	23	35
4. Max Δ CI	93	9,765	1,817	80	114

DISCUSSION

There is plenty of biomass to supply four 50 MW power plants for decades under the most aggressive scenarios (for example, scenario 2), but supply under the most conservative scenarios (for example, 3A) would be far more limited. Another alternative that we have not yet analyzed would be to operate several smaller or less heavily capitalized power plants for a shorter period of time in order to reduce haul costs and make treatment feasible over a greater area.

By any basis of calculation, most of the material removed in these treatments is merchantable and would fetch higher prices than the \$18 per green ton currently paid for biomass-sized material by power plant operators in northern California. For scenario 1, 75 percent of the total tonnage of wood removed is merchantable, with the remaining 25 percent in biomass-sized material composed of trees less than 7 inches and the tops and limbs of larger trees. And of the biomass-sized material, only 20 percent is in trees less than 7 inches (i.e., only 5 percent of the total wood tonnage removed). On a value basis, merchantable wood recovered accounts for 90 percent of the total value recovered. This helps explain why prescriptions that do not maximize net revenue or that reduce the quantity of merchantable-sized material recovered fare so poorly on a net revenue basis.

Both harvest costs and haul costs are considerable, averaging \$1634 and \$560 per acre, respectively, under scenario 1, with the haul costs for biomass alone averaging \$127 per acre. And with the configuration of four processing sites we specified, haul costs alone averaged \$8.53 per green ton, nearly half the \$18 per green ton that biomass was assumed to fetch upon delivery, suggesting strongly that biomass rarely pays its own way out of the woods, given that harvest costs averaged \$22 per ton over all size classes of material, and are surely greater for biomass-sized material.

The average net revenue per acre under scenario 1 was \$493, though on some acres, the net revenue is much greater, and on others, it is negative, sometimes considerably so. For some plots, if none of the biomass-sized material was hauled to processing sites but was instead left at the landing, the net revenue per acre would be greater, but in all likelihood, *in situ* disposal costs for this material, for example by burning, would likely drive net revenue to zero or below. Leaving the biomass-sized material in the woods would reduce harvest costs and increase net revenue, but make the estimated fire risk reduction benefits more dubious.

While it is possible to focus on acres where net revenue is positive, for example, under scenario 1A, this results in a 51 percent reduction in the area treated relative to the area that could be treated effectively, and calls into question whether the fuels reduction achieved would be effective at a landscape scale. Furthermore, some caveats must be taken into account in interpreting this analysis that could even reduce the estimate of 2.2 million acres that could be treated effectively and generate positive net revenue. At almost every decision point requiring an assumption, we assumed maximum land availability, minimum cost and maximum revenue. For example, we assumed that all non-reserved acres would be allocated to a fuels-reduction treatment. In fact, some private landowners might well choose other prescriptions that generate more net revenue and achieve less or no fuel reduction benefit, while others would be unwilling to consider any treatment. And, much of the National Forest land in the study area may be in late successional reserves, riparian reserves, or other designated uses that could be considered incompatible with the fuel reduction treatments we've considered. Nor did we include the costs of planning, administration, site clean-up, environmental assessments, or litigation. In estimating accessibility, we assumed that any road on the map actually exists on the ground and would be passable by the equipment needed to transport equipment to the site and material from the site to a processing facility. In haul cost calculations, the nature of the grid-based cost accumulation carries the implicit assumption that any 250 m cell containing a road contains a road heading in the direction of the processing site. Furthermore, the price used for biomass-sized material derives from a competitive market price paid by a large-capacity biomass-fired power plant; yet in this analysis, we dispersed biomass conversion facilities to assure a source of supply sufficient to provide feedstocks for a number of years, but this geographic separation also makes them unlikely to compete with one another. So the cost and value calculations and the area availability calculations embedded in this analysis *represent best-case conditions and are optimistic*. We also assumed that all treatable lands were treated immediately; however, this would be unrealistic and even if spread out over a few years, would still generate wood at a rate so much greater than current harvest patterns, that wood product prices would likely be substantially depressed, reducing net revenue even below the estimates reported here.

Other caveats are that we did not consider existing processing capacity, either for biomass or merchantable material, so our results are not a justification for adding new capacity, particularly in places like Shasta County that

already have substantial capacity. Nor did we factor in the capital costs of building any processing capacity. Adding biomass processing facilities at additional sites (beyond the four modeled in this analysis) would reduce the haul costs for many acres, thereby increasing net revenue. However, the plants would need to have smaller capacity, and economies of scale, and the assumed biomass price, could be compromised.

Key strengths of the BioSum analytic framework are:

1) it is based on a statistically representative sample of the entire landscape, 2) it is connected to detailed ground observations that permit an extremely high level of resolution in characterizing outcomes (for example, knowing the species and size distribution of the material recovered, and being able to model the improvement in crown fire potential), 3) the raster-based haul cost module enables a level of spatial detail not previously attempted without imposing enormous costs for first building an error-free vector based road network, and 4) the approach is adaptable to any place in the United States, by virtue of its reliance on FIA data (available nationwide as part of a National Program), publicly available models (for example, FVS and STHARVEST), and even topologically inferior GIS road coverages.

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SPATIAL OPTIMIZATION OF FUEL MANAGEMENT ACTIVITIES

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ABSTRACT

This paper presents preliminary work associated with scheduling fuel management treatments to achieve timber harvest and landscape pattern goals. Four landscape patterns of management activities are modeled (dispersed, clumped, random, and regular). The overall intent of this research is to examine the effects of spatial and temporal placement of fuel management activities on resulting wildfire behavior although we do not provide results on wildfire behavior here. However, in this paper, we describe the forest planning scheduling processes that provide solutions that both place activities in a pattern on the landscape, and achieve commodity production goals. Results indicate that the scheduling methodology developed with this preliminary research is adequate in allowing one to optimize the spatial pattern of management units across a landscape while attempting to also achieve a commodity production goal. The scheduling methodologies developed in this study are expected to facilitate an understanding of the impact of the spatial variation of management activities on wildfire behavior and management goals.

INTRODUCTION

The use of fuel management treatments in western forests can reduce undesirable consequences of wildfires (cost, sizes, ecological damage, threats to developed areas) only if wildfire behavior is modified at the landscape-scale ($\sim 10^3$ - 10^6 acres). Individual management activities can be expected to modify fire behavior on a local scale, but alone, may have negligible impact on the overall growth and behavior of larger fires. The cumulative effects of individual fuel management activities on fire behavior may depend heavily upon their spatial pattern, as the behavior of fires may only be sensitive to management activities when they are scaled and arranged to disrupt the progress of the fire.

To this point in time, research on landscape effects of fuel management activities has been mostly theoretical. Observations of fuel patterns in the forests of California (van Wagtenonk 1995, Parsons and van Wagtenonk 1996)

support the idea that spatial fragmentation of fuels can affect fire size and behavior. Isolated management activities, however, may have no effect on the growth and progress of large fires (Dunn 1989). Several basic spatial patterns of management activities can be distinguished based on their overlap, or the ability of nearby treated units to disrupt fire growth. Random patterns of fuels (Finney 2003) have no requirement for overlap and therefore reduce spread rate in a sigmoidal fashion, meaning that relatively large proportions of the landscape must be treated to substantially reduce fire sizes. Parallel strips (Fujioka 1985, Martin 1988, Catchpole and others 1989) completely overlap in one direction, and are the most efficient at reducing fire spread rates, as only small fractions of the landscape need to be treated. However, this strategy unrealistically requires fires to always move perpendicular to the strips. Regular patterns of dispersed treatments (Finney 2001) partially overlap and can reduce spread rate, and are more flexible in accommodating spatial constraints because they are not necessarily spatially connected.

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Several landscape simulation approaches are currently used for spatially modeling fire and forest development (i.e., Keane and others 1997, Jones and Chew 1999, Mladenoff and He 1999). Some of these have been proposed for modeling effects of treatments and for optimizing the scheduling of fuel treatment. None, however, account for the topological effects of fuel management activities with respect to landscape fire behavior. This requirement suggests the use of integer or heuristic scheduling models (rather than linear programming) due to the use of spatial information, and the fine-scale conditions of landscape units.

The overall objective of this study is to understand how the spatial pattern of fuel management activities influences characteristics of fire behavior. In this paper, however, we describe preliminary work aimed at the development of methodologies for arranging fuel management activities in desired patterns across a landscape while meeting other management goals. These scheduling processes utilize heuristic techniques, and are expected to facilitate a variety of studies that center on the spatial variation of management activities, and the associated effects on management goals.

STUDY SITE AND DATA PREPARATION

In a recent study (Hirte 2002), vegetation changes and timber harvest under several management prescriptions had been simulated in private lands (approximately 11,000 acres) located in the Upper Grand Ronde River basin in northeastern Oregon (fig. 1). Most of this area is surrounded by U.S. Forest Service land (Wallowa-Whitman National Forest). GIS databases and forest structure data developed for the previous study were used for scheduling fuel management activities. When scheduling activities across the landscape, we use centroids of management units to represent their location. The x, y coordinates of the centroids were generated and saved using ArcView software and its extensions. In addition, scheduling of fuel management activities requires some attribute data accompanied with GIS databases describing specific vegetation structure of each management unit. All required attribute data (forest structure data) were exported in the ASCII format, and made suitable for the various scheduling procedures (described below). The yield data represents changes in stand condition under 5 management prescriptions during 5 ten-year management periods (50 years). These prescriptions were not optimized for economic nor ecologic goals. They were developed to represent private forest management activities consistent with a survey of forest landowners conducted by the Oregon Department of Forestry in the late 1990's. Hirte

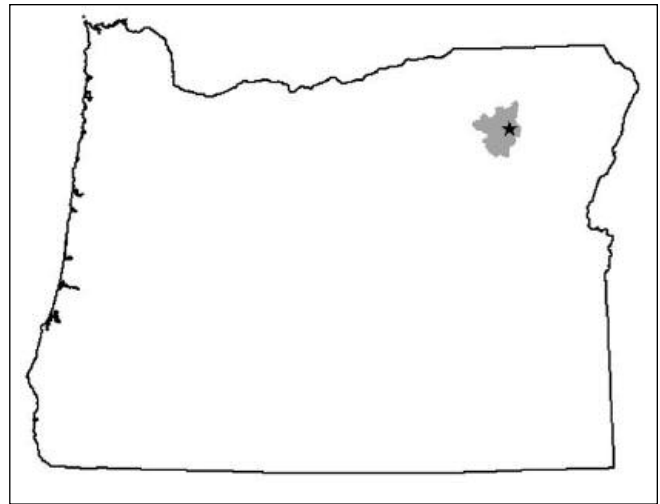


Figure 1—Study site: Upper Grand Ronde river basin in eastern Oregon.

(2002) described the results of the survey, and used the same prescriptions we use, yet on a smaller portion of our landscape, and for optimizing different goals. In sum, the survey of private landowners was simply used to help us determine the types of prescriptions that would be reasonable for this area. Readers are encouraged to contact the Oregon Department of Forestry (Salem, OR) for more detail on the survey of private landowners.

SCHEDULING OF SPATIAL PATTERNS OF FUEL MANAGEMENT ACTIVITIES

Four spatial patterns of fuel management activities were examined in this research, which included three basic landscape patterns (dispersed pattern, clustered pattern, and random pattern) and an artificial pattern (regular pattern). These spatial patterns of fuel management activities were scheduled with two heuristic modeling techniques: the Great Deluge Algorithm (GDA) and Tabu Search (TS). GDA was introduced by Dueck (1993) and applied to forest planning problems in Bettinger and others (2002). Tabu Search was initially developed by Glover (1989) and applied to forest planning problems in Bettinger and others (1997, 1998, and 2002).

Scheduling procedures were repeated 30 times for each spatial pattern, to find the best solution that spatially optimizes the pattern across a landscape. Each repetition started with a random schedule of management activities to make the 30 resulting solutions independent. For quantifying the effects of solutions more accurately, a control solution with no management activities scheduled was generated.

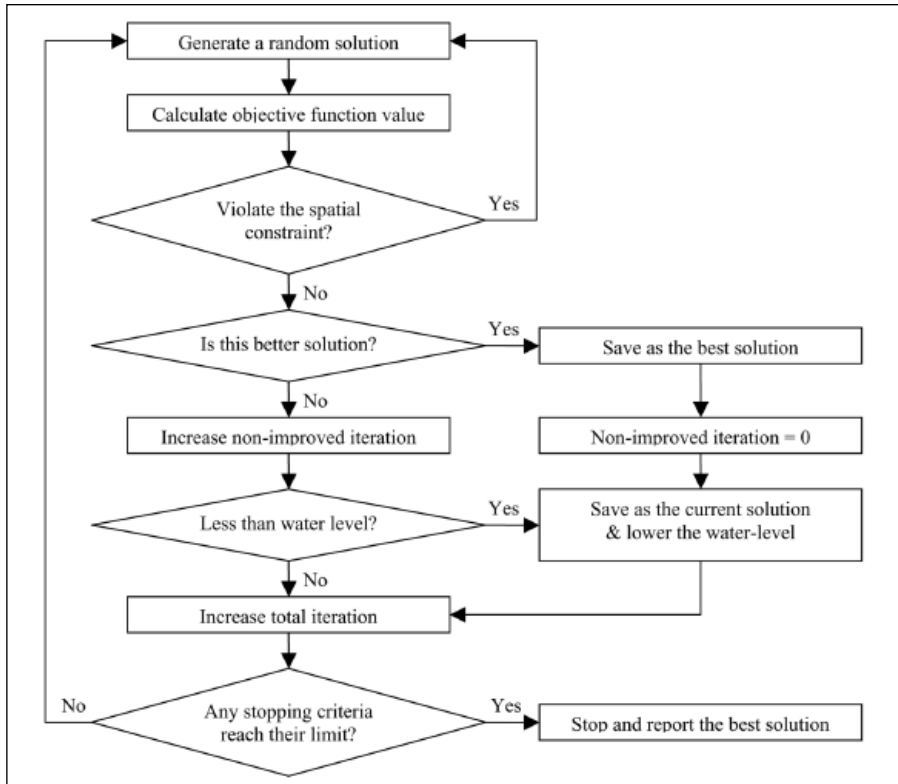


Figure 2—Flowchart of scheduling processes for dispersed, clumped, and random landscape pattern.

Dispersed Pattern of Fuel Management Activities

A dispersed pattern is a pattern in which management units are widely spread across the landscape, minimizing clustering. Here, ideal dispersed patterns are assumed to maximize total distance between management units, and minimize deviations between actual harvest volume and a harvest volume target. In order to generate a pattern as close to the ideal pattern, the following objective function was developed.

Minimize

$$WH \sum_{k=1}^P \left(\left| \sum_{i=1}^{N_k} H_{ik} \right| - T \right) - WD \sum_{k=1}^P \left(\sum_{i=1}^{N_k-1} \sum_{j=i+1}^{N_k} D_{ij} \right) \quad [1]$$

Where:

WH : Weight corresponding to the even harvest to the target

WD : Weight corresponding to the dispersion ($WH + WD = 1$)

H_{ik} : Harvest volume from unit i in time period k ($i = 1, 2, \dots, N_k, k = 1, 2, \dots, P$)

T : Target volume of timber harvesting ($T = 1,000$ MBF (thousand board feet))

D_{ij} : Distance between centroids of unit i and j ($i = 1, 2, \dots, N_k-1, j = 2, 3, \dots, N_k$)

i, j : Index of management units scheduled for harvest

k : Index of management periods

P : Total number of time periods ($P = 5$)

N_k : The set of management units scheduled for harvest in time period k

A scheduling procedure based on the above function seeks a solution that minimizes the difference between actual harvest volume and a harvest volume target, and maximizes the total distance between centroids of management units. Original GDA seeks a solution with a higher peak (higher objective function value) as increasing water-level (threshold value), and finally produces an optimized solution which is expected to have highest peak (maximum objective function value). Since the optimized solution in this research was expected to have the minimum objective function value, the algorithm was modified to seek a solution with a lower bottom as discharging water from a lake (fig. 2). In addition, a spatial constraint was applied for limiting the size of clearcuts to a maximum of 120 acres. This constraint is based on the unit restriction model introduced by Murray (1999):

$$x_{i,k} + x_{j,k} \leq 1 \quad \forall i, k, j \in S_i \quad [2]$$

$x_{i,k}, x_{j,k}$: 1, if unit i or j is scheduled for harvest in period k. Otherwise, 0.

S_i : set of harvest units adjacent to unit i

Thus, if a solution violated this spatial constraint, it would be rejected no matter what objective function value resulted. 3 stopping criteria were used in the modified version of GDA: total iterations, non-improved iterations, and water-level. Parameters related to these stopping criteria were set as follows:

- Maximum total iterations: 5,000,000
- Maximum non-improved iterations: 1,000,000
- Initial water-level: 100,000
- Discharging speed: 1
- Minimum water-level: -100,000

Objective function values might obviously vary according to the weights assumed, so 9 weight combinations (0.9, 0.8, 0.7, ..., and 0.1) were tested to determine the most appropriate weights for both patterning and even flow objective. The entire process described in the figure 2 was repeated 10 times for each weight combination with the above parameters. From these test trials, a weight values (WH = 0.4 and WD = 0.6) were chosen for further processing. With the selected weight combination and the same parameters, the entire process was repeated 20 more times. The weights we have assumed are arbitrary, and obviously one can envision larger sets of weights using more detailed categories, but the added value of assessing this level of detail in weighting the objectives is speculative. The choice of weights was made by evaluating the point where dramatic differences in the objective values occurred (i.e., the threshold where a change in weights caused dramatic declines in the objective function value). Therefore, the choice of weights made here and with the other scheduling techniques described in this paper was made using our judgement in an assessment of trial runs of the scheduling model (i.e., by determining at what point along the range of weights better solutions are found).

Clumped Pattern

A clumped pattern is assumed to be a pattern in which management units are clustered on the landscape. Here, the ideal clumped pattern is assumed to minimize the total distance between management units and minimize the deviation between actual harvest volume and a harvest volume target. While the dispersed pattern is expected to maximize total distance between management units, the clumped pattern is expected to minimize it. Therefore, equation 1 was modified to accept this distinction by adding the two portions of the objective function as follows:

Minimize

$$WH \sum_{k=1}^P \left(\left| \left(\sum_{i=1}^{N_k} H_{ik} \right) - T \right| \right) + WD \sum_{k=1}^P \left(\sum_{i=1}^{N_k-1} \sum_{j=i+1}^{N_k} D_{ij} \right) \quad [3]$$

The scheduling procedure seeks a solution that minimizes the difference between actual harvest volume and harvest volume target and also minimizes the total distance between centroids of management units. In addition, the spatial constraint limiting the size of clearcuts to a maximum of 120 acres was applied. The scheduling process for the simulation of clumped pattern was the same as that of dispersed pattern (GDA). However, some of the parameters related to the stopping criteria – initial water level and minimum water level – were altered based on trial runs of the GDA model. Listed below are the parameters used in the GDA scheduling process.

- Maximum total iterations: 5,000,000
- Maximum non-improved iterations: 1,000,000
- Initial water-level: 500,000
- Discharging speed: 1
- Minimum water-level: 0

Nine weight combinations were also tested and the most appropriate weight values (WH = 0.1 and WD = 0.9) were chosen from the test trials.

Random Pattern

A random pattern is a pattern in which management units are randomly allocated across landscape. Within the GDA, management units are randomly chosen and random prescriptions are assigned. Solutions generated with this process are assumed to be random across the landscape (although the pattern may be influenced by the actual pattern of vegetation in the study area). Therefore, dispersion of management units is not a factor in scheduling a random pattern. Deviation between actual harvest volume and the harvest volume target is the only criterion for evaluating the acceptability of a solution. Thus, the latter portion of equations 1 and 2, corresponding to the dispersion of management units, was not included in the objective function for the random pattern. Therefore, a solution that provides the smallest deviation between actual harvest volume and the harvest volume target is generated from the scheduling process.

Minimize

$$\sum_{k=1}^P \left(\left| \left(\sum_{i=1}^{N_k} H_{ik} \right) - T \right| \right) \quad [4]$$

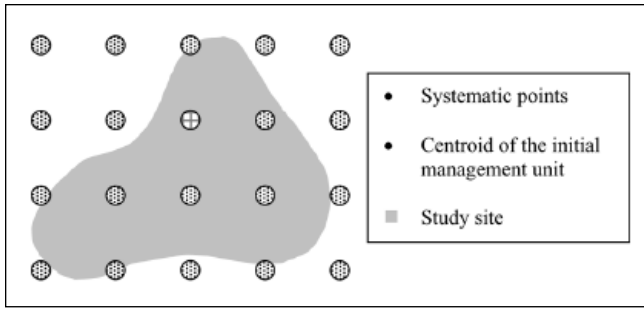


Figure 3—Systematic points generated to facilitate modeling the regular landscape pattern.

Most of the GDA parameters are the same as those used in the development of dispersed and clumped patterns, but a few have been altered based on the trial runs of the GDA model. Although composed of randomly selected units, solutions violating the spatial constraint for a large clearcut patch were rejected.

- Maximum total iterations: 5,000,000
- Maximum non-improved iterations: 1,000,000
- Initial water-level: 100,000
- Discharging speed: 1
- Minimum water-level: 0

Regular Pattern

A regular pattern is a pattern in which management units are systematically allocated across landscape using a constant spatial interval. Ideally, units scheduled for harvest in the regular pattern are expected to have the same distance to four neighbor units (northern, southern, eastern & western). The “interval”, therefore, could be defined as desired distance between centroids of management units that produce an ideal regular pattern. To enable one to generate a regular pattern, a different approach was developed and utilized for dispersing management units. It is based on the following idea:

- Select one initial management unit
- Acquire the x, y coordinate of centroid of the unit
- Generate “systematic points” by adding or subtracting a given interval to x, y coordinate of the centroid (fig. 3)
- Calculate distance between each systematic point and centroids of all units
- Find the nearest centroid for each systematic point
- Check whether each systematic point is located within the boundary of the study site
- Exclude systematic points located outside of the study site
- Save the management unit nearest to each systematic point

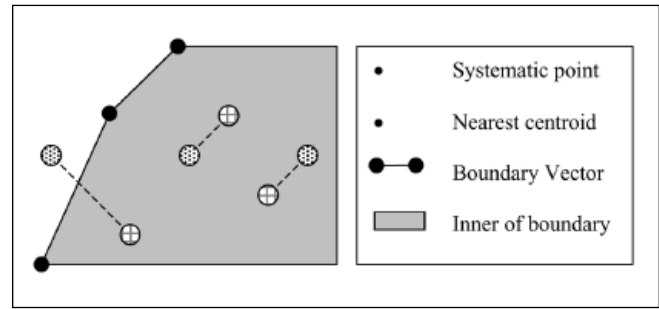


Figure 4—Vectors between systematic points and their nearest unit centroids.

- Generate a solution by assigning a feasible prescription to the saved units
- Calculate the objective function value and evaluate the solution

One of the issues related to the above idea is how to exclude systematic points located outside of the study site. In order to automate this process, inspecting whether a systematic point is out of the study site was possible by testing whether a vector connecting a systematic point and its nearest unit centroid is intersected by any boundary vector surrounding the study site. That is to say, if a systematic point were located outside of the boundary, the vector connecting the systematic point and its nearest unit centroid should be intersected by at least one boundary vector (fig. 4). To inspect whether two vectors intersect, a two-step process introduced by Loudon (1999) was used in the program: a quick rejection test and a straddle test. If both tests succeed, two vectors intersect and thereby, the systematic point is out of the study site.

The quick rejection test is initiated by constructing a rectangle called a bounding box that surrounds each vector. A vector between a systematic point and its nearest unit centroid has two end nodes, $n_1 = (x_1, y_1)$ and $n_2 = (x_2, y_2)$. The bounding box of the vector is a rectangle with lower left point $(\min(x_1, x_2), \min(y_1, y_2))$ and upper right point $(\max(x_1, x_2), \max(y_1, y_2))$. Also, a boundary vector has two end nodes, $n_3 = (x_3, y_3)$ and $n_4 = (x_4, y_4)$, and a bounding box with lower left point $(\min(x_3, x_4), \min(y_3, y_4))$ and upper right point $(\max(x_3, x_4), \max(y_3, y_4))$. If bounding boxes of the two vectors intersect, all of the following tests must be true (fig. 5):

$$\begin{aligned} \max(x_1, x_2) &\geq \min(x_3, x_4) & \max(x_3, x_4) &\geq \min(x_1, x_2) \\ \max(y_1, y_2) &\geq \min(y_3, y_4) & \max(y_3, y_4) &\geq \min(y_1, y_2) \end{aligned}$$

A straddle test follows only when the quick rejection test succeeds. To examine whether a vector straddles another,

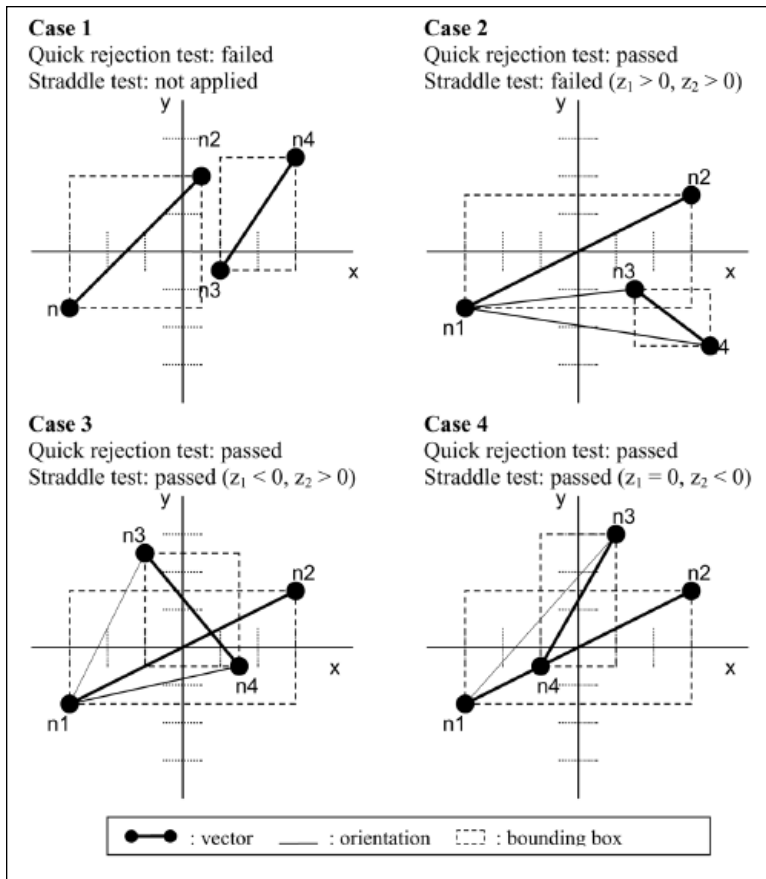


Figure 5—Examples of the quick rejection test and the straddle test for use in the generation of the regular landscape pattern.

the orientation of n_3 relative to n_2 is compared with that of n_4 relative to n_2 . Orientation of n_3 and n_4 convey whether the nodes are clockwise or counterclockwise from n_2 with respect to n_1 . The orientation of n_3 and n_4 are determined by following equations:

$$z_1 = (x_3 - x_1)(y_2 - y_1) - (x_2 - x_1)(y_3 - y_1)$$

$$z_2 = (x_4 - x_1)(y_2 - y_1) - (x_2 - x_1)(y_4 - y_1)$$

If the sign of z_1 and z_2 are different, or either one is 0, the vectors straddle each other, and the two vectors intersect. Figure 5 describes results of the quick rejection test and the straddle test based on 4 different cases.

Unlike the scheduling of dispersed, clumped, or random patterns, Tabu Search (TS), instead of GDA, was used in the scheduling of the regular pattern (fig. 6). TS generally consumes much processing time for its neighborhood search. However, limited numbers of neighbors would have been searched in this case because prescriptions were assigned only to the selected units. Therefore, TS might be more efficient in scheduling than GDA when developing a regular pattern. Since management units have already been chosen

before prescriptions are assigned to them, assigning a prescription to management units has no influence on the dispersion of management units in the scheduling of regular pattern. As the result, dispersion of management units was not counted in the objective function. In addition, according to the current prescriptions, a unit scheduled for harvest in the first time period might be scheduled to be harvested again in one of the following time periods. This means a set of prescriptions assigned to management units for one time period could affect scheduling of other following time period. By this reason, a solution that guarantees the regular pattern over the entire planning horizon is rarely obtained. Therefore, the scheduling process seeks a solution that optimizes the harvest in the first time period.

$$\left| \left(\sum_{i=1}^N H_{it} \right) - T \right| \quad [5]$$

Two limitations of this scheduling process are: 1) even though units have been identified to be contained within the regular pattern, a treatment is not guaranteed to be assigned to each, and 2) only those units and prescriptions available are used to attempt to achieve even-flow harvest.

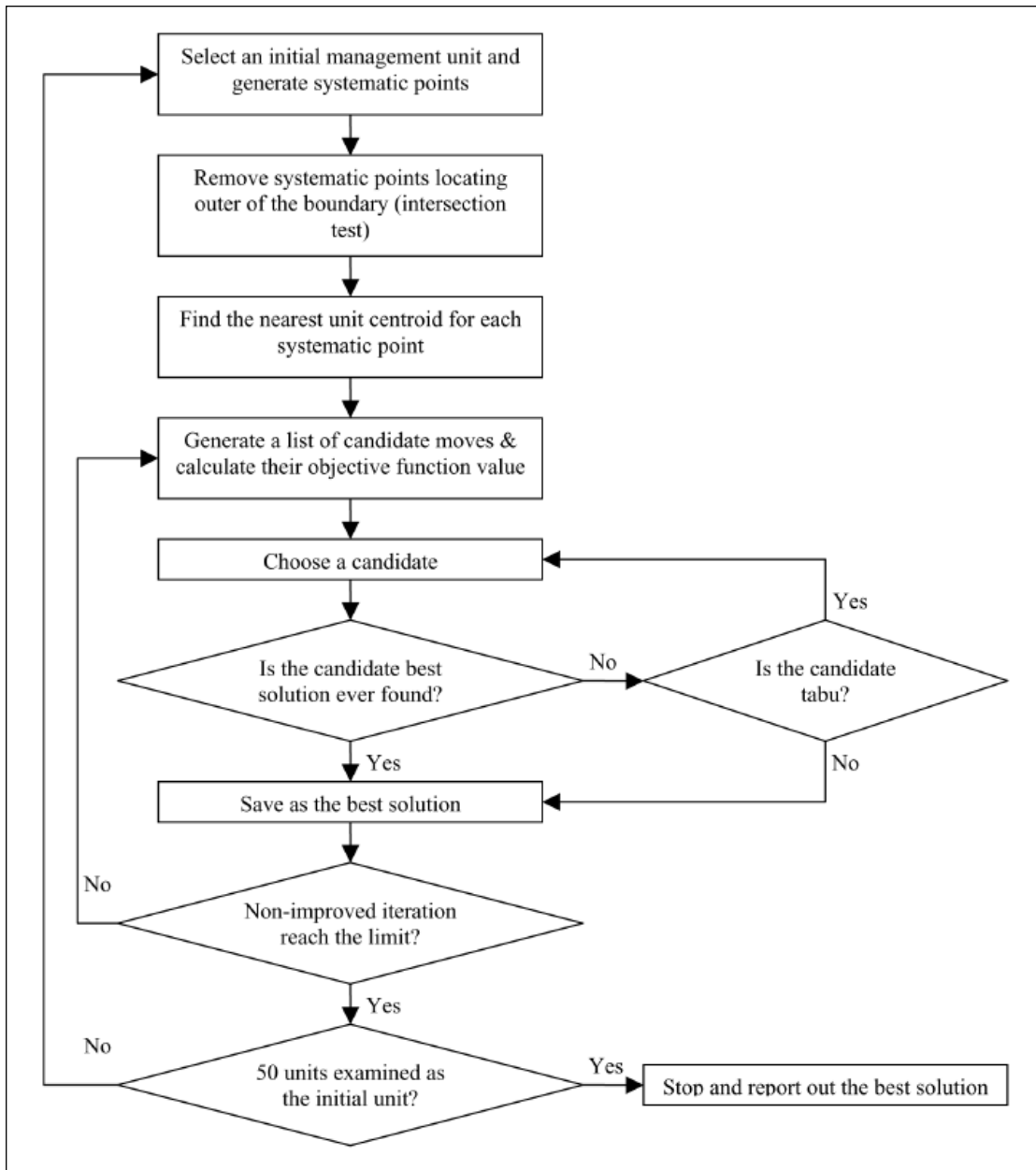


Figure 6—Flowchart of scheduling process for the regular landscape pattern.

Since limited amount of information is available to specify the most efficient interval between management units for reducing the fire damage, a 3.0 mile interval was assumed, although other intervals could also be used. The entire scheduling process described in the figure 6 was repeated 30 times. In each run of the process, 50 management units were randomly selected and examined as the initial unit for generating systematic points. Parameters related to the TS scheduling process include:

- Maximum non-improved iterations: 1,000
- Size of tabu list: 10

RESULTS

The scheduling methodology developed in this research acceptably allocated fuel management activities in desired spatial patterns while meeting a commodity production goal. Two criteria were used to assess how well the scheduling process worked: a visual assessment of the pattern of

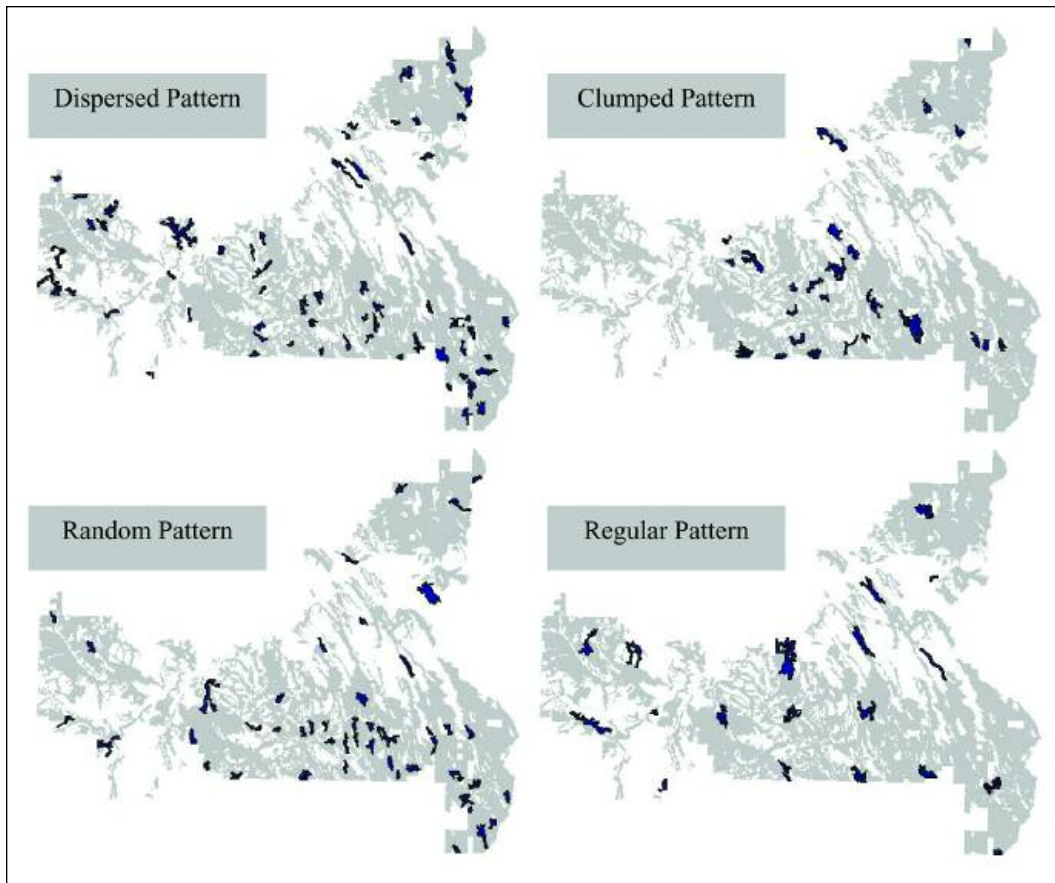


Figure 7—Spatial patterns of management units developed by the scheduling processes.

Table 1—Harvest volume for the best solutions generated by the scheduling models.

Spatial pattern	Harvest volume (MBF)					Total
	Period 1	Period 2	Period 3	Period 4	Period 5	
Dispersed	1,001,607	1,001,827	1,003,161	1,007,219	1,001,348	5,015,172
Clumped	997,463	995,970	999,370	997,787	995,731	4,986,321
Random	1,000,091	999,675	1,000,175	999,948	1,000,177	5,000,066
Regular	994,765	—	—	—	—	—

Table 2—Total number of and area of management units scheduled for harvest.

Spatial pattern	# of Units	Area (Acres)		
		Total	Thinning	Clearcut
Dispersed	80	353	34 (9.6%)	319 (90.4%)
Clumped	34	209	7 (3.3%)	202 (96.7%)
Random	61	262	21 (8.0%)	241 (92.0%)
Regular	34	246	33 (13.4%)	213 (86.6%)

scheduled activities (i.e., do the scheduled activities look as if they have been scheduled across the landscape in the pattern desired?), and an assessment of the objective (i.e., was an even-flow of timber harvest volume achieved, and was it high?). While no statistical tests were utilized to test the hypotheses that these goals were met, we feel confident that the model is adequate for optimizing the spatial pattern of management activities. More reasonable criteria will be necessary for evaluating the patterns produced, such as using FRAGSTATS, and one of the landscape metrics provided, to compare the patterns of various schedules. We leave this for further study.

Figure 7 represents management units which were scheduled for harvest by best solutions retained from the scheduling process. Figure 7 clearly verifies the distinction between the spatial patterns. Also, as shown in the table 1, the best solutions produced an acceptable even-flow harvest level, as compared to the target volume (1,000 MBF). Harvest volumes of each spatial pattern are quite close to the target volume during each time period. These results enable us to draw a conclusion that the methodology developed in this research was adequate to optimize the spatial pattern of management units across a real landscape while seeking to achieve a commodity production goal.

Total area of management units scheduled for thinning or clearcut varied by the pattern modeled (table 2). The dispersed pattern and clumped pattern were particularly distinctive in the total harvest area. For example, much more area was scheduled for harvest in the dispersed pattern compared to the others. Also, the area of thinning in the clumped pattern is much lower than that in other patterns. These observations suggest that management units with lower stand volumes tend to be selected in the scheduling process of the dispersed pattern. On the contrary, in scheduling the clumped pattern, management units with higher stand volumes tend to be selected and scheduled for clearcut treatments.

DISCUSSION

We have described heuristic techniques for distributing management activities across a landscape in specific patterns, while seeking to achieve a commodity production goal. Based on preliminary observations of the results of these scheduling processes, we feel we have an adequate system for achieving multiple goals across large landscapes and long time frames. In future work, we will use FARSITE (Finney 1999) to spatially model fires on the landscape originating from a number of ignition points. Characteristics

of resulting fires such as fire size, fire line intensity, and flame length will be measured, and then statistically compared to quantify the effect of each spatial pattern of management activity on the risk of intense wildfire. In addition, after preliminary tests of the entire modeling methodology, we will expand this research to a larger landscape. Several issues remain to be resolved in the further study. For example, in scheduling a regular pattern, the efficient interval between systematic points for reducing the risk of wildfire is not known and the pattern was not optimized through the entire time horizon. Thus, more attention to these issues will be applied in the further study.

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SIMULATING FUEL REDUCTION SCENARIOS ON A WILDLAND-URBAN INTERFACE IN NORTHEASTERN OREGON

Alan A. Ager¹, R. James Barbour², and Jane L. Hayes³

ABSTRACT

We analyzed the long-term effects of fuels reduction treatments around a wildland-urban interface located in the Blue Mountains near La Grande, Oregon. The study area is targeted for fuels reduction treatments on both private and federal lands to reduce the risk of severe wildfire and associated damage to property and homes. We modeled a number of hypothetical fuel treatment scenarios and examined the resulting changes in fuel characteristics, fire potential, and stand structure over time. Aggressive thinning alternatives showed significant reductions in stand characteristics that contribute to severe crown fires, such as height to live crown and crown bulk density for the landscape as a whole. However, simulations with extensive thinning showed larger overall flame lengths and torching compared to a no management scenario. Significant changes in stand structure and other characteristics were noted for the thinning versus no management scenarios. Work is ongoing to refine the simulation methods and test a wider range of treatment alternatives. The study motivated a discussion of the long-term problem of managing forest fuels in areas like the Blue Mountains.

INTRODUCTION

Fuels reduction programs have been initiated on many areas throughout the western US, even though the long-term effects of these treatments for reducing severe wildfires on large landscape has not received much attention. While case studies show that stand-level treatments can reduce fire severity (Fule and others 2001; Kalabodkidis and Omi 1998; Pollet and Omi 2002; Stephens 1998), the effect of treatments on large forested landscapes over time and the consideration of other resource constraints remains an experimental topic (Finney 2001; Johnson and others 1998; Barbour and others 2004). Also problematic are the mechanics of using existing stand-based fire and vegetation simulation models (Wykoff and others 1982; Reinhardt and Crookston 2003) on large landscapes and extracting landscape-scale measures of fire behavior that are meaningful to the general public. Methods for the latter are in wide demand for use in project-level planning for fuels reduction treatments on Federal and other lands.

As part of a larger project to examine landscape management issues in the Blue Mountains of Eastern Oregon (Hayes and others 2004) we simulated a number of fuel management scenarios on a key wildland-urban interface near La Grande, Oregon. The Mt. Emily area and surrounding community was identified in the National Fire Plan as "high risk" due to the intermingling of homes and vegetation, potential fire behavior, and existing fire protection capabilities (Wallace 2003). The forests have accumulated high loadings of live and dead fuels after decades of fire exclusion and a large spruce budworm epidemic in the 1980s that resulted in extensive mortality (Quigley and others 2001). A number of state, federal, and local agencies and organizations are coordinating efforts to reduce stand density and ladder and surface fuels with the goal of reducing flame heights, spotting, and crown fire potential, as well as provide defensible space for fire-fighting crews to safely approach future wildfires (Wallace 2003).

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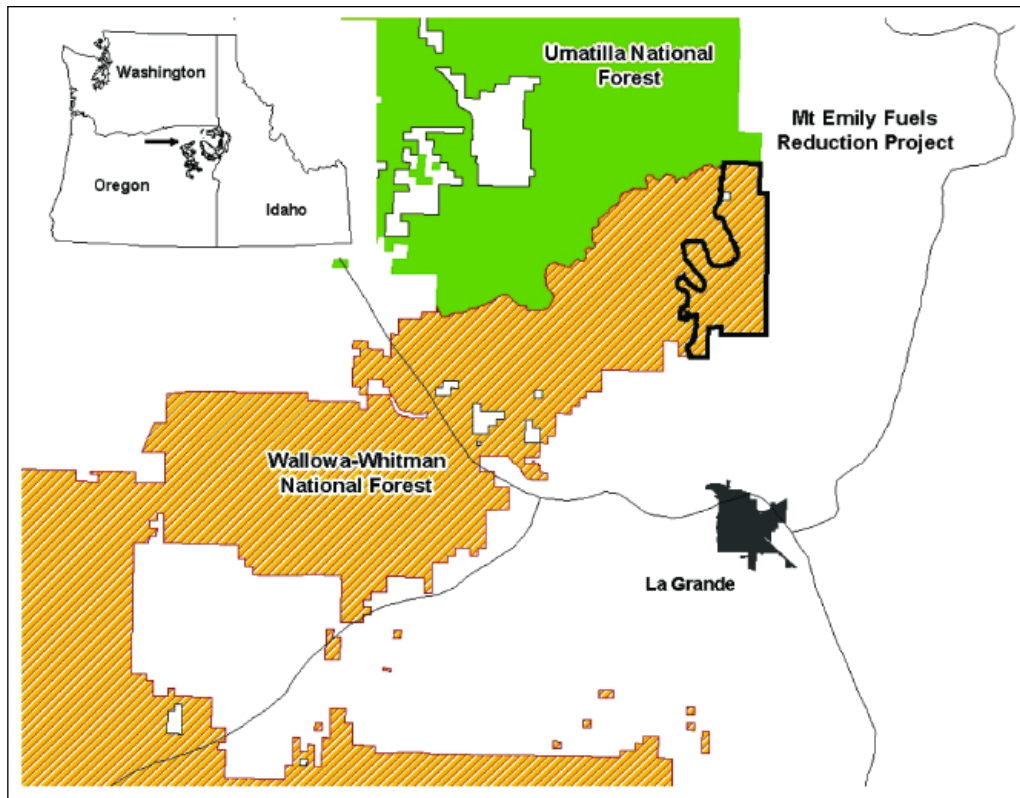


Figure 1—Vicinity map of the Mt Emily Study area.

The Mt. Emily project provided an opportunity to explore a number of questions related to landscape analysis of fuel treatment initiatives. We analyzed a broad set of hypothetical management alternatives that are beyond those being proposed for the Mt. Emily area in terms of treatment extent and intensity, with the goal of examining a number of strategic issues including: 1) How often are treatments needed to maintain desired vegetation conditions; 2) How effective are different types of treatments; and 3) What is the long-term effect of fuels treatments on fire behavior, fuels, and other resources. We report preliminary results of our work to address these and related questions.

MATERIALS AND METHODS

Study Area

The Mt Emily wildland-urban interface (WUI) is a 16-mile long area immediately north of La Grande, Oregon where the forested slopes of Mt. Emily and adjacent ridges descend to the agricultural lands in the Grande Ronde Valley (fig 1). For analysis purposes, a boundary around the area was established, containing 40,368 acres including federal, state, and privately owned lands. About 30,348

acres within the study area are classified as forested lands based on potential vegetation data. Approximately 25,139 acres within the larger analysis area are Forest Service lands, administered by the Wallowa-Whitman (9,346 acres) and Umatilla (14,230 acres) National Forests. Forest Service lands are managed for a number of objectives including big game winter and summer range, dedicated old growth and roadless. Surface fuel loading ranges from 15 to 80 tons per acre with excessive dead ladder fuels in a large number of the stands. Fuel accumulations accelerated after the 1980s spruce budworm epidemic that caused extensive mortality within the grand fir (*Abies grandis*) and Douglas-fir (*Pseudotsuga menziesii*) stands in the project area (Wallace 2003). The area has experienced 129 documented fire starts since 1970, including both lightning and human caused fires. Ninety-nine percent of the fires have been contained within the first twenty-four hours, and only one fire has grown to any significant size (Frizell fire, 250 acres) in recorded fire history.

Treatment Scenarios

Fuels specialists on the Wallowa - Whitman National Forest developed a range of different fuel treatments for about 3,000 acres that prescribe: 1) mechanical thinning

trees under 21 inches to reduce crown bulk density and ladder fuels; 2) Site removal of fuels when they exceed 25 tons per acre; 3) Underburning after treatment to reduce surface fuels (Wallace 2003); and 4) Piling and burning of surface fuels. The choice of treatment(s) for a given stand was dependent on a number of factors related to stand conditions, management goals, and management restrictions, and was the subject of considerable debate among specialists and managers. The treatments were strategically located to reduce fire spread, create defensible space for suppression activities, and protect utilities like the Mt. Emily electronic site.

For the purpose of examining long-term effects of fuel treatments, we used the general treatment methods described above and simulated a broader, simplified set of seven hypothetical scenarios as follows:

1. No Management or Natural Disturbance [NOMAN].
2. Long Term Aggressive Thinning [LTAT]. Thin from below all stands that exceed 55 percent of the maximum stand density index (SDI) to 35 percent of the maximum SDI; site removal of fuels followed by underburning. Management is applied to all ownerships over time as needed.
3. Long Term Moderate Thinning [LTMT]. Same as LTAT except that thinning is triggered at 65 percent of maximum SDI and trees are removed until 45 percent of SDI is reached.
4. Thinning with Maintenance Burns [LTATMBURN]. Same as LTAT with the addition of decadal underburning of stands that are thinned for the entire period of the simulation.
5. Long Term Aggressive Thinning with Maintenance Burns on Forest Service lands only [LTATMBURNFS]. Same as LTATMBURN except that treatments are only applied on Forest Service lands administered by the Wallowa - Whitman National Forest. The remaining Forest Service lands in the project area are in a roadless area administered by the Umatilla National Forest and were not considered for treatment in any of the scenarios.
6. Long Term Aggressive Thinning with Maintenance Burns on Forest Service lands only, 21-inch diameter limit [LTATMBURNFS21]. Same as LTATMBURNFS except that the Region 6 old growth screens that prevent harvesting of trees greater than 21 inches is implemented.
7. Short Term Aggressive Thinning [STAT]. Same as LTAT except that stands are treated in the first decade only of the simulation. Management is applied to all ownerships.

We emphasize that these scenarios are hypothetical, and were formulated to better understand how existing models and typical Blue Mountain landscapes respond to long term management scenarios.

Vegetation and Fuels Data

We developed an initial vegetation database consisting of data on trees per acre by species and 1-inch diameter class for each stand using data from stand exams, photo-interpretation, and field reconnaissance. The resolution of the data was coarse in some areas, but adequately represented the project area for purposes of the present study. Where stand exam data did not exist we generated approximate tree lists from photo-interpretation of 1:12000 color resource photos from 1998. Photo-interpreted data consisted of canopy closure estimates by size class and species. These data were converted to trees per acre by diameter class using relationships between crown diameter and tree diameter developed from stand exam data at the La Grande Ranger District. Extensive field checks of the data were completed over the course of the study.

Detailed fuels data were obtained from stand exams and supplemented with a sub-sample of stands that were chosen to represent average fuel conditions for different fire regimes and commonly observed fuel models (Wallace 2003, Anderson 1982). Fuels were sampled with line transects according to Hilbruner and Wordell (1992) on a sample of 6 stands chosen to represent dominant fuel conditions. These data were used to adjust the initial fuels and default fuel loadings for the dense conifer stands (fuel models 8 and 10, Anderson 1982). Default values (Reinhardt and Crookston 2003; Anderson 1982) were used for the remaining fuel models found in the project area.

Models

For each of the 1060 stands in the project area we projected vegetation with the Blue Mountains Variant of the Forest Vegetation Simulator (FVS) (Wyckoff and others 1982), a distance-independent individual tree growth model. We simulated decadal time steps and report simulations for 60 years. We used a forest regeneration model (Wilson and Maguire in prep.) that was developed from extensive seedling survey data obtained from the La Grande Ranger District. Mechanical thinning was simulated within FVS using prescriptions developed for thinning studies in the Blue Mountains (Rainville 2002). Specifically, stands were thinned once they exceeded 55 percent of maximum SDI, thinning from below until the stand SDI was 35 percent of maximum. Maximum SDI values were specific to each plant

association and target species (Cochran and others 1994). The thinning prescriptions targeted removal of late-seral species like grand fir in mixed-species stands, favoring early seral species like western larch (*Larix occidentalis*) and ponderosa pine (*Pinus ponderosa*). Although the prescriptions used were relatively generic for the diversity of ecological settings and management goals in the project area, they were adequate for the present study.

Potential fire effects, dead and down fuel dynamics, and underburns were simulated with the Fire and Fuels extension (FFE) to FVS (Reinhardt and Crookston 2003) and FlamMap (Finney in prep). Due to space limitations the FlamMap results are not presented here. The FFE FUELMOVE keyword was used to simulate removal of the larger surface fuels, under the assumption that 90 percent of the 3 to 6 inch and 40 percent of the 1 to 3 inch materials would be removed from the site. Underburning followed thinning and fuel removal treatments, and was simulated with the FFE SIMFIRE keyword using typical weather for burning treatments on the La Grande Ranger District (table 1). Potential wildfire effects on each stand were simulated using the FFE POTFIRE keyword. Weather conditions for simulating potential wildfire effects were derived from the J Ridge (Station 351414), Black Mountain (Station 351314), and Black Mountain 2 (Station 351317) remote automated weather stations. The Black Mountain Stations are located 10 miles east, and the J-Ridge stations are located 25 miles south of the project area on national forest land. Weather data for June to September from the years 1986 to 2002 were analyzed in Fire - Family Plus (Bradshaw and McCormick 2000) to generate 90th and 97th percentile temperature, wind speed, and fuel moisture values (table 1). Outputs were analyzed for crown fire activity, flame length, crowning and torching index, and changes in fuel models over time. The 10-minute average wind speeds generated in Fire- Family Plus were converted to maximum velocity gusts using the tables developed by NOAA (<http://www.seawfo.noaa.gov/fire/olm/fire/10togust.htm>).

We measured forest structure (O'Hara and others 1996) for the scenarios using the cover extension to FVS (Crookston and Stage 1999).

RESULTS

Stand Development

The scenario that simulated long-term thinning of all lands in the study area (LTAT) resulted in the treatment of about 23 percent (7,032 acres) of the forested area per decade, averaged over the 60 year simulation (table 2). The same prescription with decadal maintenance burns thinned

stands in about 15 percent of the study area (4,568 acres) per decade (LTATMBURN). Thus the addition of the maintenance burns reduced the area thinned by 8 percent per the decade. The LTAT scenario removed an average 6,394 MCF of merchantable material per decade (table 2), with the other scenarios resulting in lesser values commensurate with the acres treated. Thinning only Forest Service lands within the study area (LTATMBURNFS scenario) called for thinning only about 1,212 acres, and removed 1,154 MCF per decade (table 2). Thinning to the upper SDI management zone (LTMT) called for thinning about 6,291 acres per decade, or 21 percent of the forested area (table 2). For the landscape as a whole, the overall SDI was maintained at 135 for the LTAT scenario, while SDI for the no management scenario rapidly increased and eventually tapered off at 215 over the 60-year simulation period (table 2). The thinning schedule over time was most irregular for the LTAT scenario, and it was apparent that heavy thinning in the beginning of the simulation produced pulses of regeneration that required thinning in the future. The pulse of regeneration in the first decade is consistent with field observations. A large number of stands in the cool moist ecological settings have experienced severe mortality from spruce budworm, which has opened up the stands and set the stage for regeneration.

The LTAT and LTATMBURN thinning management scenarios resulted in large changes in crown bulk density and crown base height (fig. 2). By 2020 the average crown bulk density under both scenarios was reduced to 0.04 kg/m³ compared to almost 0.1 kg/m³ for the no management scenario. Crown base height was higher for the thinning scenarios, the difference being almost 15 feet by the year 2020. Trends in both crown bulk density and live crown height were strongly affected by regeneration in the early decades.

Stand structural characteristics showed a number of changes over time and differences among the scenarios were apparent (fig. 3). In the no management scenario, simulations indicated large increases in the stem exclusion (SE) structural stage, and by 2030, over half of the forested lands were in this structural stage. The effect of thinning within the LTAT or LTATMBURN scenarios was to convert the stem exclusion stage to single-stratum old forest. Thinning also increased the proportion of stands in the under-story re-initiation stage as well (UR, fig 3).

The STAT scenarios that called for only a single thinning at the beginning of the simulation had little effect on the landscape through time (table 2). Likewise, recurrent

Table 1—Weather and fuel moisture parameters used in potential fire simulations and prescribed fires. The 90th and 97th percentile conditions were determined from analysis of local weather stations. See methods for additional details on weather station data and calculation of percentile values and velocity of wind gusts.

Variable	90 th Percentile Values	97 th Percentile Values	Maintenance Burns
Temperature (degrees F)	85°	90°	70°
1 hour fuel moisture (percent)	4	3	6
10 hour fuel moisture (percent)	6	4	12
100 hour fuel moisture (percent)	7	6	16
1,000 hour fuel moisture (percent)	9	7	26
Live fuel moisture (percent)	74	64	100
Duff moisture (percent)	42	20	—
10-minute average wind speed (mph) at 20 feet above ground	8	9	—
Maximum gusts	23	24	—

thinning and underburning of only Forest Service lands (LTATMBURNFS) showed relatively minor changes compared to the no action alternative (table 2) which could be expected given that only about 25% of the area is available for treatment in this scenario.

Fuels

Changes in fuel models among the scenarios generally followed expected trends (fig. 4). For the no management scenario, there was a rapid decrease in fuel model 5 acres (brush type), an increase in model 8 acres (closed canopy conifer), and, after 50 years, a dramatic increase in fuel model 10 acres (closed canopy with high surface fuels) (fig. 4). The change in fuel models reflected a landscape with active regeneration in the early part of the simulation, with stands building up down fuels and increasing mortality through time. In contrast, the LTAT alternative showed a large reduction in fuel model 8 as stands were thinned and converted to fuel models 2 and 5 (fig. 4). There was also an increase in fuel model 11 (closed canopy with high activity fuels) in the first 20 years, from thinning residue. The thinning treatments did not result in an overall decrease in surface fuels (table 2) even though we assumed that a large portion of the residual fuels (90 percent of the 3 to 6 inch and 40 percent of the 1 to 3 inch materials would be removed from the site as part of the treatments. Scenarios that called for lighter thinning (LTMT) and 10-year maintenance burns did not significantly reduce downed fuels either when measured as an average for the landscape.

Potential fire analysis

Acres of potential active crown fire increased in the first 30 years for all scenarios, with the no management scenario exceeding all other scenarios (fig. 5). For the LTAT

scenario, acres increased from about 500 to 3000 acres between years 2000 to 2020, declining thereafter, and at 2030, acres of potential active crown fires were reduced to nearly 0. Acres of potential active crown fire also showed a decreasing trend for the no management scenario after about 30 years, although the acres with a crowning index less than 24 (meaning that they will carry a crown fire in 24 mph wind) remained high throughout the simulation while rapidly decreasing for the thinning scenarios (table 2). Although the LTAT and LTATMBURN simulations showed reduced acres of potential active crown fire, they resulted in a significant increase in passive crown fires (torching) throughout the simulation (fig. 5). The increase in torching was not simply the net result of decreased active crown fire (fig 5.) since the increases were much larger than the decrease in active crown fires. Also, the future trend in passive crown fire acres continued to increase in the LTAT scenario after the acreages of active crown were negligible. Passive crown fire for the no management scenario initially decreased until 2030 and stayed relatively constant thereafter. Increased torching in the aggressive thinning alternatives was caused by the increased fuel loadings and acreages of the grass and brush fuel models, which have a higher inherent flame length (Anderson 1982).

DISCUSSION

Our simulations oversimplified the design of fuel treatment scenarios on the Mt. Emily landscape by not considering the spatial arrangement of treatments over time (Finney 2001, Finney and Cohen 2002). We also relied primarily on landscape averages to present the results, which can mask important trends at the stand level. In addition, there are many aspects of the FVS Fire and Fuels Extension

Table 2—Results of simulations for selected management scenarios examined in the study. See text for definition of scenario labels. Variable CI24 is the acres that had a crowning index below 24, meaning that the stand can carry a crown fire in the presence of 24 miles per hour wind (97th percentile gust wind speed, Table 1).

	NOMAN				LTAT				LTATMBURN				LTATMBURNFS			
	Year				Year				Year				Year			
	2000	2020	2040	2060	2000	2020	2040	2060	2000	2020	2040	2060	2000	2020	2040	2060
Acres thinned per decade	0	0	0	0	3699	6566	4825	6773	3699	5614	3356	4461	1442	1377	403	775
Stand density index	95	199	256	281	95	136	149	123	95	131	123	134	95	183	217	222
Decadal thinning volume (merch. MCF)	0	0	0	0	3973	3389	3234	8475	3973	2759	1904	5077	1630	923	277	736
Flame length moderate fire (ft)	3.2	1.8	1.9	2.3	3.4	3.1	3.1	3.5	3.4	3.1	3.3	3.5	3.2	2.2	2.3	2.6
Flame length severe fire (ft)	11.7	11.4	10.2	9.8	12.1	11.7	11.8	12.0	12.1	11.6	11.4	11.8	11.8	11.4	10.8	9.9
CI24 (acres)	10663	20148	14958	14566	9761	12615	3652	833	9761	12600	2905	588	10355	18760	12330	11632

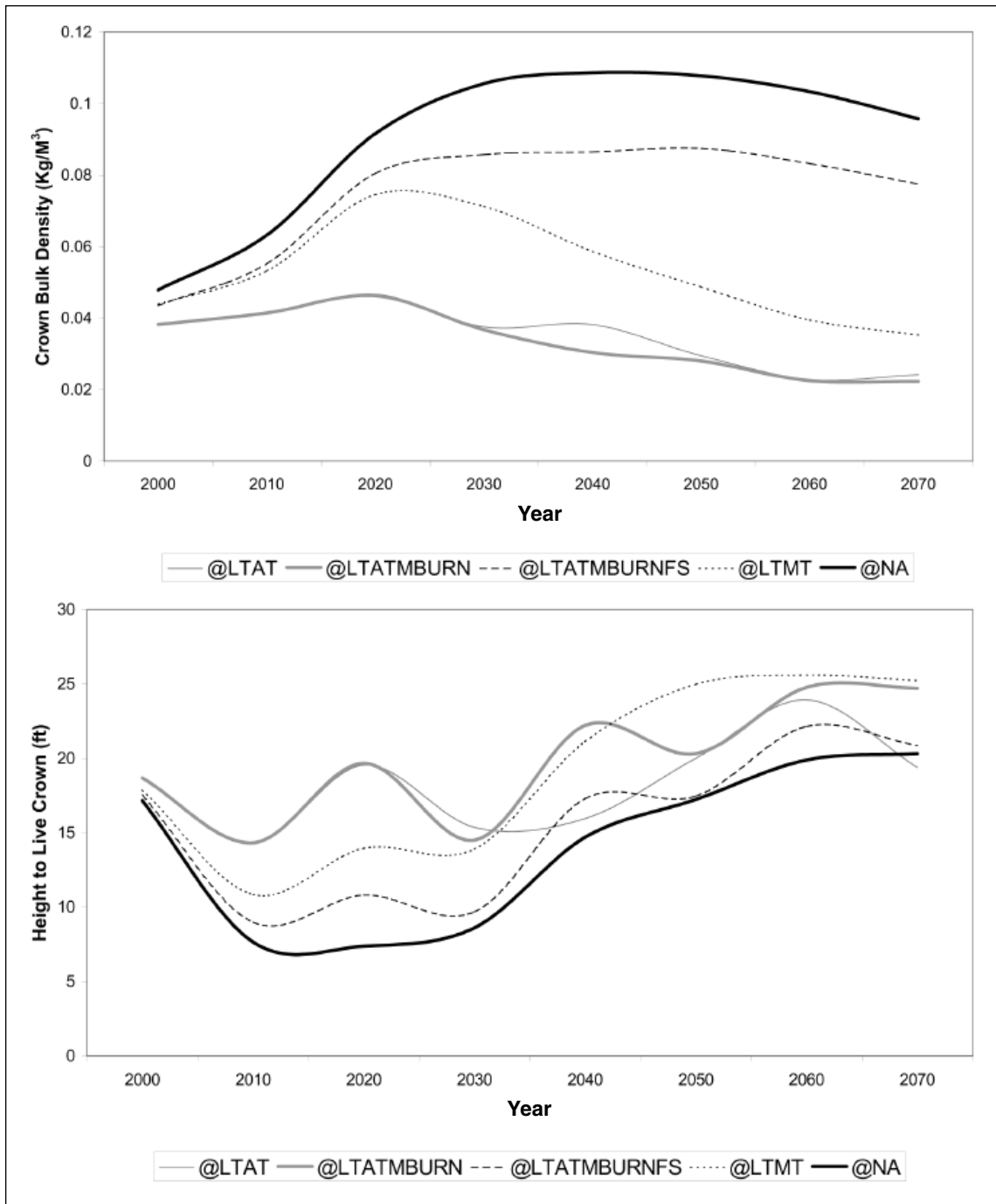


Figure 2—Results of simulations showing changes over time in crown bulk density (top) and live crown height (bottom) for selected scenarios examined in the study.

that have not undergone rigorous examination, and thus results we present pertaining to fuels and potential fire need to be viewed with some caution. One area in particular that needs attention is the assignment of fuel model 5 to stands that are dominated by conifer regeneration. These

stands may or may not behave like the fuel model 5 in a wildfire depending on species composition and other factors not considered in the model. Nevertheless, the effect of thinning treatments had marked landscape-level effects on parameters like crown bulk density and live crown height,

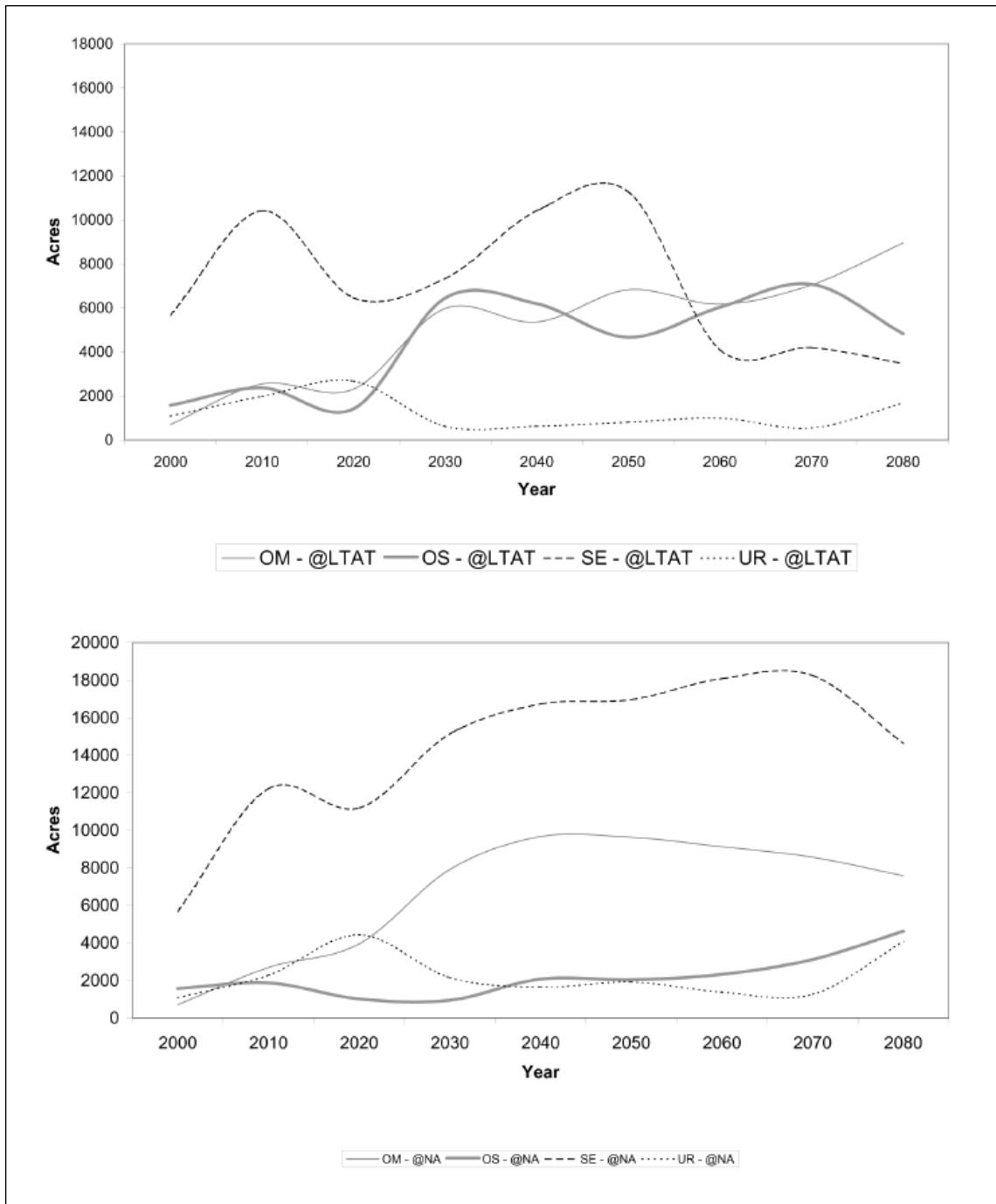


Figure 3—Results of simulations showing changes over time in forest structure for the no management (NOMAN, top) and long-term aggressive thinning (LTAT, bottom) scenarios. Structure classifications follow O’Hara et al. (1996) and were determined with the FVS cover extension (Crookston and Stage 1999).

both of which are strong determinants of crown fire activity. For instance, the average crown bulk density after 30 years of treatment was 0.01 kg/m^3 , which is below the 0.050 kg/m^3 level required to sustain active crown fires (Keys

and O’Hara 2002). These changes were reflected in the lower proportion of the stands that exhibited active crown fire behavior in the potential fire simulations, and later on, a decrease in the crowning index. It was interesting to find

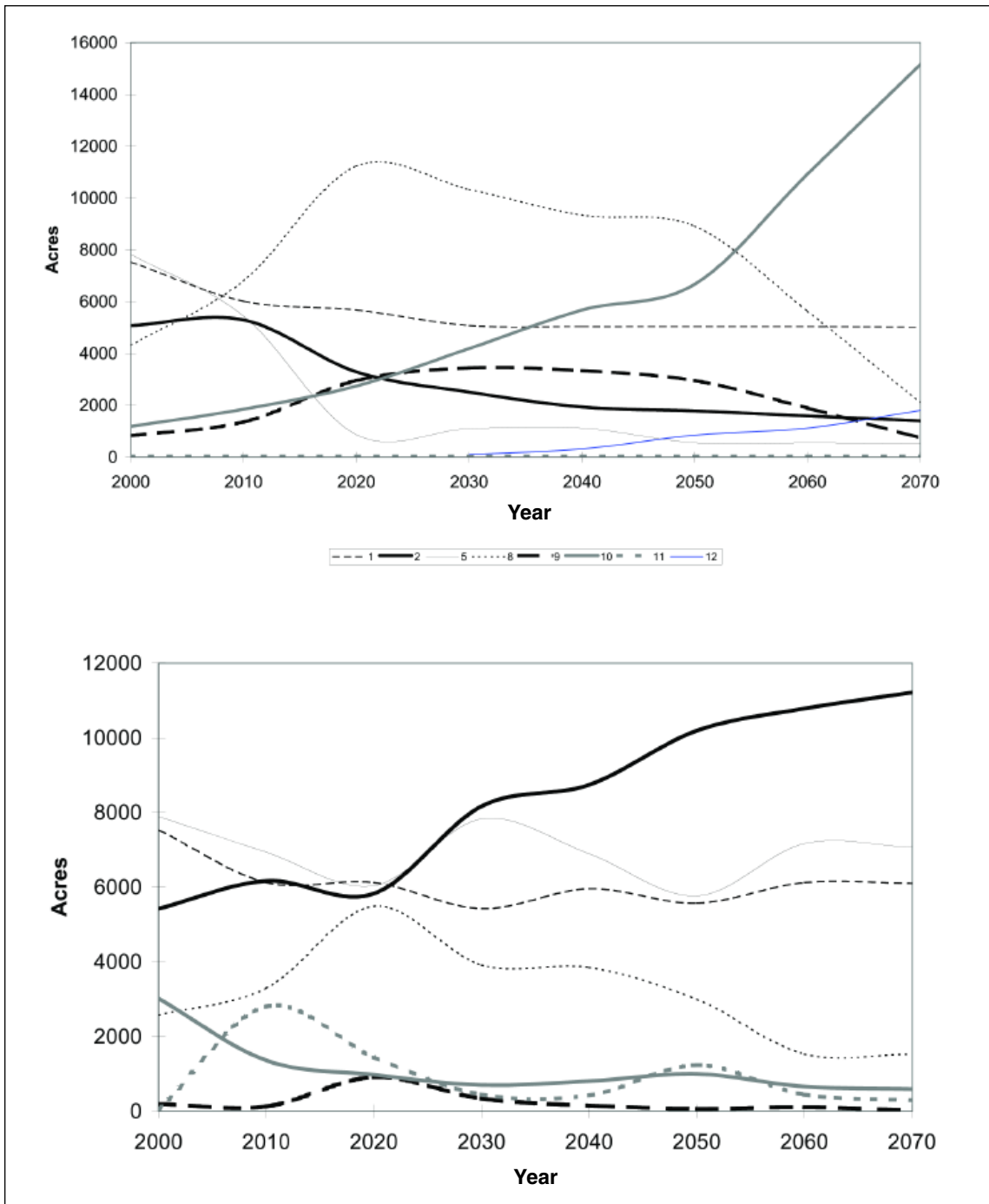


Figure 4—Results of simulations showing changes over time in fuel models for the no management (NOMAN, top) and long-term aggressive thinning (LTAT, bottom) scenarios.

that acreage of active crown fire sharply decreased after 40 years for the no management scenario. Examination of the acreages that could sustain a crown fire under 97th percentile weather conditions for the no management scenario (table 2) showed that while crown fire could not be initiated,

a large portion of the project area could sustain a crown fire spreading from an adjacent stand. If we had simulated small disturbances like windthrow and root disease pockets, regeneration would probably provide the ladder fuels needed to initiate a crown fire and alter the results.

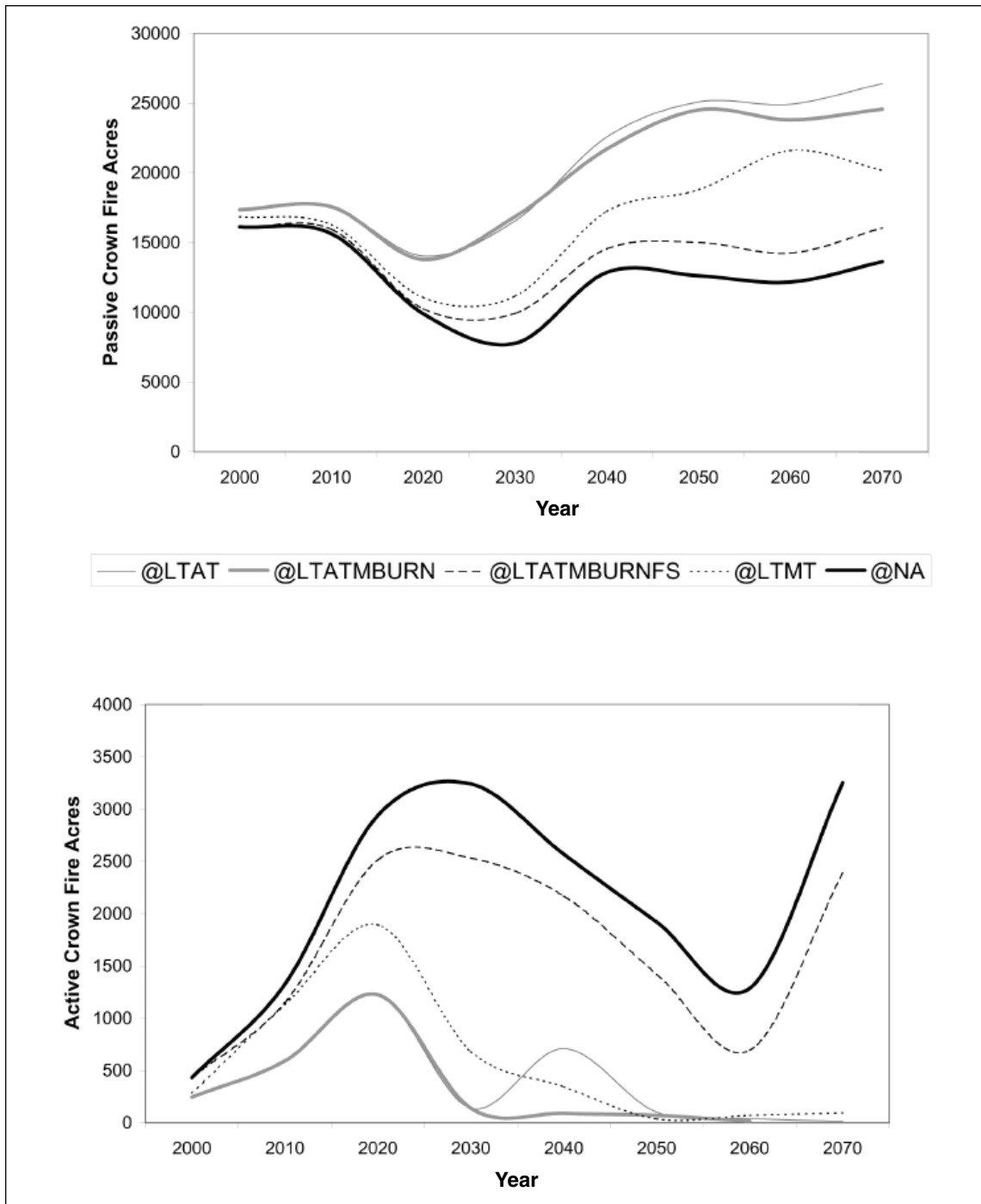


Figure 5—Results of simulations showing changes over time in acres of potential passive (top) and active (bottom) crown fire for the no management (NOMAN) and long-term aggressive thinning (LTAT) scenarios.

It was also interesting to find that thinning resulted in a large increase in passive crown fires (torching) and a small increase in average flame length for the landscape as a whole. Thinning treatments resulted in a larger proportion

of the area assigned to fuel models 2 and 5 (grass, brush), which by default, have higher flame lengths and spread rates, contributing to a higher potential for torching (Anderson 1982). In addition, activity fuels most likely contributed

to the torching potential. Although the fuel models 2 and 5 have relatively high flame lengths and spread rates, they burn at low intensities relative to crown fires, and fire suppression in these fuel types is more effective (Finney 2001). A number of empirical observations have shown that treatments like those simulated here lower the intensity, spread rates, and tree mortality from wildfires.

The scenarios that simulated treatment of the Forest Service lands only showed a relatively minor response for the study area as a whole (table 2), although in part this result is strongly influenced by the size of the study area relative to the Forest Service land base. In any case, the LTATMBURNFS scenario reinforces the importance of cooperation among landowners to bring about fuels treatments on all areas. It is important to recognize that we did not attempt to model an array of resource constraints on Forest Service lands that would further limit treatments.

The mechanical thinning scenarios provide some indication of future treatment schedules for landscapes like the Mt. Emily WUI, which is useful information for strategic planning efforts that are underway on the National Forests in the Blue Mountains province. Treatment schedules for different scenarios can be used to forecast fiber supply and net revenues of thinning treatments over the long run. Under a scenario that calls for thinning based on a relative density measure like SDI, a shorthand method to calculate treatment rates can be approximated as

$$\text{Treated acres/year} = (\text{Watershed Acres}) / (F'[\text{SDI}_{\text{max}}] - F'[\text{SDI}_{\text{min}}])$$

Where SDI_{max} and SDI_{min} are the values of SDI at the upper and lower management threshold and $F'(t)$ is the inverse of the function that predicts SDI change over time. The latter can be derived from stand growth simulations and averaged for all stands in a landscape.

The current and future density problems in areas like Mt. Emily demand additional ecological discussions (Tiedeman and others 2000) and perhaps new and innovative solutions. Thinning, fuels treatments, and underburning have well-documented beneficial effects on overstocked stands in terms of general forest health and wildfire risk. However, thinning overstocked stands induces waves of regeneration and sets the stage for future development of ladder fuels and high crown bulk density. If recurring treatments are not applied, the initial thinning will be counter to long-term landscape goals (Keyes and O'Hara 2002). The long-term treatment of fuels is made difficult by the finding that most restoration treatments in the Blue Mountains have negative net values under current economic conditions (Rainville

2000) and a variety of resource values must be considered on the Federal land base.

While fire suppression and removal of fire tolerant species has been a major factor in the development of fire-prone conditions, there are many processes besides wildfire that regulate stand density through time in coniferous forests. For instance, thinning treatments can enhance seed production in residual trees (Reukema 1961), leave a favorable substrate for seed germination (Schopmeyer 1974), and degrade habitat for small mammals (Tiedemann and others 2000) that consume conifer seed (Sylvester and others 1994). Thus treatments may set the stage for prolific conifer regeneration and, eventually, dense stands with high crown fire potential. New research is needed to find ways to manage seed production, seed survival, germination and seedling establishment after underburning and mechanical treatments.

There are many issues that need to be explored with the simulation approach we have used here, such as the spatio-temporal patterns of treatments (Finney 2001), interactions between wildfire and other disturbances (Quigley and others 2001), and secondary effects of fuels treatments on other resources including wildlife and forest productivity (Tiedemann and others 2000; Johnson and Miyanishi 1995). For instance, optimal spatial patterns of shaded fuel breaks (Finney 2001) could fragment stands of late-old structure considered important to keystone wildlife species like American marten (*Martes americana*) (Hargis and others 1999). On the other hand, these treatment patterns might create desired foraging habitat for Canada lynx (*Lynx canadensis*) (Aubry and others 2000) and Rocky Mountain elk (*Cervus elaphus*). Frequent burning can reduce foraging substrate (down wood) for a number of important avian and mammal species that feed on ants and other insects (Torgersen and Bull 1995). Economic questions about the kinds of investments that will be needed in the long term to finance forest restoration treatments (Christiansen and others 2002) have not been addressed in a way that reflect spatially explicit harvesting and transportation costs. All of these issues contribute to a long-term landscape design questions of how to achieve restoration goals in the Blue Mountains (Quigley and others 2001) within a constraint matrix that includes riparian buffers, roadless area, visual objectives, and habitat for listed species.

Many improvements are needed to the simulations we presented here, and work is in progress towards that end. We are analyzing the different scenarios in terms of wood utilization, habitat for selected wildlife species, and insect

and disease risks for the Mt Emily WUI. We are also developing mortality models for insects and disease using a multi-agent approach (Roberts and Weatherby 1997). Mechanical thinning prescriptions are being refined for the different ecological settings and management goals within the project area. These refinements will be used for additional simulations on the Mt Emily area to gain further insights into the long-term problem of managing for multiple resource objectives in the Blue Mountains.

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**STAND
OPTIMIZATION
AND HARVEST
OPERATION**

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ESTIMATING THE HARVESTING POTENTIAL FOR HIGHLY MECHANIZED HARVESTING SYSTEMS IN SMALL-SCALE FORESTRY BY USING A GIS MODEL

Peter Rauch¹

ABSTRACT

There is an increasing demand by the wood industry for small-diameter timber in Austria. On the one hand, there is a large green stock, but on the other hand, the continuous supply – especially out of the numerous small forest plots - is a problem. In Austria, forest owners' co-operatives bundle the supply of round wood coming out of the small forest plots. The only information the manager of a forest owners' co-operative actually has are some personal data from the members of his co-operative and the size of their forests. The main reason for this lack of data is that there are no forest management data available.

For a forest owners' co-operative with 240 members representing 9,000 ha (22,230 acre) of forest land a basic information system has been set up. The prototyping of the model has been done for a tracked harvester. The model estimates areas where machinability of the stand and trafficability of the terrain both are fitting to the harvester configuration. Validations of the model results show that it matches the reality of the mountainous research area quite well.

INTRODUCTION

There is an increasing demand of the wood industry for small-diameter timber in Austria. On the one hand, there is a large green stock, but on the other hand, the continuous supply – especially out of the numerous small forest plots - is a problem. The Austrian Forest Inventory shows tending arrears with a harvesting potential of 40.5 million m³ for Austria's small-scale forests alone. Demand for small-diameter timber could be satisfied if in small forest plots more thinnings were done by mechanised harvesting systems. Analyses of current data of the forest owners' cooperative Leoben (Country of Styria, Austria) show that only for a small part of the cooperative's forest plots there are forest stand data available and in most cases these data are not up-to-date any more. Furthermore, basic cadastral data of the members' forest plots is also lacking. A similar situation holds true for most of the other Austrian forest owners' cooperatives.

Aims—The project has pursued the following aims by implementing a GIS model for estimating the harvesting potential for highly mechanised harvesting systems in small-scale forestry:

- Increase the amount of small-diameter timber harvested in the forest owners' cooperative (FOC) Leoben,
- reduce tending arrears,
- develop a useful basic forest map.

THE GIS MODEL

According to Reinberg (1998) the basic requirements of a model that is a simplified picture of reality are (i) its similarity to the real system, (ii) being as simple as possible, (iii) having the possibility to adapt, and (iv) having a variable resolution. The demands for simplicity and for similarity to the real system contradict each other to a

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certain degree. But even complex real situations should not lead to exorbitant complex models.

Spors and others (1992) name the following hard decision factors, i.e., factors that cannot be compensated, for estimating potential areas for harvesters with GIS: danger level of the site (site classification on the basis of substratum and water regime), inclination, d.b.h., and tree species characteristics. Based on those data harvester areas can be estimated on a regional scale.

Lan (2001) names the following parameters which determine whether harvesters can be applied: (i) topographical conditions, such as inclination and the bearing capacity of the soil, (ii) stand parameters, (iii) soil type, and (iv) other environmental constraints. More models for intensive timber production will be introduced in the near future (Johnsen and others 2001) and the question where to use which harvesting technique is one of the central tasks in forest harvesting operations (Eichrodt 2003).

Synthesising the work of Spors and Lan one can say that the application of a harvester depends on both trafficability and machinability of a forest area.

Adaptation of the model for the special conditions in small forest plots

For the FOC Leoben there is none of the geodata available named by Spors and Lan. The only exception is a digital terrain model. To estimate harvester areas under small forest plot conditions some adaptations of the described models have to be made. First of all, one should try to use as much already available data as possible in the model. This principle ensures that the model is adaptable to other regions with small forest plot conditions. In their study dealing with process models in forestry Johnsen and others (2001) stress differences in data quality between complex and data-intensive scientific models and applications for forest managers which need data that is simpler and more easily available. The model developed in this paper can be assigned to the second type, the forest management applications, for two reasons: first, because of the (poor) quality of the input data and, second, because of the intention to support timber harvest in practise.

The model is a prototype adapted to the machine configuration of the FOC's tracked harvester (Robin) and to regional characteristics of the district of Leoben. The main parameters of the machine configuration are gradeability that mainly limits trafficable area and minimum and maximum d.b.h. suitable to the harvesting head.

For estimating harvester trafficability of the area of the district of Leoben the digital terrain model of the Federal Office of Metrology and Surveying (BEV) is the only one available at the moment. Despite its wide raster (50 meters between two measurement points) it is still good enough to deduce topographical and morphological terrain data (Schreier and Lavkulich 1979). Decision criteria inclination (deduced from the digital terrain model) is as well a so-called hard factor (Spors and others 1992) as the main topographical condition for estimating harvester trafficability (Lan 2001).

In this project I had to do without these data because site classification maps were not available for the study area and because mapping the scattered forest plots of the FOC Leoben would have been too labour intensive. The additional value of site classification data would not make up for the additional costs (see Meyer and others 2001).

Caused by the weather, water content of soil and depending soil parameters like Californian bearing rate change permanently. Therefore the model works under the assumption of gradeability under dry soil conditions.

Since for the FOC Leoben there were no forest stand data available, the basic stand data needed for the model had to be collected. In order to get up-to-date stand data in an acceptable amount of time, the stages of development of the forest have been determined by stereoscopic interpretation of aerial images. This technique has been used frequently and is known as field tested (Schmidtke and others 2000). The harvesting area was defined on the basis of the maximum d.b.h. suitable to the harvesting head (Logmax 3000) of the tracked harvester used. With that stands with d.b.h. of less than 20 cm (pole stage) as well as stands with d.b.h. of up to 34 cm (small-diameter timber tree) were selected as harvesting areas. Property borders have been determined on the basis of the digital land register map from BEV which is available for the whole district of Leoben.

Process Model—To create the GIS model for estimating harvester suitable stands the following process model was used:

1. build up a forest owners' database,
2. join the forest owners' database with the digital land register map,
3. estimate borders of stands and their stage of development as well as further stand data (tree species, tree heights) by stereoscopic interpretation of aerial images,
4. implement GIS model,

- validate GIS model using terrestrially mapped stands as reference.

Build up a forest owners' database—For building up a forest owners' database (which should include the whole forest area owned by members of the FOC Leoben) the following steps had to be taken:

- collect the cadastral basic data from each member (lot codes),
- determine land register data via internet on the basis of lot codes,
- put the results of the inquire in a forest owners' database using hand made software and
- check the results of the inquiry (e.g., cancel entries of non-members, check completeness of data).

After having collected the cadastral basic data from each member, land register data could be determined via internet. Because of the quite complex land register system it took several iterations to get all the required data for the FOC's members. Lot codes and owner data were put in a database.

Joining the forest owners' database with the digital land register map—In Austria each parcel of land has a unique lot code. On the basis of this lot code the forest owners' database was joined with the digital land register map. A layer of the wood lots of all members and the connection with the forest owners' database are the results of this operation.

Stereoscopic interpretation of aerial images—In order to get the stand data needed for the GIS model (stand borders and stage of development) in an acceptable amount of time and for an acceptable amount of money, stereoscopic interpretations of aerial images were carried out. The results of the stereoscopic interpretations of aerial images are based on expert's opinion and because of subjective influences flawed with inaccuracy (Schmidtke and others 2000; Kätsch 2001). Nevertheless the data quality expected should be good enough for the modelling purpose at hand.

Digital, panchromatic orthophotos from BEV and real colour aerial images from a private enterprise have been used. The real colour photo flight includes 396 images and has an average image scale of 1:19,000.

With a stereoscopic device (AvioPret from Wild) using the stereo pairs of real colour images the borders of the forest stands can be seen in three dimensions. As the real colour images are not to scale the exact geometric delimitation was supported by orthophoto that was shown on a

Table 1—Stages of development estimated by stereoscopic interpretation of aerial images

Stage of development	Characteristic
Regeneration, culture	Before canopy is closed
Thicket stage	d.b.h. less than 10 cm
Pole stage	d.b.h. between 10 and 19 cm
Small-diameter timber tree	d.b.h. from 20 to 34 cm
Medium timber tree	d.b.h. from 35 to 50 cm
Big timber tree	d.b.h. more than 50 cm

computer monitor in ArcView. A digital land register map was used to show the borders of the forest plots which have to be edited. Table 1 shows the stages of development that were used for describing the age phase of a stand.

After the delimitation further stand data (such as tree height, canopy density and stem number) are estimated and put in a database. Only stands with a minimum area of 1000 m² were utilized because smaller areas could not have been located exactly when they are drawn onto a layer overlaying the orthophoto.

Implementation of the GIS model—In order to get an assessment of the harvester suitability of the stands the different layers of themes were joined with the Simple Additive Weighting Method. This method is the most common for multi-attribute decision support (Malczewski 1999). Application of this method in a GIS takes the following steps:

- define evaluation criteria and standardise layers,
- define evaluation weights for criteria and
- generate resulting layer as score of weights per grid.

Modelbuilder, an extension to ArcView, supports this method and is used to implement the model. All layers (inclination, stage of development, storm damages and other damages) are transformed into grid format. This, finally, enables spatial analyses of harvester suitability of the stands of the FOC Leoben. Assessment of input parameters with a solving algorithm is possible if clear relations between assessment criteria are given (Czeranka 1999). Following Spors and Lan the suitability of stands for harvesters is mainly limited by trafficability (here estimated only by inclination) and stand parameters (here estimated only by stage of development). Data of damaged plots are digitally available for the whole country of Styria and are used because these damages are another restriction for harvester suitability. Criteria weights and rules for connecting input parameters are documented in table 2.

Table 2—Model algorithm

Input theme	% Influence	Input field	Input label	Scale value
Stand Grid	49	Value		
		10	Forest roads, etc.	Restricted
		20	Regeneration	Restricted
		30	Thicket stage	Restricted
		40	Pole stage	-1
		51	Small-diameter timber tree	-1
		52	Medium timber tree	Restricted
		53	Big timber tree	Restricted
		60	Non forest area	Restricted
Trafficability	49	No data	No data	Restricted
		Value		
		1	Harvester+forwarder	-1
		2	Harvester+cable	1
		3	Motor manuell+cable	Restricted
Storm Damage	1	No data	No data	Restricted
		Value		
		0	Peripheral area	0
		1	Main area	Restricted
Other non biotic Damages	1	No data	No data	0
		Value		
		3	hail	0
		5	Forest fire	Restricted
		No data	No data	0

Value trafficability is inclination:1 means inclination from 0 to 50 percent, 2 from 51 to 60 percent, 3 more than 60 percent. The column “% Influence” gives the weight in percent that an input theme has in respect to the overall result. Each 5x5m grid with an input value that eliminates a harvester to work is dropped from the solution area. This is done by setting their scale values as restricted. The solution area is showing therefore harvester suitable grids only.

The implemented algorithm sums up products of percentage weights of a single parameter given in an input theme and scale values for estimating the Gridcode for each 5x5m cell. Areas with attributes that disable a harvester (for example stands “thinned” by storm) are excluded from the possible solution space. Their scale value is set as restricted. A cell is assumed as harvester-suitable if the d.b.h. estimated by stereoscopic interpretation of aerial images as well as trafficability assessed by inclination are fitting the machine configuration of Robin and if at the same time the stand is free of damages.

For example if a 5x5m Grid is part of a stand in pole stage with an inclination of this part of 53% and if there are no storm or other biotic damages the Gridcode is estimated as follows: Gridcode for that area = $(0.49 \times (-1)) + 0.49 \times 1 + 0.01 \times 0 + 0.01 \times 0$.

Scale values of the input theme ‘stand grid’ are set so that Gridcodes differ if logging can be done by a forwarder

(scale value -1) or only by a cable system (scale value 1). So the models computes for harvester-suitable cells if logging can be done with a forwarder or a cable system (see figure 1).

Finally, the output layer of the model has to be connected with the databases to provide – besides the information of harvester suitability – all available data on forest stand and owner. This can be done by using functionality of geometric analyses (for example: merge, intersect, union, spatial join). As a result, for each estimated harvester-suitable thinning area stand data as well as land register data can be shown (figure 2).

Validation—To validate the quality of the results parameters used in the model were measured in some reference stands. The terrestrially mapped stands were digitalised and parameters were put in a database. Stands were selected only when they could be easily identified on orthophotos and if corresponding colour images were of good quality.

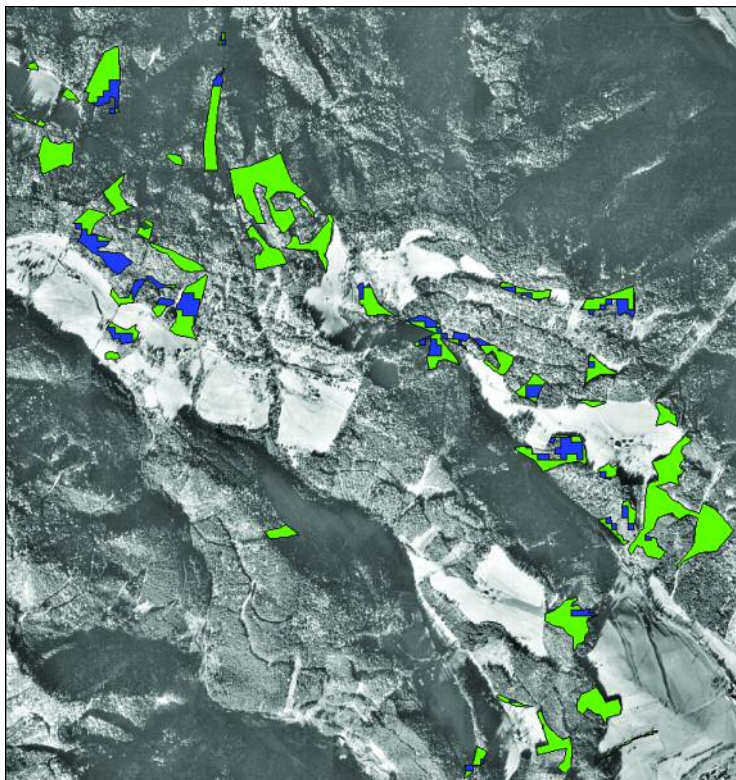


Figure 1—Harvester suitable areas (Grid, section): light gray areas are also forwarder suitable, dark gray areas for cable extraction only.

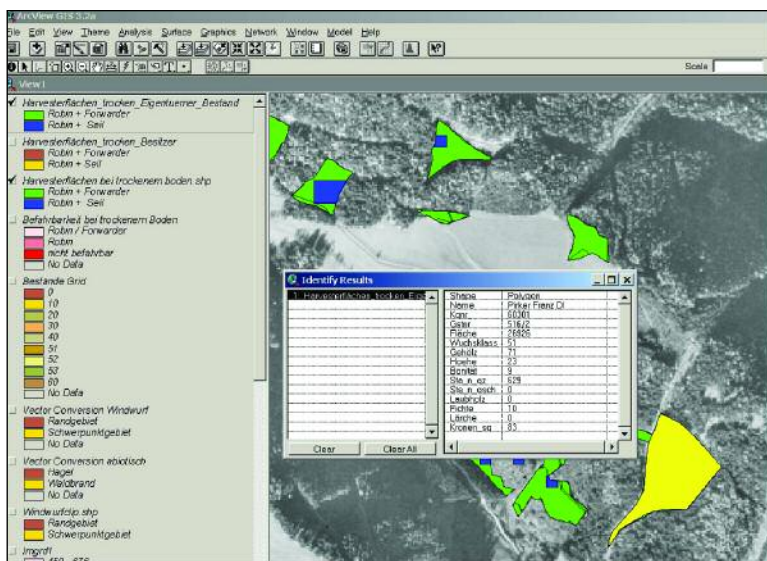


Figure 2—Harvester suitable areas (Shape, section) with stand and owner data shown for the light gray stand area.

That was done in order to minimize errors of inaccuracy in position when comparing terrestrial mapping with stereoscopic interpretation or with model results. A total of 77 stands representing 36 ha could be used to validate model results for an area of 5,000 ha with about 2,500 different stands. Furthermore all areas where the harvester had been

already working could be used for validation (in total 40 ha extra). Due to the high effort to draw forest maps and to measure parameters on site the sample size is restricted to the area indicated.

Validation is split in (i) validation of model-estimated trafficability, (ii) validation of suitability to harvesting head to

estimate accuracy of input data for these parameters and (iii) validation of the model result.

Validation of suitability to harvesting head—In order to reduce the influence of inaccuracy in position the comparison of results of stereoscopic interpretation of stage of development (that were used for estimating average d.b.h. of stand) with on-site measurement of average d.b.h. was restricted to areas larger than 1,000 m².

Stereoscopic interpretation estimated 45 percent of the reference area exactly according to the stage of development as classified on site (figure 3). Further 38 percent were estimated within a range of plus / minus one stage of development. The most errors occurred in the differentiation between pole stage and small-diameter timber tree. But since both of these stages of development fit to the harvesting head this error can be tolerated for the model's purpose. So if we combine pole stage and small diameter tree to one category stereoscopic interpretation estimated 83 percent of the reference area correctly. This leads to the conclusion that the method used is appropriate to get useful stand data cheaply and quickly.

An overestimation for two stages of development occurred for 10 percent of reference area. This happened because of light and open structures of stands that leads to a canopy surface which is normally characteristic for older stands. Stands overestimated by three or four stages of development resulted from inaccuracy in position between stand borders digitised on orthophoto and seen on stereoscopic images.

Validation of harvester trafficability—The model reveals trafficability for 77 percent of the reference area according to terrestrial measurements. In addition, the model points out all areas where the harvester has already been working as harvester trafficable. On the one hand, errors occur because of inaccuracies of the digital terrain model (mostly underestimation of inclination) and on the other hand because some areas are not trafficable even if the inclination is suitable. Observed underestimation of inclination derived from the digital terrain model is in accordance with results of other GIS models using inclination as derived parameter (Wilson and others 2000).

Validation of harvester and forwarder trafficability—Trying to estimate if a forwarder can be used or not fails in 52 percent. The limits of trafficability of a forwarder are easier reached than those of a tracked harvester. Slight

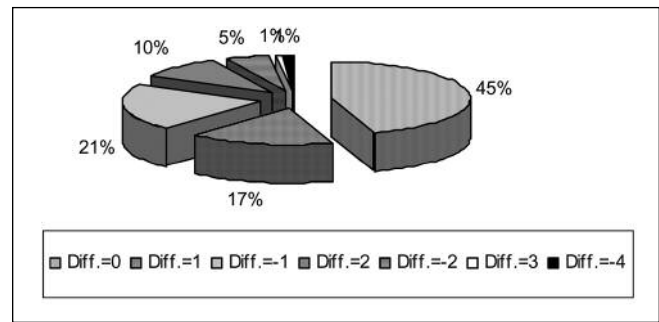


Figure 3—Difference between stereoscopic interpretation and terrestrial measurement of stage of development.

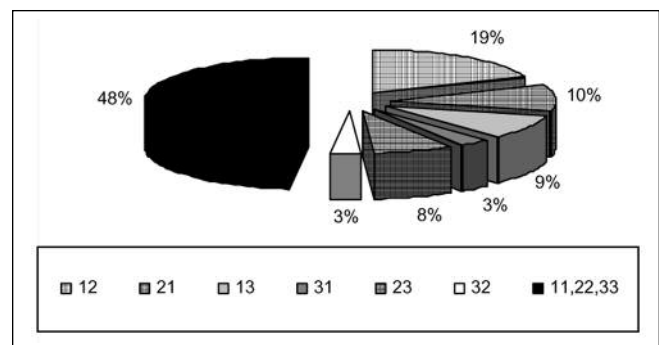


Figure 4—Comparison of harvester and forwarder trafficability estimated by the GIS model with terrestrial judgement.

cross slope and barriers as well as steep acclivities stop a fully loaded forwarder. All parameters mentioned are not included in the actual model and therefore the model is not able to estimate a suitable logging system.

Figure 4 shows the comparison of the forwarder trafficability estimated on one hand by the GIS model (first digit) and on the other hand by terrestrial judgement (second digit). Gridcode 1 means that the area is suitable for harvester and forwarder, Gridcode 2 that it is only harvester suitable and Gridcode 3 that is neither suitable for harvester nor for forwarder. So for example a Gridcode combination of 12 means that the GIS model estimates that area as harvester and forwarder trafficable and the terrestrial judgement says it is only harvester trafficable.

Validation of the GIS model results—The described GIS model estimates harvester suitability correctly for 71 percent of the reference stands. This rate of accuracy identifies the model as suitable for use in practise (at least for the area of investigation). Errors are to equal parts errors in estimating trafficability or suitability for the harvesting head or a combination of both.

CONCLUSIONS

The FOC Leoben can use the model results as a marketing instrument to find owners of large harvester suitable thinning areas. To the owners of these areas the possibilities and advantages of mechanised harvesting systems can be pointed out. For a contracted thinning area some more nearby potential harvester areas can be found and their owners contacted. The model has a further surplus value because it provides digital maps of forest stands of the FOC Leoben for the first time as a basis for various planning tasks.

More accurate basic data (like a better digital terrain model, soil parameters and actual stand data) would be needed to estimate forwarder suitability. But collecting these data would cause significant additional costs. More exact terrain models generated by laser scanning with standard deviation in height inaccuracy of less than 15 cm in comparison to terrestrial measurements (Wever 1999) or plus /minus 25 cm in flat wooden areas (Pfeiffer and others 1999) could help to estimate forwarder suitability.

Even automated identification of stage of development and stands could be done by comparing crown surface model gained from the first pulse mode of laser scanning with last pulse mode information that usually describes terrain surface (Ziegler and others 2000). Another possibility to automate stand identification is to use spectral analyses from Landsat TM EWDI (Enhanced Wetness Difference Imagery) as is done for monitoring forest harvesting and thinning activities (Franklin and others 2001).

In the future, these technologies could be useful to estimate suitability of mechanised harvesting systems in a more automated way.

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MEETING ORDER-BOOK CONSTRAINTS BY ADAPTIVE CONTROL OF BUCKING ON HARVESTERS

Glen Murphy¹, Hamish Marshall² and Barbara Hock²

ABSTRACT

Modern mechanized harvesters are often fitted with sensors that measure stem dimensions and with computers that optimally buck each stem based on stem dimensions, qualities, log prices, and desired specifications. Optimally bucking *individual stems*, based on market prices, is unlikely to provide yields that meet order book constraints at the harvest unit or forest level.

An adaptive control heuristic was developed by embedding an individual stem optimal bucking dynamic programming procedure in a threshold accepting algorithm which adjusts relative prices and minimum small end diameter specifications to meet order book constraints.

The heuristic was tested on four stands where the location and detailed stem description of every tree was known.

The adaptive control heuristic is described, results from a series of tests on its performance are presented, and the use of stem information collected during pre-harvest inventory and by the harvester as it works its way through a harvest unit are compared.

KEYWORDS: Threshold accepting, heuristic, optimal bucking, inventory.

INTRODUCTION

Background

There are a number of approaches to optimally bucking trees. If the market is supply constrained, in other words, the market will take as much volume of each log type as each forest owner can produce at the stated market prices, then the forest owner's objective should be to maximize the value of each and every individual tree. This is known as bucking-to-value. A number of mathematical formulations and computer models using dynamic programming (DP) and shortest path (SPN)/longest path (LPN) network algorithms have been developed to optimize the value of individual stems (for example, Pnevmaticos and Mann 1972,

Briggs 1980, Geerts and Twaddle 1985, Nasberg 1985, Sessions and others 1988).

Unfortunately, from a forest owner's point of view, supply constrained markets are the exception rather than the rule. Markets are more likely to be demand constrained. They are also likely to include agreements between customers and suppliers that relate to specifications but are not reflected in market prices. In addition, the owner is likely to be faced with operational constraints related to the minimum economically viable volume of each log-type that can be produced at a given site in an acceptable timeframe.

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Demand and operational constraints mean that each forest owner is likely to have an order book which contains a list of customers along with the volumes and proportions they require of each log-type at specific points in time. Experience has shown that optimally bucking individual stems based on market prices is unlikely to yield the products with the attributes and quantities that will meet order book constraints at the stand or forest level (Sessions and others 1989). Bucking-to-order therefore requires a different solution procedure than bucking-to-value.

Bucking-to-order formulations usually use a two-level hierarchical approach with the lower level model optimizing the bucking of individual stems and the upper level model meeting constraints through the selection of the best bucking patterns (prices and specifications). Eng and Daellenbach (1985) and Mendoza and Bare (1986) used a DP algorithm at the lower level and a linear programming (LP) formulation at the upper level to solve this problem. Nasberg (1985) and Laroze and Greber (1997) used network algorithms at the lower level and LP algorithms at the upper level. These four sets of authors maximized net value at the upper level and provided one or more bucking patterns that were appropriate to each of hundreds of stem classes per stand (a class contained stems with similar size and quality features).

Sessions and others (1989) noted, however, that there are two problems with the practical implementation of the type of formulation described in the previous paragraph: (1) identifying which stem class each tree belongs to, and (2) determining what bucking pattern should be applied to each tree within the stem class. They proposed a single, weighted-price set which is applicable to all trees within a stand. This approach is also used by Pickens and others (1997) and Kivenen and Uusitalo (2002) in their model formulations.

Sessions and others (1989) used a SPN algorithm at the lower level and a binary search algorithm at the upper level to adjust the relative price of a single preferred log type. Laroze and Greber (1997) used a rule-based algorithm at the lower level to evaluate bucking patterns and a tabu search algorithm at the upper level to adjust log specifications (minimum small-end diameters and acceptable qualities) where multiple log types were constrained. Pickens and others (1997) used a DP algorithm at the lower level and LP algorithm at the upper level to adjust the relative prices of multiple log types. The objective at the upper level for Sessions and others (1989), Laroze and Greber (1997) and Pickens and others (1997) was to maximize net value.

Kivenen and Uusitalo (2002) used a DP algorithm at the lower level and a fuzzy logic algorithm at the upper level to adjust the relative prices of multiple log types. Instead of maximizing net value at the upper level, however, they maximized the apportionment degree – a measure of how closely the actual distribution of log-types meets the target distribution. The apportionment degree concept was originally proposed as a measure of success for optimal bucking patterns by Bergstrand (1989). Kivinen and others (2003) compared it with three other “goodness-of-fit” measures and commented that none of the three alternatives outperformed apportionment degree.

Sources of stem data and within-stand variability

If perfect information on stem location, stem dimensions, and qualities in each stem was available on every tree in a stand it would be theoretically possible, using a two-level hierarchical approach, to determine the set of relative prices and specifications that would exactly meet order book constraints at the stand and block (sub-stand felled by a harvester) level prior to harvesting. Perfect information is rarely available, however.

Some pre-harvest inventory systems provide detailed descriptions of a small sample of stems which can be used as the basis for determining relative prices and specifications prior to the harvester moving into a stand (Deadman and Goulding 1979). How well the order book constraints are met at the stand-level depends on how representative the trees selected for the inventory are.

Duffner (1980) describes an adaptive price control system which was used in a centralized log processing yard in Europe in the 1970's to adjust prices based on whether too many or too few logs of a certain type were produced. Similar approaches are applicable to harvesting and bucking trees within a stand.

Once the harvester begins to harvest the stand, more stem information becomes available. Prices and specifications can then be adjusted based on “better” information. Using time-of-harvest information for better decision-making is already a common feature on modern harvesters. For example, Ponsse harvesters store information on the previous 80 stems harvested and use the “closest” eight trees as the basis for predicting stem taper (M. Laurila, Ponsse Oy, pers. comm. 2003).

Natural variability due to site and genetics, along with variability introduced by man's uneven treatment of a stand, mean that even if order book constraints could be met

Table 1—Characteristics of Test Stands

	EVEN	UNEVEN	FROST	WHAKA
Total Area (ha)	10.0	10.0	10.0	1.9
Density (stems per ha)	375	375	375	249
Mean d.b.h. (cm)	45.0	44.8	45.2	48.5
Total Volume (m ³)	5990	5960	6374	1062
Number of blocks	25	25	25	10

exactly at the stand-level they may not be met at the block level. Controlling the amount of variation may be of just as much importance to the forest owner and customer as the degree to which the order book constraints are met overall. Malinen and others (2001) used relative root mean squared error as a measure of variation to evaluate estimations of sawtimber volume and sawtimber/pulpwood ratio in their study of harvester and pre-harvest inventory generated databases.

Both pre-harvest inventory information and time-of-harvest information could be used for adaptively controlling prices and specifications to better meet order book constraints and minimize variation at the block level.

Study Objective

The objective of our research was to develop and test an adaptive control heuristic that uses stem data collected in the past to predict appropriate prices and log specifications to meet market and operational constraints in the future.

METHODS

Test Stands

Four stands were used to evaluate the adaptive control heuristic. Stand details are provided in Table 1. All stands had been pruned and were of similar mean diameter at breast height (d.b.h.); about 45 cm. The location of every tree in each stand was known. One of the stands (WHAKA) was a real-world *Pinus radiata* plantation stand in the central North Island of New Zealand. The other three stands were virtual stands generated to represent a variety of forest conditions and based on radiata pine tree characteristics.

The lower limbs had been removed (pruned) from all trees to a height of approximately 6 m in the EVEN stand. Selection for pruning was uneven in the UNEVEN stand; 100 percent of trees were pruned in the middle of the stand decreasing to 70 percent at the edges of the stand. This

mimicked situations where pruning contract supervision or funds were inadequate to ensure all final crop trees in the stand were pruned.

The FROST stand mimicked a situation where there was a frost effect in the center of the stand; tree size was small in the center and increased towards the edges of the stand. All trees were pruned in the FROST stand.

Stem Data Sources and Harvesting Pattern

Fifteen circular pre-harvest inventory plots were systematically located in each of the EVEN, UNEVEN, and FROST stands and five square plots were located in the WHAKA stand. The inventory plots occupied 3 percent of total area in each stand.

To evaluate the effects of within stand variability on adaptive control, the EVEN, UNEVEN, and FROST stands were broken up into 25 blocks of equal area and the WHAKA stand was broken up into 10 similar-sized blocks. A serpentine harvesting pattern where the strip width was approximately 20 m wide was used for all four stands.

We evaluated the effects of using two types of stem data for determining the best price and log-specification set to use when harvesting the next block: (1) pre-harvest inventory data and (2) data from the previously harvested block.

Market Requirements for Test Stands

The same market requirements were applied to all four test stands (Table 2). Five log-types (Pruned Domestic Sawlog, Unpruned Export Sawlog, Domestic Sawlog #1, Domestic Sawlog #2, and Pulp) plus waste were included. All log-types included multiple lengths; some in multiples of 0.3 m, others in multiples of 0.1 m. A total of 51 lengths were included in the analyses. Each log-type, and some sub-groups of log-types, had target proportions of volume that were required. For example, the order book target proportion for Pruned Domestic Sawlogs was 15 percent of the total volume harvested.

Table 2—Market requirements and constraints for the four test stands

Log-types	Lengths (m)	Minimum small end diameters (mm)	Relative market prices (\$/m ³)	Target proportions (percent)
Pruned Domestic Sawlog	3.7-6.1	350	100	15
Unpruned Export Sawlog 12.2m	12.2	260	67	25
Unpruned Export Sawlog 8.2m	8.2	260	61	6
Domestic Sawlog #1	3.7-6.1	200	47	12
Domestic Sawlog #2 Longs	4.9-6.1	200	33	8
Domestic Sawlog #2 Shorts	3.7-4.6	350	32	7
Pulp	3.7-6.1	100	17	24
Waste	0.1-6.0	0	0	8

Additional Constraints:

- Minimum average SED for Domestic Sawlog #1 is 250 mm
- 12.2 m Unpruned Export Sawlogs should be at least 75 percent of the combined total volume for all Unpruned Export Sawlogs

In addition to these constraints, we included two others; a minimum average SED for Domestic Sawlog #1 logs of 250 mm and no less than 75 percent of the combined volume of the 8 m and 12 m Unpruned Export Sawlogs could be in 12 m lengths. Penalties to the objective function were applied if these two constraints were not met.

Adaptive Control Heuristic

A two-level hierarchical adaptive control heuristic, which we called FASTBUCK, was developed and implemented in Microsoft Visual Basic™ 6.0. A DP algorithm was used to control optimal bucking of single stems at the lower level based on relative prices and log specifications. The DP was similar to that described by Deadman and Goulding (1979) and its aim was to maximize the total value of each stem. The DP was imbedded in a threshold accepting (TA) algorithm (Dueck and Scheuer 1990) (fig. 1) which aimed to maximize the apportionment degree (AD%) from the total number of stems included in the sample by adjusting SED's or relative prices³. At the end of the search procedure, the set of prices and log specifications that yielded the highest AD% at any time throughout the search was considered to be the solution.

Apportionment degree is defined as:

$$AD \% = 100 * (1 - \sum_{j=1}^n |D_{aj} - D_{rj}| / 2)$$

where:

n = number of log-types

j = log-type number

D_{aj} = Actual decimal portion of total volume that is log-type j

D_{rj} = Required decimal portion of total volume that was wanted as log-type j

Penalties were applied to the AD% objective function if the minimum average SED constraint for Domestic Sawlog #1 or the minimum proportion constraint for Unpruned Export Sawlog 12 m were not met. These penalties were arbitrarily set at 1 percent per mm below the minimum average SED and 0.5 percent per 1 percent below the target proportion of Unpruned Export Sawlog 12 m volume.

³ Some authors only adjust relative price to control product yield (Sessions and others 1989) while others adjust log specifications (Larozé and Greber 1997). We have noted that logging supervisors sometimes tighten log specifications to reduce product yield if too much of a product is being produced. We have chosen to include both price and SED adjustments in our formulation. Some limits were put on SED and relative price changes. SED could not be dropped below the real market limit and price could not be increased above the real market price for Pruned Domestic Sawlogs.

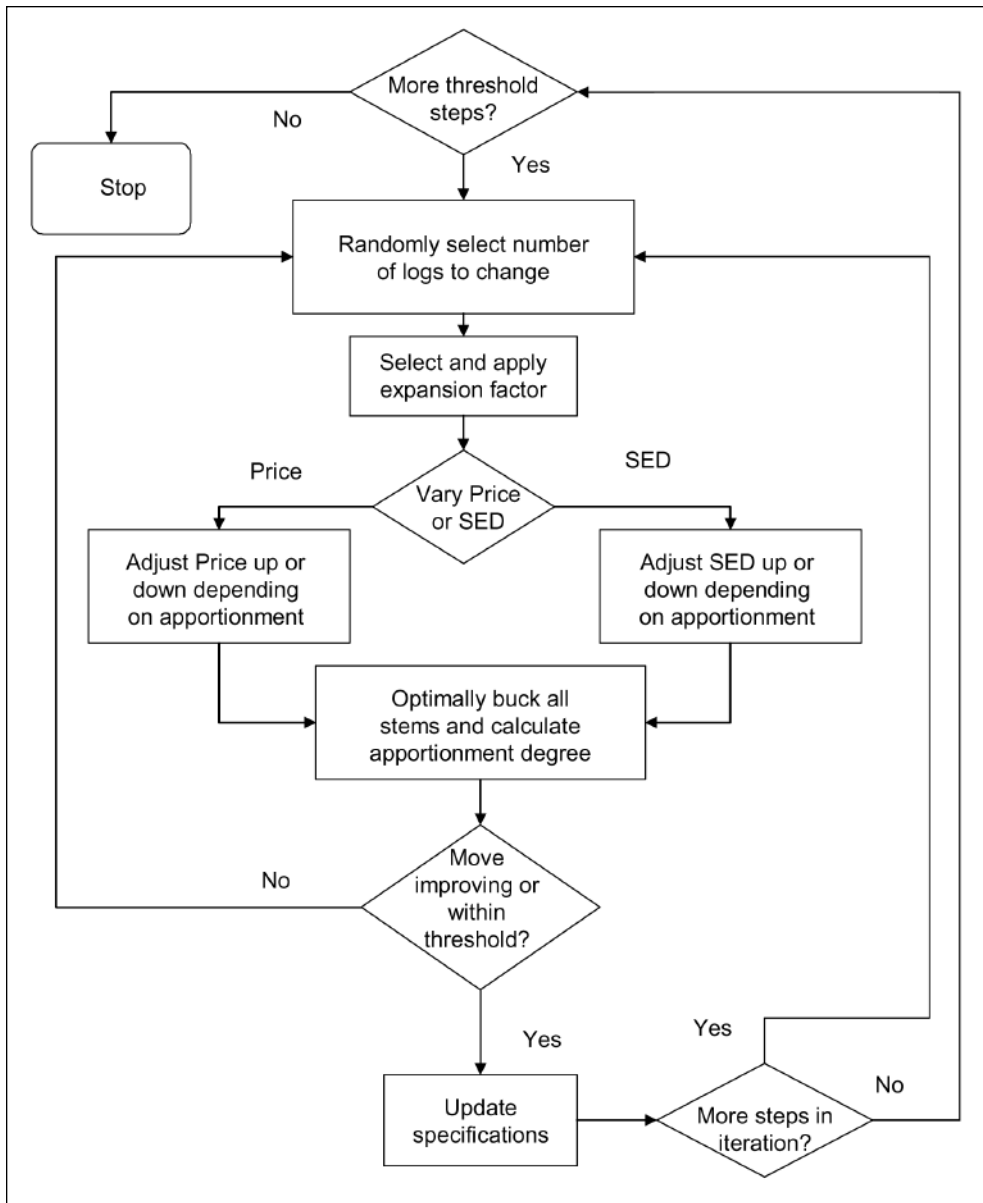


Figure 1—Adaptive control heuristic implemented in FASTBUCK.

Tuning Search Parameters

Fine tuning of search parameters is itself a significant combinatorial problem; possible combinations of such parameters as number of threshold steps, threshold step size, number of iterations per run, number of runs per evaluation, number of logs-types changed per iteration, etc. can be very large. Initial tuning was carried out on a stand with similar characteristics to the EVEN stand. Comments from the literature on the application of threshold accepting and other heuristics were also taken into account in selecting the search parameter values. Based on the tuning of our heuristic, we carried out all further analyses using:

- five threshold steps, decreasing from 0.050 to 0.001,
- variations in both price and SED,
- a maximum of two log-types changed per iteration,
- a maximum expansion factor of two for price or SED increments,
- a single run per evaluation, and
- 1,000 iterations per run (a conservative decision since 500 iterations may have been adequate).

Assessing Within-Stand Variation in AD%

Within-stand variation between blocks was calculated using the following formula:

$$RMSE\% = 100 * \overline{AD\%}^{-1} * \sqrt{\sum_{k=1}^m (AD\%_k - \hat{AD\%}_k)^2 / (m-1)}$$

where:

RMSE% = relative root mean square error for AD% between blocks within a stand

$\overline{AD\%}$ = mean predicted AD% for all blocks within a stand

$AD\%_k$ = actual AD% for block k

$\hat{AD\%}_k$ = predicted AD% for block k

m = number of blocks in the stand

RESULTS

Adaptive Control Heuristic Effectiveness

The adaptive control heuristic was able to provide sets of relative prices and log specifications that could be used on a harvester to better meet order book constraints than would be obtained from using market prices and specifications. An example of the improvement can be seen in Figure 2 for the pre-harvest inventory data set from the WHAKA stand. The difference is also evident in the AD% values for this data-set which were 70.3 percent and 96.2 percent for the market prices and adaptively controlled prices respectively; an improvement of about 26 percent. Similar levels of improvement were found for pre-harvest inventory datasets for the EVEN (~27 percent), UNEVEN (~22 percent) and FROST stands (~21 percent).

The highest AD% found was 99.6 percent in the FROST stand for a single block. It must be noted, however, that the maximum AD% found in a search is partly a function of the heuristic and partly a function of what is available in the set of stems being evaluated. For example, if none of the trees in a stem data set had been pruned, the maximum AD% that could be found for the market conditions included in our study would have been 85 percent.

Solution times depended on the number of stems in a block and the number of iterations each block of trees was optimally bucked per run. Approximately 11 stems per second were optimally bucked using a Pentium IV processor. Optimally bucking a block of 150 stems 1000 times (iterations) would, therefore, take about 3.8 hours per run.

Effect of Sources of Stem Data

Table 3 summarizes the results for the four stands harvested using a serpentine pattern. Since detailed descriptions of every stem in the four test stands are known with perfect knowledge, we can compare the effect of using different sources of stem data in the adaptive control heuristic on predicted total volume, AD%, and RMSE%.

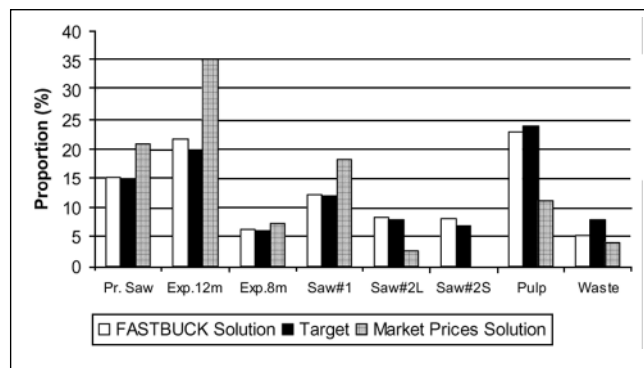


Figure 2—Proportion of total volume by log-type for the WHAKA stand pre-harvest inventory data-set as obtained through using the adaptive control heuristic (FASTBUCK), as required (Target), and as obtained by optimal bucking based solely on market prices (Market Prices Solution).

Total predicted volume, based on the 3 percent inventory, was 5 percent and 19 percent too high for the UNEVEN and WHAKA stands, the same as actual total volume for the FROST stand, and 8 percent too low for the EVEN stand.

When no attempts were made to adaptively control prices and specifications, in other words, market prices and specifications were used to optimally buck all stems in each stand, AD% values ranging from 64 to 71 percent were obtained. These values included penalties for not meeting the 12 m Unpruned Export Sawlog proportion constraint for the EVEN, UNEVEN, and FROST stands. This constraint was met for the WHAKA stand. All stands met the minimum average SED constraint for Domestic Sawlog #1.

When stem data from the pre-harvest inventories were used as the basis for deriving adaptively controlled prices and log specifications, it was predicted that AD% values would improve by about 22 percent; In other words, AD% ranging from 87 to 96 percent depending on the stand. When these inventory-based, adaptively controlled prices and log specifications were then applied to the blocks to be harvested in each of the four stands, all stands had actual AD% values ($AD\%_{Inv}$) that were lower than the predicted AD% values. The EVEN and UNEVEN Stands were about 1 percent lower, the FROST stand was about 5 percent lower, and the WHAKA stand was about 7 percent lower than predicted. The variation between blocks (RMSE%) was relatively low for the EVEN and UNEVEN stands (~3 percent), relatively high for the WHAKA stand (~13 percent), and very high for the FROST stand (~30 percent).

Table 3—Effect of different sources of data on how well the adaptive control heuristic meets order book constraints at the stand and block level based on apportionment degree (AD%) and relative root mean squared error (RMSE% - shown in brackets) performance measures.

Performance Measures	Stand Name			
	EVEN	UNEVEN	FROST	WHAKA
Predicted total volume based on 3 percent pre-harvest inventory (m ³)	5,533	6,291	6,359	1,262
Actual total volume (m ³)	5,990	5,970	6,374	1,063
AD% resulting from optimally bucking all stems using market prices and log specifications	68.8	63.9	69.7	71.0
Predicted AD% based only on the 3 percent Pre-harvest inventory, adaptively controlled prices, and log specifications	87.1	86.8	91.6	96.2
Actual AD% and RMSE% based on bucking all stems using adaptively controlled prices and log specifications derived from the 3 percent pre-harvest inventory (AD%_Inv)	86.5 [2.4]	86.0 [3.4]	87.1 [29.5]	89.4 [13.2]
Actual AD% and RMSE% based on bucking all stems using adaptively controlled prices and log specifications derived from the previous Block's stems data (AD%_Block)	87.7 [4.4]	87.6 [3.7]	90.9 [12.9]	97.0 [9.8]

When stem data from the previously harvested block were used as the basis for deriving adaptively controlled prices and log specifications, actual AD% values (AD%_Block) were better for all four stands than actual AD%_Inv values, and better than predicted AD%_Inv values for all but the FROST stand. The RMSE% was slightly higher for the EVEN and UNEVEN stands, and substantially lower for the FROST and WHAKA stands than was found for the inventory-derived prices and log specifications.

DISCUSSION AND CONCLUSIONS

The adaptive control heuristic described in this paper was able to provide a single list of relative prices and log specifications which could be applied to all stems within a stand, or sub-stand, and which could better meet order book constraints than when market prices and log specifications were used to optimally buck individual stems. The heuristic used AD%, with penalties for not meeting some market constraints, as its performance measure for success. We were able to find solutions with AD% values of over 99.5 percent for some blocks of trees within a stand but this was partly a function of the heuristic and partly a function of what was available in the set of stems being evaluated.

The heuristic starts by using market prices and log specifications to optimally buck the stems and evaluate the AD% for that solution. Alternative start points could be to

randomly allocate relative prices to each log-type or to set all log-types to the same relative price. Siedentopf (1995), however, found no advantage in selecting a random start point for job shop scheduling problems solved with a threshold accepting algorithm. We believe there is some advantage in watching the adaptive control heuristic move from the unconstrained solution, based on market prices and log specifications, towards those which meet order book constraints.

Some heuristics explore a systematic grid around the current solution and select the move which maximizes the objective function. With five log-types and two variables (price and SED) a full exploration of the closest neighbors on the systematic grid would require over one thousand lots of optimal bucking of stems per iteration at the lower level using the DP. Since most of the solution time for the heuristic is taken up by the DP bucking of hundreds of stems per iteration, a full search of the systematic grid is not feasible in practical terms. Bettinger and others (2002) comment that 2-opt moves, where two variables were changed at the same time, were better than 1-opt moves when using tabu search heuristics with harvest scheduling problems. We chose to use multiple changes in a single move per iteration. Our limited tests showed that multiple changes were better than a single change per iteration; in some cases leading to a 7% improvement in AD%.

Achieving 100 percent for the AD% from a stand will not ensure that all market constraints are met, particularly where specific quantities, as opposed to relative quantities, are required. For example, if the total volume in a stand was only 5,000 m³ it would be impossible to meet order book constraints for log-types totaling 6,000 m³ even if the log-types were available in the correct proportions. Despite these problems, there is need for improved adaptive control heuristics that can be used on harvesters to help meet volume as well as proportion requirements.

The evaluation of different sources of stem data showed that *predicted* AD% values, based on pre-harvest inventory information, could be obtained at the stand level provided that relative prices and log specifications were adaptively controlled on a block by block basis. It was found, however, that pre-harvest inventory stem data were not as good as stem data from the previously harvested block if the pre-harvest inventory data were used to fine-tune prices and specifications prior to harvest, and no further changes were made throughout the harvest of the stand. This result is similar to the findings of Kivinen and Uusitalo (2002) who commented that “no gain can be achieved by pre-harvest inventorying of stands and fine-tuning the price lists with this imperfect knowledge”. Stand inventories, of course, have a role to play in tactical and strategic management of forest resources. Using stem data from the previously harvested block to adjust prices and specifications for the current block gave the highest AD% values for all of the test stands.

Waiting for the whole stand to be completed before finally meeting order book constraints is not an option for many wood suppliers. Managing within stand variation is, therefore, of considerable interest. We found that stand conditions have a large effect on the between block variation in AD%, as measured by RMSE%. The FROST and WHAKA stands had substantially larger RMSE% than the EVEN and UNEVEN stands.

Using a sub-sample of the trees harvested in the previous block, or from even earlier harvested blocks, may allow for faster solution times if the selected sub-sample closely reflects the trees in the current block to be harvested. As noted earlier in this paper, Ponsse harvesters use a system where the eight most similar trees to the current tree being harvested are used to predict stem taper. Malinen and others (2001) provide evidence that such a system has application at the forest level – between stands. The challenge at the sub-stand level will be to find parameters which reflect both size and quality attributes of trees so that the trees with

the “most similar” characteristics in the harvester stem database can be easily found.

In a report on five merchandising computers that adaptively control bucking on a tree-by-tree basis, effectively a block size of one tree, Sondell and others (2002) noted that AD% rose quickly to about 85 percent for three computers, more slowly to about 80 percent for one computer, and to a maximum of about 60 percent for the fifth computer. The five computers were tested in a Grade 3 spruce stand in Sweden

FURTHER WORK

While the results from this study have shown that the application of an adaptive control procedure would better meet order book constraints than solely using market prices and log specifications, much work still remains to be done. Further research in the area of adaptive control would seek to:

- evaluate the adaptive control heuristic presented in this paper in a wider range of stands,
- investigate new objective functions other than maximizing AD% and evaluate the effects of different constraint penalty functions (for example, exponential functions to heavily penalize solutions which are far-removed from the constraints),
- determine how many stems from the previously harvested block are required to obtain acceptable AD% values; how small a block can be used,
- determine how short the search-length can be and still yield acceptable AD% values,
- investigate which data sources are important; ones that are spatially related, ones that are temporally related, or ones that are most similar,
- evaluate the effects of different weighting factors on data sources, and
- determine the impact of harvester work methods and measurement accuracy on AD% and RMSE%.

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EFFECTS OF STOCHASTIC STUMPAGE PRICES ON OPTIMAL TIMBER ROTATIONS DETERMINED BY DYNAMIC PROGRAMMING

Matthew H. Pelkki¹

ABSTRACT

A three-state forward-recursive dynamic programming simulation was used to investigate the effects of stochastic stumpage prices on optimal rotation length, thinning strategies, timing, and intensity of intermediate harvests in shortleaf pine plantations in the south-central United States. Historical timber stumpage price data shows that 2-year changes in stumpage prices can range from -49% to +96%. Under stochastic stumpage prices, optimal rotation length and soil expectation values varied greatly. Rotation lengths ranged from 40 to 118 years and soil expectation values ranged from \$173/ac to \$2818/ac. Thinning from above was the strategy chosen in 96% of all observed intermediate harvest, with typical entries occurring late in the second, third, and fourth decades of the plantation, with progressive thinnings removing an increasing percentage of basal area. Perfect knowledge of future stumpage prices was found to increase land expectation value by an average of 48%, indicating the possible returns from good "market timing" of harvests.

INTRODUCTION

Forward recursive dynamic programming is a long-accepted method in stand-level optimization research to solve optimal rotation-length and density problems (Amidon and Akin 1968, Schreuder 1971). During the last thirty years, advances in the application of dynamic programming have included the use of state neighborhoods to permit the use of continuous variables in discrete-state dynamic programming formulations (Brodie and Kao 1979, Pelkki 1997b), the use of individual-tree growth and yield models to permit optimization under various stand-level constraints or multiple objectives (Riitters et al. 1982, Kirillova and Pelkki 2003), heuristics (Arthaud and Pelkki 1996), and region-limiting methods (Paredes and Brodie 1987). These and other studies (Arthaud and Klemperer 1988, Valsta 1990) have found optimal results using deterministic prices in their return or objective functions. Stochastic price functions can be applied to both backward- and forward-recursive dynamic programming formulations.

Stochastic price functions will simulate realistic price changes according to the parameters used in the underlying frequency distribution. These parameters reflect our assumptions about future market conditions, particularly about the rate of future price increases or decreases, and the amount of variation or uncertainty in future prices over short periods of time. Both overall price trends and price stability are important factors when making intermediate or final harvest decisions. This study reports the impacts of stochastic prices on aspects of optimal financial timber rotations (rotation length, timing, intensity, and method of thinnings) for shortleaf pine (*Pinus echinata*, L.) plantations in the south-central United States. The optimal timber rotations are determined through the use of repeated simulations where forward-recursive dynamic programming is used to determine the optimal solution.

METHODS

A forward-recursive dynamic programming method was used in this study. The objective function can be defined mathematically in equation 1:

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$$f_N(Y_N) = \sum_{n=0}^N r_n(T_n) \quad (1)$$

Where the variables and functions can be defined as:

T_n – a management action with resulting physical outputs at stage n

r_n – is the net present value of the action T_n

Y_N – is the ending state for the problem, in this case, the final harvest is a clearfelling operation.

The objective function (1) is subject to several constraints, the first of which links states in a particular stage (Y_n) to states in a subsequent stage (Y_{n+1}) through the growth and yield function (G_{n+1}) and the applied management action (T_n). This relationship is shown in equation 2:

$$Y_n + G_{n+1}(Y_n) - T_n = Y_{n+1} \quad \text{for } n = 0, 1, 2, 3, \dots, N-1 \quad (2)$$

Two additional bookkeeping constraints, equations three and four, define a state in a stage prior to any management activity (X_n) and also define that the final action (T_N) is a clearfelling harvest.

$$X_n - T_n = Y_n \quad (3)$$

$$X_N - T_N = Y_N = 0 \quad (4)$$

Finally, a recursive relationship explains how the policies (management actions) in each stage are linked together sequentially to form an optimal policy or set of management actions over an entire rotation:

$$f_n(Y_n) = \max_{(Y_{n-1}, T_n)} [r(X_n, T_n) + f_{n-1}(Y_{n-1})] \quad (5)$$

Implementing this dynamic programming formulation in a computer simulation requires several elements. First, state and stage variables must be defined. For a forward-recursive formulation, stand age is the most straightforward choice for the stage variable. In this study, the stage (growth) interval was set at two years. Many possibilities exist for choosing state variables. Descriptors for density include basal area, number of trees, total volume, and average diameter. Other state variables could include number of previous thinnings, previous thinning strategy or type, species composition, or average tree quality. Previous research (Pelkki 1997b) has shown that many combinations of state variables can lead to an optimal solution as long as the state neighborhood is small enough that any path entering the state has the same future growth and value potential. In this way, the principle of optimality (Dykstra 1984) is not violated. In this study, number of trees per acre (TPA) and cubic foot volume per acre (ft.³/ac) were chosen as state variables.

The neighborhoods or intervals for these variables were set at + 10 TPA and + 10 ft.³/ac. A third state descriptor, number of previous thinnings (NTh) was added to the formulation. This prevented state with different numbers of thinnings to be compared to each other and also permitted the total number of thinnings in any policy set for a rotation to be restricted to three or less.

The initial stage and state condition was a 10-year old shortleaf pine plantation tree list taken from Smalley and Bailey (1974) for a plantation of 500 trees per acre with a site index of 82 feet at 50 years. While multiple starting conditions could have been considered, the purpose of this research was to study the impacts of stochastic price functions on dynamic programming results, and previous research (Pelkki 1997a) had indicated that this planting density was optimal. Stand establishment costs were \$131 per acre and based on South wide average costs for planting and site preparation (Dubois et al. 2003).

An individual-tree growth model based on the TWIGS growth and yield system (Miner et al. 1987) was used to project stand states forward in time, representing the function $G_{n+1}()$ from equation 2. The model used a parameter set fit for the Southeast United States.

Various thinning regimes were programmed to represent possible management actions (T_n) imposed upon unthinned but projected states (X_n) in any stage. These actions included thinning from below (TfB), thinning from above (TfA), thinning from above and below (TAB), and mechanical row thinning (TM). These four thinning strategies could be applied at levels removing between 10% and 50% of the initial state's (T_{n-1}) basal area, in 10% increments. Finally, management actions of clearcutting (CC) and "do nothing" (DN) were also applied to each initial management state (T_n).

The return function, $r_n()$ was based on a net present value equation applied to the physical outputs from each action T_n applied to initial state X_n . Thus, every completed state Y_n included a residual tree list, a harvested tree list, state parameters, and present value for action T_n , and cumulative present value for any previous thinning actions in the policy leading from the starting state in stage 0 to that particular state. Volume equations from TWIGS (Miner et al. 1987) converted the individual trees to sawtimber and pulpwood volumes, to which stumpage prices were applied and then a present value was calculated as shown in equation 6.

$$r_n(T_n) = \frac{P_n \times V(T_n) - F - PCT}{(1 + i)^{nw}} \quad (6)$$

The variable w represents the width of the stage interval, which in this case was 2 years, and the variable i represents the cost of capital or the hurdle rate, which for all simulations was set at a nominal rate of 8%. The variable F represents a fixed entry cost of \$40 per acre on all harvests, and PCT represents the cost of removing premerchantable stems. Furthermore, the value P_n is reduced by 15% in all thinning operations to reflect the reduced efficiency and higher costs of partial removals.

The values P_n were derived from a stochastic price function. Historic two-year stumpage price changes were determined from timber prices reported by Timber Mart-South (Timber Mart-South 1981-2001) and from the State of Louisiana (LDA&F, 2002). Table 1 shows the minimum, maximum and mean 2-year nominal price changes observed in both data sets for pine sawtimber and pulpwood stumpage prices. Due to the length of time available for the Louisiana dataset, it was selected to model the frequency distribution of prices for this study with a skewed triangular distribution based on minimum, mean, and maximum two-year price changes.

It is worthwhile to note that timber stumpage prices are typically correlated over time (Haight and Holmes 1991, Yin and Newman 1995) and can be modeled with time series analyses. The purpose of this study is not to predict future prices but rather to observe optimal stand rotations under conditions of stochastic prices based on a frequency distribution that is based on historical data patterns.

As mentioned previously, the dynamic programming formulation was constrained to three thinnings. This was necessary as initial, unrestrained simulations selected thinning every time there was a rise in prices. Reducing the number of allowable intermediate harvests to a reasonable number (3) solved this problem.

With the dynamic programming model in place, thirty stochastic runs were completed. Analysis of each run included the economic returns under a particular price projection, the rotation length, thinning strategies, intensities, and timing of thinnings used.

RESULTS AND DISCUSSION

General results for the 30 dynamic programming simulations are provided in table 2. An average rotation age of

Table 1—Two-year nominal changes in southern pine stumpage prices.

Source: Timber Mart-South (1981 to 2001)			
Product	Minimum	Maximum	Mean
Pine sawtimber	-32%	+96%	9%
Pine pulpwood	-51%	+73%	5%

Source: Louisiana Quarterly Report of Timber Products (1955 to 2001) ¹			
Product	Minimum	Maximum	Mean
Pine sawtimber	-43%	+84%	14%
Pine pulpwood	-49%	+51%	9%

¹ Frequency distribution for this study based on parameters from LA dataset.

Table 2—Summary of observations on soil expectation value and rotation age from a shortleaf pine plantation under repeated simulations using a stochastic price function.

	Soil Expectation Value (\$/ac)	Rotation Age
Mean	\$ 966.5	71
Min	\$ 173.3	40
Max	\$ 2818.5	118
SE	\$ 113.6	3
N = 30		

71 years resulted in a soil expectation value (SEV) of \$966.50 per acre. Table 3 shows the yields for a “typical” 70-year rotation with the three thinnings from above that were most frequently observed in the 30 simulations. Typical rotation lengths for shortleaf pine in the central United States range from 40 to 60 years under conditions of price uncertainty or under the assumption of constant prices. The rotation lengths and economic returns may appear high for shortleaf pine, but the reader should remember that the stochastic price model had an average undiscounted 2-year price nominal increase of 14% for sawtimber and 9% for pulpwood stumpage. The two-year discount rate was 16.64% (nominal annual rate of 8%), which accounts for the relatively high values. Table 4 provides some statistics relative to the prices generated in the simulations. Based on the triangular distribution parameters presented in table 1 from Louisiana, we can see that over a one hundred year time frame that sawtimber stumpages prices increase to an average of \$116 per board foot. While this seems incredible, it is in fact an average increase of 6.4% per year or 13.3% every two years, which is less than the average historical

Table 3—Simulated per acre yields from the most frequently observed thinning schedule and rotation length.

Stage	Stand Age	Harvest activity	Sawtimber yield (bf/ac)	Pulpwood yield (ft. ³ /ac)
0	10	Start	—	—
9	28	Thin from above 20% of basal area	2,370	—
13	36	Thin from above, 50% of basal area	5,009	215
19	48	Thin from above, 50% of basal area	4,481	—
30	70	Final harvest	6,362	34
Total per acre production over rotation			18,222	249

Table 4—Simulation-based pulpwood and sawtimber price statistics for selected stages.

Stage	Rotation Age	Pulpwood price \$/CCF				Sawtimber price \$/MBF			
		Mean	Min	Max	St. Dev.	Mean	Min	Max	St. Dev.
0	10	\$24	\$24	\$24	\$0	\$227	\$227	\$227	\$0
5	20	\$28	\$10	\$47	\$9	\$404	\$198	\$868	\$175
10	30	\$32	\$8	\$60	\$14	\$680	\$213	\$1380	\$321
15	40	\$36	\$5	\$81	\$19	\$1074	\$242	\$2469	\$554
20	50	\$44	\$4	\$172	\$31	\$1687	\$263	\$3062	\$857
25	60	\$55	\$6	\$359	\$62	\$2525	\$238	\$7496	\$1720
30	70	\$72	\$5	\$434	\$90	\$5601	\$374	\$22361	\$5656
35	80	\$89	\$5	\$594	\$121	\$11175	\$679	\$56807	\$14162
40	90	\$107	\$13	\$687	\$153	\$24421	\$2119	\$66429	\$21461
45	100	\$96	\$23	\$403	\$112	\$71514	\$2883	\$459913	\$111,549
50	110	\$75	\$25	\$216	\$67	\$116133	\$23760	\$260646	\$73662

price increases in Louisiana from 1955 to 2001. Rotation lengths and values for bare land would undoubtedly be lower under less optimistic future price assumptions.

Furthermore, the forward-recursive nature of dynamic programming allowed the simulation to have “perfect information” regarding price changes. Since a “do-nothing” alternative was simulated from all states, the solution network preserved states that had not been harvested at every stage, permitting the optimal policy to choose the timing of all harvests with perfect knowledge of prices throughout a rotation. While this is an unrealistic assumption, a more realistic calculation of economic returns will be discussed below, as well as an estimate of the value of “perfect market information.”

Of the four thinning strategies permitted, thinning from above (TfA) was observed in 96% of the cases (n = 86/90). Table 5 shows frequency and median stand age and intensity for all four thinning strategies. All simulations used three

thinnings, with intensities generally increasing in later thinning operations. Thinning from above and below (TAB) was infrequently observed (n = 4/90), and with so few observations, generalizations cannot be made. Mechanical or row thinning and thinning from below were never observed in the 30 simulations.

Because the dynamic programming formulation had perfect knowledge of the future, it is understandable that 65% (n=58) of the thinning actions came at the end of a run of stumpage price increases. However, a considerable number of thinnings were observed either in the middle (30%, n = 27) or during a decline (6%, n = 5) in stumpage prices. These operations were all first or second thinnings, indicating that the timing of final thinnings and harvests to high market prices is more important and that mid-rotation thinnings play an important role in maintaining growth rates.

In order to calculate a more realistic SEV for the results of this study, the median observed times for thinning and

Table 5—Observed thinning strategy, timing, and intensity for a shortleaf pine plantation under repeated simulations using stochastic prices.

Thinning Strategy	Frequency of use	First thinning	Second thinning	Third thinning	Median age median intensity	Median age median intensity	Median age median intensity
Thinning from above	96%	28	20%	36	50%	48	50%
Thinning from above and below	4%	26	20%	30	30%	—	—
Mechanical thinning	0%	—	—	—	—	—	—
Thinning from below	0%	—	—	—	—	—	—

final harvest, as reported in table 4, were resimulated under the recorded prices for each of the 30 simulations. By adhering to a fixed schedule of thinnings and a pre-determined rotation age, the SEV was reduced 10% to 65%, with an average SEV of \$641 per acre, a 34% reduction from a situation of “perfect knowledge.” Looking at this from the basis of imperfect knowledge, soil expectation values could increase from 12% to 287% with perfect knowledge of future prices, with an average increase of 48%.

The practical application of these results depends on your assumptions of the behavior of stumpage markets into the future. In 1955, sawtimber stumpage sold for \$31/MBF in Louisiana, and in 1997, the selling price was \$412/MBF. Had landowners known this would occur (perfect knowledge), then selling 35-year old pine stands in 1990, when stumpage prices were \$184 per MBF would have been irrational. Perhaps the most critical decision for forest landowners is their “belief” in the direction of future stumpage prices. If future softwood stumpage prices are as much as \$5.60 per board foot in the year 2064 (as suggested by table 3), rotation lengths of 70 years will be economically optimal. Larger questions dealing with future supply and demand interactions, building material substitutions, and consumer tastes and preferences will certainly effect the rise in future stumpage prices. The U.S. Forest Service estimates that timber stumpage markets will be much weaker through the year 2050, with prices increasing but at a much slower rate than from the period 1952-2000 (Haynes, 2003). If this is indeed the situation, then optimal rotation lengths will shorten and thinning will probably be from below or mechanical to hasten the production of sawtimber. For forest managers and landowners, thinning from above can prolong rotation lengths and preserve future harvesting options under situations where the landowner expects higher future prices.

Future research will address some of the limitations of this work. The number of observations using this type of empirical approach is rather small. Increasing the number of sample runs to 100 or 200 runs will allow for a more thorough analysis of conditions under which thinning strategies other than thinning from above are employed. Altering the parameters of the triangular stochastic price function, and examining sensitivity to site quality and cost of capital should also yield useful results. Also, testing sensitivity to constraints on the number of intermediate harvests and thinning strategies permitted under stochastic prices might elucidate more information about system behavior and optimal harvesting patterns.

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DETERMINING THINNING REGIMES TO REACH STAND DENSITY TARGETS FOR ANY-AGED STAND MANAGEMENT IN THE BLUE MOUNTAINS OF EASTERN OREGON

David Graetz¹ and Pete Bettinger²

ABSTRACT

A stand-level optimization procedure, using the RLS-PATH algorithm, was developed to allow the development of management prescriptions that address ecological or biological goals for eastern Oregon forests. The procedure requires that stand-level goals be defined by basic tree-level data (e.g., basal area, trees per acre, species, etc.). It then seeks to minimize the deviations of stand conditions relative to these goals over a 100-year time frame. A distance-independent, single-tree growth model is embedded within a user-friendly program called SLOMO that also executes and solves the stand-level optimization problem. A variety of constraints can be turned on and off and thus can be used to determine surrogate shadow prices in meeting those constraints. An example stand from the Upper Grande Ronde Watershed will be used to demonstrate the capabilities of SLOMO.

INTRODUCTION

Stand-level management planning assumes that each stand, in isolation of other stands in a forest, is to be managed in the best manner possible. Decisions regarding the management of forested stands have traditionally been based on expert knowledge and field experience with a number of different treatment regimes (Palahí and Pukkala 2003). The optimum combination of the number of entries, the timing of entries, and the type of treatments applied to a stand is difficult to determine through these non-computerized processes, since generally only a small portion of the potential combinations of treatments have been evaluated. Operations research techniques applied to the stand-level management started appearing in the literature in the 1960s (Chappelle and Nelson 1964; Hool 1966; Amidon and Akin 1968). Since that time a plethora of research has been done to solve problems for even-aged, uneven-aged, and any-aged stand management using a variety of optimization methods.

Stand-level optimization methods have evolved with the changing demands placed on forests. Initially the goals were to maximize economic or commodity production values, yet more recently have placed emphasis on non-commodity values. The approaches that can be used to develop optimal stand-level management prescriptions include the Hooke and Jeeves (1961) method (Roise 1986a, 1986b; Haight and Monserud 1990a, 1990b; Yoshimoto and others 1990; Valsta 1990; Haight and others 1992; Thorsen and Helles 1998), other non-linear programming methods (Adams and Ek 1974; Kao and Brodie 1980; Roise 1986a; Haight and others 1992; Bare and Opalach 1987; Gove and Fairweather 1992), dynamic programming (Hool 1966; Amidon and Akin 1968; Brodie and others 1978; Brodie and Kao 1979; Kao and Brodie 1979; Chen and others 1980a, 1980b; Haight and others 1985a; Arthaud and Klemperer 1988; Yoshimoto and others 1990; Brukas and Brodie 1999), and other heuristics or amalgamations of various methods (Buongiorno and Michie 1980; Bullard and others 1985; Valsta 1990; Gong 1992; Wikstrom and Eriksson 2000; Wikstrom 2001).

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Most stand-level optimization methodology reported in the literature focuses on meeting forest economic or commodity production goals and not so much on biological or ecological goals. There are, however, some exceptions. Haight and others (1985a) tracked biological indicators in the development of stand prescriptions, although they were not influential in developing the management prescriptions. It wasn't until the early 1990s when literature appears showing stand-level optimization problems that incorporate non-economic or non-commodity production goals and constraints. Haight and others (1992), for example, incorporated stand density targets into the development of optimal prescriptions, using penalty functions to ensure the attainment of goals. Buongiorno and others (1994) measured the cost of maintaining tree size diversity by solving the stand-level problem with a measure of diversity in and out of the objective function as well as in and out of the constraints. The Applegate Project tackled the any-aged stand management problem by developing a stand-alone prescription generator that solved for multiple biological and ecological goals in the objective function (Wedin 1999). More recently, Wikstrom and Eriksson (2000) incorporated biological measures of green tree retention, broad-leaved tree importance, coarse woody debris, and tree-size diversity into the objective function of an even-aged stand management problem.

Dynamic programming (DP) approaches have the ability to avoid local optima in the final solution to a stand-level problem (Yoshimoto and others 1990). As well, DP has characteristics and capabilities that provide a useful solution framework for the timing and intensity of typical silvicultural actions such as thinning, fertilization, pest control and rotation age decisions (Hann and Brodie 1980; Paredes and Brodie 1987). However, when DP is employed, the number of computations required, as well as the storage space required, increases exponentially with the number of state variables assumed (Hann and Brodie 1980; Martin and Ek 1981; Haight and others 1985; Yoshimoto and others 1990). One disadvantage of DP is the absence of shadow prices that incorporate explicit conditions of first-order optimality, data that might be provided by other optimization processes (Kao and Brodie 1980). Brodie and others (1978) indicate that the forward procedure associated with DP is more amenable to developing prescriptions that include thinning than the backward procedure.

While DP has been applied in conjunction with a number of growth and yield models, the thinning approaches have usually consisted of thinning from above, from below, or even with the distribution of diameters. A relaxation of these controls in stand-level optimization has been achieved

with non-linear programming. Non-linear programming approaches attempt to solve problems with non-concave production surfaces and have trouble locating the optimal solutions to problems (Yoshimoto and others 1990). The PATH (Projection Alternative TecHnique) algorithm (Paredes and Brodie 1987) was developed to solve for the optimal solution at every stage in a DP program, reducing the computation and storage space requirements because the problem is reduced to a one-state, one-stage DP problem. Yoshimoto and others (1988) introduced the look-ahead process to establish that the optimum solution has been located at each stage. Then Yoshimoto and others (1990) introduced a region-limited strategy combined with the PATH algorithm (RLS-PATH) that has two parts. In part one, a restricted domain of the state space is established. In part two, DP (via the PATH algorithm) is applied to the restricted domain. Once the optimal solution has been located, a new, tighter restricted domain of the state space is established. The process continues until convergence on a local optima has been established (Yoshimoto and others 1990).

The difficulty with attempting to optimize management prescriptions that include multiple thinnings is that the level and timing of each thinning affect the potential intensity and timing of subsequent thinnings (Amidon and Akin 1968). In problems with three or more thinnings, the RLS-PATH algorithm has been shown to perform better than the Hooke and Jeeves method, and with less computation time (Yoshimoto and others 1990).

This paper will look at the use of the RLS-PATH algorithm within an automated prescription generator that uses a single-tree, distant-independent growth model to project stand growth. The term "prescription" is used in this paper to refer to the overall schedule and level of activities that will occur in a stand over some planning horizon. Inherent to the term prescription is the fact that individual tree data is explicitly tracked over time and thus a prescription also implies knowledge about what a stand looks like over the planning horizon (some people use the term "regime" to describe a set of individual silvicultural "prescriptions" to occur in a stand over time – in this case the terms regime and our use of prescription are the same).

The example prescription we model is aimed at generating "general" guidelines for reducing stand density index values for stands in the Blue Mountains of eastern Oregon. The ideal of a "general guideline" is meant to address the following question – if a stand has certain characteristics (which may be shared by other stands in some landscape) and the desire is to reduce the stand density to levels that

are within some specified range, what are the general thinning (or not thin) timings and levels that could be applied to any such stand in that landscape? One solution to this question is to simply solve the problem for each individual stand. An approach we chose to take is to solve the problem for some subset of stands that have characteristics in common, and then evaluate whether timing of entry and level of activity occur with some regularity in the individual solutions. If so, that may be suggestive that certain prescriptions are highly correlated with certain stand characteristics, and thus can be considered a general prescription for similar stands sharing those characteristics (as long as the desired goal for the stands are the same). There is an analogy in this method to that of “expert opinion.” Silviculturists often determine what to do to achieve certain stand characteristics based on their own experience with similar stands. In essence, this latter method could be considered an “expert opinion” method as well. A rigorous statistical analysis of this approach would be prudent for future work in this area.

PROBLEM FORMULATION

The example problem addressed in this paper is best described as an any-aged stand management problem. Haight (1987) and Haight and Monserud (1990a) describe the any-age stand management problem as determining the best time sequence of harvest and planting levels without constraints on the stand age or size structure. Without constraints on the stand age or size structure the optimal management solution may yield stands that have irregular structures or the solution may yield stands with conventional even- or uneven-aged structure – thus the term any-aged is used. This paper will not be determining the optimal planting levels as regeneration is a stochastic element within our growth and yield model.

For an individual-tree growth model, a stand is represented by a tree list which contains a record for each tree found in the stand. These records usually include an expansion factor indicating how many trees per unit area are actually present. Additionally, a suite of attributes could be associated with each tree record, including: species, diameter at breast height (dbh), height, and crown ratio.

The problem formulation is couched in terms of harvesting decisions and growth predictions that occur at discrete time intervals (every 10 years). The problem is to determine, for each stand, the number of trees to cut in each period over the planning horizon, while minimizing the penalty scalar function associated with the stand's ability to maintain an acceptable stand density index measurement.

This paper is forgoing the traditional use of an economic criterion as the objective function. Future work by the authors will analyze the cost and benefits of any-aged stand management by including economic criteria.

The state and control vectors and variables are as follows:

- $\mathbf{s}(t)$ = stand state in period t (vector) [defined by dominate species and basal area]
- $s_i(t)$ = the attributes of tree record i at the beginning of period t (element)
- $\mathbf{x}(t)$ = cutting levels in period t (vector)
- $x_i(t)$ = percentage of record i cut in period t (element)
- $\mathbf{h}(t)$ = the harvest controls in period t (vector)
- $h_j(t)$ = percentage of trees cut in diameter group j and $h_j(t) = [0,1]$ (element)
- C_j = a unique diameter class group
- J = total number of diameter class groups = 4 (scalar)
- P = number of look-ahead periods = 5 (scalar)
- T = total number of simulation periods = 10 (scalar)
- N = total number of tree records in stand

A mapping occurs within the program such that $\mathbf{h} \rightarrow \mathbf{x}$ by the equation:

$$x_i(t) = h_j(t) \quad \forall i \in C_j, \quad \forall J \quad [1]$$

The stand density index penalty is defined by comparing the stand's calculated stand density index (SDI – using Reineke's summation method) value for the evaluation period and the next P periods against the calculated minimum and maximum SDI value for those periods.

- $d[\mathbf{s}(t)]$ = a stand's SDI value with state $\mathbf{s}(t)$ at the end of period t
- $b_u[\mathbf{s}(t)]$ = upper SDI bound for a stand with state $\mathbf{s}(t)$
- $b_l[\mathbf{s}(t)]$ = lower SDI bound for a stand with state $\mathbf{s}(t)$

Therefore, the penalty scalar function ($c[\mathbf{s}(t), \mathbf{h}(t)]$) can be defined as:

$$c = \begin{cases} \sum_t^{t+P} (d[\mathbf{s}(t)] - b_{u,l}[\mathbf{s}(t)])^2 & \text{if } d[\mathbf{s}(t)] > b_u[\mathbf{s}(t)] \\ & \text{or } d[\mathbf{s}(t)] < b_l[\mathbf{s}(t)] \\ 0 & \text{if } b_l[\mathbf{s}(t)] \leq d[\mathbf{s}(t)] \leq b_u[\mathbf{s}(t)] \end{cases} \quad [2]$$

Equation [2] is then used in the objective function as:

$$\text{Min } Z = \sum_{t=0}^T c[\mathbf{s}(t), \mathbf{h}(t)] \quad [3]$$

When equation [3] is solved, the thinning levels $h_j(t)$ will be known for each j and t .

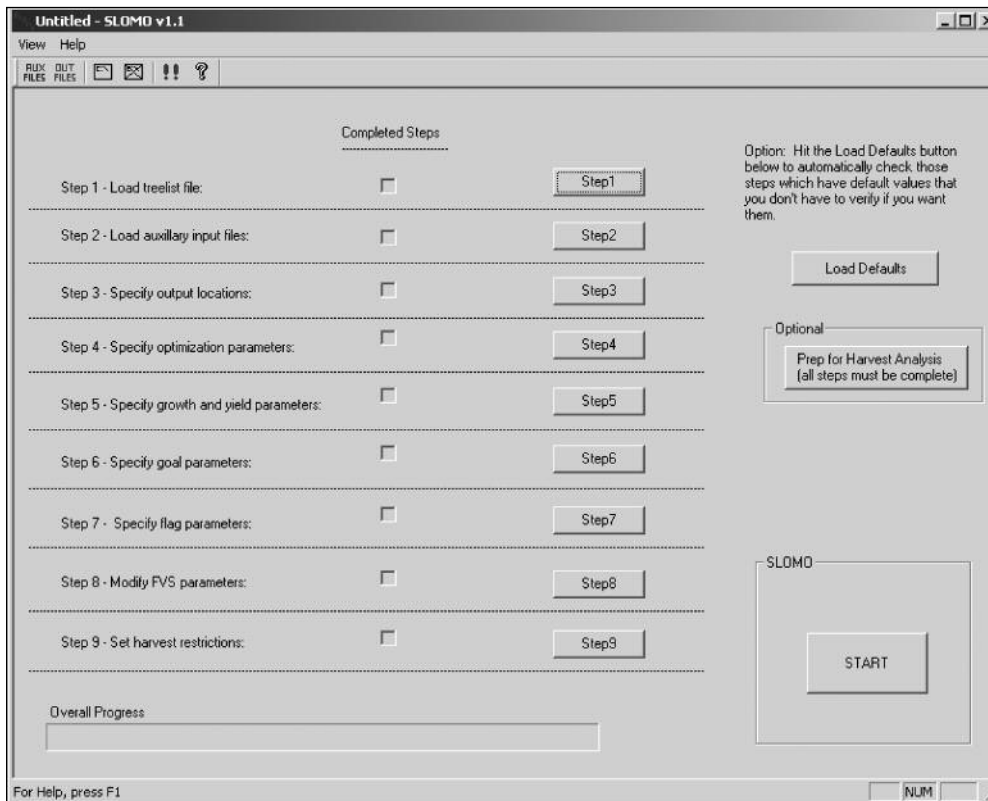


Figure 1—Main GUI interface for the SLOMO program.

SOLUTION METHOD

The optimization problem of equation [3] is solved using an RLS-PATH process described by Yoshimoto and others (1990). This algorithm allows us to partition the optimization problem into partial optimization problems, one for each stage. It should be noted that the RLS-PATH was developed out of the need to reduce computational and storage space from that required for a traditional dynamic programming formulation. As such, RLS-PATH works within a restricted subspace of traditional DP and provides “good” but not necessarily optimal solutions, but with much less computational and storage size requirements. A more thorough examination of the PATH and RLS-PATH algorithm’s is given in Yoshimoto and others (1990).

A program called Stand Level Optimization with Multiple Objectives (SLOMO) was written in the C and C++ languages to solve stand optimization problems of the type given in this study. SLOMO is designed with a graphical user interface (GUI) that allows a user to enter multiple stands and solve for multiple objectives. The user is required to go through a simple 9-step process to set up and specify all the necessary parameters, inputs, and outputs (figure 1). Inside of SLOMO the growth and yield functions from the Blue Mountain variant of the Forest Vegetation Simulator

(FVS) were incorporated (Dixon 2003). The original FVS Fortran computer code was literally translated into C and C++ code. This allowed for faster computational times as it removes the overhead associated with running FVS in its stand-alone format.

The harvest control vector, $\mathbf{h}(t)$, represents the fraction of trees harvested by diameter class for a specified period. Four meaningful diameter class breaks were defined for this study (0-4, 4-12, 12-21, 21+ in.). Meaningful in the sense that these four classes strike a balance between having a useful management utility (for either wildlife, ecological, or economic uses) and the desire to have breaks that allow enough silvicultural flexibility to manage the stand. The potential $h_j(t)$ ’s are a function of which diameter class is being evaluated. For the bottom three diameter classes (0-21 in.) the elements are 0, 20, 40, 60, 80, and 98. These values can be interpreted as follows: if $h_j(t) = 20$ for a particular iteration during the optimization process, then 20% of the trees per unit area from each record in class j will be harvested. This could be considered a proportional method of harvesting because the value of the element is applied proportionally to each record in the class. The top diameter class (21+ in.) has a slightly different setup. The elements for this class are 0, 25, 50, 75, and 98. These values can be

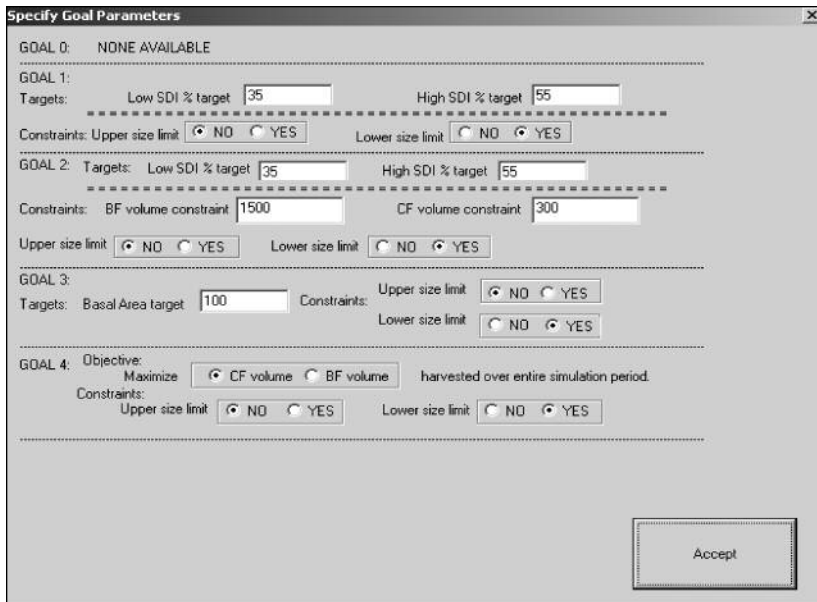


Figure 2—Step 6 of SLOMO – Specify Goal Parameters.

interpreted as follows: if $h_i(t) = 25$, then 25% of the total trees per unit area in that diameter class are harvested, either starting from the top or bottom record within that class (i.e. that record with the largest or smallest diameter). This could be considered an un-proportional method of harvesting because the element is applied un-proportionally to each record in the class.

A second purpose of this paper is to illustrate the flexibility of SLOMO in evaluating optimal prescriptions with various constraints. We have already outlined the basic formulation for a problem that attempts to minimize the penalty scalar function associated with a goal of reducing a stands SDI value over time. The earlier formulation was for an unconstrained problem. SLOMO has some built-in constraints that can be toggled on or off for particular stand goals. Figure 2 shows Step 6 of the SLOMO process, whereby the user has the ability to determine the constraints, the levels of those constraints, to a pre-defined set of stand goals. In figure 2, the section titled “Goal 1” is the area applicable for this study. In this section there are two constraints that can be used – an upper and a lower size limit. In this study, the lower size limit was 7 inches (i.e. harvesting was not allowed for any tree less than 7 inches). The upper size limit was 21 inches (i.e. no harvesting of any tree greater than 21 inches) for one example in this study, and was unlimited for a second example. These constraints, when applied, now need to be included and linked in our model formulation with the following scalar function $L[s(t), \mathbf{x}(t)]$:

$$\text{Min } Z = \sum_{t=0}^T c[s(t), \mathbf{h}(t)] \quad [3]$$

subject to

$$L = \begin{cases} x_i(t) = 0 & \text{if dbh of } s_j(t) < 7 \\ x_i(t) = 0 & \text{if dbh of } s_j(t) > 21 \end{cases} \quad [4]$$

The SDI calculations are embedded functions with the FVS system and were simply transferred into the SLOMO code. The current SDI for a stand is calculated by the summation method suggested by Long and Daniel (1990) and formally proved to be applicable to irregular structured stands by Shaw (2000).

$$\sum [TPA_i \left(\frac{dbh_i}{10}\right)^{1.605}] \quad \text{for } i = 1, \dots, N \quad [5]$$

A maximum SDI is then calculated for each stand based on a pre-calculated theoretical maximum SDI (a required input into the SLOMO model) that is then proportionately weighted by the basal area of the species actually present. The study in this paper used an upper and lower bound of 55 and 35% of the calculated weighted maximum SDI as the $b_{ul}[s(t)]$ and $b_l[s(t)]$ values as seen in equation [2]. These values were picked because there is evidence to suggest that they have significant silvicultural implications. Note from figure 2 that SLOMO allows the user the ability to change these values for any run requesting the application of Goal 1.

Table 1—Initial stand conditions.

TPA ^a	BA ^b	SDI ^c	CCF ^d	QMD ^e	CF/ACRE ^f
1009	139	233	150	5.0	4261

^a Trees per acre^b Basal area in ft² per acre^c Stand density index^d Crown competition factor^e Quadratic mean diameter^f Cubic feet per acre**Table 2—Species breakdown of some initial stand attributes.**

Stand Attribute	WL	DF	GF	LP	PP
BA	6	107	24	0	0
QMD	14.8	13.9	29.3	0.1	0.1
TPA	5	103	5	797	100

STUDY DESIGN

Stand 21323623 (hereafter just called the “stand”) is located in the La Grande Ranger district of the Wallowa-Whitman National Forest and was selected as the example stand for this study. More specifically, the stand is located in the Upper Grande Ronde Watershed and has an aspect of 10°, a slope of 54% and elevation of approximately 4,600 feet. Tables 1 and 2 show a detailed breakdown of the stand components. The species present include western larch (*Larix occidentalis* Nutt.), Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco], grand fir [*Abies grandis* (Dougl. ex D. Don) Lindl.], lodgepole pine (*Pinus contorta* Dougl. ex Loud.), and ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) (hereafter referred to as WL, DF, GF, LP, and PP, respectively).

Recall that the main objective of this paper is to demonstrate a process by which general prescription guidelines could be created for reducing and maintaining SDI values in stands that have similar characteristics. Additionally, we wish to demonstrate the ease of using SLOMO for analysis of this sort in which constraints can be turned on and off to provide the user a surrogate measure of marginal cost for applying those constraints (or different levels of constraints). As can be seen in tables 1 and 2, the example stand is initially dominated by DF and falls in our basal area category of 100 to 150 ft² ac⁻¹. Thus we identify this stand as having the characteristic DF-100. Rephrasing our main objective

with this characteristic in mind we are asking, “For stands in the Blue Mountains of eastern Oregon that are dominated by DF and have a basal area of 100 to 150 ft² – what are general prescriptions guidelines that we could follow that would reduce and maintain SDI values to levels we find acceptable?” Furthermore, we are also asking, “What are the tradeoffs of allowing harvest to occur in trees over 21 inches versus not allowing harvest of those trees, when searching for an answer to the previous question?”

Ideally we would have a number of stands with the characteristic DF-100 to run through SLOMO, and we would analyze the results to obtain general prescription guidelines. However, time constraints prevented us from accomplishing that for this particular study. In replacement, we ran one stand through SLOMO ten independent times. Although the initial conditions are exactly the same we suspect that the stochastic elements of the embedded growth and yield model create enough “displacement” of stand conditions as soon as the first growth period is encountered. In other words, even if the stand was run through the growth and yield model with no thinning or optimization occurring (a grow-only simulation), the stochastic elements of the growth and yield model will create different stands even after a single growth period. This displacement is accentuated by our optimization process because even slight differences in stand characteristics may cause slight differences in the solution $h_j(t)$'s that are found for independent runs.

Table 3—Data for one independent run with no upper size limit constraint.

Year	TPA	BA	SDI	CCF	QMD	CF/ACRE
2000	1010	139	233	150	5.0	4261
2010	1437	139	240	153	4.2	4437
2020	1367	158	258	172	4.6	5352
2030	1312	177	276	191	5.0	6152
2040	1264	195	293	208	5.3	6988
2050	1201	208	304	220	5.6	7716
2060	1099	214	304	223	6.0	7917
2070	1009	218	302	225	6.3	8219
2080	929	223	303	229	6.6	8544
2090	858	226	302	230	7.0	8637
2100	801	230	301	232	7.3	8857

Table 4—Data for one independent run with a 21-inch upper size limit.

Year	TPA	BA	SDI	CCF	QMD	CF/ACRE
2000	1010	139	233	150	5.0	4261
2010	928	118	189	119	4.8	3962
2020	882	134	204	158	5.3	4596
2030	829	132	201	156	5.4	4573
2040	798	146	220	168	5.8	5155
2050	762	145	217	165	5.9	5251
2060	717	152	224	169	6.2	5453
2070	666	156	227	169	6.6	5477
2080	619	158	227	169	6.9	5522
2090	578	160	228	169	7.1	5563
2100	544	163	229	170	7.4	5693

RESULTS AND DISCUSSION

Stand prescriptions were first optimized with SLOMO using no upper size limit constraint, and a lower size limit of 7 inches. The current view of Step 6 as seen in figure 2 shows the exact configuration of the SLOMO interface to accomplish this task. Table 3 shows a summary of the stand data for one of the ten independent runs over a 100 year planning horizon. Stand prescriptions were then optimized with SLOMO using an upper size limit of 21 inches and a lower size limit of 7 inches. Enabling the upper size limit was simply a matter of selecting the “yes” button as seen in the Goal 1 section of figure 2. Table 4 shows a summary of the stand data for one of those runs.

The main objective of this study was to determine if there were any patterns in the prescriptions that appear with regularity for stands with similar characteristics, and figures 3 and 4 enable us help us to locate some of these patterns. Figure 3, for example, represents the ten runs in which there was no upper size limit constraint imposed upon the objective function. Here we can see that in time period 1, 80% of the solutions scheduled harvests in the 21”+ diameter class (i.e. eight of the ten solutions). Additionally, 20% of the solutions scheduled harvests in the 12-21” class, and 60% scheduled harvests in the 4-12” class. Note that harvesting can occur in multiple diameter classes during any single time period. Recall also that a lower size limit of 7” was used, so we expected harvests to

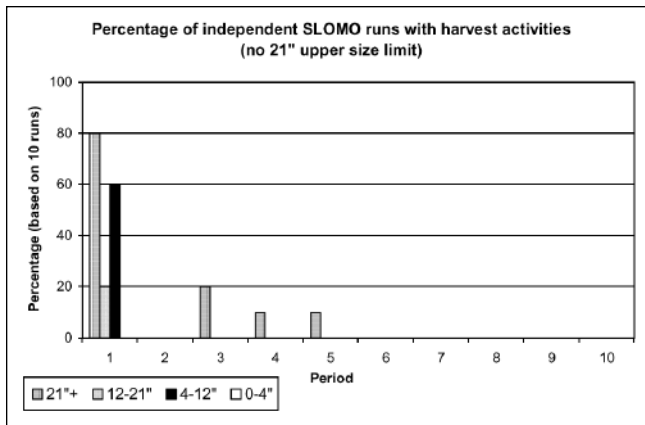


Figure 3—Potential thinning (or no thinning) timings for a DF-100 stand with no upper size limit.

be absent from 0-4" class. What is not known from viewing this figure is the intensity of harvests scheduled for each diameter class (the actual $h_j(t)$'s – note: they are available as output from SLOMO, they are just not displayed here), but only whether or not harvesting was scheduled in that class during that time period. Future work by the authors will examine the intensity of harvest question.

In examining period 1 of figure 3, one might recommend that for stands with characteristics similar to DF-100, there is a good likelihood that some level of thinning should occur in the 21"+ diameter class, and a moderate likelihood of thinning in the 4-12" class, during the first decade and if the stand goal is as stated in equation [3]. Interestingly, for this example we can see that for the remaining planning horizon there is only a very small likelihood of thinning in any later time period when prescriptions are optimized. This can be attributed to the fact that the thinning in period 1 removed a significant number of large trees. The stand was initially composed (table 2) of a DF overstory, yet with a significant component of LP and PP regeneration. After removing the larger trees, the smaller trees require a long time to grow before they are available for harvest (beyond the 7" dbh threshold). Here, we might say that to achieve the goals and adhere to the constraints of this problem, a thinning from above (to some level of density) in the first decade is required.

In contrast, we find a very different pattern in figure 4. Here the 21" dbh upper size limit constraint is imposed on the objective function. Period 1 in figure 4 reveals that

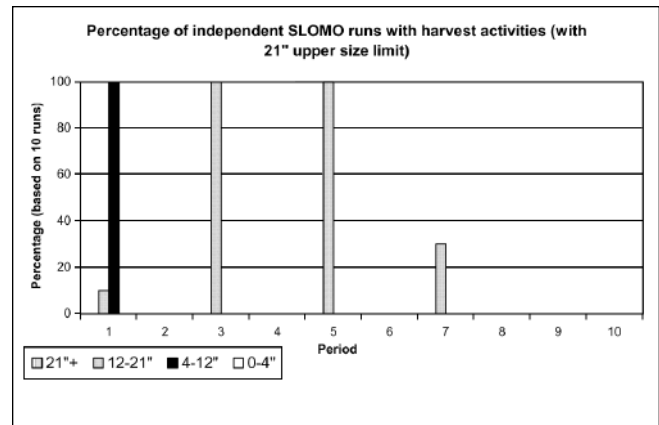


Figure 4—Potential thinning (or no thinning) timings for a DF-100 stand with a 21" upper size limit.

every solution required thinning in the 4-12" diameter class. The optimization process is thus trying to reduce the SDI by thinning the smaller diameter material. Again, only those trees with a dbh > 7" are even eligible to be thinned so the trees being thinned in this diameter class are really those with dbh's between 7 and 12 inches. Periods 3 and 5 also indicate that every solution required thinning in the 12-21" dbh class. For this set of goals and constraints, we can confidently say that the immediate need (in the first decade) is to thin in the 4-12" dbh class (to some level of density). Then return at year 30 and thin in the 12-21" dbh class, and at year 50 to again thin in the 12-21" dbh class.

CONCLUSIONS

We have described here a process for optimizing stand-level goals with an RLS-PATH algorithm embedded in a computer program called SLOMO. The SLOMO program was developed with a flexible interface to allow users to develop stand-level goals related to biological or ecological concerns. We feel that by applying this method to a number of stands of similar characteristics, that some general thinning guidelines can be developed for broad areas. By assessing figures such as those presented as figures 3 and 4 one can quickly assess whether or not general guidelines can be developed for stands that have similar structural characteristics. It is certainly recognized that individual site conditions may preclude the development of general guidelines. In this case, SLOMO can still be viewed as a tool that can be used to develop a stand-specific prescription.

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A NEURO-DYNAMIC PROGRAMMING APPROACH TO THE OPTIMAL STAND MANAGEMENT PROBLEM

Eldon Gunn¹

ABSTRACT

Some ideas of neuro-dynamic programming are illustrated by considering the problem of optimally managing a forest stand. Because reasonable growth models require state information such as height (or age), basal area, and stand diameter, as well as an indicator variable for treatments that have been performed on the stand, they can easily lead to very large state spaces. Researchers have developed sophisticated forward dynamic programming and related algorithms. However, an interest in problems that are stochastic in their basic growth dynamics, in market prices and in disturbances, ranging from insects to fire to hurricanes, requires a different approach. Neuro-dynamic programming algorithms are promising for problems with large dimension that may lack a simple model of dynamics and stochastics. This paper looks at applying these ideas in the context of a simple one species model with a view to eventual application to more complex problems.

INTRODUCTION

Forestry is full of problems that involve the control of dynamic, stochastic systems with the intent to either optimize some objective functional or to attempt to steer the system to some desired state. Often these involve large state spaces that make traditional dynamic programming prohibitive. Recent work on neuro-dynamic programming shows considerable promise for solving large dimension problems with complex dynamics.

Even-age stand harvesting has been represented as a control problem (Naslund, 1969) and the classic Faustman (1849) formula can be seen as a control policy developed from a deterministic view of the system. Some have been interested in how this control policy should be modified in the face of uncertain growth dynamics, market prices and the threat of disaster such as fire or budworm attack. Other researchers have noted that to properly model growth and response to various silvicultural interventions, a single state variable, such as volume used in the Faustman formula, is inadequate. Most growth models require a representation of something like stand average diameter, basal area, height as

well as an indicator variable of stand nature (natural, plantation, pre-commercially thinned, commercially thinned, etc.); thus four state variables, three of which are continuous. In representing multiple species stands, the state dimensions grow considerably. Even-aged stands are not the only source of large-scale dynamic stochastic control problems in forestry. For example, Islam and Martell (1997) describe a multi-dimensional queueing model of forest fire attack aircraft. If we concentrate on forest harvesting, Buongiorno (2001) has modeled uneven-age management as a Markov decision process.

The main ideas of this paper are closely based on Bertsekas and Tsitsiklis (1995) who come from a dynamic programming tradition. They point out that many of the ideas of neuro-dynamic programming have their roots in the artificial intelligence field under the name of reinforcement learning theory (Sutton and Barto, 1998)

DYNAMIC PROGRAMMING

There are many technicalities in properly detailing the nature of the problem to be solved. Because of lack of

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space, we will gloss over many of the details. Those interested in filling these in should consult Bertsekas and Tsitsiklis (1995) or Sutton and Barto (1998).

The basic dynamic programming (DP) problem involves a situation where the decision maker is aware of a current state i and is required to make a decision u . The decision u puts the system in a new state j at the beginning of the next stage with probability $p_{ij}(u)$. In a finite horizon problem, we are trying to estimate the value of being in state i with k stages remaining, assuming that we will make optimal decisions in this and all subsequent stages. That is we need to calculate

$$J_k^*(i) = \text{Max}_{u \in U(i)} \left\{ \sum_j p_{ij}(u) (g(i,u,j) + \alpha J_{k-1}^*(j)) \right\} \quad (1)$$

The explanation of this equation is that in state i at stage k we want to make a decision that maximizes the expected value of all present rewards $g(i,u,j)$ and all future rewards $J_k^*(j)$ with the future rewards discounted back to the beginning of the current stage k using the discount factor α . The functions $J_k^*(j)$ are referred to the cost-to-go functions.

We are particularly interested in the idea of policies. By a policy $\pi = \{\mu_0, \mu_1, \dots\}$, we have at each stage k , a policy function $\mu_k(i)$ that maps each state i to a particular decision $\mu_k(i) \in U(i)$. Given a policy, we can develop the idea of expected value of that policy

$$J_k^\pi(i) = \sum_j p_{ij}(\mu_k(i)) (g(i, \mu_k(i), j) + \alpha J_{k-1}^\pi(j)) \quad (2)$$

Another way of viewing the DP equation above is that of searching for the optimal policy

$$J_k^*(i) = \text{Max}_{\pi} J_k^\pi(i) \quad (3)$$

As we go to an infinite horizon framework, we are really letting $k \rightarrow \infty$ so that there is no distinction between having k periods left to go and $k-1$ periods left to go. In that case the equation (1) becomes *Bellman's equation*:

$$J^*(i) = \text{Max}_{u \in U(i)} \left\{ \sum_j p_{ij}(u) (g(i,u,j) + \alpha J^*(j)) \right\}. \quad (4)$$

In an infinite horizon framework, it makes sense to think of stationary policies, policies that depend only on the state and not the stage, $\pi = \{\mu, \mu, \mu, \dots\}$.

With stationary policies, we can also think of the expected value of a policy μ being given by:

$$J^\mu(i) = \sum_j p_{ij}(\mu(i)) (g(i, \mu(i), j) + \alpha J^\mu(j)) \quad (5)$$

Once again we can think of the DP problem as the search for the optimal policy among all stationary policies:

$$J^*(i) = \text{Max}_{\mu} J^\mu(i) \quad (6)$$

The fundamental idea of DP is the intimate connection between policies and values. If we know an optimal policy $\mu^*(i)$, then we need only solve equations (5) to calculate the optimal expected values $J^*(i)$ of being in state i . $J^*(i)$ is referred to both as the cost-to-go function or optimal value function. Alternatively, if we have the cost-to-go function $J^*(i)$, then we solve for the optimal policy $\mu^*(i)$ by carrying out the maximization operation in equation (4).

The problem of finding an optimal policy or finding the cost-to-go function is usually approached by way of recursive approximation algorithms. There are two main classes of algorithms that are usually applied, value iteration and policy iteration. There is also a third class of algorithms, linear programming, that we will not discuss here (Bertsekas and Tsitsiklis, 1995)

Value iteration: These algorithms begin with an initial estimate $J_0(i)$ for $J^*(i)$. They then use the maximization transformation in equation (1) for some or all of the states i to build up a new estimate $J_{k+1}(i)$ from $J_k(i)$. As $k \rightarrow \infty$, if we update the estimates for each i often enough, then the $J_k(i) \rightarrow J^*(i)$. Conventionally one starts with a given $J_k(i)$ and then calculates $J_{k+1}(i)$ for all states i . As Bertsekas and Tsitsiklis (1995) point out, this is not necessary and various asynchronous approaches, such as Gauss-Seidel, can be useful.

Policy iteration: These algorithms start with a given policy $\mu_k(i)$ and then calculate a cost-to-go function J^{μ_k} that corresponds to the policy $\mu_k(i)$. This requires solving the linear equations (5) for $J^{\mu_k}(i)$. Given the $J^{\mu_k}(i)$, we then update the policy to $\mu_{k+1}(i)$ by solving the max operation in (4); that is

$$\mu_{k+1}(i) = \arg \max_{u \in U(i)} \left\{ \sum_j p_{ij}(u) (g(i, \mu, j) + \alpha J^{\mu_k}(j)) \right\}$$

for some or all of the states i . We then repeat. As $k \rightarrow \infty$, $\mu_k(i) \rightarrow \mu^*(i)$. Again, conventional algorithms update the policy $\mu_k(i)$ for all i in the state space but it is possible to only update some states at each iteration.

Thus, conventional DP consists of successively building up approximations to the cost-to-go function or the policy function. We will see that neuro-dynamic programming involves more extensive approximations. In the case of policy iteration, solving the equations (5) can be difficult to do directly if the state space is large. Some algorithms iterate using equation (5) to build up an approximation of $J^{\mu_k}(i)$ and then use this approximation to calculate $\mu_{k+1}(i)$. In general, value iteration algorithms are conceptually quite simple, but often converge slowly. Policy iteration algorithms tend to converge more quickly.

Stand Management Dynamic Programming Problems

Dynamic programming has been a favourite tool for examining stand management problems. Although early work used a single state variable, it is impossible to accurately model growth and the effect of interventions without taking into account more complex states such as diameter, height (age) and stand basal area (for example Brodie, Adams Kao 1978; Brodie and Kao 1979). Recently there has been a tendency to use individual tree growth models (see Pelkki, 1994).

An interesting dichotomy in DP models can be observed. On the one hand, we find models with complex state variables but deterministic dynamics and prices (see Pelkki, 1994, and Pelkki, 2002). On the other, we find models with stochastic prices and/or dynamics but with very simple state representation (for example Haight and Holmes, 1991). We generally don't find both.

For the complex state vector typically associated with detailed growth models, advantages can be gained by using a forward DP recursion. Here we start with stage 0 corresponding to the initial state and compute

$$F_k^*(j) = \underset{i}{\text{Max}} \{ (F_{k-1}^*(i) + \alpha^{k-1} g(i, u(i, j))) \}$$

where $F_k^*(j)$ is the maximum net present value of a policy that begins stage k in state j and $u(i, j)$ is the policy decision that transforms state i to state j in one stage. (If it is impossible to transform state i to state j in one step, we adopt the convention that $g(i, u(i, j), j) = -\infty$). The advantage of a forward recursion is that it is possible to prune states that cannot be reached at a given stage. If we use a finite set of possible policy decisions, then only a finite number of states are possible at each stage.

Forward recursion requires us to know the state resulting from a decision u in state i . Hence, it cannot be used in a stochastic setting where the outcome of a decision depends on a probability distribution. As a result, stochastic DP

problems must use backward recursion. This prevents the state pruning that is at the heart of forward methods. In order to keep the size of the state space manageable, stochastic forestry DP models often use a very simplified state space and with a resulting requirement for overly simplified growth dynamics. To deal with realistic growth models in a stochastic setting, we need a way of dealing with equations (1)-(4) with high dimensional state space. Typically we will want to use infinite horizon methods in order to pick up the regeneration process typified by the Faustman formula.

There are many ways in which stochastic issues can enter into the stand management problem. A few of these include:

- i) The price(s) of the forest products are random. Something like a random walk model has been proposed by Haight and Holmes, 1991. In this case the DP problem has some of the nature of optimal stopping problems.
- ii) Natural disasters such as budworm, fire and hurricanes can force a transition to the initial regeneration state.
- iii) Natural regeneration can result in a random number of periods from the time that a stand has been regeneration harvested until the regeneration is established.
- iv) Weather and natural variation can result in variability about the assumed mean growth. Any growth model is the result of regression with the variability implicit in this.
- v) Individual tree growth models are inherently stochastic. To grow a given forest state (diameter, basal area, height), it is necessary to randomly generate a forest stand with a certain number of trees and a distribution over diameter classes. Growing such a model involves a probabilistic choice for each tree as to whether it survives for a period or not. Trees that survive are grown according to a formula developed through regression.

APPROXIMATION ISSUES – VALUE ITERATION

Forward dynamic programming typically uses the idea of a neighbourhood, in which a given state is chosen to be representative of the continuum of states within a certain radius. The larger the neighbourhood radius, the smaller the number of states to be evaluated and the easier the computations. Pelkki has shown that there are significant issues with accuracy as the neighbourhoods become larger.

The idea of representative states surrounded by neighbourhoods amounts to a piecewise constant approximation to the cost-to-go function. The first idea of neuro-dynamic programming is a continuous approximation. That is the

functions $J^*(i)$ (resp. $J^\mu(i)$, and $J_k(i)$) are approximated by continuous functions $\bar{J}^*(i,r)$ (resp. $\bar{J}^\mu(i,r)$, and $\bar{J}_k(i,r)$), where the parameter vector r has been chosen to minimize the approximation error at a finite number of states i_1, i_2, \dots, i_N .

There are many ways to do the approximation. Simple linear models (example: quadratic fit) are one possible approach. If the state variables are of the form (BA, D, H, tt) with continuous variables for basal area (BA), diameter (D) and height (H) and the discrete variable treatment type, it may be reasonable to use a separate continuous approximation on (BA, D, H) for each of the discrete values tt. The fitting approach that leads to the name neuro-dynamic programming is to let r be the parameters of a neural network architecture used to approximate $J^*(i)$ (resp. $J^\mu(i)$, and $J_k^\pi(i)$).

One idea discussed in Bertselas and Tsitsiklis (1995) is to use features, indicator variables for particular knowledge of the system under control. For example, it is easy to characterize certain states (BA, D, H, tt) as being ineligible for certain treatments. In a red spruce forest, there are certain feasible diameter ranges for pre-commercial thinning, commercial thinning and final felling. A feature can either be used to create separate linear models for each feature value or as an additional input to the neural network architecture.

This then suggests an approximate value iteration algorithm along the following line.

- i) Begin with estimates $\bar{J}_k(i_j)$, calculated at N_k points i_1, i_2, \dots, i_{N_k} .
- ii) Fit the continuous function $\bar{J}_k(i,r)$ to minimize the approximation error over i_1, i_2, \dots, i_{N_k} .
- iii) Let $k=k+1$ and identify states i_1, i_2, \dots, i_{N_k} .
- iv) Solve the recursion

$$J_k^*(i) = \text{Max}_{u \in U(i)} \left\{ \sum_j p_{ij}(u) (g(i,u,j) + \alpha \bar{J}_{k-1}^*(j,r)) \right\}$$

at the points i_1, i_2, \dots, i_{N_k} .

- v) Either stop or go to step ii) and repeat.

Similar approximate value iteration has been successfully used in the engineering community. Johnson and others (1993) report on using cubic spline approximations for hydroelectric power systems with five continuous state variables, evaluated at as few as five points along each state dimension. Shoemaker (2003) indicates an extension of these ideas to nine-dimensional stochastic DP problems.

This approach is a straightforward extension to standard DP ideas. When compared to the idea of neighbourhoods, there is now no longer the requirement to map the single state representing one neighbourhood at a given stage to another single state representing a subsequent neighbourhood. The question of accuracy is now that a sufficient number of states be examined so that the best fit approximating function is a good representation of the true cost-to-go function. However, this introduces a number of complications. The first is whether the approximating architecture $\bar{J}_k(i,r)$ is capable of modeling the actual $J_k(i)$, the second is whether the fitting of the parameter vector r has been successful in minimizing the fitting error (except in the case of linear models where this problem is trivial) and the third is whether the i_1, i_2, \dots, i_{N_k} are numerous enough and chosen appropriately.

Trying to develop this into an approach for the stand management problem raises additional issues. We are normally more interested in policy than cost-to-go functions (although cost-to-go functions do have an important interpretation as economic rent). It is unlikely that the i_1, i_2, \dots, i_{N_k} are sufficiently dense to reflect all forest states at which we would like to know a thinning/harvesting policy. There are two solutions here. One is to compute policy at a given state i' on the fly by explicitly solving the equation

$$\mu_k^*(i') = \arg \max_{u \in U(i')} \left\{ \sum_j p_{i'j}(u) (g(i',u,j) + \alpha \bar{J}^*(j,r)) \right\}.$$

The other is to compute the policy

$$\mu_k^*(i') = \arg \max_{u \in U(i')} \left\{ \sum_j p_{i'j}(u) (g(i',u,j) + \alpha \bar{J}^*(j,r)) \right\}$$

for a set of points $i' \in \{i'_1, i'_2, \dots\}$ and then develop another approximation architecture $\mu^*(i,r)$. In forestry, although the components of the state vector such as BA, D and H are continuous variables, it is realistic to think of a reasonably small finite set of decisions. In pre-commercial thinning this might consist of spacing at 6, 8, 10 or 12 ft (2, 2.5, 3, 3.5, 4 meters) and in the case of commercial thinning, the removal of 40%, 50%, 60%, 100% of basal area. In both cases, it is unrealistic to be more precise in giving instructions to thinning crews. Thus the fitting problem $\mu^*(i,r)$ really becomes a classification problem, a task to which neural networks are well suited. The classification problem is to classify the states by the appropriate policy action for that state.

POLICY ITERATION

There are several reasons to consider approximate policy iteration algorithms. First, the main focus of forest management is on policy. Most jurisdictions will have a current policy that governs its silviculture. A very natural question is can this policy be improved. Second, conventional wisdom is that policy iteration algorithms often converge faster than value iteration. There may well be a third reason. In many cases, the probabilities that govern the state transitions may not be known analytically. This is certainly the case when an individual tree growth model is used to model stand dynamics. The evaluation of a cost-to-go function (equation (5)) can be carried out using simulation when an analytic expression for $p_{ij}(u)$ is unavailable. To see the possibilities, we will describe approximate policy iteration assuming analytical probabilities are not available.

Policy iteration (and indeed value iteration) works best if we start with a reasonable initial policy (cost-to-go function of that policy). An example might be a simple diameter limit policy and simple rules for pre-commercial and commercial thinning. Once we have that policy, we can simulate it to estimate a cost-to-go function. There are a variety of issues in simulating a policy. Some of these are easier if we assume that the dynamic programming problem has been formulated as a stochastic shortest path problem (Bertsekas and Tsitsiklis, 1995, show this can always be done). A stochastic shortest path is a DP problem in which one of the states, say state 0, is absorbing with $p_{00}(u) = 1$ and $g(0, u, 0) = 0$ for all u . Starting from some initial state i , and using the established policy, we simulate the current returns and next state until we eventually encounter the absorbing state. Thus we construct a simulation path $(i_0, i_1, i_2, \dots, 0)$. Note this simulation run also constitutes a cost-to-go sample for every unique state encountered on this path. There are a number of issues about what to do if a state is encountered more than once on a simulation path. See Bertsekas and Tsitsiklis (1995) for a more extensive discussion on simulation issues. Through sufficient repeated simulations and judicious sampling, we can build up cost-to-go estimates at a number of states. We then use fitting procedures as discussed earlier to produce an approximation $\tilde{J}^\mu(i, r)$.

We then need to compute an improved policy that satisfies

$$\mu(i) = \arg \max_{u \in U(i)} \left\{ \sum_j p_{ij}(u) (g(i, u, j) + \alpha \tilde{J}(j, r)) \right\}.$$

There are again many ways to do this. If probabilities $p_{ij}(u)$ are analytically available, then for a finite number of choices in $U(i)$, we can compute the so-called Q-factors directly by

$$Q(i, u, r) = \sum_j p_{ij}(u) (g(i, u, j) + \alpha \tilde{J}(j, r)).$$

If the $p_{ij}(u)$ are not readily available, this computation can be carried out by simulation and this simulation is easier than that discussed above because it is only a one stage simulation. Then the improved policy is

$$\mu(i) = \arg \max_{u \in U(i)} Q(i, u, r).$$

Given this improved policy we can repeat this process of i) developing an estimating cost-to go function $\tilde{J}(i, r)$, ii) calculating the Q-factors $Q(i, u, r)$, and iii) calculating the next improved policy $\mu(i) = \arg \max_{u \in U(i)} Q(i, u, r)$.

At present, we are working on problems where the $p_{ij}(u)$ are available and easily computed. However, if we use the types of individual tree models used by others, such as Pelkki (1994), this will no longer be the case.

EXAMPLE APPLICATION

In this section, we give a brief outline of a DP model, where the objective is to find an optimal policy of harvest and silviculture for even-aged management of the stand. At harvest (clearcut), the stand is subject to an uncertain period of regeneration. This can be eliminated through planting the stand. Unplanted stands, once regenerated, grow as natural stands. Within certain diameter limits, they can be pre-commercially thinned (PCT). Plantations can either have early competition control or not. Those without early competition control have a certain probability of reverting to a well stocked natural stand. Plantations or PCT stands can be commercially thinned (CT) once they reach certain diameter limits. In both the case of PCT and CT, there are a range of density reduction choices available. The model maintains a four dimensional stand state; HT, height, D – diameter, BA basal area and tt – treatment condition. The DP problem is to develop a policy of what management decision to make at the beginning of a period for any state of the stand. The decisions include those indicated above as well as the decision to do nothing and let grow for one period. We use five-year periods in this work. The current model is based on a Red Spruce conifer stand.

The growth models are based on the Nova Scotia Softwood Growth and Yield Model (GNY) (NSDNR, 1993). This model is based on extensive field analysis using the

series of research permanent sample plots established and maintained by the N.S. Department of Natural Resources. The main parameter is site capability expressed as Site Index height at age 50. The model maintains height, diameter and basal area from period to period. Merchantable and sawlog volumes are computed using Honer's equations (NSDNR, 1996). GNY has essentially three growth models corresponding to:

Natural Unmanaged Stands—These stands are grown using equations developed for the provincial revised normal yield tables (NSDNR, 1990). Age implies height (and vice versa), height implies diameter and site density, which in turn implies basal area. The relationship between height and age offers the modeler the choice between using height or breast height age as the state variable. However, height is the easiest variable to measure and because of the stochastic issues involving the time to reach breast height, we choose to use it.

Natural Stands That Have Been Subject To Precommercial And Commercial Thinning—These stands are grown using a variable density model. The age-height relationship characteristic of the site is maintained. The stand average diameter is modeled as a function of site, spacing and free age. Free age is the mechanism that we use to deal with density modifications. This function is invertible so that free age can be calculated as a function of site, spacing and diameter. Given a certain site, spacing and diameter, we use the inverse function to compute the free age. If we choose to leave the spacing as is, then growth amounts to increasing the free age by one period (five years) and calculating the resulting diameter. If we do a thinning this alters both the spacing and diameter. The nature of the diameter change depends on the nature of the thinning (thinning from below, or above). Given the new diameter and spacing, we can recompute the free age and continue to grow the stand by incrementing the free age. The maximum density is a function of the diameter. The current diameter and basal area define both the current density and the spacing. Trees are grown by advancing the age (height age) and free age by five years. The diameter and height are then computed. The site density index (SDI) is computed for this diameter and, if the current density exceeds SDI, the current density is reduced to SDI, spacing is recalculated and free age recomputed to correspond to the new diameter, spacing and diameter.

Plantations That May Also Be Thinned—Plantations are also grown using the variable density growth model but the maximum density for plantations is computed using a different equation.

The dynamic programming state variable is thus (HT, BA, D, tt) where HT is height (m), BA is basal area (m^2/ha) and D is diameter (cm). The tt is a treatment indicator with the following values: 1) natural, unmanaged, 2) natural, pre-commercially thinned, 3) natural, commercially thinned, 4) plantation, spaced, 5) plantation, commercially thinned

For growth purposes, there is no necessity to distinguish between $tt=2$ and $tt=3$ or to distinguish between $tt=4$ and $tt=5$. However, the nature of revenue generated and the actions that can be taken are different in these circumstances. This is what Bertsekas and Tsitsiklis (1995) refer to as a feature.

In our calculations, for each treatment tt, we have an evaluation of the cost-to-go function at a number of discrete states i_1^t, \dots, i_N^t where each of the states i_k^t is of the form $i_k^t = (HT_k^t, BA_k^t, D_k^t, tt)$. We fit the functions $J_k(i, r)$ as five separate linear models, one for each tt state. Currently we are working with the vector r being the parameters of a second order model; that is J is a quadratic on the three variables HT, BA and D (ten parameters for the quadratic). We perform a separate fit for each of the five different values of tt. This means that there are a total of 50 parameters (10×5) that make up the r. This can be reduced since for the states with $tt=1$, the BA and D are determined from HT so that a ten term model is not necessary. In this case, J is fit as a quadratic depending on HT only.

The main issue of probabilities in the current model involves regeneration. When a stand is harvested this period and successfully regenerates, i) it can exist as a five year old natural stand in the next period. ii) if it has advanced regeneration it may exist as a ten year old (or older) stand, and iii) if it has a regeneration failure it may exist as a stand with state (0,0,0,1). Stands in this state can either be planted and converted to plantation or can be left to natural regeneration which may experience continued regeneration failure. The state dependent probabilities of successful regeneration, advanced regeneration and initial and continued regeneration failure define a stochastic model with computable $p_{ij}(u)$.

We have some very preliminary results from a code written in Visual Basic for Applications using Microsoft Excel as the interface. The code is not written for computational efficiency. All growth and volume calculations are being done on the fly. Although we believe our implementation to be correct, it has not undergone extensive validation. The model has been implemented as a value iteration

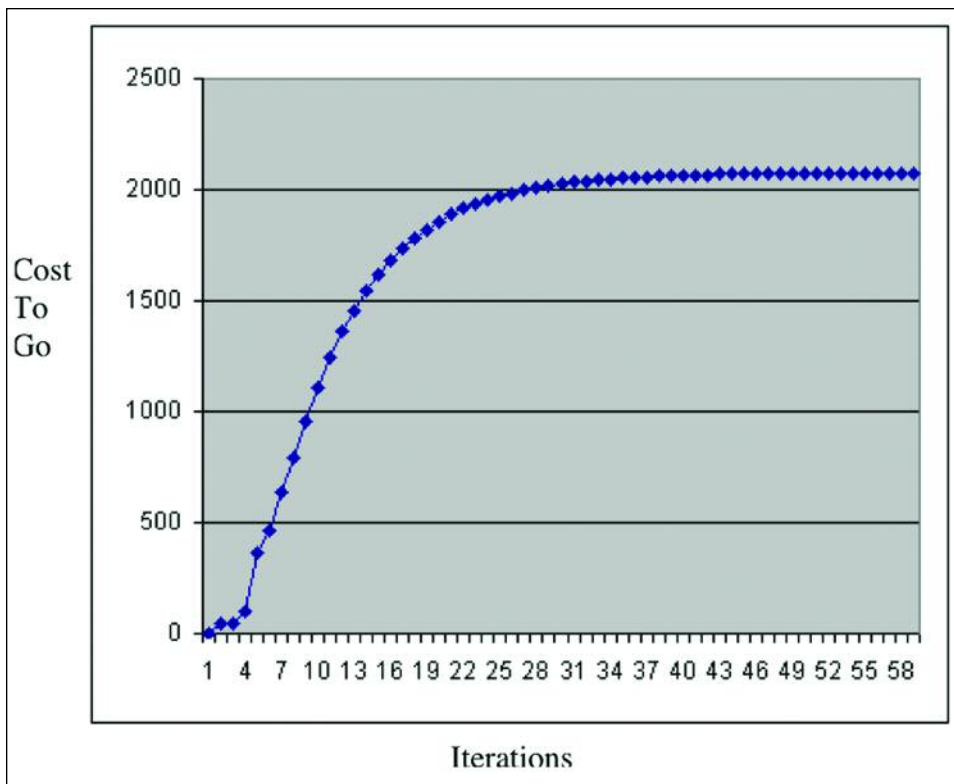


Figure 1—Cost-to Go Function Evolution.

algorithm with a total of 943 states used to directly evaluate the cost-to-go function and a quadratic model fit to these states. The states are broken down into the five treatment type tt classes as follows: 32 ($tt=1$), 196 ($tt=2$), 260 ($tt=3$), 195 ($tt=4$), 260 ($tt=5$). The states are chosen to span the attainable heights, diameters and basal areas. Note that for three continuous state variables and five treatment types, this is a quite modest number of states. The computations reported below are only for the purposes of indicating that this approach is practical and not meant to be a real study. The growth is based on Site Index 50 = 17 m (55 ft) which corresponds to Land Capability=6m³/ha/year. The computations were done with stumpage values of \$15 per m³ for pulp and \$50 per m³ for studwood and sawlogs. Planting, pre-commercial thinning and commercial thinning treatments were assumed to be costless. Starting from a cost-to-go function that is identically zero, figure 1 shows the evolution of the cost-to-go of the bare land state (0,0,0, natural) as the DP iterations proceed.

The cost-to go functions essentially stabilize after 60 iterations. The computed policy does not change from iteration 21 onward.

What this result indicates is that it is possible to do these computations with fairly modest effort and that convergence is reasonably rapid. A more extensive computational study will be necessary before we can report on accuracy and optimality of the computed results. More realistic costs and revenues will be required before it makes sense to comment on the nature of the policies calculated.

SUMMARY

Forestry will continue to pose important problems that involve the solution of large scale stochastic dynamic programming problems. Neuro-dynamic programming is an approach that shows considerable promise. The ability to deal with large dimension state spaces, and models that may exist only as a simulation, are important features of the approach.

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HARVEST SCHEDULING

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ANALYSIS AND EVALUATION OF THE R-RATIO HEURISTIC FOR FOREST SCHEDULING

Silvana R. Nobre¹ and Luiz C.E. Rodriguez²

ABSTRACT

The R-ratio heuristic for forest scheduling (Rodriguez, 1994) solves large scale 0-1 integer programming versions of the Type I harvest scheduling problem (Johnson and Scheurman, 1977). This paper reviews its foundations and describes its evolution until now. Heuristic scheduling system patterns are used to represent the problem, to describe the evaluation function and to monitor the solution process. Its logic and elements are presented based on some artificial intelligence (AI) principles proposed to build heuristic processes. An AI approach based on intelligent agents provides the basis to analyze the R-ratio's (i) escape strategy from local optima and (ii) its hybrid A*-greedy strategy to the solution search. AI concepts are also utilized to evaluate performance indicators of *efficacy*, measured by the proximity to the optimal solution of the non-integer linear programming relaxed version of the same problem, and efficiency, measured by penetrance and space complexity. For the test problems, the R-ratio strategy to escape from local optima proved efficacious given that several feasible solutions with objective function values bellow the range of 0.5% were obtained. And the R-ratio approach to find feasible solutions also proved efficient given its focus on a low cost strategy to select path searches.

KEYWORDS: Integer programming, harvest scheduling, forest management, heuristics, artificial intelligence.

INTRODUCTION

Johnson and Scheurman (1977) classified the various linear programming approaches to forest harvest scheduling into two basic types known as Model I and Model II. In Model I type problems, each decision variable defines one specific sequence of management interventions, while in Model II type problems each decision variable represents one single intervention.

Using Clutter and others (1983) representation of the basic Model I linear programming model, the following definitions are needed:

N = number of forest units
 M = number of management regimes

T = number of management periods in the planning horizon
 A_i = area of forest unit i
 X_{ik} = area of forest unit i assigned to management regime k
 D_{ik} = value (per unit of area) of management regime k in forest unit i
 v_{iktp} = volume (per unit of area) of product p harvested from forest unit i in management period t if management regime k is used
 $VMin_{tp}$ and $VMax_{tp}$ = minimum and maximum volumes of product p in period t
 i, k, p and t = identify forest units, management regimes, forest products and planning periods, respectively

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and the model becomes:

$$\text{Maximize } Z = \sum_{i=1}^N \sum_{k=1}^M D_{ik} X_{ik} \quad (1)$$

$$\sum_{k=1}^M X_{ik} \leq A_i \quad (i = 1, 2, \dots, N) \quad (2)$$

subject to:

$$\sum_{i=1}^N \sum_{k=1}^M v_{iktp} X_{ik} \geq VMin_{tp} \quad (t = 1, 2, \dots, T) \quad (p = 1, 2, \dots, P) \quad (3)$$

$$\sum_{i=1}^N \sum_{k=1}^M v_{iktp} X_{ik} \leq VMax_{tp} \quad (t = 1, 2, \dots, T) \quad (p = 1, 2, \dots, P) \quad (4)$$

The R-ratio heuristic for forest scheduling (Rodriguez, 1994) solves large scale 0-1 integer programming versions of the problem stated in sentences (1) to (4). The solution domain becomes $X_{ik} \in \{0,1\}$, D_{ik} and v_{iktp} are restated as follows:

D_{ik} = total value of management regime k used in forest unit I

v_{iktp} = total volume of product p harvested from forest unit i in management period t if management regime k is used

and sentence (2) becomes:

$$\sum_{k=1}^M X_{ik} = 1 \quad (i = 1, 2, \dots, N) \quad (5)$$

In real applications, such problems present tens or even hundreds of thousands of decision variables, and optimal solutions are hard, or even impossible, to obtain when the branch-and-bound algorithm and available computing resources are used.

This paper presents some attributes of the R-ratio heuristic for forest scheduling. Patterns are used to represent the problem, to describe the evaluation function and to monitor the solution process. In the following sections, the logic of the R-ratio heuristic and some of its elements are presented based on artificial intelligence principles proposed to build heuristic processes.

Patterns in heuristic scheduling systems

Scheduling involves assigning courses of action that consume various resources in limited supply for certain periods of time. The courses of action in forest harvest scheduling problems may be called management regimes that in turn are composed of activities or operations. Each activity requires certain amounts of specified resources and results in certain amounts of outputs.

Forest scheduling problems are often complicated by a large numbers of constraints relating activities to each other, resources to activities, and either resources or activities to desirable or undesirable consequences. Since these complicated relationships can make exact solutions for large scheduling problems very difficult, it might be helpful to simplify the problem.

Problem representation

First it is assumed that all desirable forest management regimes, defined along the planning horizon as combinations of different sequences of important forest activities, are known for each forest unit. The consumption of limited resources, and consequential outputs, are also well known for each activity in the management regime. Then, the problem reduces to the selection of one single management regime for each forest unit that results in the best scheduling value possible, the maintenance of desirable outcomes above minimum levels, and the consumption of limited resources bellow maximum levels. The idea behind the R-ratio heuristic is to provide an efficient and a successful search strategy. During the development of the R-ratio, one of the key issues was the definition of a useful evaluation function for the search.

Evaluation function

An evaluation function measures the goodness of changing the present solution. In other words, it returns a number describing the desirability (or lack thereof) of changing the present solution arrangement. The R-ratio heuristic starts with the optimal solution for the unconstrained version of the forest scheduling problem (a relaxed solution to the problem). In other words, the solution for a problem formed only by sentences (1) and (2) forms the basis $\{X_{ik} = 1 \mid D_{ik} \text{ is max}\}$.

Constraints are then reinserted, and desirability translates into the level of how well new solutions reduce minimally the objective function value with maximum reduction in the level of infeasibilities. The R-ratio heuristic uses an evaluation function that is a function of these two reductions. Specifically, the R-ratio heuristics evaluates the desirability of new solutions based in the following ratio:

$$R = \frac{\Delta^{inf}_{i,k}}{\Delta^{obj}_{i,k}}$$

where:

$\Delta^{inf}_{i,k}$: reduction in the level of infeasibilities if management regime k in management unit i becomes part of the solution; and

$\Delta^{obj}_{i,k}$: reduction in the objective function value if management regime k in management unit i becomes part of the solution.

The level of infeasibility, used to obtain $\Delta^{inf}_{i,k}$, is calculated as the sum of absolute deviations (SumAD) from the target values (below $VMint_p$ and above $VMan_p$) defined in constraints (3) and (4). The value of $\Delta^{inf}_{i,k}$ represents the variation in SumAD when a management regime is replaced in one forest unit. The larger the variation, higher is the chance of the management regime responsible for that variation to become part of the solution.

As a side effect, the replacement of regimes also induces a variation in the objective function value. That variation is represented by $\Delta^{obj}_{i,k}$. It was defined as a reduction because it is more likely for the objective function value to decrease, after a change in the basis, than to increase, given that the objective function value initially reflects the optimum solution for the unconstrained formulation of the problem.

At each iteration, a pair of values $\Delta^{inf}_{i,k}$ and $\Delta^{obj}_{i,k}$ is calculated for each variable not in the basis, producing as many R-ratios as the number of non basic variables. Very efficient routines can be programmed to produce the R-ratios, with consecutive iterations showing declining processing times.

Solution process

As mentioned before, the R-ratio heuristic starts with an optimal solution for the forest scheduling problem formed by sentences (1) and (2). Once constraints (3) and (4) are reintroduced, and given the integer nature of the problem – with the necessary assignment of one single regime for each management unit – new solutions necessarily result from replacements in the set of previously chosen management regimes. Due to the replacement process established by the heuristic, three very distinctive sets of management regimes arise: (i) the set of chosen regimes; (ii) the set of non-selected regimes; and (iii) the set of discarded regimes.

In 1994, Rodriguez proposed the R-ratio heuristic with replacements drawn from the set of non-selected regimes only. Rodriguez and McTague suggested in 1997 a new replacement strategy, with periodic visits, during the heuristic process, to the set of discarded regimes. During these visits, the regime in the set of discarded regimes, contributing the most to reduce infeasibilities, replaces the previously selected regime to the respective management unit.

Two parameters were then proposed: the iteration number α at which the heuristic visits the set of discarded regimes

for the first time, and the β number of iterations between visits to the set of discarded regimes. After a certain number of iterations, and given a feasible solution is found, all regimes in the non-selected and discarded sets are finally evaluated in terms of their potentiality to maintain the solution feasible and to improve the objective function value. Once none is found, the process is terminated. And the set of chosen regimes is presented as the best solution.

Iterative techniques, like the one above described for the R-ratio technique, play an important role among all optimization procedures. The general step of an iterative procedure goes from a current solution i to next solution j and check whether one should stop there or perform another step. Usually, one approach builds an iterative procedure starting with a neighborhood $N(i)$ defined for each feasible solution i , and the next solution j is searched among the solutions in $N(i)$.

The R-ratio technique, contrary to most iterative neighborhood search methods, does not disregard unfeasible solutions. In fact, it starts with the most probably unfeasible solution, the unconstrained optimum. During the search process, the R-ratio technique indirectly keeps track of all previously visited solutions by storing the replaced variables in a *discarded set*. Variables in this set may become part again of a future solution - feasible or not - in the next iteration.

In a certain way, the R-ratio method can be compared to Tabu Search (TS). TS is considered a neighborhood search method (Hertz, Taillard and de Werra 1995; Glover and Laguna, 1998). Similarly to a general TS procedure, the R-ratio procedure temporarily excludes a given group of prospective alternatives from the set of searchable strategies, by forbidding variables to become members of a new solution. On the other side, though, the R-ratio does not maintain fixed the size or structure of its *tabu list*, represented by the *discarded set*. And, in fact, the number of variables in the R-ratio discarded set augments as the number of iterations grows.

The *tabu list* and the *discarded set* may look similar in terms of constraining the search process, but they are built based on very different principles. Basically, the *tabu list* in a TS procedure is formed by feasible solutions in a subset of $N(i)$ forbidden to be visited by rules expressed in a systematically updated guiding memory. In the R-ratio procedure, the discarded set contains variables, highly valuable in terms of the objective function value, but undesirable given the unfeasibility they generate if introduced in the *selected set*.

The R-ratio method seems capable to compete with other heuristic techniques, including TS procedures. This paper, based on some artificial intelligence principles, presents an evaluation of the heuristic solution process provided by the R-ratio method.

Artificial intelligence principles

Nilsson (1982) refers to artificial intelligence systems as systems where a database is affected by well defined operations or production rules subject to control strategies. The R-ratio (i) manages a database with three data sets (chosen, selected and discarded regimes), (ii) establishes a production rule where the regime with the largest R-ratio enters the chosen set replacing the previously selected regime for the same management unit, and (iii) the control strategy is the routine that calculates the R-ratio for all regimes, chooses the regime with the largest R-ratio value, operates the replacement and tests the termination condition (no infeasibilities and no way to improve the objective function value).

Rich and Night (1993) and Nilsson (1982) refer to the following concepts: *state, movement and goal*. *State* is the database configuration at a certain moment. The database state is altered when a rule is applied, generating a *movement*. And the goal is the most wanted state. The set of all possible states is the problem space. In a framework of states and movements, the problem solution is the sequence of movements that takes the control system from an initial state to the goal state.

In the current implementation of the R-ratio heuristic, a state is defined by how the main structure assigns regimes to the three sets of selected, non-selected and discarded regimes. A movement is made every time one of these assignments is modified by the control system. Each transfer of regimes between sets defines a new state. The goal is the state where infeasibilities have all been eliminated.

Nilsson (1982) distinguishes two major kinds of control strategies: *irrevocable* and *tentative*. In an irrevocable control regime, an applicable rule is selected and applied irrevocably without provision for reconsideration later. In a tentative control approach, an applicable rule is selected and applied, but provision is made to return later to this point in the computation to apply some other rule. The R-ratio heuristic strategy does not work either irrevocably or tentatively. Regimes replaced by better regimes are placed in the set of discarded regimes. This set is revisited periodically. When a previously discarded regime is selected again, the resulting state does not reflect exactly the conditions prevailing when that regime was considered before.

The same author also refers to *commutative* and *decomposable* systems, and how certain conditions must exist to provide a certain freedom in the order in which rules are applied to such systems. In a commutative system the rules can be organized into an arbitrary sequence and applied to the database to produce a result independent of order. Decomposable systems generate a database that can be decomposed or split into separate components, independently treatable generating similar results to those obtained when rules are applied to the whole database. The R-ratio heuristic is commutative because changes in the replacement order, of a given set or replacements, result in the same goal state. Decomposability is not allowed by the R-ratio heuristic approach, given that the evaluation function has to be applied to the complete database in order to find the best replacement.

Rich and Knight (1991) refer to the concept of a heuristic function to guide the search process, suggesting the path to be followed in a branching process. A good heuristic function offers low costs to the heuristic solution process. But there is a trade off in terms of the quality of the goal state, and the ideal cost will have to balance longer solution paths with direct solutions. The R-ratio is a very simple ratio of two easily calculated numbers used as a heuristic function to calculate the distance from the present state to the goal state. Although simple, the concept represents the original problem very properly.

Search strategies are usually classified as *depth-first* or *breadth-first*. Supposing an initially uninformed scheme to order the nodes in a search tree, the depth-first strategy will always select the deepest node to expand; meanwhile the breadth-first strategy expands nodes along the same level of depth in the search tree. The R-ratio starts with an informed scheme to select the regimes in the initial state. These are the ones with the highest objective function value. The initial state changes as regimes are replaced, one at a time. The search occurs in the non-selected set of regimes, which by turn decreases in size as the process continues. Therefore, it can be stated that the R-ratio uses a depth-first approach each time a replacement has to be done. Provided the set of non-selected regimes is always finite and that a path will always exist, it is guaranteed the R-ratio finds a path to a final state.

The *intelligent agent* concept (Russel and Norvig, 1995) can also be utilized to evaluate the goodness of the results provided by the R-ratio heuristic. An agent perceives its environment through *sensors* and acts upon the environment through *effectors*. Intelligent agents act rationally and try to maximize a certain performance measure. Implemented as

a program, the R-ratio can be viewed as a *software agent* or a *softbot* (software robot). The environment is constituted by the innumerable arrangements formed by the regimes stored in the non-selected and discarded sets. The R-ratio softbot sensor perceives the environment calculating and evaluating the possibilities around. The agent decides rationally, maximizes its performance choosing the regime with the highest R-ratio and acts upon the environment replacing regimes in the selected set.

Softbots can be a *goal-based agents* if performance depends on the goals to be achieved, or a *reflex-agent* that simply reacts to the environment. Goal-based agents need search strategies to find its goals and easily become *problem-solving* agents. The R-ratio heuristic is based in a problem-solving agent determined to find a sequence of actions (regime replacements) in order to produce a feasible state. For the R-ratio agent, it is not sufficient to find a goal state. It is also necessary to find the shortest path from the initial-state to the goal-state, because chances are the reduction in the objective function value will be smaller.

Russel and Norvig (1995) define the *state space* of the problem as the set of all states reachable from the initial state by any sequence of actions. A *successor function* defines an action in terms of which state will be reached by carrying out the action in a particular state. A *path* in the state space is simply any sequence of actions leading from one state to another. A *goal test* or the *termination test* is needed by the softbot to determine if a certain state is the goal state. Finally, it may be the case that one solution is preferable to another, even though they both reach the goal. Therefore, a path cost function is a function that assigns a cost to a path.

In the R-ratio heuristic, the successor function rules the decision to visit the set of discarded regimes. It governs upon what set of regimes the replacement selection process will occur, and behaves depending on the values of α and β which are defined before the softbot starts its search. The termination test is simply based in the amount of infeasibilities, which must be ideally zero. The path cost function is the R-ratio itself calculated for all non selected regimes.

To evaluate heuristic search strategies, Russel and Norvig (1995) recommend four criteria: *completeness*, or *is the strategy guaranteed to find a solution when there is one?*; *time complexity*, or *how long does it take to find a solution?*; *space complexity*, or *how much memory does it need to perform the search?*; and *optimality*, or *does the strategy find the highest-quality solution when there are several different solutions?*

For the R-ratio heuristic agent, it can be said: (i) The agent does not make a complete search, once heading in one direction it will not return to test other paths (a *depth-first* behavior); (ii) time spent by the agent is small and decreases as the search gets to an end; (iii) it is not demanding in terms of consuming computational resources, given that there is no need to save information from previous states; and (iv) there is no guarantee that the agent will find the optimal solution, but given a final feasible solution is obtained, the search strategy will maintain the agent very close to it.

To overcome the limitations brought by the incomplete search strategy taken by the R-ratio agent, Rodriguez and McTague (1997) suggested multiple runs with different values for the α and β parameters used in each run. Given the very low number of iterations taken by the R-ratio search strategy to find a final state on each run, the practical results obtained by their suggestion revealed very promising. After several runs, the best solution will be the one with the highest objective function value among the feasible final states.

The R-ratio agent replaces one regime from the previous state by another that offers higher feasibility levels and minimum reduction in the objective function value. It is like expanding to a more promising node in the tree search. Basically the heuristic function tries to minimize the estimated cost to reach the goal state. The R-ratio search is not based solely in this kind of strategy, also known as *best-first-search*, or *greedy search*. But it resembles the behavior expected from greedy searches approaches.

A greedy search minimizes the estimated cost to reach the goal, and thereby cuts the search cost considerably. But it is neither optimal nor complete. A slightly different approach is used by the A* search (Russel and Norvig, 1995), which follows a minimum cost path that results from adding two different costs: the cost to get to the state and the cost to get to the goal state. The completeness and optimality of the A* search can be proved.

Given that the R-ratio strategy already starts with the optimal unconstrained integer solution, generally an unfeasible solution for the constrained integer version of the problem, the logic behind the A* search does not apply to the principles followed by the R-ratio heuristic. But there is one similarity: like the A* search, cost formed by the “cost from the initial state” plus the “cost to the final state”, the R-ratio deals with the “benefit of lowering the infeasibility level and getting close to the final state” divided by the

“cost of reducing the objective function value of the present state”. Both approaches base their movements on proxies of total costs and benefits.

Therefore, it can be said that the R-ratio has some of the characteristics of a greedy search, when it cuts the search cost considerably, and also some of the characteristics of the A* search. It can also be said that the R-ratio heuristic, although developed intuitively with no support from the Artificial Intelligence Theory, has included several of the concepts introduced by two relevant AI references (mainly Nilsson, 1982; and Russel and Norvig, 1995).

Performance evaluation

Evaluations of the R-ratio heuristic presented in this paper are based on results obtained from tests with 9 different problems. The evaluation tried to offer answers to the four main questions proposed by Russel and Norvig (1995):

- i. does the strategy guarantee a solution when there is one? (completeness);
- ii. how long does it take to find a solution? (time complexity);
- iii. how much memory does it need to perform the search? (space complexity); and
- iv. does the strategy find the highest-quality solution when there are several different solutions? (optimality).

Efficacy is measured by the proximity to the optimal solution of the non-integer linear programming. *Efficiency* is measured by means of the concepts penetrance and space complexity. The penetrance, P, according to Nilsson (1982) of a search is “the extent to which the search has focused toward a goal, rather than wandered off in irrelevant directions”. It is defined as

$$P = L / T$$

where

- L is the length of the path found to the goal (total number of iterations) and
- T is the total number of nodes generated during the search.

Adapted to the R-ratio search, T is the total amount of regimes evaluated in the set of non-selected regimes. Considering that each visit to the set of non-selected regimes has to calculate the R-ratio for every regime in the set, the number of evaluations in each iteration becomes:

$$\begin{aligned} 1^{\text{st}} \text{ iteration } & (N - U) - 1 \\ 2^{\text{nd}} \text{ iteration } & (N - U) - 2 \\ 3^{\text{rd}} \text{ iteration } & (N - U) - 3 \end{aligned}$$

$$\dots \\ n^{\text{th}} \text{ iteration } (N - U) - n$$

where

- N is the total number of possible management regimes in the problem (integer variables), and
- U is the total number of management units.

Also, let L' be the number of iterations visiting the set of non-selected regimes:

$$L' = L - 1 - \frac{(L - \alpha)}{\beta}$$

And, then, the total amount of regimes evaluated in the set of non-selected regimes along the search becomes:

$$T = \sum_{n=1}^{L'} ((N - U) - n) = (N - U)L' - \frac{L'(L' + 1)}{2}$$

Space complexity, C, evaluates the maximum number of states to be investigated by the agent. It is calculated multiplying the maximum number of iterations by the maximum quantity of possible states in each iteration. For the R-ratio search, the maximum number of iterations is the result of adding the total number of possible visits to the set of non-selected regimes plus the number of visits to the set of discarded regimes. In the set of non-selected regimes, the maximum number of visits the agent can make is equal the total number of regimes in the problem. The amount of visits to the set of discarded regimes depends on the values of α and β . Therefore, space complexity becomes:

$$C = (N + \frac{N - \alpha}{\beta} + 1) (N - U)$$

RESULTS

Table 1 presents some of the characteristics of the 9 problems used to evaluate the R-ratio forest scheduling heuristic search. Problems vary in terms of number of binary 0-1 decision variables, number of forest management units, number of periods in the planning horizon and periodical minimum volumes. Table 1 also presents three optimal objective function values, one for the continuous unconstrained, one for the continuous constrained, and one for the integer constrained versions of each problem. Reasonable amounts of time and computing resources were made available for the branch-and-bound algorithm to produce optimal solutions. For problems 5 to 9, though, the algorithm reached its limitations before finding an acceptable solution.

Several different strategies, varying the R-ratio α and β parameters generated a reasonable large set of good solutions. Table 3 reveals that for the two problems with tighter

Table 1—Dimensions and characteristics of the test problems

Problem Number	Number of Integer Decision Variables	Number of Forest Management Units	Planning Horizon (periods)	Minimum Volume Constraint (m ³)	Maximum Objective Function Value		
					Unconstrained formulation	Constrained formulation with continuous variables	Constrained formulation with integer variables
1	100	20	21	5,000	217,372.00	207,450.11	204,329.70
2	155	30	21	8,000	297,930.00	280,508.50	278,439.40
3	288	32	21	18,000	3,588,282.89	3,576,333.68	3,573,442.50
4	288	32	21	19,000	3,588,282.89	3,578,599.27	3,576,446.43
5	2,584	152	15	10,000,000	275,057,822.00	248,999,599.00	—
6	2,584	152	15	12,000,000	275,057,822.00	253,164,365.54	—
7	605	70	15	4,000,000	95,058,613.00	90,216,190.94	—
8	17,620	2,102	15	115,000,000	3,569,538,192.00	3,496,948,750.45	—
9	17,620	2,102	15	121,000,000	3,569,538,192.00	3,491,891,500.45	—

production constraints, problems 2 and 9, the R-ratio heuristic search produced the highest number of final states with no feasible solutions, 43.3% and 34.9%, respectively. For the rest of the problems, integer feasible solutions were found in between 95.9%, best case, to 76.2%, worst case. Best strategies, i.e. the ones resulting in the highest objective function values, proved to be the ones maintaining the visits to the set of non-selected regimes in the range of 68% to 87%. This means that the intensity of re-introducing previously selected regimes (visitation to the set of discarded regimes) has to be maintained between 13% and 32%. The penetrance parameter

The R-ratio heuristic found integer solutions for all 9 problems. Measurements of how efficiently and optimally the R-ratio got solutions for these problems are shown in Table 3. Worst solutions, in terms of objective function value, highest and lower cost solutions, in terms of highest and lowest number of iterations to find a solution, respectively, resulted in objective function values very close to the best solution. Of special interest, is the fact that the lowest cost solutions present the highest objective function values.

Also shown in Table 2, is the level of optimality reached by the best solutions presented by the R-ratio heuristic search. Levels above 99.8% of the objective function value were found for the problems with known optimal solutions. And most of the levels above 99.1%, except for one, when compared to the optimal objective function values of the problems formulated with continuous variables.

Finally, Table 4 shows the performance results in terms of efficiently dealing with the level of complexity of the problem. An adequate measurement of the “worst scenario” ability of the R-ratio heuristic to focus on efficient paths to find a good solution is presented in Table 4. The measurement considers the number of nodes effectively expanded by the highest cost solution found by the R-ratio heuristic, in other words, the solution that took the largest number of iterations to produce a feasible solution, divided by the total number of possible nodes to be expanded, which expresses the level of complexity of the problem. The interesting point to make when the R-ratio method is applied to large problems, is that the largest the problem the smallest the need of the R-ratio to expand nodes, making it an interesting virtue of the approach.

CONCLUSION

For the tested problems, the R-ratio strategy to escape from local optimums generated feasible solutions in the

Table 2—Performance of the R-ratio search strategy - efficiency and optimality

Problem number	Solutions generated	Worst solution		Highest cost solution		Lowest cost solution		Best R-ratio solutions		
		Iterations	% of the Best	Iterations	% of the Best	Iterations	% of the Best	% of the unconstrained	% of the (continuous)	% of the (integer)
1	744	56	95.29	101	97.37	41	98.76	93.91	98.40	99.90
2	741	151	95.24	183	99.86	59	98.82	93.31	99.10	99.84
3	631	216	98.69	251	99.01	83	99.99	99.58	99.91	99.99
4	632	234	98.91	245	99.15	83	99.93	99.63	99.90	99.96
5	1607	2001	90.48	2456	95.73	1008	99.64	89.97	99.39	—
6	1001	1642	95.43	2564	96.06	887	99.93	91.77	99.71	—
7	6878	301	90.13	335	95.92	143	99.94	94.53	99.61	—
8	304	4201	99.28	5001	99.56	3599	99.95	97.81	99.84	—
9	252	5001	98.63	5001	98.63	3853	99.88	97.56	99.73	—

Table 3—Performance of the R-ratio search strategy - penetrance

Problem number	Solutions generated	Runs with no solutions		Replacements in the set of non-selected regimes		Regime evaluations (expanded nodes)		Penetrance
		#	%	#	%	#	%	
1	744	177	23.8	35	70.0	2,188	0.022857	
2	741	321	43.3	64	64.6	5,921	0.016719	
3	631	110	17.4	74	87.0	16,206	0.005245	
4	632	26	4.1	84	82.4	17,942	0.005685	
5	1,607	260	16.2	760	66.8	1,559,520	0.000729	
6	1,001	74	7.4	614	66.9	1,304,750	0.000704	
7	6,878	576	8.4	115	68.0	54,772	0.003085	
8	304	35	11.5	3,097	84.2	43,267,682	0.000085	
9	252	88	34.9	3,376	80.3	46,692,508	0.000090	

Table 4—Performance of the R-ratio search strategy - complexity

Problem Number	Highest cost solution (no. of iterations)	No. of nodes effectively expanded	Complexity	Highest Cost/Complexity Ratio (%)	Proportion of solutions close to the global optimum
1	101	8,080	10,213	79	76.2% within 4.7%
2	183	22,875	23,906	96	56.7% within 4.7%
3	251	64,256	82,752	78	82.6% within 1.3%
4	245	62,720	80,819	78	95.9% within 1.1%
5	2456	5,972,992	8,991,104	66	83.8% within 9.5%
6	2564	6,235,648	8,320,683	75	92.6% within 4.6%
7	335	179,225	336,453	53	91.6% within 9.9%
8	5001	77,605,518	307,601,676	25	88.5% within 0.7%
9	5001	77,605,518	307,582,278	25	65.1% within 1.4%

range of 0.5% from the optimal non-integer solution. Considering the two artificial intelligence performance indicators used to analyze the R-ratio heuristic – penetrance and complexity – the R-ratio heuristic proved to be very efficient, given its focus on low cost strategies to select path searches. Also, given the obtained results, the R-ratio can be recommended as an efficient approach to find very good initial solutions for the integer version of the forest scheduling model I type problem, especially for the large scale problems usually found in real world applications.

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IMPROVED SOLUTION TECHNIQUES FOR MULTIPERIOD AREA-BASED HARVEST SCHEDULING PROBLEMS

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ABSTRACT

Area-based harvest scheduling models, where management decisions are made for relatively small units subject to a maximum harvest area restriction, are known to be very difficult to solve by exact techniques. Previous research has developed good approaches for solving small and medium sized forestry applications based on projecting the problem onto a cluster graph for which cliques can be applied. However, as multiple time periods become of interest, current approaches encounter difficulties preventing successful identification of optimal solutions. In this paper we present an approach for elasticizing timber demand constraints, which lends itself to an efficient solution technique. It is also possible using this approach to examine trade-offs between objective value performance and maintaining demand constraints.

INTRODUCTION

Mathematical modeling has been frequently used for harvest schedule planning. This has allowed several regulations and requirements to be incorporated in the planning process. These regulations are generally incorporated as restrictions to a Linear Integer Programming model and often make the problem more difficult to solve.

Regulations limiting spatial disturbances have led to constraints, typically known as maximum area restrictions, limiting the size of clear cut areas (Thompson et al. 1973, Murray 1999). Several models using these constraints have been proposed over the years, but the model known as the Area Restriction Model (ARM) has been shown to deliver the most profitable harvest schedules (Murray and Weintraub 2002). Unfortunately the ARM has proven to be very difficult to solve computationally. Although several heuristics to solve this model have been proposed (Hokans 1983,

Lockwood and Moore 1993, Barrett et al. 1998, Clark et al. 1999, Richards and Gunn 2000, Boston and Bettinger 2001), exact methods have only recently been able to solve small and medium problem instances. One such method is that developed in Goycoolea et al. (2003), focusing on a strengthened formulation known as the Cluster Packing Problem. They were able to solve modest sized problems using a commercial integer programming solver for single period application instances. While solvability for multiple planning periods is possible, adding volume production restrictions creates significant complications for problem solution.

In this work we present an alternative way of structuring volume restrictions in order to restore most of the favorable properties of the single period Cluster Packing Problem. Application results are presented which demonstrate that near optimal solutions can be obtained quickly using the developed modeling approach.

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HARVEST SCHEDULING WITH SPATIAL CONSTRAINTS

The harvest scheduling problem consists of selecting which areas of a forest will be harvested in different periods. Different types of requirements can be added to the generated harvested schedules. One environmental constraint that is generally enforced limits the contiguous area that can be harvested in any period. These constraints are generally known as maximum area restrictions (Thompson et al. 1973, Murray 1999).

We will assume that the forest is divided into sectors whose area is smaller than the maximum area that can be harvested contiguously and we will solve the harvest scheduling model known as Area Restriction Model (ARM). We will also assume a green-up time of one period. Finally we assume that each sector of the forest can only be harvested once during the planning horizon and that some kind of smoothing constraints over the volume of timber produced are desirable. Our base ARM formulation will be the Cluster Packing Problem developed in Goycoolea et al. (2003).

CLUSTER PACKING HARVEST SCHEDULING MODEL

The Cluster Packing Problem uses geographic information system (GIS) based data to model the harvest scheduling model. This data partitions the forest into small units for which area, volume and harvest profit information is available. The area of each unit is generally smaller than the maximum clear cut size specified for the Maximum Area Restrictions, so some groups of adjacent units may be harvested together.

We will define the set of Feasible Clusters (Λ) as all groups of adjacent units whose combined area does not exceed the maximum clear cut size. All of these clusters will be generated a priori by enumeration. This can be done efficiently as the maximum area restrictions generally limit the number of units in a cluster to 4 or 5 (Goycoolea et al. 2003). We will say that two clusters are incompatible if they share a unit or if they are adjacent. Forbidding the simultaneous harvesting of incompatible clusters will assure compliance with the maximum clear cut restrictions. This requirement is modeled by Goycoolea et al. (2003) using maximal cliques to impose incompatibilities. These restrictions give the formulation integrality properties that make it relatively easy to solve. Almost all instances of the single period problem are solved to optimality in the root Branch & Bound (B&B) node by CPLEX 8.1.

Maximize	$\sum_{S,t} c_{S,t} x_{S,t}$	
subject to	$\sum_{S \in \Lambda(K)} x_{S,t} \leq 1$	for each maximal clique K and for each period t
	$\sum_{S,t \in u} x_{S,t} \leq 1$	for each unit u
	$x_S \in \{0,1\}$	for each cluster $S \in \Lambda$ and for each period t
where:		
	• $c_{S,t}$ is net present value of the profit of cluster S for period t	
	• $\Lambda(K)$ is the set of all clusters that intersect maximal clique K	

Formulation 1—Multi-period period cluster packing problem.

The multi-period version of the model allows harvesting over several periods, but only allows each cell to be harvested once in the planning horizon. This model is presented in formulation 1. In this formulation variable $x_{S,t}$ is 1 if cluster S is harvested in period t and 0 otherwise. The objective is to maximize the net present value of the profit associated with the harvest schedule. The first set of constraints is a strengthened version of the constraints that force compliance with the area restrictions by forbidding two incompatible clusters from being harvested in the same period. Finally the last two sets of constraints forbid units from being harvested more than once in the planning horizon and force the variables to be binary, respectively.

This formulation preserves most of the good properties of the single period formulation and is easily solvable, as the computational results will show.

The multi-period model can be complemented with different kinds of restrictions on the volume harvested in each period. The most common restrictions include the production smoothing volume constraints and upper/lower bounds over the volume production.

One typical restriction on the harvested volume is to require total volume in a period to be within $\pm\Delta\%$ of previous periods. This can be achieved by adding the following restrictions to the multi-period model for each time period $t > 1$:

$$\left(1 - \frac{\Delta}{100}\right) \sum_S v_{S,t-1} x_{S,t-1} \leq \sum_S v_{S,t} x_{S,t} \leq \left(1 + \frac{\Delta}{100}\right) \sum_S v_{S,t-1} x_{S,t-1}$$

where $v_{S,t}$ the volume harvested if cluster S is selected to be harvested in period t.

Other restrictions that are frequently applied are minimum and maximum harvested volumes. This can be achieved by adding the following restrictions to the multi-period model for each time period t :

$$L \leq \sum_S v_{S,t} x_{S,t} \leq U$$

where U and L are the maximum and minimum volume allowed to be harvested in each period.

For both types of restrictions it is common that one of the inequalities is active, and hence acts as a fractional generating cut on the LP polytope. This fractional generating effect causes solutions to the LP relaxation to have many fractions. Furthermore, these fractions are difficult to eliminate by variable fixing. As the computational results will show, this makes the problem very difficult to solve.

ELASTIC VOLUME CONSTRAINT MODEL

One technique that can be used to minimize the fractional generating effects of volume constraints is to use an elastic version of the constraints. An elastic constraint allows a violation of the restriction, but penalizes this violation in the objective function. In this manner the volume constraints will no longer act as strong cuts, and hence, will generate almost no new fractional extreme points to the LP polytope. This will restore practically all the integrality properties of the multi-period model without volume constraints. Elastic constraints have been successfully used in similar problems (see Ehrgott and Ryan 2003).

It is very difficult to find penalties that will lead to integer solutions that do not violate volume restrictions. For this reason it is a good idea to start penalizing before the restrictions are really violated. So, for example, if we wanted to solve the problem with $\pm 15\%$ production smoothing volume constraints⁵, we could add a $\pm 14\%$ production smoothing volume constraint⁶, allow violations to these constraints, and penalize their violation in the objective function. In this way, if we just keep the violations controlled (below 1%), we will be complying with our target 15% volume constraint.

In the following section we will describe the elastic constraints for the production smoothing volume constraints. The corresponding relaxations for the upper/lower bound volume constraints are analogous.

Maximize $\sum_{S,t} c_{S,t} x_{S,t} - \sum_{t>1} p_t l_t - \sum_{t>1} \bar{p}_t u_t$	
$\sum_{S \in \Lambda(K)} x_{S,t} \leq 1$	for each maximal clique K for each period t
$\sum_{S, u \in S} x_{S,t} \leq 1$	for each unit u in V
$(1 - \frac{\Delta_E}{100}) \sum_S v_{S,t-1} x_{S,t-1} - \sum_S v_{S,t} x_{S,t} \leq l_t$	for each period $t > 1$
$\sum_S v_{S,t} x_{S,t} - (1 + \frac{\Delta_E}{100}) \sum_S v_{S,t-1} x_{S,t-1} \leq u_t$	for each period $t > 1$
$x_{S,t} \in \{0,1\} \quad l_t, u_t \geq 0$	for each cluster $S \in \Lambda$ and for each period t
with $\Delta_E < \Delta$ and $\underline{p}_t, \bar{p}_t$ to be determined independently for each t	

Formulation 2—Multi-period period cluster packing problem with elastic volume constraints

If we add elastic volume constraints to the multi-period model, we obtain the following formulation:

SHAPE * MERGEFORMAT

Formulation 2. Multi-period period cluster packing problem with elastic volume constraints

INTEGER ALLOCATION

Although penalties can be easily adjusted to control volume constraint violations for the root B&B node, it might be very difficult to do this and get integer solutions. General purpose LP based heuristics tend to have problems generating solutions with small volume constraint violations. For this reason a custom integer allocation heuristic was developed. The heuristic fixes variables and re-solves the linear relaxation of the model while trying to account for any violations that are too big.

The elastic volume constraints are crucial for the performance of the heuristic. The fractional generating effect of the volume constraints makes it very difficult to develop an LP based heuristic for the strict volume constraint model. Fixing some fractional variables to integrality in this model generally ends in the appearance of an alternate set of fractional variables, making the integer allocation process very slow. This does not happen with the elastic constraint model as the fractional generating effect of the strict volume constraints is not present. On the other hand, if the penalties are big enough, the violations will probably be reasonably controlled. Some corrections of the violations are still necessary, but they are very few due to the penalties.

⁵ i.e. with $\Delta=15\%$ in the original model

⁶ i.e. with $\Delta_E=14\%$ in the elastic model

Table 1—Characteristic features.

Instance	# of cells	# of Feasible clusters	Total # of restrictions for 15 period model without volume constraints	Total # of variables for 15 period model without volume constraints
El Dorado	1363	21412	32938	321180
rand 12 by 12 t15	144	2056	1959	30840

Table 2—Multi-period model without volume constraints results

Map	Time periods	IP time [s]	B&B nodes	1 st sol under 1% time [s]	1 st feasible time [s]	1 st feasible gap [%]
El Dorado 15	12	720	30	448	173	6.58
El Dorado 15	15	147	0	101	77	3.02
ran 12 by 12	12	501	789	24	14	33.61
ran 12 by 12	15	524	732	32	19	38.32

COMPUTATIONAL RESULTS

Computational tests were run over two instances: a real forest in Northern California called El Dorado and a randomly generated square grid with 144 units. Table 1 shows a summary of the problem characteristics.

Multi-period applications containing 12 and 15 periods where tested for both instances. The runs were made on a Pentium 4 2.0Ghz PC with 2.0 Gb of RAM running Linux. CPLEX 8.1 was used as the MIP solver and problem generation and heuristics were programmed in C++.

Multi-period model without volume constraints

Table 2 shows computational results for the multi-period model without volume constraints. A time limit of 4 hours was imposed, but for all instances it was possible to declare optimality long before that time limit. The first two columns show the instances characteristics. Columns 3 and 4 show the time and B&B nodes needed to declare optimality. Finally the last three columns show information regarding integer feasible solutions found before declaring optimality. Column 5 shows when the first solution with an LP gap⁷ of under 1% was found and columns 6 and 7 show the time the first feasible solution was found and its LP gap.

The integrality properties of this model help CPLEX 8.1 find feasible solutions very quickly and also declare optimality in little time.

Production smoothing volume constraint model

Table 3 shows the results for the production smoothing volume constraint model as solved directly by CPLEX 8.1. All tests for this table were run for 8 hours. The format of table 3 is similar to that of table 2. Additionally column 3 shows the level used for the volume constraints. As optimality could not be declared, columns 5 and 6 show the time the best feasible solution was found and its LP gap. Finally column 4 shows the total number of B&B nodes processed in the allotted time. A dash (-) indicates that a feasible solution with the required characteristics was not found.

It can be seen that CPLEX has a lot of trouble finding integer solutions. Although eventually it does find good solutions for El Dorado, computational effort is significant. No integer solutions are found for the grid instances.

Production smoothing elastic volume constraint method

Table 4 shows the results for the elastic constraint method. This method is essentially B&B over the multiple penalties elastic constraint model with constraint branching plus the integer allocation heuristic.

⁷ gap=(obj_best_lp - obj_ip)/obj_ip*100, where obj_best_lp is the greatest linear relaxation optimal value among the B&B nodes to be processed. obj_ip is the objective value of the particular integer feasible solution.

Table 3—Volume Constraint Model Results

Map	Time periods	Δ	B&B nodes	Best solution time [s]	Gap [%]	1 st sol under 1% gap [s]	1 st feasible time [s]	1 st feasible gap
El Dorado 15	12	10%	2133	18606	1.47	—	18606	1.47
El Dorado 15	15	10%	1575	18315	0.83	10839	10839	1.00
ran 12 by 12	12	10%	388	—	—	—	—	—
ran 12 by 12	15	10%	388	—	—	—	—	—
El Dorado 15	12	15%	2087	11211	0.50	10719	2323	1.51
El Dorado 15	15	15%	2067	20733	0.59	20274	20274	0.77
ran 12 by 12	12	15%	634	—	—	—	—	—
ran 12 by 12	15	15%	342	—	—	—	—	—

Table 4—Elastic Volume Constraint Method Results

Map	Time periods	Δ	B&B nodes	Best solution time [s]	Gap [%]	1 st sol under 1% gap [s]	1 st feasible time [s]	1 st feasible gap
El Dorado 15	12	10%	23	5555	0.41	1706	1706	0.43
El Dorado 15	15	10%	13	12541	0.44	4307	4307	0.45
ran 12 by 12	12	10%	75	5059	3.43	—	663	8.70
ran 12 by 12	15	10%	25	13856	4.52	—	614	14.42
El Dorado 15	12	15%	18	12216	0.30	1160	1160	0.33
El Dorado 15	15	15%	13	9916	0.29	2387	2387	0.34
ran 12 by 12	12	15%	199	9684	2.29	—	312	5.07
ran 12 by 12	15	15%	20	9124	4.97	—	504	7.99

The format of table 4 is the same as table 3 with the exception of the meaning of Δ and how the gaps are calculated. Δ corresponds to the strict volume constraint we are trying to comply with. Again we use $\Delta_E=(\Delta-1)\%$ and allow only 1% violation to solve the exact volume constraint with level $\Delta\%$. LP gaps are calculated with respect to the LP solution of the corresponding exact $\Delta\%$ volume constraint model, so they can be compared to the gaps reported in table 3.

Penalties for each constraint are set independently so that the root LP has less than 1% violation, but they are then kept fixed in the B&B tree. A time limit of only 4 hours, instead of 8, was used for these tests.

Although with this method fewer B&B nodes are processed, we can get good solutions quickly for El Dorado

and we can also get integer solutions for the grid instances quickly. However, their quality is not good. It should be noted though that the grids were purposefully generated so that it is very difficult to get integer solutions that comply with the volume constraints tightly. Thus, large gaps between the IP and LP solutions for the grid cases are expected. If we compare these results with table 3, we see that the elastic constraint method is much faster than the strict volume constraint model. Integer feasible solutions with similar objective values are found up to 150 times faster⁸ with this method.

CONCLUSIONS

By eliminating the fractional generating effect of the strict volume constraints, it is much easier to obtain integer feasible solutions. For this reason the elastic constraint method allows good solutions to be obtained much earlier

⁸ CPLEX was run for 24 hours for the strict volume constraint model for the ran12by12 instance with 15 periods. Only one solution with a 9% gap was found after 22 hours.

than when solving the strict volume constraint model directly.

It should be noted also that restrictions on harvested volume are generally guides instead of strict requirements, so small violations would likely be acceptable. It is clear that allowing these small violations (for example by allowing violations slightly over 1% of the 14% volume constraint) will give superior results. This provides yet another reason for not using strict volume constraints.

During the computational analysis, it was found that the integer allocation heuristic worked better when the initial LP had little or no violations of the target volume constraints. Because of this, it might be useful to adjust penalties each time a volume restriction is violated in the B&B tree. This would also guarantee that integer solutions found in leafs of the B&B tree would comply with the target volume constraints. We are currently implementing this dynamic adjustment of penalties to be added to the B&B based integer allocation method.

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EXTREME POLICIES MODELED WITHIN THE LANDSCAPE MANAGEMENT POLICY SIMULATOR (LAMPS)

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ABSTRACT

Several variations on the current behavior of four major landowner groups in the Coast Range of Oregon were simulated using the LAMPS model. The simulation of current and future behavior is termed the Base Case, and assumptions regarding this behavior were derived from numerous meetings with landowner groups associated with the management of Coast Range forests. The extreme policies we model are deviations from the Base Case: limit the maximum clearcut size to 40 acres; set a minimum harvest age of 80 years; assume that entire Coast Range forests are managed by a single landowner group. Results show that minor reductions in harvest levels and net present value are projected when the 40-acre maximum clearcut size is assumed. When the 80-year minimum harvest age is assumed, major reductions in both harvest levels and net present value are projected from Base Case levels. Significant increases are projected for both harvest levels and net present value when we assume that the entire Coast Range is managed by either industrial or non-industrial landowners. These results may follow intuition, but until now have not been quantified for such a large area and long time frame.

INTRODUCTION

The Landscape Management Policy Simulator (LAMPS) was developed within the CLAMS project (CLAMS 2003) to evaluate alternative forest management policies within the Coast Range of Oregon. The Coast Range analysis area of CLAMS contains about 2.8 million ha of land, spanning the area from the Columbia River south to the northern edge of the Siskiyou National Forest, and from the Pacific Ocean east to the Willamette River. The area contains a patchwork of land ownerships, most notably the Siuslaw National Forest, a significant portion of the of the Bureau of Land Management forests in Oregon, the Tillamook State Forest, several large industrial tree farms, and 400,000 ha of small, non-industrial private forestland.

LAMPS was initially designed to enable the simulation of the “Base Case” forest management strategy of four

major landowner groups: federal, state, industry, and non-industrial private. Over the past five years, 75-100 meetings with industrial, federal and state stakeholders were held to determine their current and future management intentions and to assess whether the LAMPS simulation process was adequately modeling their behavior. In addition, surveys of industrial and non-industrial management behavior, conducted by the Oregon Department of Forestry, provided valuable information regarding the behavior of these ownership groups.

In addition to modeling the Base Case, much of the CLAMS modeling work over the past five years has been devoted to modeling minor variations to these policies. This work has been guided by the Oregon Department of Forestry and the Oregon Board of Forestry. Emphasis has been placed on understanding the impacts of potential changes to policies, to allow both managers and policy makers to think through the policies prior to making

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decisions. LAMPS simulations along with subsequent geographic information system (GIS) analysis provide stakeholders with a spatial perspective on forest policies, which should supplement the typical tabular analyses that describe potential harvest levels and acres treated for various forest policies.

This research was aimed at exploring unfamiliar areas of the solution space that might be considered extreme points in the solution space. The policies modeled here are neither Law, nor likely to be implemented any time soon, if ever. They include a major diversion from the maximum clearcut size allowed on private lands, a restriction requiring a high minimum average age of harvested stands on all lands, and an examination of the capability of the landscape to produce timber volume if one were to assume that a single landowner group managed the Coast Range using the current and future management assumptions contained in the Base Case policy scenario.

METHODS

LAMPS is a simulation model that allows one to simulate separately the policies of the four major landowner groups in the Coast Range of Oregon. Details of the processes and opportunities for devising alternative management policies in LAMPS can be found in Bettinger and Lennette (2004). Details regarding the mathematical structure of the LAMPS simulation processes can be found in Bettinger and others (2005). We next briefly describe the spatial database structure required for LAMPS simulations as well as a brief description of the scheduling processes for federal, state, industrial, and non-industrial management.

The level of spatial detail required for a scheduling process such as LAMPS is generally negotiated among planning teams. Within the CLAMS project, it was deemed important to maintain fine spatial detail to facilitate modeling of wildlife habitat and geomorphological processes. Therefore, the team decided to recognize aggregations of pixels that had the same vegetation structure, distance from the stream system, and land allocation. These basic simulation units averaged approximately 2 pixels in size. The number of original pixels available from a raster GIS vegetation database developed using a gradient nearest neighbor approach to classification (Ohmann and Gregory 2002) was in excess of 45 million. The number of basic simulation units modeled in LAMPS is about 23 million. Associated with each basic simulation unit were a number of forest structural conditions, including timber volume, average tree age, quadratic mean diameter, average log diameter, and

vegetation class. Management units were created by combining watersheds (developed using a 10 m digital elevation model) with land ownership boundaries and aggregated vegetation polygons (large areas of similar vegetation), and subsequent parcelization of the landscape based on the stream system and ridge lines. This process resulted in the development of approximately 441,000 management units. On average, each management unit contains about 50 basic simulation units.

Management units, containing land managed by a single landowner, can be aggregated up into either clearcut harvest blocks or interior habitat areas using a process based on the area restriction model presented by Murray (1999). The area restriction model is a concept related to the spatial aggregation of management units for spatial forest planning processes. Here, any combination of management units that are considered adjacent for planning purposes (sharing a point, line, or within some proximity of each other) can be combined for simultaneous treatment as long as the combined size does not exceed some threshold. Green-up periods, the time it takes regenerated trees in clearcut areas to reach a certain size, are used in conjunction with spatial scheduling rules to control the placement of activities across a landscape. For example, while we may control the maximum size of clearcuts with an area restriction model, we may also control the placement of subsequent clearcuts by preventing their placement next to previous clearcut until some time has passed (the length of the green-up requirement). Area restriction models have thus been used extensively to control the maximum clearcut size in tactical forest planning. They have also been used to build and maintain habitat for which habitat models suggest need be of a certain size (Bettinger et al. 2002).

Management units may also contain multiple land allocations associated with a single land owner. For example, some of the state management land allocations are based a distance from the stream system. In the case of state management, a single management unit may contain three or more land allocations. The level of forest management allowed is assigned at the land allocation level. For example, one land allocation may allow both clearcutting and thinning, partial cutting within riparian areas, and minimal residual legacy trees in regenerated stands. Another land allocation may only allow thinnings to occur, and no activity in riparian areas. The potential timber harvest volume (and hence net revenue) is assessed by determining the level of allowable activity for each basic simulation unit (based on the basic simulation unit's land allocation), and summed to the management unit level for scheduling of activities.

At a higher level of spatial aggregation, LAMPS recognizes land ownerships (federal, state, industrial, and non-industrial), each of which is simulated separately. And finally, “megasheds,” ranging in size up to about 0.65 million ha, are recognized. Given the amount of data tracked at the basic simulation unit level (timber volumes, land allocation, and others, and the status of each land allocation in each time period) and the type of computer available (one with 2 Gb RAM), this disaggregation of the Coast Range into reasonably sized megasheds was necessary. Results are then generated for each megashed, then aggregated to describe the impact of policies for the entire Coast Range.

LAMPS modeling processes

LAMPS utilizes a different modeling process for simulating the behavior of each landowner group. After attempts to understand the goals and objectives of each landowner group when viewed in aggregate (e.g., all of the industrial landowners in the Coast Range viewed as a single group), a modeling process was chosen to best represent those goals and objectives. For example, on federal land, under current policy, it is unclear whether an objective exists. A number of constraints were identified, such as (1) only a certain percentage of matrix land could be clearcut each year, (2) each watershed needed to contain a minimum percent of older forest prior to scheduling clearcuts within that watershed, and (3) clearcuts should be relatively small. Therefore, we use a Monte Carlo simulation to spatially simulate forest management activities over time on federal land, subject to the constraints. We also use a unit restriction model to control adjacency, as described in Murray (1999). State land management seeks to achieve the highest even-flow timber harvest volume over time, subject to several ecological constraints (related to achieving forest structural conditions, and maintaining a distribution of interior habitat areas). LAMPS uses binary search to simulate this behavior, and unit restriction adjacency to control clearcut sizes.

Industrial behavior is also modeled using binary search. Here, we noted that over the last 20-30 years, industrial landowners (as a whole) have tended to harvest a relatively even amount of timber each year, even though individual companies may be seeking to maximize other economic goals. In the industrial management simulation model, management units are blocked to create clearcuts that seek to fit a distribution of clearcut sizes using a dynamic deterministic process (Bettinger and Johnson 2003), which uses the area restriction model described in Murray (1999). The

non-industrial simulation process also uses this blocking approach to develop clearcuts of certain sizes, yet schedules activities using Monte Carlo simulation. The best we can gather from the behavior of non-industrial landowners is that their tendency to harvest is either based on timber prices (difficult to project a long way into the future) or landowner age (impossible to determine). The Oregon Department of Forestry developed some relationships that show the probability of harvest as a function of stand age, and we use these relationships in LAMPS to decide whether or not to harvest a management unit each time period.

A number of other aspects of management behavior are modeled in LAMPS. These were determined as important via our discussions with the landowner groups, and can be considered a brief description of the Base Case policy for the Coast Range (Table 1).

The extreme policies are modeled by changing some of the assumptions contained in the Base Case scenario. For example, to model the 40 acre maximum clearcut size policy, we simply limit all clearcuts in each of the simulation processes to a maximum of 40 acres. Previously, clearcuts were allowed to be as big as 120 acres. To model the 80-year minimum harvest age, all other Base Case policy assumptions were held constant while a minimum harvest age of 80 years was imposed on all ownerships. Previously under the Base Case, the minimum harvest ages ranged from 35-80 years, depending on the land allocation. To model the policies where we assume that the Coast Range is managed by a single landowner, we first specified that all of the land in the Coast Range was contained within one landowner group, then applied the management behavior described in the Base Case for that landowner group to the land. The only exception was that Congressionally reserved lands (wilderness areas) were maintained in federal ownership. Making this change in land ownership was relatively easy for industrial and non-industrial scenarios. The federal scenario was problematic - we could not identify late successional or riparian reserves on areas that (in the Base Case) were identified as industrial, non-industrial, or state land. State management behavior requires identifying land allocations as a function of distance from the stream system, which would require significant GIS work. Therefore, modeling all lands as if under state ownership was not pursued here. Further, in the forest industry scenario, the forest industry management intensities, which are generally higher on forest industry land in the Base Case, were applied to all lands (except those mentioned above that were not given a new ownership status).

Table 1—Major assumptions in the Base Case policy, by landowner group.

Assumption	Landowner group			
	Federal	State	Forest industry	Non-industrial private
Minimum harvest age (yrs)	50	45	35	35
Green-up period (yrs)	5	5	5	5
Maximum clearcut size (acres)	— ^a	— ^a	120	120
Riparian option ^b	1	2	3	3
Leave tree option ^c	1	2	1	1

^a Limited to the maximum size of a single management unit

^b Riparian options: 1 = No harvest within Oregon Forest Practices Act buffers, no harvest of hardwoods within 100 feet of a stream; 2 = allow partial harvest within Oregon Forest Practices Act buffers, yet no harvest of hardwoods within 100 feet of a stream; 3 = allow partial harvest within Oregon Forest Practices Act buffers.

^c Leave tree options: 1 = leave two trees consistent with the Oregon Forest Practices Act; 2 = leave 5 or 14 trees per acre per Oregon state lands forest plans.

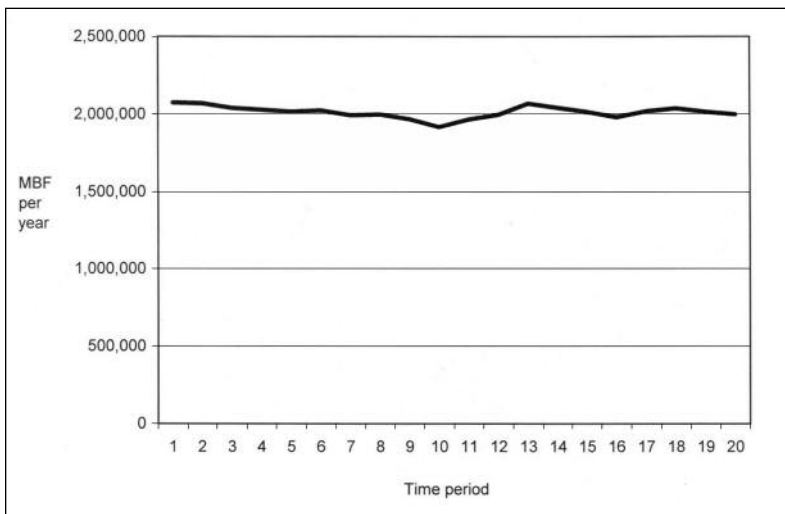


Figure 1—Projected timber harvest levels from the Base Case forest landscape policy for the Coast Range of Oregon.

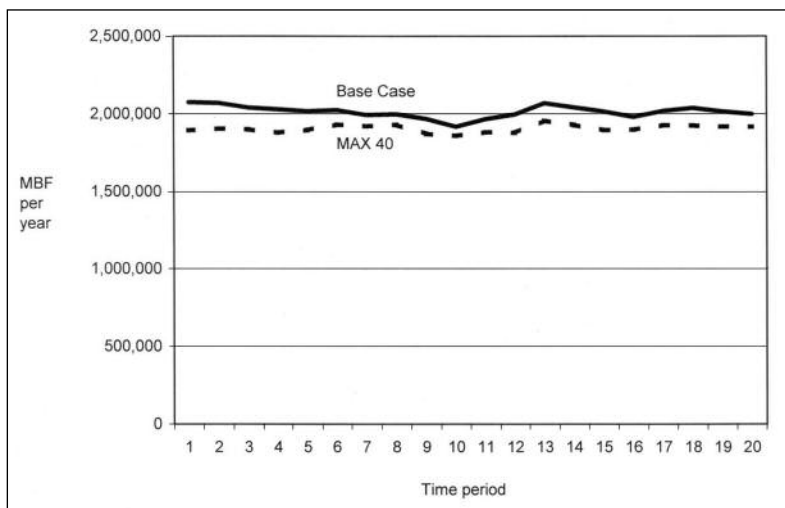


Figure 2—Projected timber harvest levels from the Base Case and the 40-acre maximum clearcut size forest landscape policy for the Coast Range of Oregon.

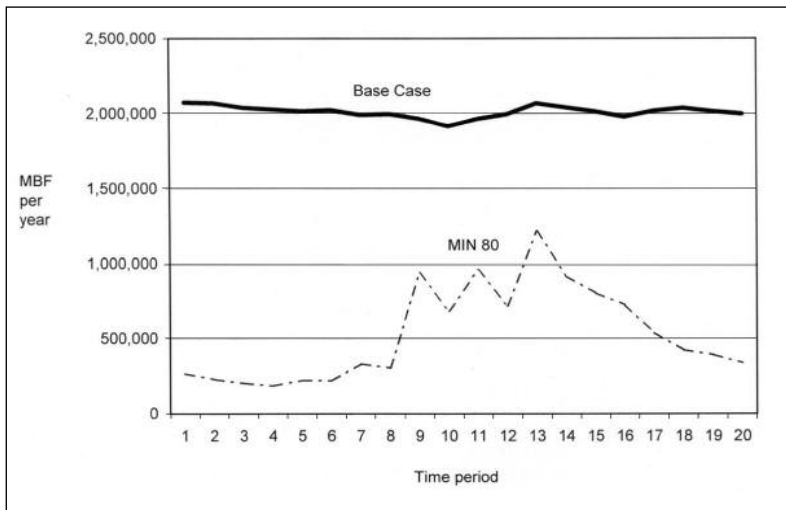


Figure 3—Projected timber harvest levels from the Base Case and the 80-year minimum harvest age forest landscape policy for the Coast Range of Oregon.

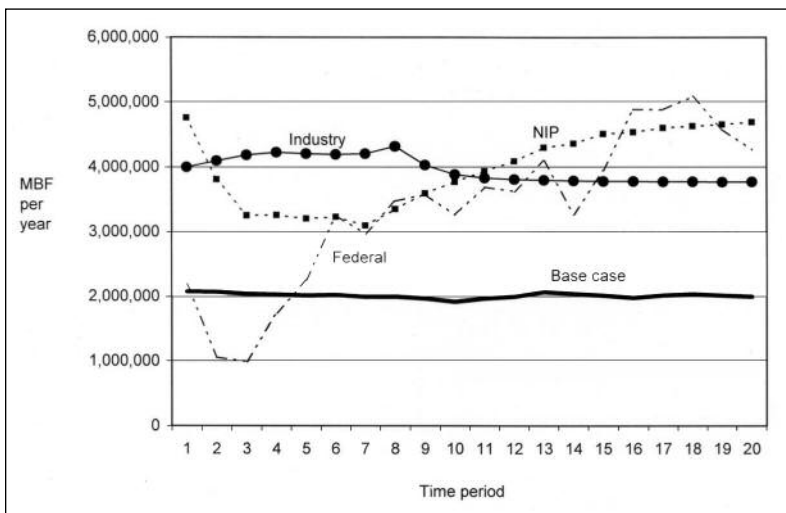


Figure 4—Projected timber harvest levels from the Base Case and the forest landscape policies related to single landowners for the Coast Range of Oregon.

RESULTS

Timber harvest volumes for the Base Case were projected to be around 2 billion board feet per year for the next 100 years (fig. 1), although only two of the landowner groups simulated had even-flow goals (forest industry and state). The net present value of the Base Case policies for the Coast Range is projected to be approximately \$12.765 billion. This takes into account harvest revenue, logging costs, site preparation costs, reforestation costs, and weed control and fertilization costs (where appropriate), and uses a 6% discount rate for each landowner group. When clearcut sizes are limited to a maximum of 40 acres, the harvest levels dropped slightly more than 5% (fig. 2), and net present value declined about 7%, to \$11.816 billion. One of the reasons that the maximum clearcut size did not have much of an effect is that the average clearcut size in the Base

Case was about 40 acres. Increasing the minimum harvest age to 80 years had a more significant effect on the Base Case (fig. 3), since much of the forest in this area of the Coast Range is significantly less than 80 years of age. The even-flow objective of the industrial land, given the harvest constraints in the first few time periods (due to the increased minimum harvest age), significantly constrained projected industrial harvest volumes. While timber harvest levels fell, on average, about 73% from the Base Case harvest levels, net present value fell almost 86%, to \$1.846 billion, due to the low harvest levels in the early time periods.

When the entire Coast Range was assumed to be under the management of a single landowner, some interesting results were noted (fig. 4). First, when simulated as being managed under an industrial management regime, projected harvest levels were significantly higher than the Base Case,

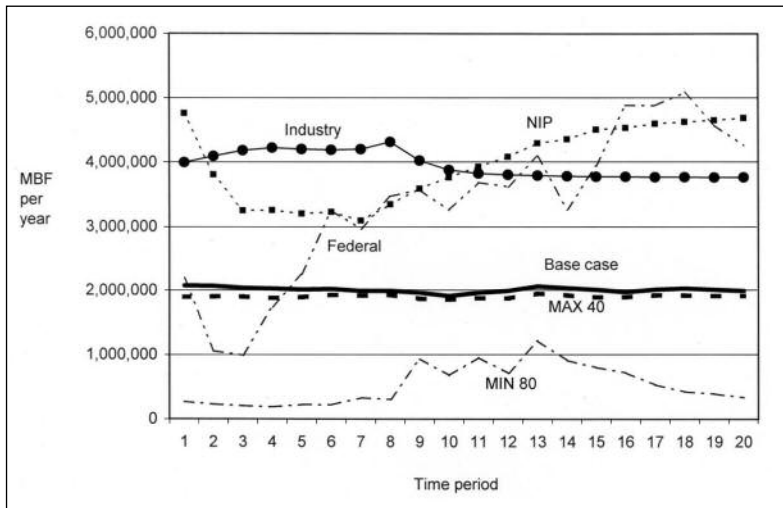


Figure 5—Projected timber harvest levels for all forest landscape policies for the Coast Range of Oregon.

as the older forests on federal and state land now facilitate higher near-term harvest levels, allowing for a high even-flow harvest level. Further, potential harvests on formerly state and federal lands are not as constrained by ecological goals as they were in the Base Case. Harvest levels were projected to be almost double the Base Case, and the net present value of the industrial ownership scenario was projected to be about 119% higher than that of the Base Case. The net present value of the non-industrial ownership scenario was projected to be about 74% higher than the Base Case, and harvest levels, while higher than the Base Case, fall from initial relatively high levels, then increase again in later time periods. We believe this to be a function of the probability of harvest process used in the non-industrial case, which is a function of the average age of the timber in each management unit. Here again, potential harvests on formerly state and federal lands are not as constrained by ecological goals as they were under the Base Case.

When the entire Coast Range was assumed to be managed under federal ownership, we find that projected harvest levels initially decline (from Base Case levels), then increase significantly in later time periods. The federal management scenario is not constrained by an even-flow goal, as are the forest industry and state management policies. The main constraint related to harvesting is that more 15% of a watershed needs to be in “older” forest before any clearcut harvesting can occur. Once this happens (after about time period 4), clear-cut harvests are only constrained by the 15% older forest goal, a limit on the total amount of clearcutting per time period (1%), and unit restriction adjacency constraints, thus projected harvest levels are very high in the later time periods, at times higher than any other scenario we modeled (fig. 4). In addition, all “federal”

lands that were not previously in federal ownership were modeled as matrix land allocations, so the true federal restrictions (related late successional reserves and riparian reserves) may have been underestimated here. The projected net present value, in fact, of the federal management scenario, is about 7% higher than the Base Case. Figure 5 shows a composite of all of the extreme policies modeled with the LAMPS simulation model.

DISCUSSION

LAMPS is a simulation model designed to assist managers and policy makers in thinking through potential forest landscape policies prior to implementation. It uses a hierarchical structure to model large-scale, long-term policies, and does so for all landowners contained in a landscape. The modeling framework is, of course, a simplification of reality. However, we have conducted numerous meetings with landowner groups who manage land in the Coast Range to determine the most appropriate course of action for modeling their behavior. Although validating such a complex simulation model is problematic, modeling current and future management behavior as close as possible to the actual behavior lends credibility to the results.

One of the major concerns of the LAMPS modeling process is the use of an even-flow goal on state and industry land. The even-flow goal significantly constrains harvest levels in some of the scenarios modeled. Standing timber volumes, in fact, generally increase over time on lands simulated with this goal. Higher total timber harvest volumes may be simulated if the even-flow goal was relaxed. Most of the simulations show a “bottleneck” period that constrains higher even-flow harvest levels. We are currently developing and testing processes to allow upward

deviations in even-flow harvest levels, leaving the constraining time period at perhaps lower harvest levels. These variable harvest levels will first ensure that the maximum even-flow volume can be achieved, then allow additional harvest without sacrificing volume from any even-flow constraining time period.

Neither the even-flow assumption nor the constraints modeled here as "extreme policies" (40-acre maximum clearcut size or 80-year minimum harvest age) are Law. The even-flow goal was obtained from evidence of recent landowner behavior. Therefore, it seemed to be an appropriate indicator of the behavior of two large landowner groups. Some might argue that in the past, industrial landowners in Oregon had the ability to use federal timber sales to buffer changes in timber markets. It remains to be seen whether this is still possible given the sharp, and recent, decline in federal timber sales. Therefore, the even-flow behavior modeled on state and industrial land may, in the future, change, and give way to a more erratic level of harvest based on maximization of economic or ecological criteria.

These extreme policies that we have modeled with LAMPS provide a perspective on a portion of the solution space that usually goes unexplored in policy analyses. More likely, when developing long-term strategic plans or evaluating the potential effects of new policies, a Base Case is modeled, and minor variations around the Base Case are examined, each reflecting likely changes to regulatory or organizational policy. We feel that by exploring other areas of the solution space, a more complete picture of the productive capacity of the Coast Range forests can be understood.

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A RELATIONAL DATA MODEL FOR THE GENERATION OF LARGE-SCALE FOREST SCHEDULING PROBLEMS

Silvana R. Nobre¹ and Luiz C. E. Rodriguez²

ABSTRACT

In Brazil, several pulp and paper companies manage large tracks of land with forest plantations. The management of these forests demands integrated database management systems. One of the functions of these systems is to provide organized information for linear programming harvest scheduling models. This paper suggests a relational data structure that facilitates the analysis, creation and storage of these models and results. Considering that users are not essentially experts in modeling and linear programming techniques, the relational model has to encapsulate complexities, to automate lots of calculations and to assume several consistency checks. Preferably these database and matrix generators have to provide a friendly environment to generate the model and to analyze the results. Advanced data modeling techniques were used to attend these goals. Basically, we describe: (i) the modeling techniques and required parameterization to represent the forest management regimes; (ii) the concept of “calculation batch” to encapsulate the linear programming routines; and (iii) the approach used to set together groups of parameters to define input data, different analysis scenarios and respective results. The approach presented in this paper develops a tool that integrates data modeling and optimization techniques contributed in Brazil for the adoption of non-trivial forest planning techniques.

KEYWORDS: Relational database, harvest scheduling, linear programming, information technology.

INTRODUCTION

The optimization techniques used in forest scheduling models are highly dependent on information technology. Brazilian foresters responsible for the forest scheduling of large pulp and paper companies have had difficulties dealing with database manipulation since they are not essentially experts in modeling and in mathematical programming techniques. Therefore, they often need IT support for making possible the use of mathematical optimization techniques.

These professionals often have to create flexible scenarios and usually demand efficient decision support tools. These demanded tools must encapsulate the complexities of large-scale forest scheduling problems, facilitating the analysis,

the creation and the storage of the parameters and the results produced by the several different scenarios studied.

Forest scheduling software ideally should be perfectly integrated to a relationally structured database. And integration, in such cases, means data, parameters and results directly read from and stored in the database. It is also desirable to make all results available to further analysis and interpretation along other information managed by other corporate systems.

The modeling data techniques suggested in this paper are intended to rationally store parameters and all data necessary to generate linear programming type I model matrices, as well as the results produced by the optimization

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process. The techniques, which make the system flexible and easy-to-use, are introduced in the following sections.

MODELING A FOREST SCHEDULING DATABASE – BASIC CONCEPTS

This paper considers that the forest scheduling problem can be modeled according to the model I type formulation presented by Johnson and Scheurman (1977). Its basic formulation can be stated as in Clutter and others (1983), considering the following quantities:

- N = number of forest units
- M = number of management regimes
- T = number of management periods in the planning horizon
- A_i = area of forest unit i
- X_{ik} = area of forest unit i assigned to management regime k
- D_{ik} = value (per unit of area) of management regime k in forest unit i
- V_{iktp} = volume (per unit of area) of product p harvested from forest unit i in management period t if management regime k is used
- $VMin_{tp}$ and $VMax_{tp}$ = minimum and maximum volumes of product p in period t

Then, the problem becomes:

$$\text{Maximize } Z = \sum_{i=1}^N \sum_{k=1}^M D_{ik} X_{ik} \quad (1)$$

$$\text{subject to: } \sum_{k=1}^M X_{ik} \leq A_i \quad (i=1,2,\dots,N) \quad (2)$$

$$\sum_{i=1}^N \sum_{k=1}^M V_{iktp} X_{ik} \geq VMin_{tp} \quad (t=1,2,\dots,T) \quad (p=1,2,\dots,P) \quad (3)$$

$$\sum_{i=1}^N \sum_{k=1}^M V_{iktp} X_{ik} \leq VMax_{tp} \quad (t=1,2,\dots,T) \quad (p=1,2,\dots,P) \quad (4)$$

The presentation of a relational database, flexible enough to generate forest models based on equations (1) to (4), is the main objective of this paper. Although used as the basis for the generation of the coefficients in the above model, a few adjustments in this relational model will easily allow for the consideration of more constraints, and even for the generation of model II type formulations.

Powerful database techniques were used to generate the relational database models described in section 3. Four

concepts have to be initially introduced for a better understanding of these techniques: (i) *scenario-setting parameterization*; (ii) *event-output decision-tree*; (iii) *calculation batch*; and (iv) *sequencing of activities in a single database*.

Scenario-setting parameterization

Seventeen different parameters are defined to support the generation of a forest scheduling model. Some parameters are numbers, such as interest rates, planning horizons, first year in the planning horizons etc. Parameters can also define event types, between events sequential rules, output types, and management regimes evaluation methods. Other parameters can yet be tables, such as: management costs, production costs, forest management units, events sequencing rules, production tables etc. The database was designed to make scenarios and parameters all related. That is, a single database where every new scenario and any previous analysis or scenario settings can be recovered altered and restored.

Event-output decision-tree

The diverse ways to manage a forest management unit, i.e. the alternative regimes, can be expressed in a decision-tree. The decision-tree is graphically represented through nodes and arcs. Nodes are the relevant events, which alter the forest production structure. Arcs can indicate what happens in between two events.

The initial node of the decision-tree is the last event occurred in the forest management unit, from which other events can occur and so forth. The decision-tree represents what can be done in a forest management unit along a given planning horizon, begins a few years before the beginning of the planning horizon and it can finish before or after the ending of the planning horizon.

The building of the decision-tree is a parameterization process. The parameters, defined by the user, determine the way the events are sequenced, and the length and quantity of possible regimes in the decision-tree. Figure 1 shows an example where two events are defined: clear-cut followed by sprouting (CS) and clear-cut followed by the renewal of the plantation (CR). In the example, the first event occurs three years before the beginning of the planning horizon, when a new rotation of the plantation sprouts from the stumps left by the clear cut.

The decision-tree depicted in Figure 1 was obtained after setting a few parameters in the database which mainly generated: (i) clear cuts followed by the complete renewal of the plantation, i.e., forest cycles of only one rotation; (ii)

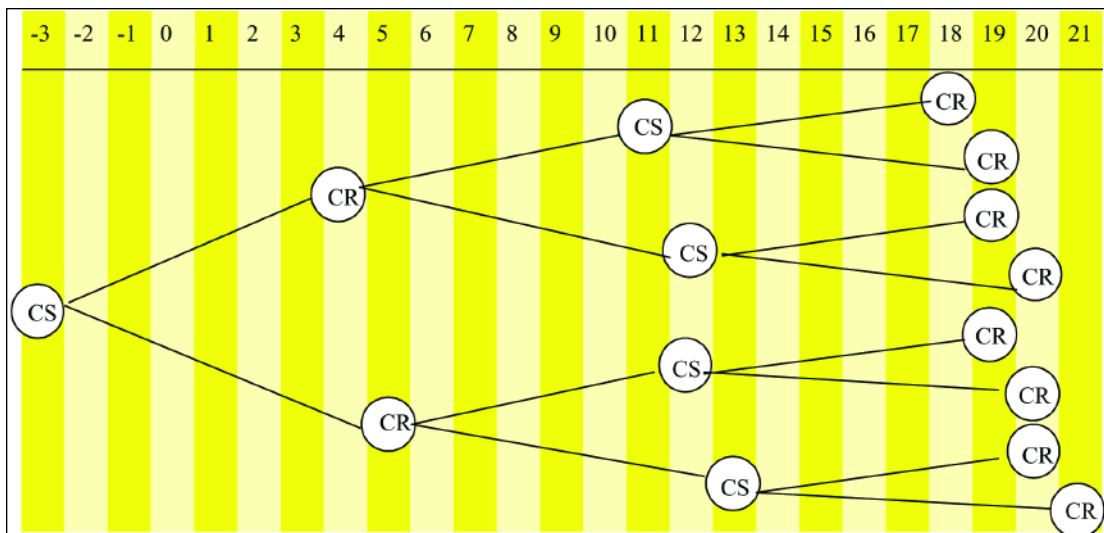


Figure 1—A decision-tree representative of possible regimes considering two relevant regimes: clear-cut followed by sprouting (CS) and clear-cut followed by the renewal of the plantation (CR).

coppice regeneration prescriptions, i.e., forest cycles of two rotations where the plantation regenerates from sprouting stumps after a first clear cut; (iii) forest rotations of either 7 or 8 years; and (iv) a planning horizon of 21 years.

Once the decision-tree is defined, the system determines the out coming consequences of the events along each branch. These outputs can be products, revenues, costs, measurable environmental impacts, or even demands. In a forest scheduling type I model, the most common outputs are usually the volumes or weights of certain products.

The sequence of several outputs, one for each node or point along the arcs of the decision-tree, is called *output flow*. Nodes and arcs are stored in the database, along with all needed data to calculate the output flow, so that each management regime can be completely evaluated. That includes forest age at each node and other essential data demanded by the calculation batch, which offers an environment to define programming sentences and other biometric routines that will produce the real output values.

The correct generation of the event-output decision-tree is crucial, given that the generation of the technical coefficients for the model I type forest scheduling matrix is totally dependent on this concept.

Calculation batch

A calculation batch is a sequence of calculation steps. Each calculation batch can be defined in order to satisfy the goals of a given scenario analysis. The batch is composed by a logical sequence of steps. There are four different step

types: (i) steps for the creation of temporary tables, (ii) steps for processing SQL statements, (iii) steps to define variables, and (iv) steps to define functions.

The steps that create tables simulate an environment where table subsets can be created from existing tables in the database. The user can further manipulate these subset tables on the following steps of the calculation batch. The SQL processing steps execute SQL sentences on any available table. And the variables and functions definition steps calculate output levels.

Throughout these steps, there is always a *target calculation* output to which a formula is assigned. Simple formulas can be used to calculate simple output quantities along the output flow. For example, in the statement “IF PW = 1 THEN RESULT:= EST_VOL”, the system checks if “PW” and “EST_VOL” are variables defined in other tables to finally assign the desired result. Complex formulas, involving several variables, internal functions and operators can also be defined, like the one below:

```

IF PW = 1 THEN BEGIN
  AGE1:= AGEINV * 12 ;
  AGE2:= AGE * 12 ;
  X1:= LN(G) * (AGE1 / AGE2) ;
  X2:= 1 - (AGE1 / AGE2) ;
  X3:= X2 * S ;
  B2EST:= EXP(X1 + B0 * X2 + B1 * X3) ;
  RESULT:= EXP(B2 - B3 / AGE2 + B4 * S + B5 *
  LN(B2EST)) ;
END
ELSE RESULT:=0;

```

Function definition steps are used to reference available system functions. The following example shows a call to the function that generates an event-output decision-tree.

[Function]
Generate Decision-Tree

Function definition steps might also need parameters, such as the one expressed below that calculates net present values (NPV). In this case, the parameter is a formula that indicates which and how output variables, in the output flow, are passed to the NPV function (where V_PW, V_SW and V_BL are values for pulpwood, sawn wood and bare land).

[Function]
Calculate NPV
[Formula]
 $V_PW + V_SW + V_BL - COST$

In fact, the calculation batch guides the process of generating the forest scheduling mathematical model. There are required steps that make the process standard, but the possibility of having user defined steps also makes the process very flexible.

Sequencing of activities in a single database

The set of required steps in the calculation batch can be grouped and sequenced as follows:

- Creation of the decision-tree for each forest management unit;
- Valuation of each management regime;
- Generation of the forest scheduling mathematical model coefficients;
- Preparation of the input data for the solver; and
- Conversion of the optimal solution produced by the solver into a forest schedule.

The user can prepare different calculation batches and evaluate several scenarios. The system allows for the creation of different decision-trees, and consequently different forest scheduling mathematical models which will generate different forest schedules.

At each step in the calculation batch, all involved elements are read and stored in the database. In order to give flexibility to the process, each step in the calculation batch must be independent from others. With this approach, which is referred in this paper as the independency principle, it is possible to stop and start the processing of the calculation batch at any step, and also to create intermediate steps without compromising the whole process (Figure 2).

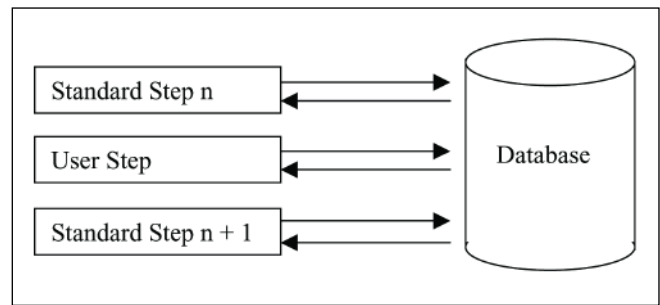


Figure 2—User steps can be included with great flexibility based in the independency principle used to design the database

The independency principle imposes the storage of intermediate results in the database, which are: generated decision-trees, output flows, information produced by the solver and final forest schedules. The main modeling techniques used to implement all four described concepts are presented in the next section.

MODELING TECHNIQUES

The most accepted and commercially used approach to project a database system is the Relational Model. A conceptual tool called Entity-Relationship Model (De Miguel and others, 2000; Korth and Silberschatz, 1995; Date, 1991; Setzer, 1990; DeMarco, 1989) is used in this paper to represent relational database structures. In this paper, simple E-R models are used to represent the logical relationships among parameters, intermediate results and final results.

Scenarios and Parameters

Each one of the seventeen types of parameters needed to generate the forest scheduling model has its own structure. All parameters have to be related to the *Scenarios* entity. A modeling technique called *generalization* was used to deal with this situation.

A generalization is used to emphasize similarities among entities and to hide their differences. The entity grouping the similarities is defined at a higher level, and the entities representing differences are defined at a lower level. The higher level entity holds the common attributes, and the lower level entities hold the specific attributes. Then the generalization becomes the relationship between the higher level entity and lower level entities (Setzer, 1990).

An entity named *ParameterSet* was created at a higher level to relate parameters and scenarios. The lower entities are the seventeen different types of parameters. Actually, when this model is implemented, the entity *ParameterSet*

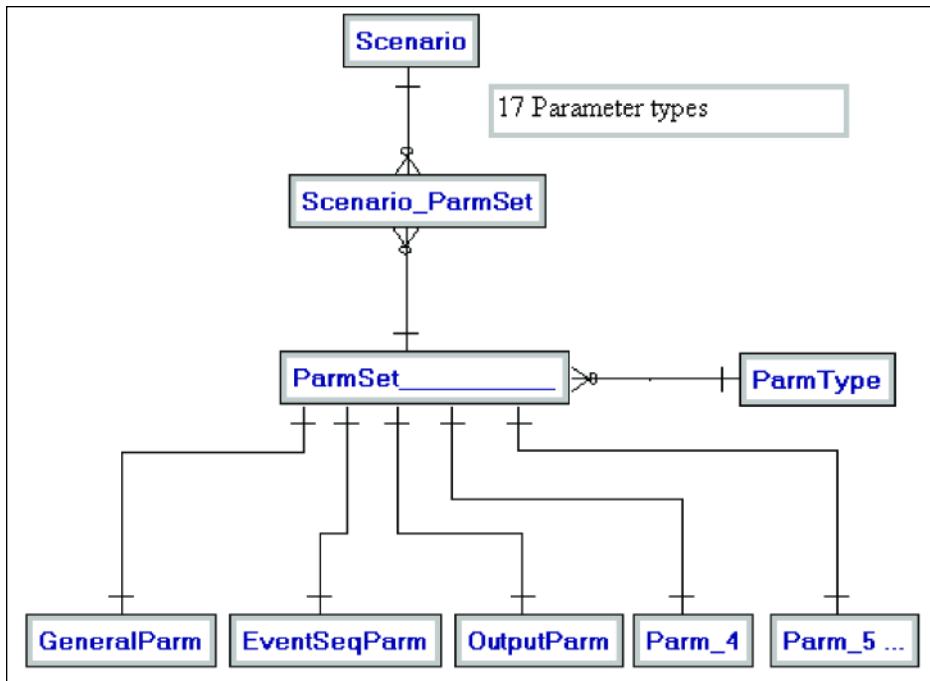


Figure 3—Application of the generalization technique to model the relationship between scenarios and parameters.

becomes a table holding all parameters set by the user. Each record in the table refers to one single parameter. Each lower entity becomes one or more tables holding the rest of the attributes of this single parameter. For example, a table of management costs is a parameter with its identification code, name and general description stored in a higher entity. The actual management costs are stored in a lower entity with a much more adequate structure to hold cost tables.

For a given analysis, one scenario refers to a single set of different parameters. And one single parameter, once set, can be used by different scenarios. This is known as a many-to-many relationship between the entity ParameterSet and Scenario. It demands one intermediate table called Scenario_ParmSet in which the relationships between scenario and parameter are registered.

The user can create several different values for each parameter type, and later associate each parameter value to a specific scenario. Figure 3 shows the E-R generalization technique applied to relate the ParameterSet and Scenario entities.

Event-Output Decision-Trees and the Output Flows

Each node must be related to the previous node to adequately represent the event-output decision-tree. The only node that does not have an associated previous node is the initial node. A database technique called *auto-relationship*

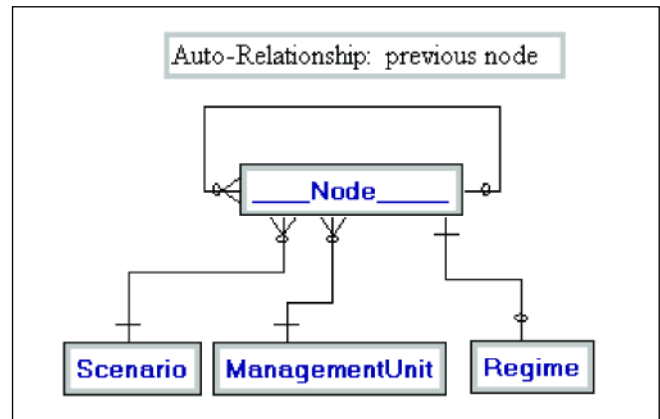


Figure 4—Application of the auto-relationship technique to model the decision tree of management regimes.

was used to model the association of an entity with itself and to represent the relationship among nodes in the event-output decision-tree.

One set of nodes forming an event-output decision-tree must be related to one scenario and one management unit. In fact, each node ends up related to one single management unit and one scenario.

The final node in each branch of an event-output decision-tree, i.e. the one finishing a sequence of events, relates specifically to the entity *Regime*. It is not necessary to relate

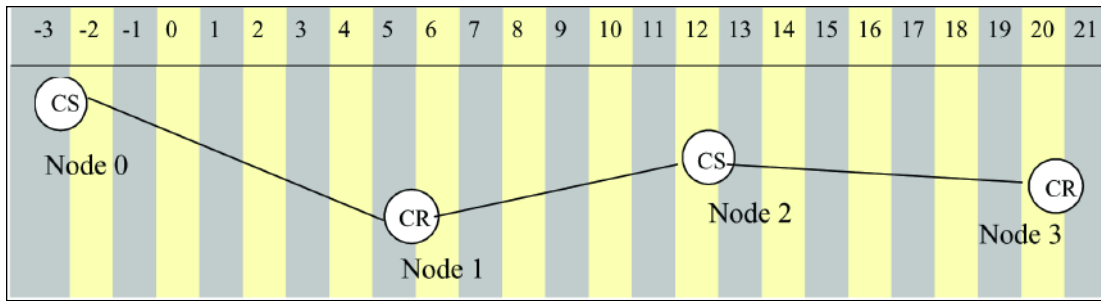


Figure 5—One of the branches the decision tree representing a management regimes.

Table 1—Records related to the output flow generated by the management regime shown in Figure 5.

Scenario	Forest Unit	Arc	Year	Age (years)	L_PW (m ³ /ha)	V_TC (US/ha)	L_WS (m ³ /ha)	V_FC (US/ha)
01	01	0 – 1	1	4	120	203	210	420
01	01	0 – 1	2	5	147	293	210	511
01	01	0 – 1	3	6	177	21	210	616
01	01	0 – 1	4	7	210	21	210	735
01	01	0 – 1	5	8	240	2030	215	840
01	01	1 – 2	6	1	0	1080	215	0
01	01	1 – 2	7	2	0	388	215	0
01	01	1 – 2	8	3	90	208	215	315
01	01	1 – 2	9	4	121	203	215	427
01	01	1 – 2	10	5	150	203	215	525
01	01	1 – 2	11	6	180	21	215	630
01	01	1 – 2	12	7	215	1050	215	749
01	01	2 – 3	13	1	0	1080	220	0
01	01	2 – 3	14	2	0	388	220	0
01	01	2 – 3	15	3	92	208	220	322
01	01	2 – 3	16	4	123	203	220	434
01	01	2 – 3	17	5	152	203	220	532
01	01	2 – 3	18	6	188	21	220	658
01	01	2 – 3	19	7	220	2030	220	770

this entity with all nodes representing it. Knowing the last node is sufficient to identify all others because of the auto-relationship technique utilized to represent the output flow. Figure 4 depicts the E-R model used to design the event-output decision-tree logical structure.

With the structure presented in Figure 4, it is possible to easily build the output flow of any management regime predicted for any management unit in a given scenario. As an example, let's consider only one of the generated regimes, for a certain forest management unit, presented in Figure 1,

and now depicted in Figure 5. Let's also define the following outputs: (i) production level of pulpwood L_PW; (ii) total cost value V_TC; (iii) 7-year old wood stock level L_WS; and (iv) value of the fixed carbon on wood V_FC.

The regime's output flow illustrated in Figure 5 would generate the records reported in Table 1. Output flows are created to each scenario, and column values are calculated according to the parameters and functions defined in the calculation batch.

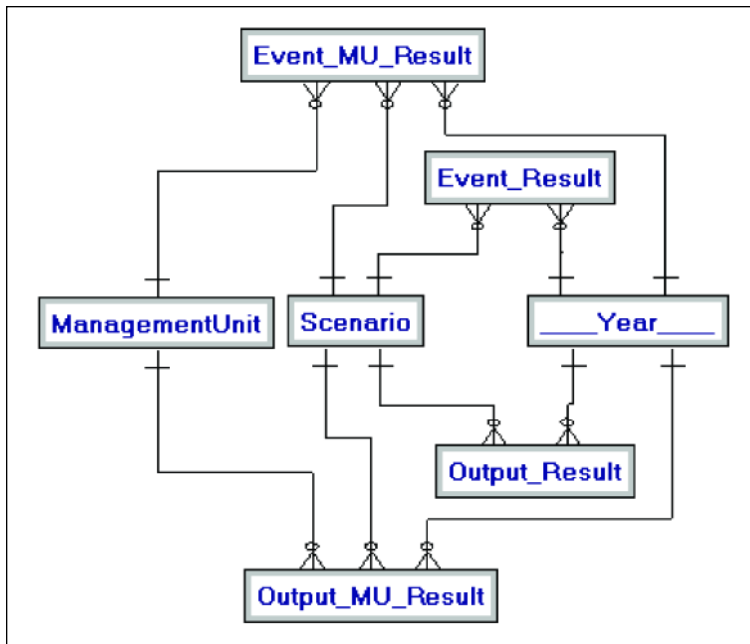


Figure 6—The database relational model to store the results produced by the solver.

When completely calculated, the output flow is the basis for the generation of the forest scheduling matrix of output coefficients. It is also the key element to calculate each regime's value and objective function coefficients. Parameters are defined by the user to inform the system which outputs will be used to evaluate the regimes. For example:

$$\text{Regime's Value:} = V_PW + V_BL - V_TC$$

The user can also inform what outputs will be used as constraints in the linear programming model.

Results of the optimization

When the matrix is calculated and generated, it is sent to the Solver. The results are saved by variable type in the database. The decision variables, that is, chosen regimes are saved on the regimes' table. Actually, the chosen area is saved on the regimes' table.

As the system creates accounting variables to each one of the constraints, these values are saved on correspondent tables. The events' annual quantities are saved on the result tables (event type); the outputs annual quantities are saved on the result tables (outputs type).

The system must interpret the Solver's results; in other words, it needs to determine the events that will happen in

each forest management unit from the regime chosen by the Solver. The results of this interpretation will also be saved on tables, as figure 6 illustrates.

Calculation batch

The calculation batch is also data, and as an entity it will be treated in the database. At the moment of the calculation, a calculation batch is applied to a scenario. The batch is entirely independent of the scenario. The user can build as many calculation batches as necessary and apply them to any scenario.

All steps in a calculation batch, required and user defined, and of any type, are saved on a table. Making a calculation batch is simply a matter of choosing instructions from this table and ordering them in a correct execution sequence.

Due to the independence principle, it is possible to create batches that execute only parts of the process. For example, it is possible to initially create a batch that builds the linear programming matrix from the calculated output flow, and to send the matrix coefficients to the solver with one set of constraint levels. Altering only the last few steps in the calculation batch makes it possible to analyze several different sets for the constraint levels. The users can then produce several rapid simulations, store the results and generate as many optimizations as necessary.

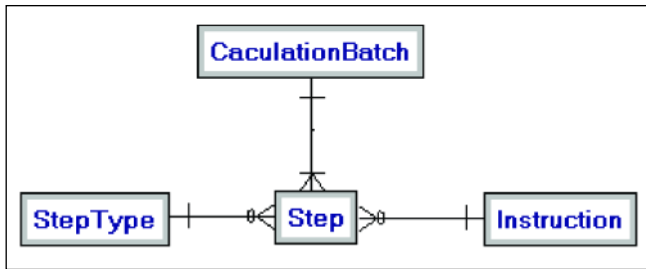


Figure 7—The database relational model to store the calculation batch.

CONCLUSIONS

This paper presents a method to model, in one single relational database, the four essential tasks generally needed to model any forest scheduling problem. The four tasks are: parameterization of different scenarios, generation of several management regimes in a decision-tree structure, calculation/evaluation of outputs and final report writing. The definition of a well defined relational structure in one single database encapsulated many of the complexities, and turned possible the development in Brazil, of a large scale forest decision support system (DSS) based on mathematical scheduling optimization techniques.

The system is being used by three large Brazilian pulp mills to manage their forests. Usually, before the acquisition of the DSS built after principles presented in this paper, weeks were needed to develop the complete formulation of the LP problem. Nowadays, formulations with hundreds of thousands of variables are generated, solved and reported in short periods of time varying from two to four hours. A normal solution for problems with approximately four hundred forest units, and one hundred alternative management regimes per forest unit, takes approximately two hours, depending on the computer memory and processor.

Many of the users of forest management decision support systems in Brazil do not have any formal training in mathematical programming techniques, and even more rarely in database management. The approach used to develop the database structure not only turned possible to hide several unnecessarily difficult data management tasks but also generated a consistent environment that helps to avoid information degeneracy, despite the training level of the user.

Rid of undesirable complexities, the user finds the process of using the system less challenging and more educational. The process ends up offering an environment to check for intermediate results, to visualize the output flows

and to analyze the impacts of altering the level of the several constraints. Basically, the user becomes really capable of analyzing several different scenarios because it becomes much easier and less time consuming.

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SHORT-TERM HARVEST SCHEDULE SENSITIVITY TO FUTURE STUMPAGE PRICE ASSUMPTIONS

Eric S. Cox¹

ABSTRACT

Forest planning models have long been used as an analytical tool for providing information to facilitate effective decision making and planning. Inherent to the financial analyses conducted with these models are assumptions concerning key financial parameters contained in the model such as discount rates, future costs, and future stumpage prices. While projecting timber prices into the future with any accuracy is an extremely difficult exercise, price forecasting is nonetheless a critical part of forest planning analyses. The ramifications of these assumptions over a long planning horizon can be significantly different product flows, activity levels, and cash flows. The purpose of this study is to investigate the impact of different future stumpage price assumptions on the short-term (5-year) timber harvest schedule for a southern pine forest, and to examine how much of the schedule is financially driven. The findings indicate that the short-term harvest schedule is sensitive to different price projections. This result is significant especially with respect to the timing of short-term timber harvest decisions to take advantage of market prices.

KEYWORDS: Stumpage prices, harvest schedule, forest planning.

INTRODUCTION

Forest planning models have long been used as an analytical tool for providing information to facilitate effective decision making and planning. Application of these models includes timber harvest scheduling, timberland acquisition and divestiture analysis, long-term sustainable wood supply forecasts, intensive silvicultural investment identification, and the determination of strategic forest management directions. Inherent to the financial analyses conducted with these models are assumptions concerning key financial parameters contained in the model such as discount rates, future costs, and future stumpage prices. Due to the uncertainty associated with projecting costs, interest rates, and timber prices, it is customary to undertake sensitivity analysis of key model parameters to examine the effect on results, and thus to further guide the decision making process.

While projecting timber prices into the future with any accuracy is an extremely difficult exercise, price forecasting is nonetheless a critical part of forest planning analyses. For example, it is well known that timber price fluctuations are a significant factor with regard to timberland returns. The ramifications of these assumptions over a long planning horizon can be significantly different product flows, activity levels, and cash flows. The purpose of this study is to investigate the impact of different future stumpage price assumptions on the short-term (5-year) timber harvest schedule. Various stumpage price projections were devised, with the resulting short-term harvest schedules compared for purposes of examining how much of the schedule is financially driven. These price projections were applied to a case study of a southern pine forest to evaluate their influence on short-term timber harvest decisions.

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BACKGROUND

The Forest—The (hypothetical) forest modeled for this study is 100,000 acres in size, and consists entirely of loblolly pine (*Pinus taeda*) plantations. There are 126 stands, and the age of these stands ranges from 1 to 30 years. A uniform age class distribution was modeled.

The Stumpage Price Projections—Three future stumpage price forecasts were modeled in this study:

1. Flat real prices over a 100-year planning horizon (*flat prices*).
2. A 1% real annual increase (over and above inflation) in all products over the planning horizon (*increasing prices*).
3. A 1% real annual increase (over and above inflation) in years 1 to 5 for all products except pine sawtimber. For pine sawtimber, there was an equal annual price decrease in years 1 to 5 such that the resulting stumpage price for pine sawtimber would equal the stumpage price for pine chip ‘n’ saw. Prices were then held flat over the remaining years of the planning horizon (*modified prices*).

The Model—A model II linear programming formulation was used to develop the timber harvest schedule for the forest in this study. The LP-based model consisted of an objective function maximizing net present value (NPV) over a 100 year planning horizon composed of 1-year periods.

In developing the harvest scheduling model, several assumptions were made, including: (1) clear-cut stands are site prepped the year following harvest and planted two years following harvest; (2) all stands that are thinned receive a post-thin fertilization the year following thinning; (3) thinning is optional, there is only one thinning per rotation, and thinning can be scheduled for ages 14-20; (4) minimum rotation age is 20; and (5) the financial analysis is before tax using a real discount rate (net of inflation) of 8%.

Growth & Yield—Growth and yield projections by product were developed using a proprietary Forest Technology Group loblolly pine plantation growth and yield model. Per acre harvest volumes generated by the growth and yield model were used as production coefficients in the harvest scheduling model.

RESULTS

A total of six harvest scheduling model runs were conducted for this study, based on the three alternative stumpage

Table 1—Average harvest ages for the first 50 years under alternative price projections.

Prices	Avg. Clearcut Age	Avg. Thin Age
Flat	24	15
Increasing	25	15
Modified	22	0

* Same results for both the unconstrained & constrained model runs.

price scenarios and two alternative model formulations: a model constrained to produce a positive cash flow (net revenue) of greater than or equal to \$25 million in each of years 1 to 5, and a model without this cash flow constraint (unconstrained). The six model results were used to evaluate the sensitivity of the short-term harvest schedule to different stumpage price projections. Comparison of the results provides valuable insight concerning the extent to which the short-term harvest schedule is financially (price) driven.

Long-Term Results—A brief look at some long-term results is valuable for gaining perspective into the impact of the different price projections on the timing of thinnings and regeneration harvests, and the mix of forest products produced. The average harvest ages over the first 50 years of the planning horizon are shown in Table 1.

As expected, the rotation age is longest under the increasing prices scenario, and shortest under the modified prices scenario. Under modified prices, there are no thinnings scheduled after year 10, as there is no price premium attached to the production of sawtimber.

Average annual pine harvest volumes by product over the first 50 years of the planning horizon are summarized for both the unconstrained and constrained models in table 2.

As expected, the flat and increasing price scenarios result in a mix of products weighted towards the production of sawtimber (PST), while the modified prices scenario results in a product mix heavy to the production of chip ‘n’ saw (PCNS). Further, due to a shorter rotation with no thinnings, the modified prices scenario results in a greater total pine harvest volume. Lastly, comparison of results between the unconstrained and constrained models shows no appreciable difference.

Short-Term Results—Again, for this study the short-term has been defined to be the first five years of the model. The short-term results to be examined here are harvest acres, harvested stands, silvicultural costs, harvest volumes, and net revenue. Acres clear-cut and thinned under the

Table 2—Average annual pine harvest volumes by product under alternative price projections and model formulations for mixes of sawtimber (PST), chip ‘n’ saw (PCNS), and pulpwood (PPWD) production.

Model run	Unconstrained			Model run	Constrained		
	Flat	Increasing	Modified		Flat	Increasing	Modified
PST	306,085	331,087	135,498	PST	305,901	329,009	135,625
PCNS	162,384	149,418	414,697	PCNS	162,622	153,085	402,900
PPWD	205,224	194,012	190,827	PPWD	205,705	198,258	184,499
Total	673,693	674,518	741,022	Total	674,228	680,352	723,024

Table 3—Total and annual acres clear-cut under alternative price projections and model formulations for years 1-5.

Year	Unconstrained			Year	Constrained		
	Flat	Increasing	Modified		Flat	Increasing	Modified
1	27,159	24,714	27,635	1	12,460	12,222	12,524
2	3,087	4,310	7,056	2	6,223	5,644	7,347
3	417	1,639	2,500	3	7,729	7,933	8,268
4	3,384	859	6,294	4	7,702	7,196	8,921
5	3,194	4,192	2,942	5	9,739	8,275	12,940
Total	37,241	35,713	46,427	Total	43,415	41,269	50,000

Table 4—Total and annual acres thinned under alternative price projections and model formulations for years 1-5.

Year	Unconstrained			Year	Constrained		
	Flat	Increasing	Modified		Flat	Increasing	Modified
1	10,429	10,429	3,106	1	8,737	9,489	1,389
2	5,635	5,635	1,310	2	5,635	5,159	1,726
3	4,053	4,053	3,750	3	4,053	4,529	3,750
4	1,667	1,667	0	4	0	1,667	0
5	3,333	3,333	1,667	5	5,000	3,333	2,500
Total	25,117	25,117	9,832	Total	23,425	24,177	9,365

different price projections are summarized in tables 3 and 4 respectively.

As expected, the modified prices scenario results in the highest total acres clear-cut and the lowest total acres thinned. Also, clear-cut acres are greater in the constrained model for all three price projections. The increasing prices scenario had the lowest total acres clear-cut under both model formulations.

Comparison of results between the unconstrained and constrained models with regard to acres thinned shows

slightly fewer acres thinned in the constrained models. Worth noting for the unconstrained model is that the same thinning acreages are chosen under both flat and increasing prices.

The silvicultural costs under the different price projections and model formulations are summarized in table 5.

For the unconstrained model, total silvicultural costs are highest under the modified prices scenario. This reflects the much higher stand establishment costs associated with this price scenario having the highest number of acres clear-cut.

Table 5—Total and annual silvicultural costs under alternative price projections and model formulations for years 1-5.

Year	Unconstrained			Year	Constrained		
	Flat	Increasing	Modified		Flat	Increasing	Modified
1	683,334	683,334	783,335	1	683,334	683,334	783,335
2	6,486,808	5,997,916	6,106,918	2	3,428,603	3,433,655	2,964,540
3	3,960,007	3,947,785	4,608,023	3	3,043,784	2,869,635	3,108,929
4	766,215	1,138,995	1,578,340	4	2,470,472	2,571,172	2,762,547
5	987,188	610,470	1,746,381	5	2,456,033	2,583,728	2,877,255
Total	12,883,553	12,378,500	14,822,998	Total	12,082,226	12,096,525	12,496,607

Silvicultural costs in the constrained model are lower in comparison to the unconstrained model for all three price projections. With flat prices, stand establishment costs are lower due to fewer acres clear-cut during years 1 to 4. Primarily, this reflects lower planting and herbaceous weed control costs. In addition, fewer acres thinned results in lower post-thin fertilization costs.

With increasing prices, the higher number of acres clear-cut during years 1 to 4 resulted in increased site prep costs. But this was offset by lower planting and herbaceous costs, and slightly lower post-thin fertilization costs.

With modified prices, stand establishment costs are significantly lower in the constrained model due to fewer acres clear-cut during years 1 to 4 (about 6400 acres less).

Total and annual pine harvest volumes by product under the different price projections are summarized for both the unconstrained and constrained models in table 6. Additionally, these total harvest volumes by product are shown in figure 1a for the unconstrained model, and figure 1b for the constrained model.

For both model formulations, there is less pulpwood (PPWD) harvested under modified prices due to the lower number of acres thinned, while the higher number of acres clear-cut under this price scenario results in a higher PCNS harvest and a slightly higher PST harvest.

For the unconstrained model, total pine harvest volumes range from 4.9 million tons (increasing prices) to 5.2 million tons (modified prices). For the constrained model, total pine harvest volumes range from 5.6 million tons (increasing prices) to 5.8 million tons (both flat and modified prices).

Thus, constraining the model to meet or exceed a minimum cash flow target results in higher harvest volumes for each product (and, as follows, in total), and a slightly narrower difference in total harvest volume between the different price projections. These results are in line with expectations.

Total and annual net revenue under the different price projections is shown in figure 2a for the unconstrained model and figure 2b for the constrained model. Note that net revenue as reported here is not the objective function value, which is NPV.

For the unconstrained model, total net revenue is highest under the modified prices scenario. This follows from this price scenario having the highest harvest volume, particularly concerning PCNS and PST. Net revenue is negative in year three for all pricing scenarios due to 1) a low number of acres clear-cut and a higher number of acres thinned, and 2) the significant number of acres clear-cut in year one are planted and receive herbaceous treatment in year three. Total net revenue ranges from \$129 million (both increasing and flat prices) to \$140 million (modified prices).

As described previously, the constrained model employed a minimum positive cash flow constraint covering years 1 to 5. Total net revenue is higher in comparison to the unconstrained model for all three price projections. Total net revenue ranges from \$153 million (increasing prices) to \$157 million (modified prices), with all of the difference in net revenue occurring in year 1. Following from the earlier outcomes regarding harvest volumes, constraining the model results in higher total net revenue, and a narrower difference in total net revenue between the different price projections (from \$11 million to \$4 million).

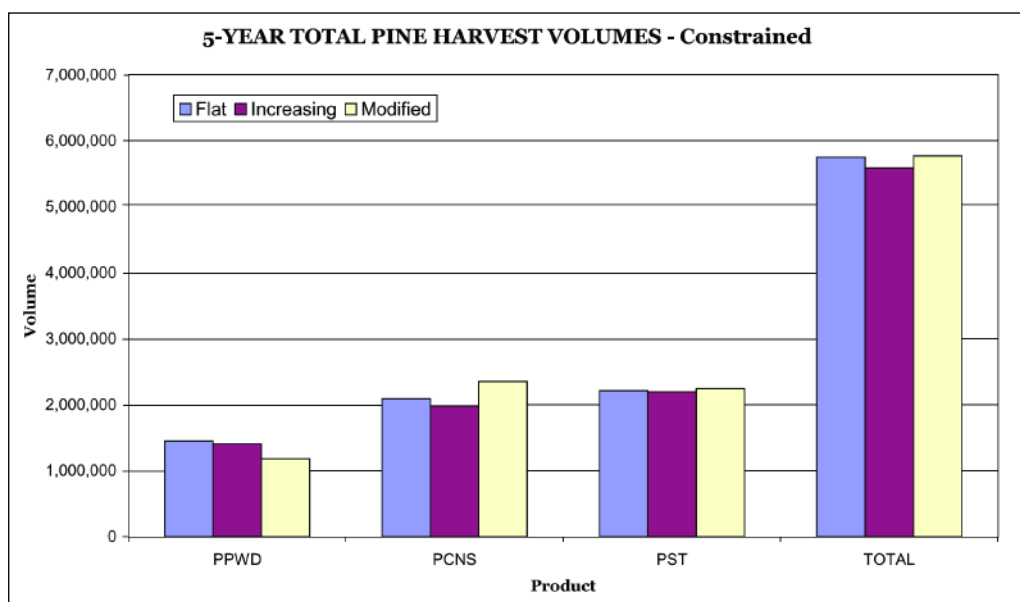
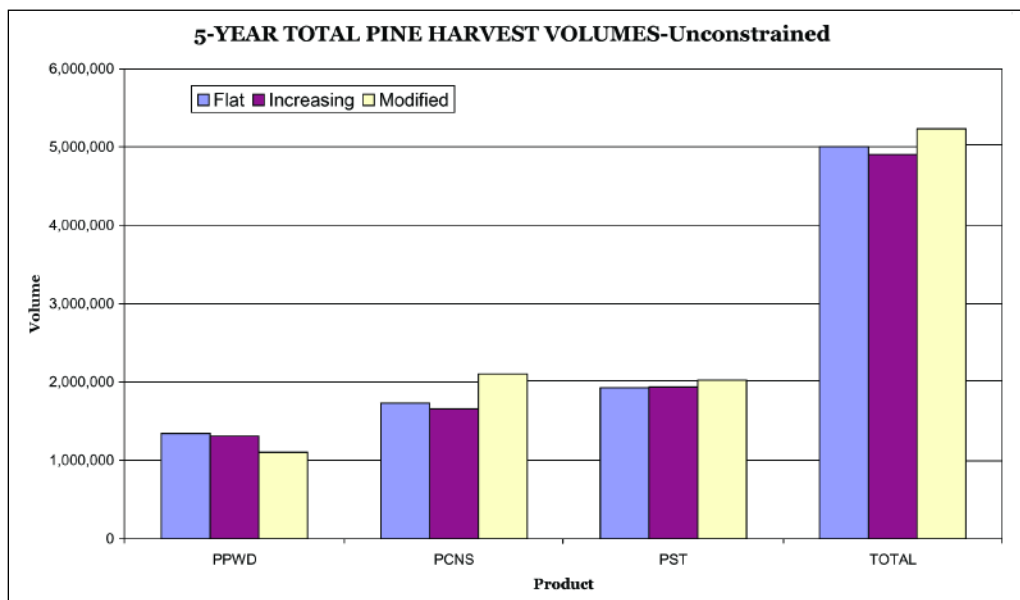


Figure 1—Total pine harvest volumes by product under alternative price projections for a) the unconstrained model, and b) the constrained model.

CONCLUSIONS

The results of this study indicate that the short-term harvest schedule is sensitive to the different price projections modeled in both the unconstrained and constrained models. This result is significant especially with respect to the timing of short-term timber harvest decisions to take advantage of market prices. Financial objectives may indicate the need for flexibility concerning targeting short-term harvesting decisions in response to market prices. That is, the timing of harvests with regard to the mix of forest products

produced is important, especially as it concerns financial goals.

The price sensitivity is related to both the forest examined in this study and the model formulation of the harvest scheduling problem. The uniform age class distribution of this forest allowed flexibility in relation to the stands scheduled for harvest and the timing of these short-term harvest decisions. The model formulation also provided flexibility. Some examples of this flexibility are that thinning is optional, and age 20 stands could be either thinned or clear-cut. Lastly,

Table 6—Total and annual pine harvest volumes by product under alternative price projections and model formulations for years 1-5.

Year	Unconstrained								
	PPWD			PCNS			PST		
	Flat	Increasing	Modified	Flat	Increasing	Modified	Flat	Increasing	Modified
1	722,153	654,352	500,924	1,198,969	1,067,491	1,106,572	1,531,317	1,508,183	1,557,361
2	234,418	268,907	205,360	201,826	278,260	453,921	101,855	118,566	230,744
3	95,186	127,031	165,140	3,071	68,838	92,748	0	17,622	13,028
4	150,324	106,672	113,054	196,491	47,419	293,817	2,30,036	36,985	145,776
5	145,222	156,068	2,877,255	130,792	195,008	2,877,255	67,125	257,554	79,189
Total	1,347,303	1,313,030	1,104,814	1,731,149	1,657,017	2,105,187	1,930,333	1,938,910	2,026,099

Year	Constrained								
	PPWD			PCNS			PST		
	Flat	Increasing	Modified	Flat	Increasing	Modified	Flat	Increasing	Modified
1	310,789	320,668	110,804	330,277	345,046	198,816	1,009,552	965,723	1,174,429
2	310,018	283,265	163,818	381,305	340,721	408,714	353,200	378,586	364,057
3	239,549	271,101	288,135	420,467	452,737	533,330	324,869	280,922	270,560
4	200,645	278,631	219,233	452,835	420,761	575,352	292,002	289,778	255,876
5	388,624	254,948	398,489	505,272	423,879	636,373	235,333	283,670	177,455
Total	1,449,625	1,408,612	1,180,570	2,090,156	1,983,145	2,352,585	2,214,955	2,198,679	2,242,379

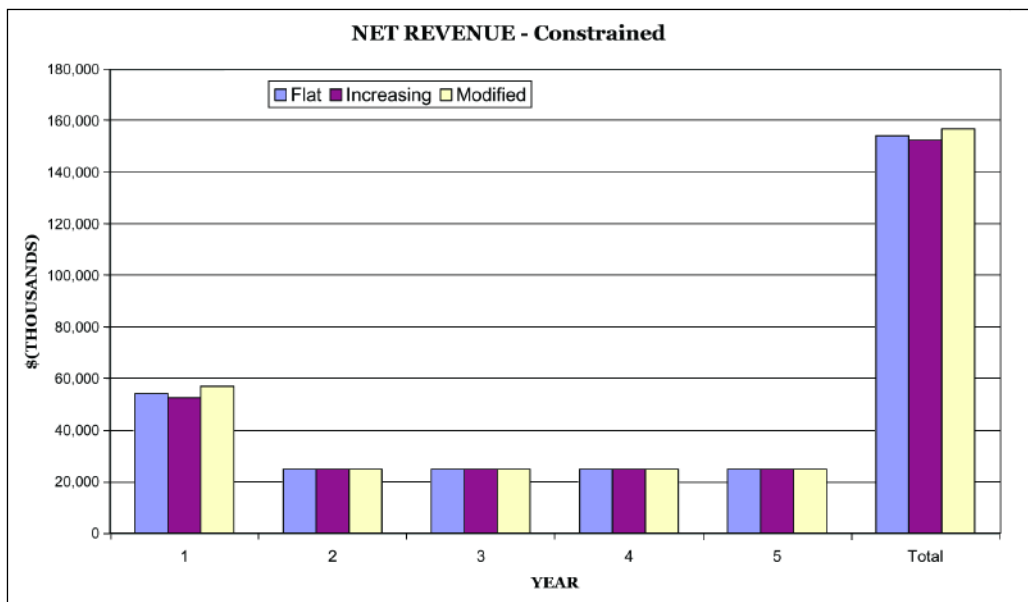
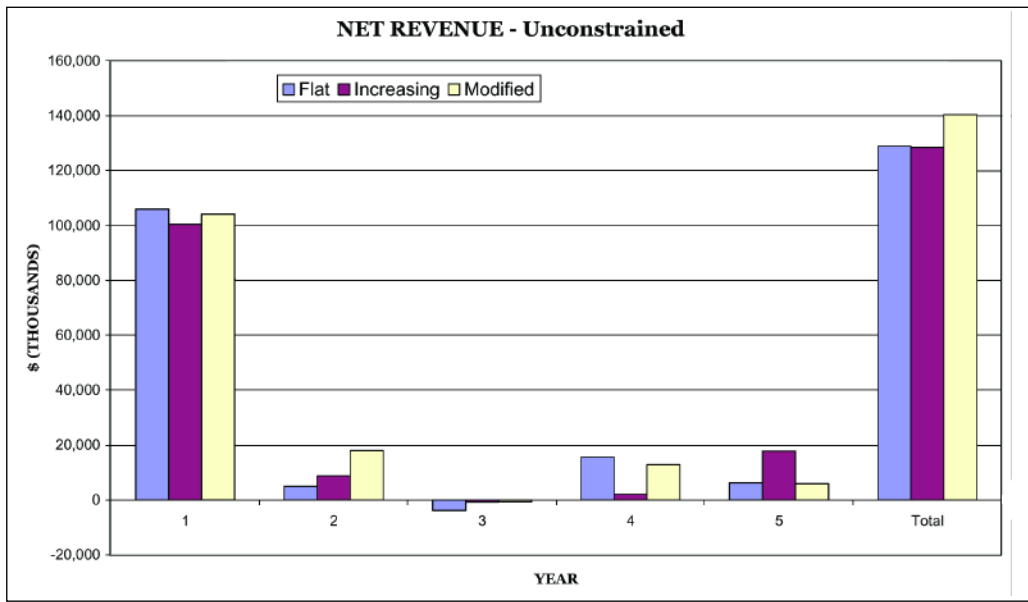


Figure 2—Total and annual net revenue under alternative price projections for a) the unconstrained model, and b) the constrained model.

with regard to the constrained model, the cash flow constraint was not so burdensome as to entirely dictate the solution.

Along these lines, there are several factors worthy of investigation in terms of their impact on the sensitivity of the short-term timber harvest schedule to different future stumpage price assumptions. A few of these factors would include:

1. A skewed age class distribution or age class gaps. Clearly, forest age class structure would be a key

driver with respect to price sensitivity. A younger forest with limited merchantable stands in the short-term would likely result in a more biologically driven solution. An older forest with many slow-growing stands would likely result in a more biologically driven solution. That is, the sensitivity to the prices modeled could be muted in both these instances where the forest age class structure dictates the solution.

2. Forest policy constraints. Much like the cash flow constraint, other forest policy constraints are likely to reduce price sensitivity.

3. Price increases/decreases by product. As many analyses have confirmed, this can have a significant impact with regard to optimal silvicultural prescriptions. Thus, model sensitivity to price could differ with the price projections modeled.
4. Spatial harvest planning. Large contiguous blocks of the same species of very similar age can significantly affect the results of operational harvest planning due to adjacency issues, perhaps reducing the effect of the prices modeled.

Further investigation of these or other factors would make important contributions to the theme of stumpage price sensitivity of short-term forest planning results.

DECISION SUPPORT IN GERMAN FORESTRY BY USING INDUSTRIAL SIMULATION SOFTWARE

Martin Hemm¹ and Anne-Katrin Bruchner²

ABSTRACT

Simulation software is a common planning tool in manufacturing industries. The question is: Is it possible to improve the selection of a forestry logging system by modifying manufacturing software to enable it to model a forestry problem? Preliminary tests show that it may be possible to adapt commercially available simulation software to realistic forest harvesting problems in a way that provides an analytical and visual perspective on the capabilities of various logging systems.

KEYWORDS: Simulation, modeling, harvest planning, decision support, forest operations.

INTRODUCTION

Enterprises in the forest sector today have to compete on a global timber market. To fulfill the requirements of their customers and to compete with international timber prices it is necessary to reduce operational and transport costs in the timber harvesting process.

The challenge of forestry today is to maintain a market oriented timber supply and to become a proactive industry instead of a reactive one. Most harvesting operations are planned for silvicultural regimes, i.e. single trees have to be cut in order to provide space for the remaining ones and to improve the quality of the stand. With growing investments into machines, in the future economical aspects are going to be even more important for the positioning of an enterprise on a global timber market. Low operational costs and high technical productivity of the machinery will become increasingly necessary for forest operations. Improvement of the integral logistics management can only be achieved by taking a close look at all elements of the production chain (Warkotsch, Ziesak 1998).

The main task of forest logistics is to manage the material and information flow in all segments of the wood supply chain. In order to be able to respond to the industrial dynamics it is important for the forest enterprises to know precisely their production layout and stand inventory at any time. Planning processes within the operational system that are based on an up-to-date inventory of the raw material could be optimized by using supporting tools like industrial simulation software. Due to the silvicultural approach in Germany approximate information about the spatial location of the selected trees is necessary.

RESEARCH METHODOLOGY AND APPLIED SIMULATION TECHNIQUE

Evaluation of simulation programs for harvest planning

An evaluation of different forestry-based calculating and planning tools from various countries gave an insight into already existing software applications. In a study made by Hemm (2002) seven simulation programs for supporting the planning process of forestry operations were tested. The investigation included software packages from Canada,

In: Bevers, Michael; Barrett, Tara M., comps. 2005. *Systems Analysis in Forest Resources: Proceedings of the 2003 Symposium*. General Technical Report PNW-GTR-656. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

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Finland, Sweden, Chile and USA. Most of these simulation tools are designed for regional silvicultural specifics and local harvesting problems, which makes it difficult to use them in Germany without any necessary modifications. Due to these results, the department decided to create a new tool, which should assist in finding the most efficient machine combination for harvesting and logging processes and could also be used as an e-learning tool for universities and forest schools.

The next step of the research study was to evaluate simulation software that could be adapted to complex systems such as the forestry production chain. Eight different software packages were compared and evaluated in a multiple goal analysis by means of a catalogue of criteria containing several specific forest requirements. In the beginning the requirements of the programs on production layout, manufacturing process and products were tested.

This step has been followed by an intensive investigation of one selected product, AutoMod™, made by Brooks Automation Inc., USA. AutoMod is parameter-driven and requires computer language based programming as well as visual interactive programming by means of a manufacturing simulator. Within this discrete simulation a material handling system can be defined with all its physical components in an editing environment in which the logic is also programmed. A simulation can then be run in a simulation environment creating a detailed 3-D real-time visualization of the system (Banks, Carson, Nelson 1999).

Simulating realities

Simulation software is designed to analyse, plan and control material handling systems. It is useful for analysing large and complex real-world situations that can not be solved by mathematical operations research models. A large number of variables, parameters and also functions can be handled.

An advantage of modeling is that it does not disturb the real system, and therefore it is possible to test various decision-making scenarios without interference. Additionally it will take only a short period of time to simulate a certain system, because it is possible to compress time. Furthermore simulated data is much cheaper to collect than similar data from a real-world system. A computer based simulation model describes the operation of the system and its individual components whose behaviour can be predicted. This feature allows a study of the interaction between individual processes in the system (Bruchner 2002). To simulate the realities occurring in forestry, there are two sequent steps to

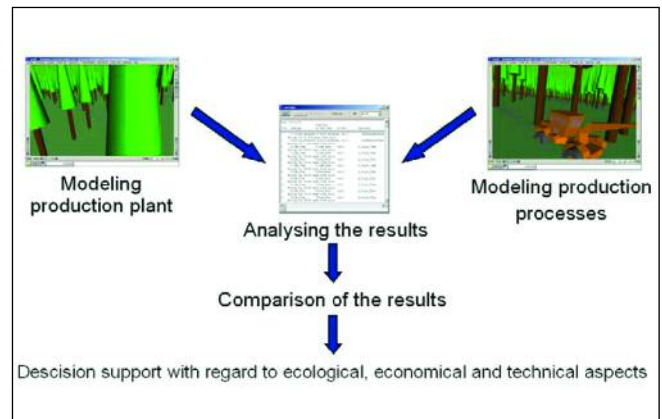


Figure 1—Development of a decision support tool.

take: Modeling of the production plant and modeling of the production process (fig. 1).

Modeling the production plant

The production plant represented by the stand was modeled by using a stand simulator called “SILVA”, developed at the Technical University of Munich (Pretzsch, Biber and Dursky 2002). The research focused on a stand of one hectare size located in Southern Germany. Cruise data was taken from systematic samples placed in this certain stand. Then, on the basis of the cruise data the stand was reproduced in SILVA and a tree list was generated by the program, including information about tree number, tree species, dbh and height as well as x- and y-coordinates for every single tree.

This information, listed in a MS Excel table, has been transferred to AutoMod™ and the stand generated by SILVA was reproduced as production plant in the AutoMod™ virtual reality environment. On the basis of this information, the times of the harvester for positioning its aggregate and processing are calculated for every single tree.

But the information, which is necessary to calculate productivity during the simulation was still missing: the number of assortments of each tree and their volumes.

Creating assortments and volumes

To solve that problem a calculation software called “Holzernte”, developed at the FVA Freiburg, Germany, was applied (Hradetzky, Schopfer 2001). Input data for “Holzernte” is a list of trees to cut during a planned harvesting operation. On the basis of this input data the user is able to define the pile he wants to accumulate. Holzernte

Table 1—Input-interface

with assortment list	TRUE		
percentage trees to cut (%)	15		
log length (meter)	4,5		
fuel cost (Å/l)	0,85		
Harvester			
velocity harvester on forest road (m/min)	167		
velocity harvester from tree to tree (m/min)	13,26		
fuel consumption traveling (l/h)	8		
crane range (m)	10		
MTBF (exponential - mean - units : min)	150		
MTTR (triangular - min. + most likely + max - units : min)	5	30	250
preparation time (triangular - min. + most likely + max - units : min)	10	12	14
Forwarder			
velocity empty (m/min)	127		
velocity loaded (m/min)	69,8		
fuel consumption traveling (l/h)	8		
MTBF (exponential - mean - units : min)	150		
MTTR (normal - mean + standard deviation - units : min)	5	30	480
preparation time (triangular - min. + most likely + max - units : min)	10	12	14
time loading per cycle (triangular - min. + most likely + max - units : min)	8	17	30
time unloading per cycle (triangular - min. + most likely + max - units : min)	4	5	6,5
loading capacity (m ³)	10		

then calculates the assortments and their volume for every specified pile. At the end of the calculating process, a MS Access table including the assortments and volumes is generated.

This table was connected with AutoMod™, which was done by means of a Visual Basic link. Provided with the tree data the model of the one hectare big stand was generated in AutoMod™.

Roadway modeling

One feature in AutoMod™ allows to draw a road system (Banks 1999). In the model there are a rectangular extraction lines and one forest road implemented. The roadways in the model have special attributes, which make it possible to define the roads either as extraction line or as forest road. On the roadways there have been placed control points at regular intervals of one meter. The control points are marks for the machines driving on the roadways, where they can stop and start processing. Next to the forest road two depots were created, in which the logged assortments are stored.

MODELING THE PRODUCTION PROCESS

After modeling the production plant, the next step was to simulate the production processes. Therefore one harvesting (harvester) and one primary transportation (forwarder) scenario had been selected. An interface was generated, in which the user has to define machine parameters. These parameters can be varied for every new simulation run.

The input-interface

For both of the machines, harvester and forwarder, as well as for some general parameters a special input-interface was developed (table 1).

In the following section you will find short explanations of the most important parameters, which are the basic requirements for simulating the harvesting and logging processes (table 2).

Simulation process

Each simulation run starts with the compilation of the model. The trees, roadways and machines are generated in a virtual reality (fig. 2).

Table 2—Explanations of the input-parameters

parameter	definition
assortment list / percentage trees to cut	There are two different options to identify those trees, which should be cut. The first way is about using an assortment list. The trees of this list have already been chosen for cutting during the stand simulation in SILVA. The second way can be taken by the user in case there is no assortment list defined. In AutoMod™ one is able to fill in a percentage value of the trees to be cut. Then, the number of trees, which accord to the given percentage value is selected by random.
log length	The log length given in meters can be chosen by the user, if there is no assortment list with predefined log length existing.
MTBF (mean time between failure)	Describes the time between two breakdowns of harvester or forwarder.
MTTR (mean time until repair)	Describes the length of the breakdowns by the help of a triangular function with minimum, most likely and maximum values.
preparation time, time loading and unloading per cycle (forwarder)	Also described by a triangular function.

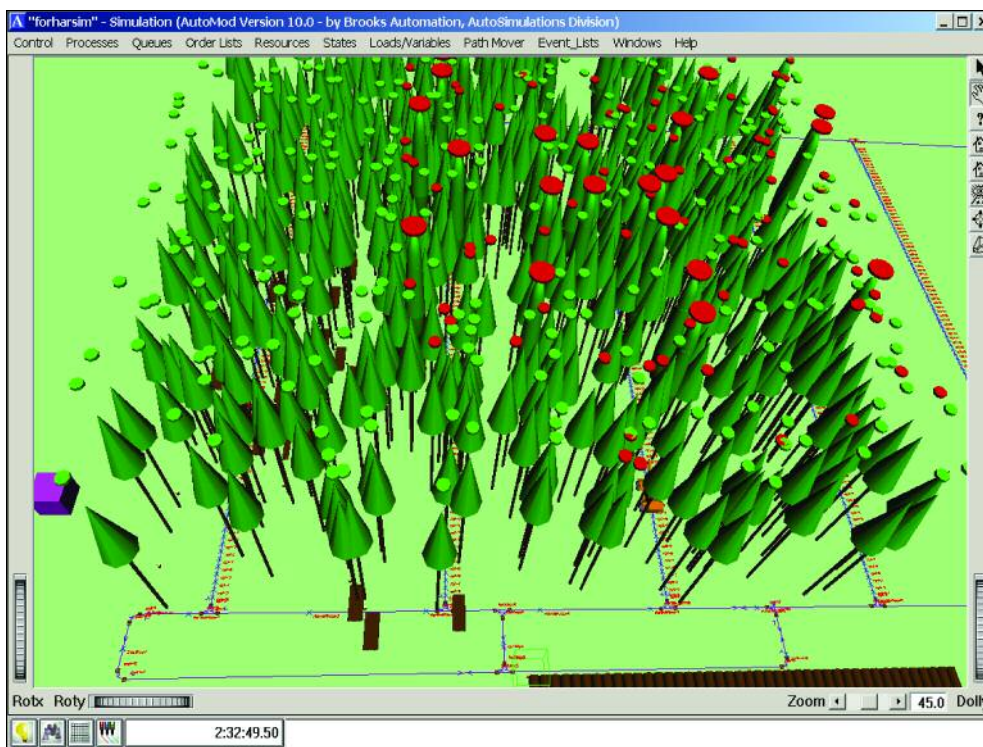


Figure 2—Virtual Reality environment of the model

Table 3—Output-interface

HARVESTER			FORWARDER		
	Time (min)	Percentage		Time (min)	Percentage
Preparation time	12	1,87%	Preparation time	11	1,08%
traveling	48	7,32%			
Spruce			Spruce		
Positioning	18	2,71%	Loading	382	38,52%
Cutting + Processing	269	40,98%	Unloading	104	9,91%
Delays (social, breakdowns)	310	47,12%	Traveling empty	33	3,19%
Total Spruce	597	91%	Traveling loaded	8	0,78%
Beech			Delays (social, breakdowns)	459	43,81%
Positioning	0	0,00%	Total Spruce	987	94%
Cutting + Processing	0	0,00%	Beech		
Delays (social, breakdowns)	0	0,00%	Loading	0	0,00%
Total Beech	0	0%	Unloading	0	0,00%
TOTAL	657	100%	Traveling empty	0	0,00%
General			Traveling loaded	0	0,00%
smh Harvester	5		Delays (social, breakdowns)	0	0,00%
pmh Harvester	222		total Beech	0	0%
m ³ transported Harvester	20,28		Industrial Wood		
TAP Harvester (m ³ /pmh)	759		Loading	24	2,27%
Productivity Harvester [m ³ /smh]			Unloading	11	1,04%
driving distance Harvester (m)	11		Traveling empty	4	0,42%
Fuel consumption					
	Quantity	Cost	Traveling loaded	11	1,01%
- traveling (l)	6,41	5,45	Delays (social, breakdowns)	0	0,00%
- using resource (ml)	55302	47	Total industrial wood	50	5%
Total (l)	62	52	TOTAL	1047	100%
DEPOT			General		
	# Logs	Volume (m ³)	smh Forwarder		
Spruce			pmh Forwarder	10	
Spruce Ind. Wood	147	13	m ³ transported	222	
H1	0	0	TAP (m ³ /pmh)	23,07	
H2	0	0	Produktivität [m ³ /smh]	4618	
H3	0	0	zurückgelegte Wegstrecke (m)		
H4	0	0	Fuel consumption		
H5	0	0		Quantity	Cost
total spruce	1278	222	traveling (l)	7,50	6,38
Beech			Trip info		
Beech Ind. wood	0	0	Ave nr of segments transported per roundtrip:		58
L1	0	0	Ave volume of the segments loaded on the forwarder per forwarding cycle		10
L2	0	0	Number of trips		22
L3	0	0			
L4	0	0			
L5	0	0			
L6	0	0			
total Beech	0	0			
Industrial wood					
total industrial wood	147	13			
Trees cut					
# trees forest	78	% forest trees of total			14
# trees extr.line	81	% extr.line trees of total			15
# trees cut in total	159	% trees cut in total			29

After having finished its preparation process, the harvester starts driving on the extraction line to the nearest tree to be cut. It stops on the control point, which is the closest to the tree. There it starts to cut and process the tree and takes down the logs next to the extraction line before moving to the next tree.

The forwarder follows the harvester in a predefined distance and starts hauling the assortments. When the forwarder

has reached its maximum loading capacity, it returns to a depot, which is placed near the forest road and unloads the assortments.

During this working process a breakdown may occur. In that case the machine stands still at its current position until the repair is finished. If the harvester is down for a longer time, this also may have an impact on the forwarder's productivity.

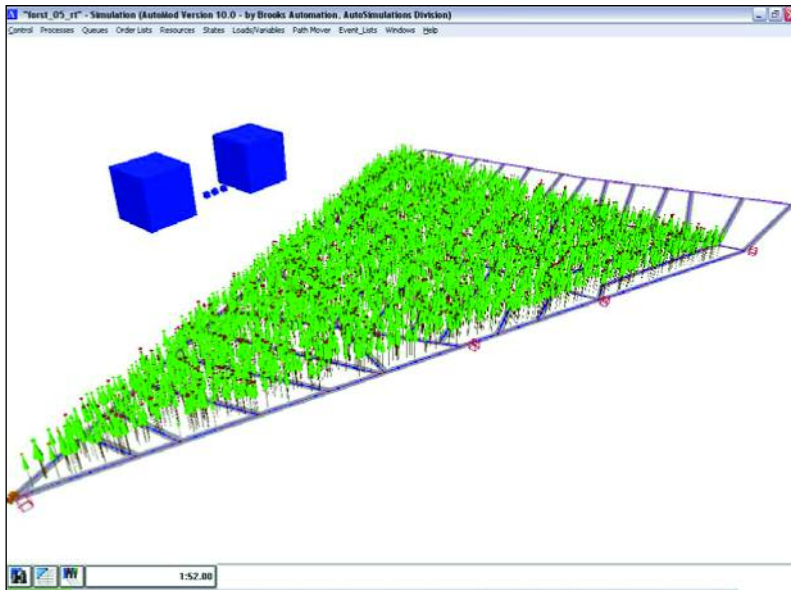


Figure 3—Model of 11 hectare stand and its extraction lines system

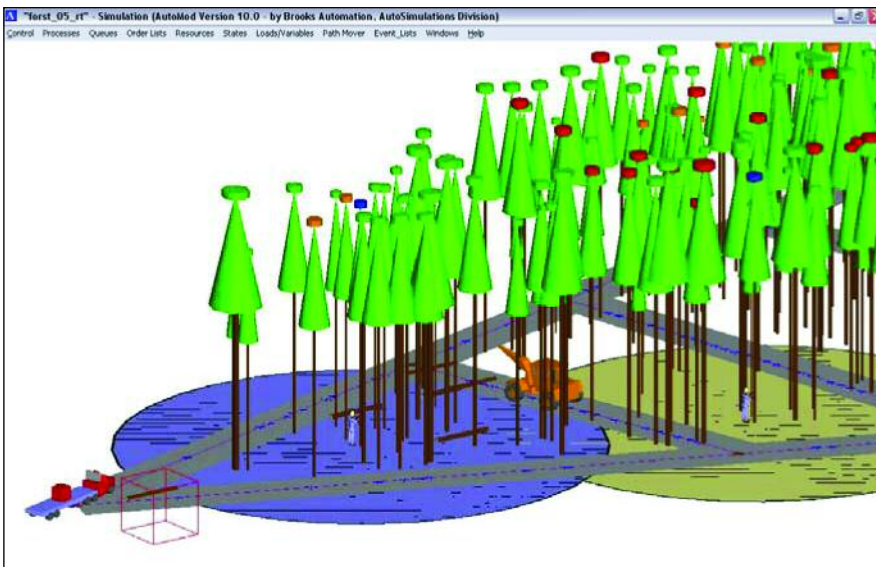


Figure 4—Model of chainsaw operations and logging process with a skidder

The simulation run ends, when all marked trees are cut and processed by the harvester and all logs are unloaded at the depots by the forwarder.

The model was validated by comparing the output with several time study results in terms of productivity and energy consumption. The data needed to develop this model and also to validate it derives from different time studies made in Germany and Austria. The validation runs were based on two kinds of data variation:

- 1) the stand data was changed while the machine parameters remained the same
- 2) machine data was changed while only one specific stand was the basis for the model

The validation proved that the model executes the specified logic and performs all functions as expected. Furthermore the whole process of building the model once more showed how the quality of the results depends on the data that has been used to create it.



Figure 5—Input-interface for chainsaw operations

RESULTS OF THE MODEL

At the end of each run AutoMod™ creates an output window. Three columns show the results for harvester, forwarder and depot calculated during the simulation (table 3). The specific values can be seen at table 3. Concerning the depot, the information is split into stem wood classes H1 to H5 and industrial wood.

The output-interface delivers the results of one run. In AutoMod™ it is possible to do multiple runs with different settings in the input-interface and in this case multiple output-interfaces are produced. That for example allows the user to compare the output of different scenarios with different types of harvesters and get a decision support.

ADVANCED MODEL

After validation of the first model had been finished the next modeling process included an extension of several attributes. Therefore the following features were integrated:

- enlargement of the model => the simulated stand is expanded to 11 hectares
- inclusion of a digital terrain model
- inclusion of a digital soil map
- modeling of an extraction lines system which was measured and mapped (fig. 3)

- simulation of different harvesting and logging systems => new operations include skidder, horse logging and manual felling (fig. 4). This required a new user interface (fig. 5).

The last part of the project will contain a simulation of different tree species and mixed stands as well as some combinations of different harvesting and logging systems. To complete the whole project successfully, it will be necessary to obtain enough data, which allows detailed calculations and satisfying reproduction of realities.

CONCLUSION

Industrial simulation software can be a flexible tool for modeling production processes in the wood supply chain as well as in pulp, paper and timber industry. Various simulation programs are available but only a few of them could be used to reproduce such complex forestry systems. To model different timber harvesting scenarios it is necessary to create a model of a forest enterprise which represents the production area as close to reality as possible and provide actual inventory data about material, machines and stand conditions. The main purpose is to create an instrument for planning and controlling all production processes.

The AutoMod™ harvest planning model can be used as decision support tool:

The results calculated during several simulation runs contain detailed data on economical, ecological and technical aspects, which are useful for a forest enterprise to see the positive and negative effects of different harvesting systems and logging operations on their budget and the environment.

e-learning component:

At universities and forest schools the impact of system changes can be demonstrated to show students the coherences and effects aroused by their decisions.

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**MILL SUPPLY AND
FOREST PRODUCT
MARKETS**

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ELASTICITIES OF DEMAND FOR INTERNATIONAL FOREST PRODUCT IMPORTS

*Extended Abstract*¹

J.A. Turner², and J. Buongiorno³

ABSTRACT

Models of the derived demand for forest product imports were estimated for major forest products, with data from 64 countries for 1970 to 1987, and tested with data from 1988 to 1997. The best results were obtained with a dynamic model estimated by the Arellano-Bond method. For most products the demand for imports was price inelastic and income elastic.

INTRODUCTION

Estimates of price and income elasticities of import demand are needed to predict the effects of tariff liberalization and other policies on international forest product markets (Zhu and others 2001). These elasticities are key elements of models like the Global Forest Products Model (GFPM, Buongiorno and others 2003).

The utilization of international panel data (Chou and Buongiorno 1984; Uusivuori and Kuulivainen 2001) have helped generalize import elasticity estimates, but with attendant difficulties, such as bias and inconsistency in dynamic models estimated by fixed or random effects (Hsiao 1986).

The main objective of this study was to better estimate the demand for forest product imports. Panel data from 64 countries for 1970 to 1987, was used to estimate static and dynamic models by five estimation methods. The results were judged according to economic theory, statistical characteristics, and out of sample predictive accuracy.

THEORETICAL MODELS

The static form of the derived demand for imports in country i at time t , was:

$$\ln(Q_{it}) = a_0 + a_1 \ln\left(\frac{P_{itq}}{P_{it0}}\right) + a_2 \ln(Y_{it}) + \varepsilon_{it} \quad (1)$$

where Y_{it} , is the gross national output, P_{itq} and P_{it0} are, respectively, indices of the import price of the particular forest product and the price of all other goods and services in the economy, and the residual term is $\varepsilon_{it} = \alpha_i + u_{it}$, where α_i is an unobserved effect that varies between countries, and u_{it} is a time-varying effect within the country.

The dynamic model, based on adaptive expectations/partial adjustment theory (Johnston 1984) was:

$$\ln(Q_{it}) = a_0' + \gamma a_1 \ln\left(\frac{P_{itq}}{P_{it0}}\right) + \gamma a_2 \ln(Y_{it}) + (1-\gamma)(Q_{i,t-1}) + \varepsilon_{it}' \quad (2)$$

where $0 \leq \gamma \leq 1$ is the adjustment speed.

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DATA

Data on annual imports and unit value of imports were obtained for 1970 to 1997 for 64 countries and the main forest products, from the Food and Agriculture Organization FAOStat database.

Import prices were computed from the import values reported by the FAO in nominal U.S. dollars. This price was converted to local currency using the local exchange rate from the World Development Indicators database (WDI), deflated with the GDP deflator (from the WDI), and then converted to international dollars to reflect purchasing power parity (World Bank 2003). The import demand shifter, (Y) was real GDP, expressed in international dollars.

MODEL ESTIMATION AND TESTING

Models (1) and (2) were estimated with data from 1970 to 1987. The following methods were used:

Pooled OLS—Minimized the sum of squares of the residuals. The significance of the unobserved country effect indicated omitted-variable bias.

First Differencing—Eliminated the unobserved country effect by differencing the variables over adjacent years (Wooldridge 2000).

Fixed Effects—Removed the unobserved country effect by replacing variables by their distance to their mean within each country and over time.

Random Effects—Assumed that the unobserved country effect varies randomly across countries. The serial correlation of the residuals was handled by calculating the feasible generalized least squares estimator (Wooldridge 2000) by maximum likelihood. We checked the consistency of the estimates with Hausman's (1978) test.

Arellano and Bond's (1991) Method—Is intended to avoid inconsistent estimates due to the correlation of the lagged dependent variable with the residuals in model (2).

First order serial correlation was tested as in Wooldridge (2000), and robust standard errors were calculated with White's (1980) method.

For each model, imports were forecast for each country and product from 1988 to 1997, conditional on imports in 1988, the elasticity estimates, and the observed prices and

Table 1—Post-sample forecasting accuracy¹, from 1988 to 1997, of static and dynamic models estimated with different methods.

Product	Static Model			Dynamic Model			Arellano-Bond		
	Pooled OLS	First Differencing	Fixed Effects	Random Effects	Pooled OLS	First Differencing		Fixed Effects	Random Effects
Roundwood	0.93	0.98	0.98	0.97	0.00	0.98	0.00	0.00	0.93
Sawnwood	0.80	0.97	0.94	0.94	0.00	0.97	0.86	0.11	0.96
Plywood & veneer	0.83	0.92	0.91	0.91	0.00	0.91	0.94	0.70	0.87
Particleboard	0.56	0.72	0.69	0.68	0.00	0.72	0.71	0.00	0.49
Fiberboard	0.74	0.77	0.75	0.75	0.00	0.78	0.65	0.54	0.70
Chemical Pulp	0.90	0.98	0.96	0.95	0.00	0.98	0.94	0.00	0.94
Recovered Paper	0.73	0.67	0.75	0.79	0.30	0.66	0.71	0.68	0.66
Newsprint	0.96	0.97	0.97	0.97	0.16	0.98	0.96	0.96	0.97
Printing and Writing Paper	0.75	0.87	0.83	0.83	0.00	0.89	0.64	0.25	0.73
Other Paper & Paperboard	0.87	0.92	0.91	0.91	0.10	0.92	0.79	0.74	0.87

¹ Coefficient of determination (R^2) in regression of predicted imports on observed imports, across all countries and years. Bold characters indicate the best forecasts.

Table 2—Multi criteria comparison of static and dynamic models estimated with different methods.

Criterion	Static Model				Dynamic Model				
	Pooled OLS	First Differencing	Fixed Effects	Random Effects	Pooled OLS	First Differencing	Fixed Effects	Random Effects	Arellano-Bond
	Correct sign ^a	10	10	10	10	10	10	10	10
Price	10	10	10	10	10	10	10	10	10
Income	10	8	9	9	9	8	9	10	9
Significance ^b	10	9	8	10	10	9	7	10	9
Price	0	0	0	0	0	0	10	0	0
Income	-10	-9	-10	-10	-7	-1	-2	-6	-1
Goodness of fit ^c	-10	0	-10	-10	0	0	0	0	0
Autocorrelation ^d	0	0	0	-3	-10	-10	-10	-10	0
Significant >0.5	0	5	1	1	0	8	1	0	0
Endogeneity ^e	20	33	18	17	22	34	35	24	36
Forecasting accuracy ^f									
Total									

^a Number of products with the signs of price and income elasticities consistent with economic theory.

^b Number of products with elasticities significantly different from zero at the 5% level.

^c Number of products with the lowest within-sample RMSE.

^d Number of products for which there was significant autocorrelation, and the autocorrelation was greater than 0.5.

^e Number of products with explanatory variables correlated with the error term.

^f Number of products for which the R^2 of the observed against the predicted imports was highest (table 1).

Table 3—Long-term price and income elasticity of import demand from the dynamic model estimated with the Arellano-Bond method, 1970 to 1987.

Commodity	Price	Income
Roundwood	-0.74 (0.42)	2.21 (0.86)*
Sawnwood	-0.49 (0.18)**	2.71 (0.68)**
Plywood/ veneer	-0.81 (0.21)**	2.74 (0.58)**
Particleboard	-0.70 (0.29)*	5.70 (1.41)**
Fiberboard	-1.53 (0.31)**	1.76 (1.23)
Chemical Pulp	-0.48 (0.18)**	2.72 (0.62)**
Recovered Paper	0.01 (0.15)	2.50 (1.30)
Newsprint	-0.50 (0.22)*	1.13 (0.41)**
Printing and Writing Paper	-1.20 (0.32)**	1.47 (0.59)*
Other Paper and Paperboard	-0.74 (0.27)**	1.14 (0.34)**

*, ** Significant at 5% or 1% level, respectively.

GDP from 1988 to 1997. The forecasting equation was based on the differential form of model (2):

$$\ln(\hat{Q}_{i,t+1}) = \ln(\hat{Q}_{i,t}) + \hat{a}_1(\ln(P_{t+1}) - \ln(P_{it})) + \hat{a}_2(\ln(Y_{i,t+1}) - \ln(Y_{it})) + \hat{a}_3(\ln(\hat{Q}_t) - \ln(\hat{Q}_{t-1}))$$

where $\hat{a}_3 = 0$ for the static model.

The forecasting accuracy was measured by the coefficient of determination in a regression of observed on predicted imports, across all countries and years from 1988 to 1997.

SUMMARY OF RESULTS

Long-Term Post-Sample Forecasting Errors

The R^2 's of actual on observed imports from 1988 to 1997 are in table 1. The dynamic model estimated by first differencing gave the best predictions for eight of the ten products. However, the static model estimated by first differencing gave predictions that were nearly as accurate for all products.

The worst predictions were obtained, for all products, with the dynamic model estimated by pooled OLS. Very poor predictions were also obtained for some products with the dynamic model estimated either with fixed or random effects.

Multi-criteria evaluation

To compare the different models and the estimation methods, we scored each model-method combination according to the criteria in table 2. Estimation of the static and dynamic models, by all methods gave the theoretically

expected sign for the elasticities. In most cases the elasticities were significantly different from zero. The best fit was obtained with the dynamic model estimated by fixed effects. There was less serial correlation in the dynamic than in the static formulation. Endogeneity was a problem mostly for the dynamic model estimated by pooled OLS, first differencing, and fixed and random effects. The dynamic model estimated by first differencing was most accurate in post-sample forecasting.

The totals in the last row of table 2 give equal weight to each of the six criteria. However, if the particular interest in using these models was for predicting future import demand then forecasting accuracy would be weighted relatively more. Giving equal weight to each of the six criteria suggests that the dynamic formulation estimated with the Arellano-Bond method gave the best empirical models of the demand for forest product imports. The long-term elasticities implied by the Arellano-Bond method are in table 3. Most elasticities had the expected theoretical sign and were statistically significant. Imports were inelastic with respect to price for most products, except fiberboard, and printing and writing paper. For all products, imports were elastic with respect to income.

ACKNOWLEDGMENTS

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A DEMAND-BASED SCENARIO OPTIMIZATION MODEL FOR SUPPLY OF RAW MATERIAL TO THE FOREST INDUSTRY

Daniel Hultqvist¹, Leif Olsson²

ABSTRACT

There are usually many sources for the supply of raw material to a pulp or paper mill in Sweden. The decision-maker can procure raw material from the company's own forest(s), buy in from the owners of small forests, swap with other forest operators or purchase on the international market. Wood chips for these mills are brought from sawmills and have their own transportation system, but are included in the model presented here. Optimizing the supply of raw material at a tactical planning level is a challenging task, and can only be managed properly if elements of uncertainty are considered. The solution would otherwise give few options when disturbances occur, for example when weather conditions change. The deterministic equivalent of the scenario model is formulated and solved as a convex mixed integer quadratic model. In this paper, we have focused on model building since this is a challenging task in itself. The model is tested on one small sample problem and one full-scale problem. We show how to simulate and evaluate different strategies in the flow of raw materials, from harvesting operations to delivery at the mills. In our study, the full-scale problem has been solved within reasonable time using commercially available software, and the solution indicates that the hedging effect in the stochastic solution adds flexibility. Future work will involve the development of stochastic programming algorithms to solve large-scale instances of the problem using parallel computing.

KEYWORDS: Stochastic programming, forest logistics, flexibility, load-bearing capacity, mixed-integer quadratic programming.

INTRODUCTION

In recent years, the forest companies in Sweden have moved their focus from harvest decisions, which have been relatively well investigated, to forest logistics (Karlsson and others 2002, and Karlsson 2002) and especially road investments (Olsson 2005; Olsson 2003 and Arvidsson and others 2000), and storage of roundwood (Persson and others 2002; Persson & Elowsson. 2002). Case studies have indicated that optimal solutions for the road investment problem can be calculated in an efficient manner, as

shown by Olsson (2003 and 2005) and by Arvidsson and others (2000).

As opposed to road investments, there are no definitive figures for the cost of roundwood storage. Although studies exist, such as those by Persson and others (2002) and Persson & Elowsson (2002), it is in general very hard to estimate the cost of loss in value. It is also difficult to estimate how roundwood of low quality will affect the quality of the end product at different mills. The problem will vary depending on the assortment, weather conditions and the

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industrial process, as well as storage location etc. Hence, only “rule of thumb” estimations of the costs are used here. Furthermore, it cannot be assumed that decisions involving harvesting, transport and the forest industry are independent from storage decisions, as first put forward by Barros & Weintraub (1982) and more recently by, for instance, Karlsson (2002). There are also studies that indicate substantial gains if the process at the mills is integrated with the planning of the raw material procurement (Arlinger and others 2000).

Here we describe and test an optimization model that integrates different aspects of the raw material supply chain from harvesting to industrial processing. The model focuses on procurement of raw material from forest owned by the mill. We have, however, included the purchase of roundwood on the domestic and international market in the model.

For sawmills, the raw material supply is a pure roundwood supply chain problem. This is not the case for pulp or paper mills, however, where raw material procurement also includes the supply of wood chips. This is transported from the saw mills to the pulp and paper mills on special trucks. This approach makes integrated planning an important task for the staff at forest companies, and is also the main thrust of our integrated optimization model presented here. Nonetheless, the supply of wood chips is rather easily managed, since it only considers transportation from sawmills to pulp or paper mills by main roads. Hence, this paper will concentrate on activities involving the roundwood supply chain.

In contrast to other attempts to optimize the raw material supply with purely deterministic models as in, for example Karlsson (2002), our stochastic model focuses on procurement with respect to uncertain load-bearing capacity of roads and harvesting grounds.

We have developed a scenario optimization model (Birge & Louveaux 1997; Kall & Wallace 1994) with dynamic information constraints (Lohmander & Olsson 2003). The deterministic equivalent is directly implemented as a convex mixed integer quadratic model (Wolsey 1997).

We describe the features of the model using a sample problem and show that it is possible to solve a full-scale stochastic model with commercial software (Anon. 2002) and a standard PC to near optimality within a reasonable length of time, with a limited set of scenarios and periods. Nevertheless, later our intention is to use decomposition techniques to solve the problem in parallel. Useful decomposition algorithms exist for this type of problem as

described by, for instance, Linderoth & Wright (2003), and affords the opportunity of solving more complex models.

Cost estimations, detailed mathematical formulation and detailed problem definition have not been included here, since space is limited. However, a much more detailed presentation of this work can be found in Hultqvist & Olsson (2004).

An outline of the remainder of this paper follows.

We start with an overall description of the raw material supply problem being considered, together with our assumptions. In section three, we present a verbal description of the mixed integer quadratic model. In section four, we present a sample problem and a full-scaled problem. In section five, we present results from the optimization of a sample problem, and also some results from the modelling of a full-scale problem. The last section contains the discussion and concluding remarks.

OVERVIEW OF THE PROBLEM

We only present an overview of the raw material supply chain problem here, and solve the scenario model for a period of six months. A detailed description of all component parts can be found in Hultqvist & Olsson (2004). The activities in the roundwood supply chain are described below.

- The first step is to harvest the trees with the harvester and put the trees in log piles.
- Then the log piles are picked up with a forwarder and transported to a roadside storage area. We assume that there are no costs related to roundwood storage in the actual forest, since good planning will keep forest storage at a low level. If using a harwarder, a combined machine which is both a harvester and a forwarder, this problem does not even exist.
- We also have the opportunity to buy roundwood from small forest-owners and pick it up at the roadside.
- Stumpage is included as additional harvest sites among the company’s own forest. In Sweden, these sites must be harvested within three years.
- It is possible to harvest sites that are not accessible during the spring thaw in advance. The harvested roundwood is then hauled to a road that will be accessible during the thawing period, and stored at the roadside until required. This form of pre-hauling is common in Sweden.
- We then haul the roundwood on the roads to a storage terminal, a better road or directly to the mills.

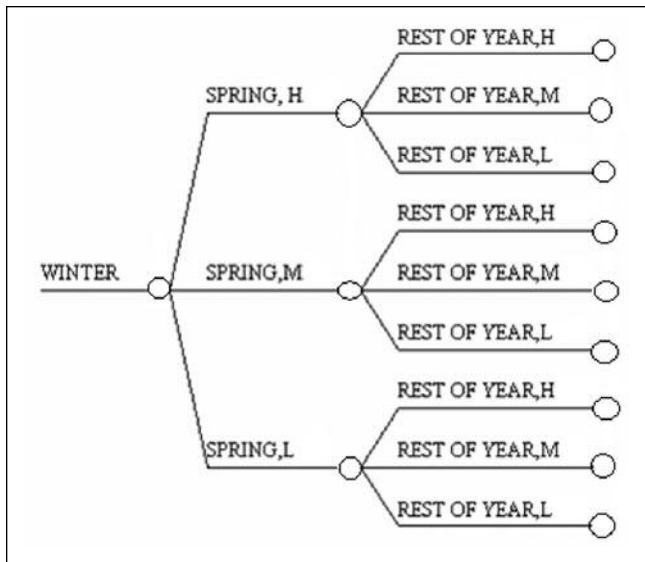


Figure 1—The event tree of the optimization model represents different outcomes of the stochastic variables. These variables describe the water content of the ground and roads.

- If it is not possible, or too expensive, to procure a sufficient volume of roundwood for the mills from the company's own forest, we must purchase wood on the roundwood market or, to solve short-term problems, use the security stock.
- Infrastructure investments are not considered in the model since these are long-term decisions, as described in Olsson (2003) and Olsson (2005).
- The model can handle railway transportation.

The other part of the raw material procurement for pulp and paper mills involves wood chips.

- Wood chips for pulp and paper mills are procured from sawmills, and have their own transportation system. Haulage of wood chips is done on roads that are always accessible.

The description above has of course been simplified to give an overall impression, and more details are given in Hultqvist & Olsson (2004). However, one essential part of the model is that road transportation of the roundwood is affected by the load-bearing capacity of the roads, as described by Hossein (1999). The variation in load-bearing capacity of a road depends mostly on weather phenomena, and must be modeled as uncertain. In the model presented here we use scenarios, also called events, as depicted in Fig. 1 to include uncertainties in load-bearing capacity of the roads and the ground. This approach is well described

in Lohmander & Olsson (2003), and is the common way of modeling uncertainty in the stochastic programming community (Birge & Louveaux 1997; Kall & Wallace 1994).

The event tree (Fig. 1) considers uncertainty in load-bearing capacity of the ground and roads. These stochastic events have the following definitions.

- L = Low water content in the ground, keeping more roads and harvest areas open.
- M = Normal water content in the ground, keeping a normal number of roads and harvest areas open.
- H = High water content in the ground, causing more roads to be closed and making more harvest areas than usual unavailable.

We assume that it is equally likely that there will be dry, wet or normal weather conditions in our general model. However, in reality, the scenario distribution can be estimated from historical weather data, for any geographical area, and generated with moment-matching scenario generation, for example (Höyland and others 2003). Our main point here is, however, that even a uniform distribution includes more flexibility in the solutions than a pure deterministic model. This flexibility gives solutions that hedge against future disturbances (Wallace 2000 and Wallace 2003). This general hedging effect is the main reason why we use a stochastic model here.

MATHEMATICAL MODEL

The mathematical model is only described in words here, since a full description would take up too much space. A detailed mathematical description of the convex mixed-integer quadratic model can be found in Hultqvist & Olsson (2004).

The objective function

The purpose of the objective function is to minimize the cost of supplying the industries with the volumes demanded. The costs included are described below.

Harvest:

- I) The time-dependent cost of harvesting.
- II) The fixed cost for harvesting machines.
- III) The cost of transporting the crew to and from the harvest site.

Transportation and roads:

- IV) The initial cost of harvesting at a site. This includes transportation of equipment and some maintenance of roads.

- VI) The volume-dependent haulage cost.
- VII) The cost of pre-hauling to accessible road(s) during the thawing period.

Storage:

- VIII) The volume-dependent storage cost.
- IX) The cost of unloading and measuring incoming volumes at storage terminals and mills.
- X) The cost of loading outgoing volumes at the terminals.
- XI) The fixed cost of having and using storage terminals.

Markets:

- XII) The cost of buying roundwood on the open domestic market.
- XIII) The collection cost for roundwood purchased on the domestic market.
- XIV) The cost of buying roundwood on the international market.

Sawmills:

- XV) The extra cost of having more than one assortment at a sawmill.

Railroads:

- XVI) The fixed cost for operating a railroad system.
- XVII) The volume-dependent cost of railroad transportation, including loading and unloading from truck to train.

Wood chips:

- XVIII) The transportation and purchase cost of wood chips from saw mills to pulp or paper mills.

Constraints

There are many model constraints, described below, which must be considered for the raw material supply problem.

Harvest:

- 1) The relative part harvested in each time period and in each scenario must be less than one. This constraint sets a binary variable that indicates whether anything is harvested during a specific time period and scenario.
- 2) The sum of the parts harvested in all time periods, for each harvest site and for each path through the scenario tree, cannot be greater than the total volume available.
- 3) The number of time periods within which a specific area can be harvested is restricted to two. This is done to simplify the model and to get better behaviour from the solution. All harvest sites can be harvested in one time period or less. If harvesting of a site starts at the end of one time period, it will be allowed to continue

into the next period, but there is no reason for it to continue into a third period. This would only lead to a waste of capacity, to have machines standing still at that site. It will also set the binary variable that indicates whether some volume is harvested in the area.

- 4) If an area is harvested during two consecutive time periods, a binary variable is set to one to ensure that no start-up cost is charged for the second time period.
- 5) The number of areas that are harvested in two consecutive time periods is restricted to the actual number of harvesting teams available.
- 6) This constraint is constructed to indicate whether an area is being harvested during two non-consecutive time periods. If this is the case, a binary variable is set to give the extra cost this implies.
- 7) All the activities that a harvesting team is involved in are converted into hours so that it will be possible to include time restrictions in the model. This covers both harvest and transfer times. If the next time period is the thawing period, harvest hours for this period are added to the previous period. The reason for this is that areas with harvest volumes needed during thawing are harvested during the winter and pre-hauled to a location that is accessible under the thawing period.
- 8) The number of harvest hours can be restricted, both with respect to the minimum and the maximum number of available hours. A binary variable for each time period is set if any harvesting take place. This gives the fixed harvesting costs for machines, set at II in the objective function.
- 9) For each assortment, the difference between outgoing and ingoing flow of roundwood at a harvest node must equal the volume harvested at the node, since the whole of the harvested volume should be transported from the harvest site.

Transportation and roads:

- 10) At a crossroads, the ingoing and outgoing volume of roundwood must be the same for each assortment, since this represents transshipment nodes in the network.
- 11) The total volume transported on a road can be restricted. This is useful on small roads that cannot handle much traffic in an appropriate way.
- 12) The number of hours that can be used for transport of roundwood can be restricted. This, then, would include time for loading, unloading and driving.

Storage:

- 13) At the first time period, initial storage volume and volume transported into the storage must equal what is transported out and stored for later use.
- 14) Stored volumes from earlier time periods and the volume transported for storage must equal storage for later use or the volume transported out from the storage.
- 15) In the final time period, stored volume and the volume transported for storage minus the volume transported out of storage must be greater than or equal to a fixed volume. This volume is set in advance, and represents the final minimum storage level.
- 16) The total volume stored must be less than or equal to the maximum storage capacity at each storage node.
- 17) For each assortment in storage, a minimum volume (safety level) can be set. This forces the model to always keep a given amount of an assortment in storage.

Mills:

- 18) The volume delivered to mills from other owners can have a maximum and a minimum restriction. The volume transported to a mill, the volume of roundwood bought on the open market and the volume delivered from other mill owners due to swapping is summed into a continuous variable. The model can thereby decide the cheapest way of supplying the mill with roundwood of different assortments from different sources.
- 19) The volume transported to a mill, bought on the open market and delivered from other mill owners due to swapping, is also summed into a continuous variable as described above.
- 20) The sum of all assortments must equal the total demand at the mill for each time period. This condition ensures that the total demand volume is correct, even if the sum of demand for all the different assortments is less.
- 21) For each assortment except one used by a saw mill, an extra location cost is added.
- 22) For each time period and assortment, the volume delivered at a mill is not allowed to be less than the minimum volume demand at that mill.

Wood chips:

- 23) At sawmills, some portion of the demand will be returned into the system as wood chips to be delivered to pulp or paper mills. This portion can be specified here.

- 24) The volume of wood chips delivered at a pulp or paper mill must meet the demand.

Markets:

- 25) There is a limitation as to how much roundwood can be bought from the domestic market. This is due to the fact that the domestic market is usually limited, or that it might be impractical to buy roundwood from too far away.
- 26) Even when buying on the open international market, there might be limitations on how much can be bought. These restrictions are related to transport capacity, or exist for political reasons.

Railroads:

- 27) The volume transported into a railroad terminal by trucks is transported out of the same terminal by train.
- 28) There is a volume limitation as to how much roundwood can be transported by a railroad during each time period. When a railroad system is used, a binary variable is set to give the fixed cost of using a railroad system.

Variables:

- 29) All continuous variables are equal to or greater than zero in the model.

Problems

We have tested the model on the sample problem depicted in Fig.2, as well as on a full-scale problem (Fig. 4). The sample problem is as small as it can be and still consist of all the interesting parts in the supply chain, in other words harvest areas, roads of different classes, a storage terminal, a saw mill and a pulp or paper mill.

These roads have different classes, depending on the construction of the road (Fig. 3). The paved roads are all A-class roads. The classes B through D are all gravel roads. Their accessibility is described in Table 1 and has been taken from Löfroth and others (2000).

The real case problem depicted below involves 450 roads and 320 harvest areas. The road network covers an area of about 11,500 km² in the central part of Sweden (Fig 4).

RESULTS

All the results given below have been computed on a 2.0 GHz Pentium 4 desktop computer with 512 Mb internal memory. The program used for the calculations was Lingo

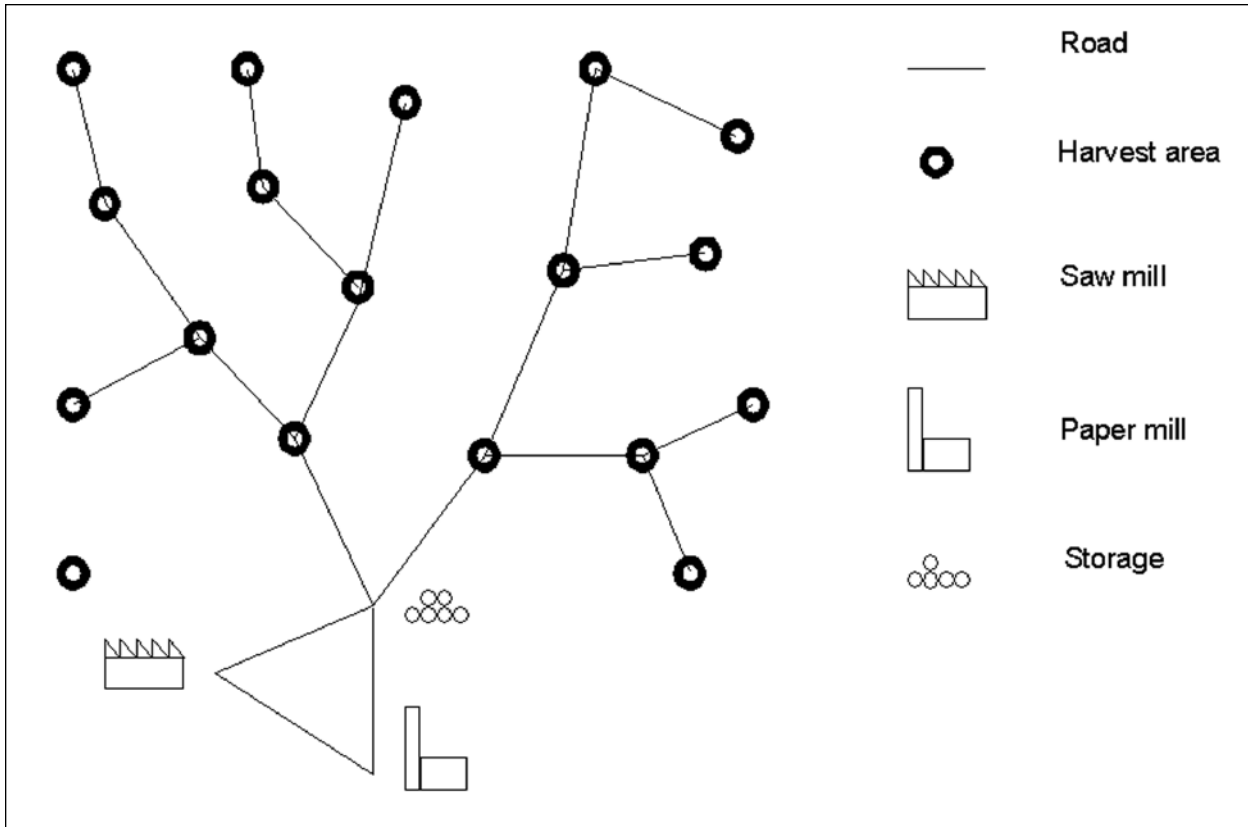


Figure 2—A sample problem depicted as a network, with 18 possible harvest areas and 20 roads. The network has one storage location, one sawmill and one pulp/paper mill.

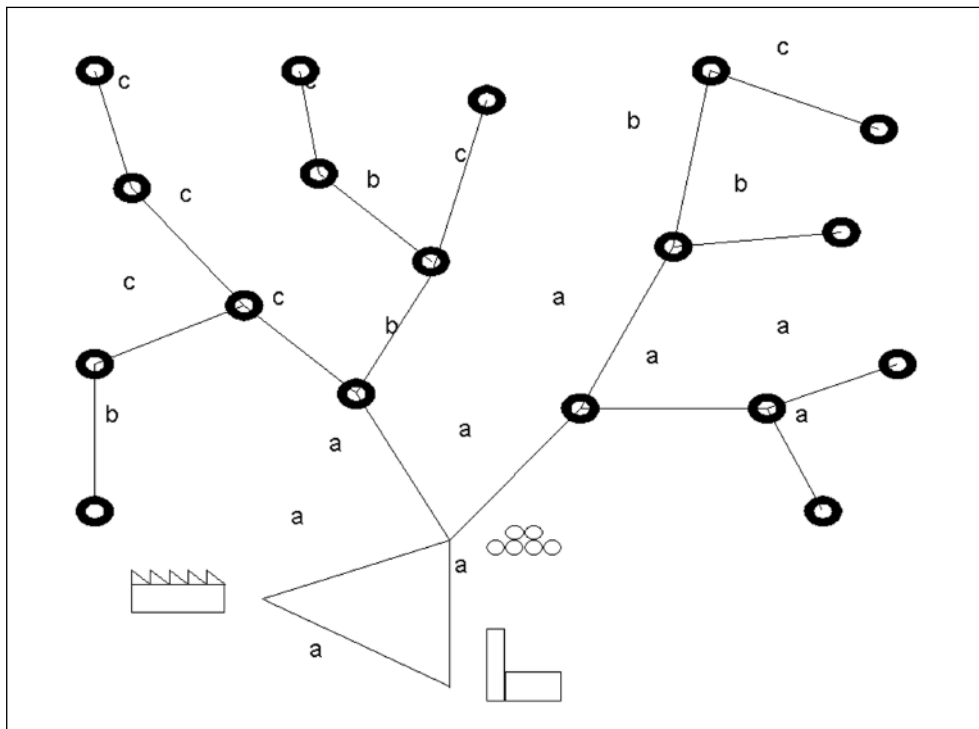


Figure 3—The classifications for each of the 20 roads in the sample problem.

Table 1—Times when the roads of different classes are open or closed. The meaning of the notation for different scenarios is described above.

Road class	Winter	Spring Low	Spring Medium	Spring High	Summer Low	Summer Medium	Summer High
A	Open	Open	Open	Open	Open	Open	Open
B	Open	Closed	Closed	Closed	Open	Open	Open
C	Open	Closed	Closed	Closed	Open	Open	Closed
D	Open	Closed	Closed	Closed	Open	Closed	Closed

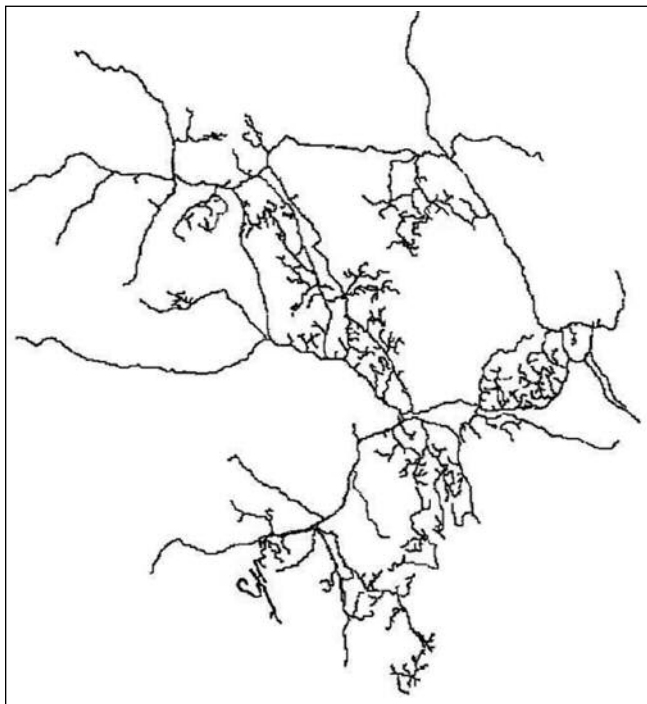


Figure 4—The full-scale road network located in the central part of Sweden.

8.0 from Lindo Systems (Anon 2002). The difference in the solution time for the stochastic and deterministic versions of the model applied to the sample problem was small (Table 2).

As seen in Table 2, the differences in solution time were substantial for the larger real case problem.

For the large real case, an optimal solution for the stochastic model could not be found within reasonable time. A solution less than 0.1 per cent from global optimum was found within a minute of calculation. For the deterministic problem, the same level of near-optimum solution was also

Table 2—Size and solution time for the stochastic and deterministic model formulations of the sample problem.

	Stochastic Programming	Deterministic Programming
Variables	2 311	626
Integer variables	344	153
Quadratic variables	13	3
Constraints	2 927	661
Iterations	12 486	4 000 - 40 000
Solution time	54 seconds	5-40 seconds

found within a minute of calculation. Even if the parameters of the problems were changed to give a first solution almost 20 per cent from global optimum, a solution less than 0.5 per cent from global optimum was found within a minute or two of calculation. Before the actual calculations start, the program generates and scales the matrices. This takes just a few seconds for a small problem. However, for a large stochastic problem this takes over one hour. (Table 3)

For the sample problem, the same eight harvest sites were harvested using both the stochastic model and all scenarios with the deterministic model. These sites can be seen in Figure 5.

Even though the same eight harvest areas are chosen to be harvested during the planning horizon, there are some differences between the stochastic and the deterministic approaches. These differences are related to when any particular site is picked to be harvested in time. For the large problem it is mainly the same areas that are harvested, but there are exceptions. Some harvest areas found in the deterministic solutions are not in the stochastic solution, and the other way around. There are also the same differences between the two types of solution as found in the sample problem, in other words when an area is to be harvested in time.

Table 3—Size and solution time for the large real case problem with stochastic and deterministic model formulation. The global optimal solution for the stochastic programming problem could not be found within a reasonable time frame. The solution obtained after 1 hour of calculation is not improved, more then very marginally, even when the computer was left running for closer to a week.

	Stochastic Programming	Deterministic Programming
Variables	39 363	10 353
Integer variables	5 779	2 569
Quadratic variables	13	3
Constraints	48 883	10 417
Iterations	—	50 000 - 850 000
Generation and scaling time	1 hour 6 minutes	3 minutes 42 seconds
Calculation time to near-optimum solution	1 minute	0.5 – 2 minutes
Calculation time to global optimum solution	—	0.25 – 5 hours

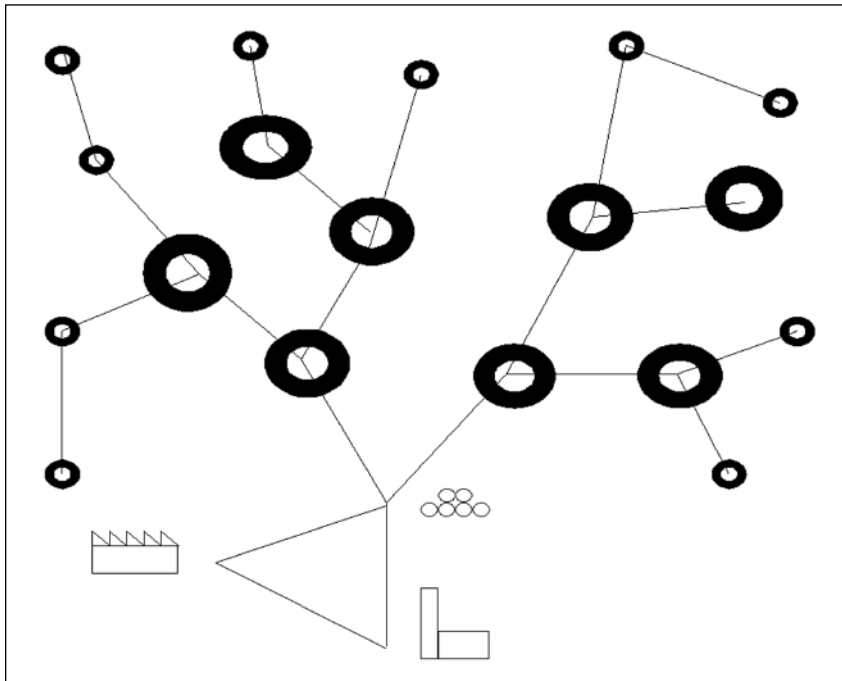


Figure 5—The sites harvested in the sample problem.

DISCUSSION

The Small Sample Problem

The difference between the stochastic and deterministic solutions for the sample problem is mainly a question of when to harvest. The areas to harvest in both types of problem are the same, but they are not harvested in the same order. The reason that the same areas are harvested is probably due to the very small problem size and to the fact that a large proportion of the available volume of roundwood

is harvested. This limits the number of solutions available. The sites chosen are closest to the mills and usually have good ground and bearing capacity of roads, in other words accessibility. Not all of the selected harvest sites are available during all time periods. Hence, for some areas the harvested volume has to be pre-hauled. This comes with an extra cost of transportation, making it a more expensive way of supplying the mills. Pre-hauling occurred in the stochastic solution and in five of the nine deterministic solutions.

The Large Real Case Problem

For the large problem, the stochastic and deterministic models do not always choose the same harvest areas. The solutions are mainly the same, but there are areas in the stochastic solution that are not in the deterministic solution. There are also sites in the deterministic solution that are not present in the stochastic solution. For those that are the same, there are (just as for the sample problem) differences in when they are harvested. The fact that there are harvest sites chosen in the stochastic solution that are not even present in the solutions for the deterministic problem indicates that uncertainty in load-bearing capacity of roads and harvest sites does matter. One must remember that the stochastic programming solution hedges against uncertainty, making the model generate more stable solutions.

One important problem with the stochastic formulation is that it is not possible to solve it to a global optimum within a reasonable time. What has been called the real case above is only part of the real-world supply chain. It represents one out of five districts supplying a pulp mill in the center of Sweden. Hence, if we were to use this model to solve the whole supply chain, we would need an alternative approach to making use of a desktop computer. One approach would be to use a cluster of computers to solve smaller parts of the problem. Algorithms are available for this, which solves the stochastic problem by solving many deterministic equivalences in each iteration. This would make it possible to solve larger problems much more quickly and with a higher degree of detail in the model.

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ANALYSIS OF AN EXTENSIVE THINNING PROGRAM ON EASTERN OREGON NATIONAL FORESTS BY USING A DYNAMIC SPATIAL EQUILIBRIUM MARKET MODEL WITH ENDOGENOUS INDUSTRY CAPACITY

Greg Latta¹ and Darius Adams²

ABSTRACT

An intertemporal, spatial equilibrium model of the eastern Oregon forest products sector was employed to estimate the impacts of a thinning program to help restore ecosystem health on national forests in the region. Harvest and silvicultural decisions of private landowners and the output and capacity investment decisions of mills were endogenous. Thinning treatment areas were considered in the spatial context of the model, but only thinning areas with non-zero board foot volume were included. Simulations suggested that 63% of the treatable area and 91% of the board foot volume in thinning areas could be removed in a 20-year program with no stumpage charges or hazard removal costs. These volumes would replace declining private harvests in the first decade but would not reduce the projected long-term drop in regional cut. Projected reductions in mill numbers would be postponed until after 2030.

INTRODUCTION

The eastern Oregon forest products sector is an industry in decline. Precipitated in part by the near elimination of national forest harvest, the sector has lost more than half of its processing capacity since the early 1990's. Based on private timber resources alone, further reductions in harvest seem likely (Adams and Latta, 2003). At the same time, wide-scale thinning programs have been proposed to reduce volumes in overstocked stands on national forests in the face of growing concerns about forest health, fire hazards and extreme fire behavior³. This paper employs a dynamic, spatial equilibrium model of the eastern Oregon log market to examine the potential harvest, price and milling capacity impacts of such programs.

A MODEL OF THE EASTERN OREGON FOREST SECTOR

The model developed here builds on the work by Krumland and McKillop (1990) and Bare and others (1995)

in identifying timber supply/harvest activities on private lands at the finest possible geographic scale for a range of silvicultural options. This supply module is coupled with a representation of demand in an intertemporal optimization model of the eastern Oregon softwood log market following work by Adams and others (1996), Schillinger and others (2003) and Adams and Latta (2003). Total harvest, market prices, flows from forests to mills, and volumes processed by mills are endogenous, as are silvicultural investment decisions on private lands. Transportation costs between timber harvest sources and log processing centers are explicit. Decisions to maintain, expand, contract or close processing capacity are also endogenous based on costs and profit potential. National forest thinning options are introduced as additional harvest sources. The analysis provides estimates of the effects of a thinning program on mill locations and processing capacity and of the proportion of national forest thinning opportunities that could be economically undertaken with existing mill technology.

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³ The Healthy Forests Restoration Act of 2003 authorizes such programs on public lands.

Because data limitations prevent estimation of demand directly at the mill level, we employ a simple proportioning procedure to disaggregate regional demand estimates to individual mills. This demand includes a processing capacity variable (representing quasi-fixed capital stock). Output is bounded above by capacity and below by a minimum economic level of capacity utilization. Capacity can be maintained or expanded in a three-level cost structure (maintain, replace depreciation, expand) or left idle to deteriorate. Firms decide on their optimal intertemporal capacity strategy based on the present value of future costs and returns⁴.

Log Supply

Inventory data for this study derive from the Forest Service's 1999 remeasurement of permanent plots on private forestland in eastern Oregon. Our work employed a preliminary version of this inventory, which differs somewhat from the draft final release [see Azuma and others (2002) for a description of inventory methods and broad results]. The primary differences lie in recomputation of some site index values, assignment of vegetation type for some plots and expansion factors. In this inventory, plots are divided into "condition classes", which are portions of the plot comprising uniform vegetation type, stand size, stocking and previous harvest treatment. Data cover 529 condition classes on 492 plots on timberland and other forestland. We treat the condition class as the basic resource unit with separate yield projections for each class.

Management practices were divided into reserve (no harvest), even and uneven-aged classes with three increasing levels of intensity in non-reserve groups, termed management intensity classes (MIC), as shown in Table 1. These regimes were adapted from work by Bare and others (1995) in an analysis of harvest potential in roughly comparable forest types in eastern Washington. They are expressed in threshold form. That is, stands must meet minimum stocking conditions before harvest can occur and harvests must exceed minimum removal volumes. Allocation of land to the uneven-aged option can occur only at the start of the projection and is irrevocable (there is no switching between uneven and even-aged MICs). As a consequence, several timing options for taking the first partial cut in uneven-aged regimes were introduced in the activities employed in the optimization (stand volume could rise above minimum thresholds to varying degrees before the first cut in the projection was made).

Estimates of the 1999 allocation of private lands to these several classes were derived from responses to surveys of industrial owners and Oregon Department of Forestry field foresters regarding current and prospective future management actions on private lands in Oregon. This initial allocation can be forced on the model solution as an "exogenous" allocation to initial MIC classes. The model also allows endogenous determination of the initial MIC allocation based on the specific objective of the projection. This is the approach employed throughout this study. Differences in aggregate harvest projections arising from the exogenous and endogenous initial allocations are small as described in Adams and Latta (2003).

Projections of current and future inventory volumes and stand conditions for all condition classes and MIC's were derived from the Forest Service's Forest Vegetation Simulator (FVS) stand projection system (see <http://www.fs.fed.us/fmnc/fvs/>). Three variants of FVS, corresponding to the three different vegetation zones in eastern Oregon, were employed.

There have been fairly clear trends in the area of timberland in nonindustrial private forest (NIPF) ownership in eastern Oregon over the past two decades. In recent years, shifts to non-forest uses have been an important part of NIPF losses [Azuma and others (2002)]. Of course, past trends need not accurately characterize future land base changes. The results reported here assume a constant land base. The regional harvest impacts of continued trend reductions in the NIPF base are examined in Adams and Latta (2003).

Log flows from all public ownerships are taken as exogenous and insensitive to price. The geographic location of public supplies is explicit and subject to appropriate harvest and transport costs, but harvest volumes do not vary with price or other endogenous elements of the model. As discussed below, augmented public supplies from a forest health thinning program are treated in a similar fashion.

Log Demand

Demand Equations. Mill locations, approximate output, and capacity were derived from industry directories [see, for example, Random Lengths, 2003)]. During the first projection period (1996-2000) the sector comprised 15 lumber mills at 13 locations or processing centers in the

⁴ This view of the capacity decision is similar to that employed in so-called "third generation" econometric profit function models with endogenous capital stock. Firms are seen as choosing their capital stock trajectories (simultaneously with output) so as to maximize the firm's present net worth. See, for example, Stevens (1995).

Table 1—Silvicultural regimes (management intensity classes or MICs) for non-reserve groups used in the eastern Oregon analysis.

EVEN-AGE	UNEVEN-AGE
Clearcut if stand volume at least 12 MBF/acre residual. Natural regeneration.	Cut if stand volume at least 7 MBF/acre, leaving 4 MBF/acre in trees 7 inches and larger.
Clearcut if stand volume at least 13 MBF/acre residual. Plant to 250 trees/acre.	Cut if stand volume at least 9 MBF/acre, leaving 5 MBF/acre in trees 7 inches and larger.
Clearcut if stand volume at least 16 MBF/acre. Plant to 250 trees/acre, and thin to 175 trees/acre when stand height at least 15 feet.	Cut if stand volume at least 9 MBF/acre, leaving 4 MBF/acre residual in trees 7 inches and larger, underplant 100-150 trees per acre.

MBF = thousand board feet

region⁵. Data are not available to estimate log demand and other production characteristics at the mill or processing center level. As a consequence we estimate log demand for the regional industry then disaggregate these relations to the mills using approximate methods.

Regional log demand was estimated using a normalized, restricted quadratic profit function. The industry was assumed to have one output (lumber), with residues treated as by-products. Inputs include three categories: logs, labor and other variable inputs. Capital stock (measured here as physical processing capacity) is treated as quasi-fixed and technology is represented by a time trend. The industries are assumed to be competitive, attempting to maximize profits subject to endogenous prices of logs and exogenous prices of output, labor and other variable inputs. Since products from the region compete in international markets and represent a small share of overall market volume⁶, treatment of output price as exogenous seems justified.

The empirical model consisted of the log demand equation together with the output supply, labor demand and profit function equations. Normally distributed stochastic disturbances with zero mean and constant variance were appended to each equation. Dummy variables were included to represent the dramatic effects of recession in the years 1980-1982. Time series data with annual observations from 1970 to 1999 were used in the estimation. Descriptions of data development and sources are given in Adams and Latta (2003).

Since virtually all of the data series exhibited some evidence of nonstationarity, coefficients were estimated with data in first difference form using iterative nonlinear three stage least squares. The instrument set included current and lagged values of exogenous variables and lagged values of the endogenous variables. Symmetry was assumed and global convexity was imposed as described by Wiley and others (1973). Parameter estimates, asymptotic t-ratios and goodness-of-fit statistics for the log demand equation are given in table 2. These parameter estimates yield unconditional (Marshallian) own-price elasticities of wood demand for lumber production of -.29 (at sample means). Breusch-Godfrey tests on residuals of the log demand equation lead to rejection of the hypothesis of 1st and 2nd order autocorrelation at the .01 level.

Lacking time series data on mill inputs, outputs and costs, we estimated mill log demands by scaling the regional demand equation to the mill level using estimated mill outputs in 1998. This amounts to assuming that log demand at each mill has the same elasticities for log price and other demand variables as the regional equation. Similar assumptions have been used in other studies to derive demand elasticities at finer geographic scales [see, for example, Kutcher (1983) and Adams and Haynes (1996)], but this is a relatively restricted approach.

Capacity constraints. Additional relations were added to the model to allow mill capacity to change over time, shifting both the log demand equation and the capacity

⁵ The one remaining plywood mill in the region closes in the fourth period of our projection and does not reopen.

⁶ Eastern Oregon lumber output was 1.6% of total US consumption in 1999 and 2.0% in 2002.

Table 2—Iterative 3SLS estimates of log demand equation coefficients for lumber mills with elasticities (at sample means) and associated asymptotic standard errors.

Variable	Coefficient	Standard Error of Coefficient	Elasticity	Standard Error of Elasticity
Wood Price	-.1266	.0420	-.287	.095
Output Price	.1401	.0494	.465	.164
Labor Price	-.5354	.3619	-.112	.076
Capacity _{t-1}	.6238	.1633	.879	.230
Trend	.3562x10 ⁻³	.7830x10 ⁻³	-.005	.011
Dummy 1980-82	.2537	.0491		

Equation estimated with variables as first differences. Squared simple correlation of actual and predicted differenced values 0.661.

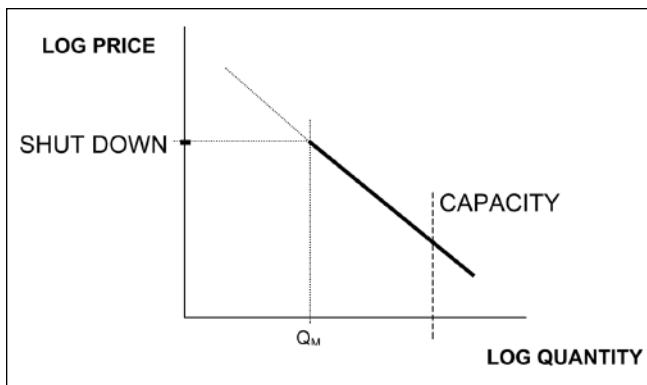


Figure 1—Log demand curve with capacity upper bound and minimum output (shut down-start up) point.

bounds on log demand. Since we only consider log demand (and not product output) in the model, a mill's physical production capacity is reflected in an upper bound on log demand (see figure 1). Over time, capacity follows the usual inventory identity: capacity this period is equal to capacity last period less depreciation plus investment. Additional capacity can be purchased in a three-tiered cost structure. Basic maintenance is required on all capacity and a low level of cost is charged for this maintenance so long as output is positive. This maintenance does not offset depreciation losses but is required to keep the mill running. A second tier involves repair and replacement of depreciated equipment. These costs do not expand capacity but simply maintain the current maximum output level. A third tier involves investment in new capacity to expand output beyond current levels. This is the most costly form of capacity and reflects new production lines or the costs of returning capacity to operational levels some time after a mill has closed.

Two additional constraints are placed on mills' capacity changes and output to mimic observed behavior. First, a mill's operating rate (output/capacity) can not fall below a preset minimum level unless the mill shuts down (output goes to zero). This is shown as the discontinuity in the log demand curve in Figure 1 at Q_M . This level of log use would correspond to the point of minimum average variable cost on the output marginal cost curve in traditional cost curve analysis. In the present case, as log price rises up the log demand curve the marginal cost of output would shift up. At a constant output price, minimum average variable cost would eventually meet, then exceed, price. The firm's optimal strategy is to shut down, rather than lose more than its variable costs, and log demand drops to zero. We approximate this shut down-start up point with a minimum operating rate.

A second restriction sets a minimum permissible capacity size for each mill. This constraint posits that there is some minimum mill size below which it is not economic to operate. To be profitable and competitive, a mill must be at least some minimum size. In effect this threshold establishes a barrier to entry, or in the present case re-entry, to the regional industry. If a mill drops out of production and its capacity is allowed to depreciate, it must invest to bring capacity at least to the minimum threshold before restarting production.

Overall Model Structure

The model can be characterized as an optimizing, intertemporal, price endogenous, spatial equilibrium market model. Projections are made over some period (typically 100 years or more) using 5-year time intervals (years in figure are interval midpoints). Solutions are found by maximizing the present value of the willingness-to-pay integral under the demand curves less costs of timber growing, log

processing and handling (including capacity investment) over the projection period. Results reported here use a 6% discount rate. Logs flow from condition classes (denoted by the subscript “CC” below) to processing facilities (the subscript “MILLS”). Capacity acts both to shift the log demand (willingness to pay) function and to bound the level of log demand (termed log “receipts”) at each mill. The approach to timber inventory accounting might be viewed as a combination of Johnson and Scheurman’s (1976) model I and II forms. Even-aged stands are classified in part by dates of origin and next harvest, uneven-aged stands by the specific regime (MIC) in which they are enrolled.

The general structure of the model is outlined below (the time subscript is suppressed, except where essential, to simplify the notation):

$$(1) \text{ MAX } \sum_{\text{TIME}} [\sum_{\text{MILLS}} \text{Willingness to pay} \\ (\text{Receipts}_{\text{MILLS}}, \text{Capacity}^{(i-1)}_{\text{EOR}}) \\ - \text{Capacity costs (Maintenance, Depreciation, Expansion)} \\ - \text{Transport costs (CC} \rightarrow \text{MILLS)} \\ - \text{Harvest costs} \\ - \text{Planting and silvicultural costs}] (1 + r)^{-\text{TIME}} \\ + \text{Discounted Terminal Inventory Contribution}$$

Subject to:

- (2) All CCs must be allocated to some MIC in each period
- (3) Even-aged planting \leq area harvested in new and existing even-aged stands this period
- (4) $\text{Harvest}_{\text{CC}} = (\text{Final Harvests} + \text{Thinnings})_{\text{EVEN-AGED AREAS}} + (\text{Partial Cuts})_{\text{UNEVEN-AGED AREAS}}$
- (5) $\text{Harvest}_{\text{CC}} \geq \sum_{\text{MILLS}} \text{Shipments}_{\text{CC}, \text{MILLS}} + \text{Exports}_{\text{CC}}$
- (6) $\sum_{\text{CC}} \text{Shipments}_{\text{CC}, \text{MILLS}} + \text{Imports} + \text{Public} \geq \text{Receipts}_{\text{MILLS}}$
- (7) $\text{Receipts}_{\text{MILLS}} \leq \text{Capacity}_{\text{MILLS}}$
- (8) $\text{Receipts}_{\text{MILLS}} \geq \mu \text{Capacity}_{\text{MILLS}}$ or zero.
- (9) $\text{Capacity}_{\text{MILLS}} = \text{Capacity}_{\text{MILLS}, \text{TIME-1}}(1-\sigma)^5 + \text{Maintenance}_{\text{MILLS}} + \text{Expansion}_{\text{MILLS}}$
- (10) $\text{Capacity}_{\text{MILLS}} \geq \xi \text{Capacity}_{\text{MILLS}, \text{INITIAL PERIOD}}$
- (11) $\text{Capacity}^{(i)}_{\text{EOR}} = \sum_{\text{MILLS}} \text{Capacity}^{(i)}_{\text{MILLS}}$
- (12) Convexity Constraints (piece-wise linearization of area under demand functions)
- (13) Non-negativity

where

$\text{Capacity}_{\text{EOR}}$ is total eastern Oregon log processing capacity, as defined in (11),

CC subscript refers to the basic condition class units that make up the inventory,

MILLS subscript refers to the individual mills or log processing units,

(i) and (i-1) superscripts refers to the solution iteration number (see discussion below),

r is the discount rate,

σ is the capacity depreciation rate,

μ is the minimum operating rate, and

ξ is the minimum ratio of current to initial capacity (minimum plant size).

In the objective function (1), willingness-to-pay, the integral of the area under the demand curves, is a function of both log receipts and regional capacity (both endogenous). Constraints (2) and (3) are the standard accounting requirements for Johnson and Scheurman’s (1976) models I and II. Harvests (4) for each condition class in each period are the sum of final harvests and thinnings from even-aged areas plus partial cuts from uneven-aged areas. Each condition class in the sample represents a specific area in the inventory (determined by the class’s area expansion factor from the sample). In the solution, the area represented by each condition class can be broken down into a number of even and uneven-aged treatments that may vary over time. The logs harvested from each plot may be shipped to mills within the region or to destinations outside the region (5). Exports have accounted for about 25% of total eastern Oregon harvest and flow to an array of destinations in western Oregon. They are treated as exogenous in this analysis at a fixed 25% of total cut. Receipts at mills (6) comprise intra-regional log shipments from private lands, plus receipts from public lands, plus imports from outside the region. Imports are small and are treated as exogenous. Constraints (7)-(11) encompass the capacity model discussed above: receipts (mill output measured in units of log input) must be less than capacity (7) and greater than the minimum operating rate (8), capacity evolves over time according to the standard inventory identity (9), with depreciation at a fixed rate (σ) and additions due either to maintenance activity or expansion, capacity can be no smaller than a minimum plant size defined as a fraction of initial period capacity (10), and regional capacity is the sum of capacity at all mills (11).

Treatment of nonlinearities. Since the demand functions are linear, the willingness-to-pay integral in (1) is quadratic in mill receipts. This function also depends on current industry capacity ($\text{Capacity}_{\text{EOR}}$), which is endogenous and a further source of nonlinearity in the objective. To linearize the objective we employ two devices. Mill receipts (log demand) in each period are defined as a fraction of capacity in a set of discrete steps as (again with time subscripts suppressed):

$$(14) \text{Receipts}_{\text{MILLS}} = \sum_{\text{STEPS}} \text{UTIL}_{\text{STEPS}} \text{CLEVEL}_{\text{MILLS,STEPS}} \\ \text{CAPACITY}_{\text{MILLS}}^{(i-1)}$$

where

$\text{UTIL}_{\text{STEPS}}$ is a fixed vector of capacity utilization levels defined on the steps $[0, \mu, \mu + \xi, \mu + 2\xi, \dots, 1]$ with μ defined above,

$\text{CLEVEL}_{\text{MILLS,STEPS}}$ is an endogenous (0,1) variable indicating which $\text{UTIL}_{\text{STEPS}}$ is employed, and

$\text{CAPACITY}_{\text{MILLS}}^{(i-1)}$ is the current capacity of a mill from the previous $(i-1)$ solution iteration.

Since CLEVEL is a binary variable (0,1), the squared receipts term that would appear in the willingness-to-pay integral in the objective function can be expressed as a product of squared (exogenous) UTIL and CAPACITY terms and a single CLEVEL term, thus eliminating the potential nonlinearity in the receipts variables.

We eliminated the nonlinear product of receipts and capacity (in both the definition of receipts and in the objective function) by means of an iterative solution approach. In the first iteration, current capacity values in (13) and in the objective function ($\text{CAPACITY}^{(i-1)}_{\text{EOR}}$) are replaced by an estimate of equilibrium capacity. At the end of the first iteration, revised values of capacity are available from the solution [computed in constraints (8) and (11)]. These are used, in turn, in the second iteration. This process continues until the changes in capacity between iterations fall below some tolerance. In application, we found that 5-7 iterations yielded relatively stable values, depending on the values employed in the initial iteration.

The overall model formulation involves both discrete, binary variables (CLEVEL) and an array of continuous variables (including capacity, harvest, receipts, shipments and investment) and was solved using a mixed integer linear programming algorithm. The model was coded in GAMS (Brooke and others 2003) and used the CPLEX solver. Typical base case problems without a public thinning program involved approximately 120,000 constraints and 760,000 activities.

ANALYSIS OF AN EXTENSIVE THINNING PROGRAM ON NATIONAL FORESTS

Millions of acres of the national forests in eastern Oregon are at increased risk of damage by fire, insects and

disease due to overly dense stocking, stemming in part from a long history of indiscriminate fire suppression and from cutting practices that focused on ponderosa pine. The “forest health” issue has attained some prominence in recent years as a result of several seasons of large wildfires and increased attention from the media and high-level policy-makers. Thinning these stands, to accelerate growth of the residual stems, has been proposed as one possible (albeit controversial) approach to restoration. As Wilson, Maguire and Barbour (2002) observe, however, the economic feasibility of such a thinning program will depend on the costs of entering the effected stands and removing the material, the quality of the material to be removed and the impacts of large volumes of thinned material on market prices and the processing industry.

In this study we examine one hypothetical thinning program on national forests in eastern Oregon. The eastern Oregon forest sector model described above is run with and without the program and impacts assessed from differences. In the base market model (without thinning) public harvests are not sensitive to market conditions, entering in constraints (6) as exogenous additions to mill receipts. The thinning program is simulated by appending to the set of private inventory condition classes a group of sample plots representing national forest lands that might be thinned. Each public plot (expanded to represent its total area) has harvest and haul costs and associated sawtimber thinning volumes. Thinnings must be completed within the first 20 years of the projection (program duration). The model is then rerun and allowed to pick the plots and volume to be thinned over time.

Data for this analysis came from Wilson, Maguire and Barbour (2002). Plots from the Forest Service’s Continuous Vegetation Survey inventory system were examined to identify those that were “densely stocked”, defined as plots with stand density indexes (SDIs) in excess of 75% of the maximum SDI for their respective forest types. Tree removals were then computed for these stands to reduce SDI to 50% of the maximum, cutting from below (smallest first). In our market analysis we employ only the board foot volumes, measured for trees at least 9 inches in DBH, and use only the plots with non-zero board foot volume. Given the details of the thinning and plot characteristics, we computed harvesting costs (to the roadside) for the thinnings using the cost model of Fight, Gicqueau, and Hartsough (1999)⁷. In their study Wilson, Maguire and

⁷ Harvesting costs in the Fight, Gicqueau, and Hartsough (1999) model vary with a wide range of logging technology and site conditions. We use their default assumptions for all inputs except stem diameter, volume per acre to be removed, trees per acre to be removed, move-in distance, slope, and whether the harvest is a thin or not (all are thins in our case).

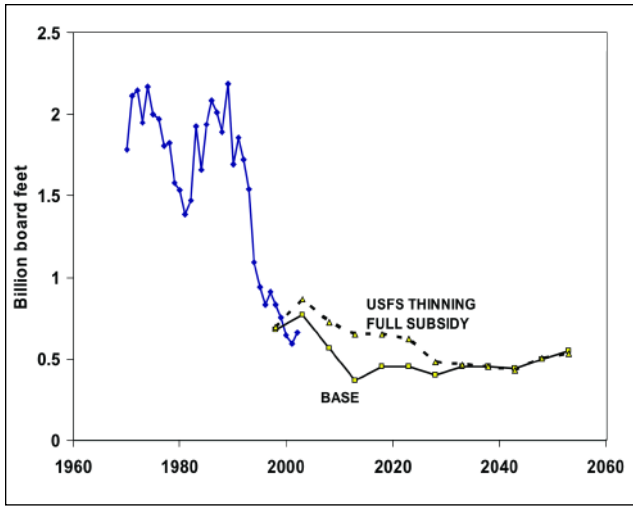


Figure 2—Historical and projected timber harvest in eastern Oregon (all owners), with and without a thinning program on national forests. Historical data from Oregon Department of Forestry.

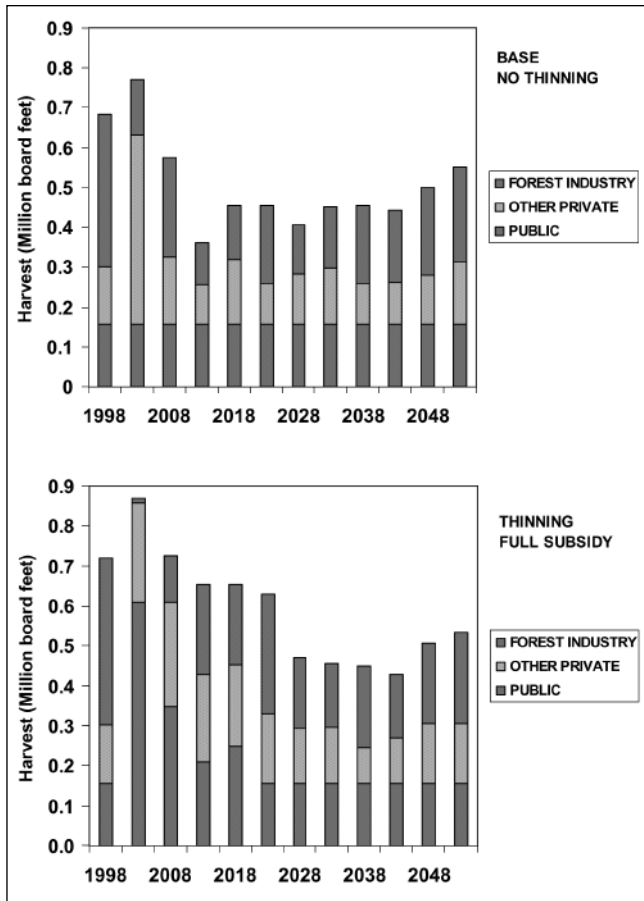


Figure 3—Timber harvest by owner, with and without a thinning program on national forests.

Barbour (2002) identify some 1.95 million acres of densely-stocked stands on public lands (adjusted for removal of wilderness and roadless areas) in eastern Oregon with 4.4 billion board feet of sawtimber thinning volume.

We assume that the Forest Service pays (subsidizes) all the costs of removing the non-merchantable volumes (live or dead trees less than 9 inches DBH) in these thinnings. Initially we also assume that sawtimber thinning volumes are made available with no stumpage fee. Thinning operators must pay the (substantially higher) harvesting costs of removing the thinning volumes but no other costs. We call this the “Full Subsidy” scenario. In a later simulation we add a simple fixed stumpage charge for the thinned sawtimber volumes to examine cost sensitivity.

Figure 2 shows total timber harvest in the base (no thin) and thinning (full subsidy) cases. Base case harvest continues to fall along historical trends until 2013. This is a reflection of the inability of both industry and NIPF lands to maintain recent historical harvest levels [see Adams and Latta 2003 for discussion]. Private harvests rise after the 2013 period but do not return to 1998-2002 levels for the remainder of the projection. Harvest by owner is detailed in figure 3. With a full subsidy thinning program, a large volume of public timber is harvested in the first program period (2001-2005). Initially public timber almost entirely replaces industrial harvest. Public harvest declines in subsequent periods, and the ownership mix moves back toward pre-program proportions. Private cut remains somewhat higher, however, as a result of the inventory “savings” allowed by the thinning program. The harvest trough in 2013 in the base case is displaced to 2043 in the thinning program and is less severe.

Changes in log consumption at mills mirrors patterns in the aggregate regional harvest, with higher volumes through the 2030 period in the thinning case. Driven by restrictions in private timber harvest, mill numbers in the base case decline rapidly after 2003, recovering to the 10-12 mill range after 2028 (figure 4). Under the thinning program, with higher harvest volumes, the current number of mills continues to operate until after 2033. Numbers then fall to the upper level of the base case range.

There appears to be no significant relationship between mill size and the volumes of thinnings taken from the national forests (bigger mills don’t necessarily get more of the thinnings). In the analysis, thinning use is governed instead by proximity to areas available for thinning (transport costs) and the harvest costs associated with the areas that are accessible to a specific mill.

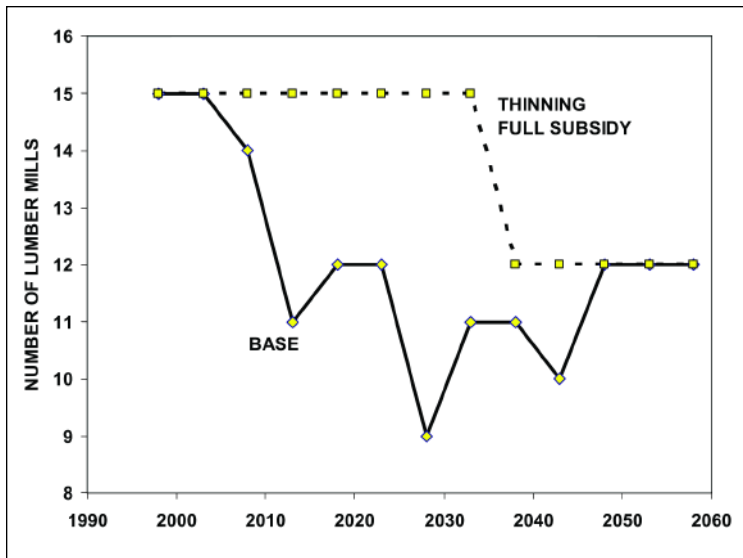


Figure 4—Number of lumber mills operating in eastern Oregon, with and without a thinning program on national forests.

Table 3—Area (in acres) and volume (in MBF) treated and untreated in an example thinning program on national forests in eastern Oregon.

	Acreage	MBF Volume
Treated in Period 1	332,552	2,269,835
Treated in Period 2	290,751	973,202
Treated in Period 3	112,962	269,934
Treated in Period 4	235,370	455,050
Total Treated	971,635	3,968,020
Percent of Thinning Program	63%	91%
Total Untreated	564,180	412,995
Percent of Thinning Program	37%	9%
Total in Thinning Program	1,535,815	4,381,015
Total Overstocked Area	1,953,149	
Percent overstocked in thinning program ^a	79%	

MBF = thousand board feet

^a Area involved in the thinning program included only those acres with non-zero board foot volume

Of the 1.5 million acres of densely-stocked stands included in the thinning program, we project that about 63% would be accessed for treatment under a full subsidy program (table 3). This would remove about 4.0 billion board feet of timber over a 20 year period, or about 91% of the total board foot volume on all areas in the thinning program. The total area in need of treatment (as identified by Wilson, Maguire and Barbour (2002)) less lands in wilderness and inventory roadless areas was about 1.95 million acres. Thus our analysis suggests that about 50% of this area could be treated under a full subsidy program.

In the thinning program simulation we assumed that the national forests made no charge for the thinned sawtimber and operators did not pay the costs of removing the non-merchantable material. Some procedure would be needed to select the firms to harvest the wood, but the only costs would be those of harvesting and transportation. A program of this sort should yield a relatively large area of thinned stands and a high volume of thinned sawtimber. We also examined a case in which additional charges were levied for the sawtimber. These additional costs might be viewed as fees for the value of merchantable logs removed or as a

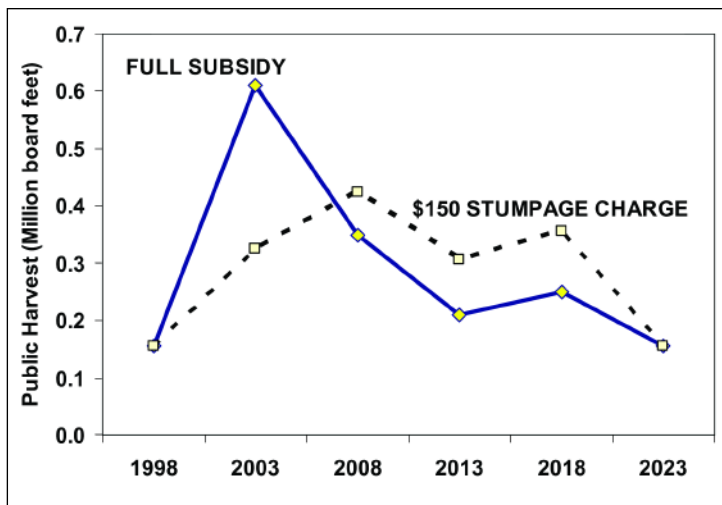


Figure 5—Public harvests under a thinning program with no sawtimber stumpage charges (FULL SUBSIDY) and with a \$150 per MBF stumpage charge (\$150 STUMPAGE CHARGE).

proxy for the cost of removing unmerchantable trees and dead wood as part of the thinning activity (if these costs were proportional to the sawtimber volumes removed). Figure 5 shows the public harvest results from the imposition of a \$150 per MBF stumpage charge. The thinning program essentially represents a stock that can be drawn down at any time during the 20 year program period. Increasing the cost of this material causes thinning harvests to be partly postponed into the third and fourth periods.

DISCUSSION

Given the decline in private harvests in eastern Oregon projected in the base case, an extensive thinning program on national forests in eastern Oregon over the next two to three decades would be well-timed. Results suggest that about 2/3 of the overstocked area that has trees large enough to yield board foot volume would be thinned under a full subsidy program. Total harvest in the region would eventually fall to levels foreseen in the base case, but not until after 2030. The program and its aftermath would also keep mill numbers at current levels for an additional 30 years. The analysis indicated that public cut from the thinning program would largely replace harvests from industrial lands and a sizable portion of the cut from NIPF lands in the first program period. Thereafter, private harvests would move back toward base levels but with a larger inventory and somewhat higher long-term harvest potential. Geographically the largest portion of untreated/unthinned plots and those with no board foot volume are located in the central Oregon (eastern Cascades subregion). Because only those plots with positive board foot thinning volume were included in the analysis, we obtained a higher proportion of area treated than is commonly believed possible for such a program.

To develop these projections we constructed a model of the eastern Oregon forest products sector at the log market level with explicit representation of individual mills. While this model appears to hold some promise for examining the increasingly complex questions related to forest health restoration measures on public lands in eastern Oregon, we recognize that it has limitations that will be challenges for future research. Unlike many past studies, the log demand relations were estimated from a profit function model that included capacity explicitly as a measure of quasi-fixed capital stock. The estimation did not, however, provide values for the critical parameters for minimum operating rate and minimum mill size. Also, absent cost and operating data at the mill level, we estimated mill-level demand by proportioning the regional log demand curve, assuming homogenous logs and uniform products produced by all mills. Ideally, these estimates would be derived for individual mills recognizing efficiency, cost and output quality differences across the mill population.

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THE POTENTIAL OF ARCLOGISTICS 3 ROUTE FOR SOLVING FORESTRY TRANSPORTATION PROBLEMS

Hamish Marshall and Kevin Boston¹

ABSTRACT

For many years the forestry industry has utilized the data storage, analytical and data visualization power of geographical information systems (GIS) to improve their operations. One area where the forest industry has been slow to utilize the power of GIS is in the planning and management of their transportation systems. As the industry moves more towards customer driven supply chain management systems, the forest industry will need to intensify the management of their transportation systems. This paper reviews ESRI's ArcLogistics software suitability to solve modern log truck routing and scheduling problems faced by the forest industry. The results of the scenarios show that the functionality of ArcLogistics is probably insufficient to be used by large forestry companies for their day-to-day scheduling. However, it may prove to be a cost effective tool for medium to small forest companies to evaluate the effects of transport and inventory policies.

INTRODUCTION

The transportation of logs from the forest to the mill is a main component of the forest supply chain. Log transportation is the single largest cost for many forest companies around the world. In the southern United States, log transportation accounts for nearly 50% of the delivered cost of wood fiber (McDonald, Rummer, Taylor and Valenzuela, 2001). In New Zealand, forest industry log transportation accounts for 20 to 30% of the seedling to mill-door discounted costs (Carson 1989).

The size of logging trucks makes them an imposing vehicle on the public roads; the result is a negative public interaction with the forest products industry. Accidents involving logging trucks appear to draw considerable media attention regarding the dangers of logging trucks (Greene and Jackson 1995). There is also an increased public intolerance to the sight of logging trucks within residential areas. The forestry industry needs to develop new transportation plans that avoid these residential areas to reduce potential negative interactions.

Murphy (2003) solved the transportation plan for two case studies in New Zealand that showed similar reductions to the other two modelling efforts with a reduction in fleet size between 25 and 50%.

Despite the potential gains that can be made through improved transportation planning and the considerable interest by forest industries worldwide (Barrett, Prisley and Shaffer 2001, Cossens 1993, Palmgren 2001) there are very few logistic planning systems available to the forestry industry. Probably the most well known of the commercially available systems is ASICAM. It produces a daily plan using a heuristic-based simulation model that assigns and builds routes to the available trucks and loaders to satisfy supply and demand constraints. ASICAM resulted in a 32% reduction in truck fleet size in Chile (Epstein, Morales, Seron, and Weintraub 1999).

Additional work has been completed in Finland and Sweden with the development of EPO and RUTT-OPT, which are customized forest logistics planning systems (Palmgren 2001). Two case studies were completed using

In: Bevers, Michael; Barrett, Tara M., comps. 2005. *Systems Analysis in Forest Resources: Proceedings of the 2003 Symposium*. General Technical Report PNW-GTR-656. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

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RUTT-OPT that showed a large forest company could reduce its fleet size by 30% through improved truck utilization. A small wood chip company was able to reduce its total distance driven by 8%, achieving both the cost savings and improving public safety with a reduction in road traffic (Palmgren 2001).

There are a number of other transportation software systems commercially available that are not specifically designed for solving forest logistic problems, these include TransCAD developed by Caliper Corporation, SHORTREC developed by ORTEC and ArcLogistics 3 Route developed by Environmental Systems Research Institute (ESRI), which is reviewed in this paper.

ESRI is the world leader in Geographical Information Systems (GIS) and holds a 72% of the market share for GIS products (Ecity, 2003). ArcLogistics 3 Route (ArcLogistics) is a stand-alone product developed to solve transportation and routing problems for delivery businesses where a truckload of goods is picked up at one location and then delivered to a number of customers at different locations. ArcLogistics Route improves these businesses by delivering goods or services more efficiently with reduced costs and improved customer service. Unlike ESRI's other products, ArcLogistics does not require a full ArcGIS licence to run. ArcLogistics uses the Dynamap/ Transportation U.S street data which is included with the package. The database includes node elevations and features such as one-way streets, physical turn restrictions, calculated speed information and a geo-reference database that allows the precise location of the customer to be found using the customer's address.

ArcLogistics requires the user to describe the vehicle type and driver. This includes information on individual truck capacities, cost information in terms of fixed cost, \$ per mile, \$ per hour and \$ per overtime hour. Users can also specify working hours, details about lunch breaks, as well as information on start and end locations and times. This data is used to determine optimal routes.

Orders can be entered using the user interface or by importing them from a database. Once all the necessary information has been entered, the optimal routes and schedule are generated. ArcLogistics develops an origin-to-destination matrix that creates the possible routes from the supply to the demand nodes. Good solutions are found to the problem using a tabu search heuristic. Although the quality of solutions produced by ArcLogistic were not tested in this paper, the tabu search heuristic has been found to produce excellent solutions to both transportation

problems (Gendreau, Hertz and Laporte 1994) and other forestry problems (Bettinger, Graetz, Boston, Sessions, and Chung 2002). The results are displayed using both graphical and tabular reports. The tabular reports were found to be the most useful method for reporting for the analysis completed in this paper. If one were using ArcLogistics for day-to-day scheduling and routing of a fleet of trucks, the quantity of information displayed in the graphical reports would be extremely useful.

ArcLogistics was developed to solve problems where the truck has a single pickup point and multiple delivery points per load. These differ from the logistic problems that normally exist in the forestry industry where either a truck is filled at a single location and delivered to another location, or the more complex case (as in Scandinavia) where the order is collected from a number of spatial locations and delivered to one location. The objective of this paper was to investigate the potential of ESRI ArcLogistics 3 Route software for both operational scheduling and routing of trucks in the forest industry.

METHOD

To test the suitability of ArcLogistics to solve simple forestry transportation problems, a set of small hypothetical test problems were developed. ArcLogistics will need the following functionality to successfully solve these problems:

- Be able to route trucks from forest to mill and back to the forest.
- Restrict available routes from the network.
- Restrict loading and unloading hours to meet local restrictions and mill operating hours.
- Specifying the maximum driver hours.
- Place different priorities on customer orders, so that high priority customers are served first if there is a deficit of trucks.

The hypothetical problems used the Oregon State University McDonald-Dunn Research Forest located near Corvallis, Oregon. The model has ten harvesting sites (supply nodes) and five mill locations (demand nodes). These include four local sawmills and one pulp mill. The model also had one garaging location where the trucks had to return at the end of the day. For this problem, a total of 60 orders were generated. Each order specified the supply location, the address of the customer and the total volume/weight of the order. The "base model" specified the following constraints:

- Trucks can only be loaded between 3 am and 4 pm in the forest.

Table 1—Results from the Five Different Scenarios

Scenario	Number of Trucks Used	Total Cost	Percentage of Orders Delivered	Average Miles Traveled per Truck	Average Drive Time per Truck
Base	8	\$ 3059.79	100 %	241	82 %
1a	5	\$ 1917.19	81 %	345	84 %
1b	8	\$ 3059.79	100 %	241	82 %
2	8	\$ 3076.59	100 %	243	82 %
3	6	\$ 2445.01	85 %	220	87 %

- Trucks can only be unloaded between 5 am and 6 pm at the mills.
- Trucks must return to their garages at the end of the day.
- The drivers can only drive for 12 hours a day.
- The capacity of the trucks is 40 tonnes. No split loads (loads to two destinations) were allowed.

Three scenarios were derived from this base model to test different features of ArcLogistics. Scenario one was designed to test ArcLogistics functionality with a surplus and deficit supply of trucks. This scenario was first run with three fewer trucks available than in the base model. It was then rerun with 5 more trucks than in the base model to simulate a situation where there was an oversupply of trucks.

Scenario two was developed to test ArcLogistics functionality regarding a mill's desire to operate its log inventory using a just-in-time (JIT) inventory control system. Logs are required to be delivered within a set time period. The orders for one of the mills in the base model were altered so that each order had to be delivered within a pre-defined one-hour time slot. These delivery times were evenly distributed through the day. This scenario was designed to simulate having orders to be delivered to a mill that was operating a JIT inventory management system.

Scenario three was designed to test the priority orders system in ArcLogistics. The model used an insufficient supply of trucks to complete all loads but a subset of the orders had a higher priority for fulfilment than the others. This will allow for the company to satisfy customers based on a priority system.

RESULTS

The scenarios were compared using several measures produced from the ArcLogistics reports. The first measure was simply the total cost of the deliveries made. The second

was the percentage of the total orders that were actually delivered. The two other measures were used to measure truck utilization; average mileage traveled per truck, average proportion of the day (12 hours) spent driving per truck. Table 1 gives a summary of these four measures for each of the scenarios.

Base scenario

The base model took 50 seconds to solve using the default setting. The model produced a solution in which all the orders were allocated to trucks while not breaking any of the constraints. The total cost for the base model was \$3059.79. The utilization average for the trucks, the amount of time the truck was driving, was 82% of the 12-hour day.

Scenario 1

ArcLogistics performed as would be hoped, when a surplus of trucks existed. ArcLogistics allocated the orders to trucks in a manner that minimizes the trucks required. This is opposed to allocating the orders to all the trucks, creating a situation in which the majority of the trucks are only utilized for part of the day, which is in most cases an undesirable situation. When too few trucks are included in the model, ArcLogistics chose to not deliver the orders that have the highest delivery cost, those orders that took the longest time to deliver. The total cost when there was a deficit of trucks was just over a \$1000 less than the base scenario. This is due to the lack of trucks, meaning that not all orders were delivered and hence no transportation cost was incurred from the undelivered orders. The average cost of delivery for an order also went down from \$ 41.91 for the base scenario to \$32.49 when only 5 trucks were supplied to the model. This indicates that the model is, as stated in the documentation, minimizing cost.

Scenario 2

The results from the JIT application showed that this management option usually requires more resources as it contains additional delivery time constraints. Upon detailed analysis of each truck's delivery schedule, it was found that

ArcLogistics had successfully complied with the “just-in-time” constraints placed on the individual orders. The total cost for delivering the order had increased to \$3079.59. Under this scenario, the average number of miles traveled per truck increased, but the average utilization percentage of the 12 hours spent driving remained the same. The scenario did show that ArcLogistics could be used to investigate the effects that JIT management at sawmills will have on transportation costs and logistics.

Scenario 3

In Scenario 1, when the model had too few trucks to deliver all the orders, the model did not satisfy the orders with the longer distances. However in Scenario 3 these orders had a higher priority placed on them than the other orders. ArcLogistics delivers these orders first and did not fulfill the low priority orders. This allows ArcLogistics to develop transportation plans that will meet those critical orders such as wood needed to meet an export order to avoid demurrage or deliver wood to a wood processing facility that must have raw material to maintain their operations. The total cost of this scenario was less than the base model for the same reason as stated in scenario 1. In this scenario the average cost per order was \$39.43. The truck utilization remained 87% of the 12 possible hours that they could drive per day.

DISCUSSION AND CONCLUSION

The scenarios developed and solved in this paper show that although ArcLogistics was not designed to solve forestry transportation problems, it can be adapted to solve many of the common problems, but it does have some limitations that may reduce its use in the forestry industry. This paper does not include an examination of solution quality of the tabu search heuristic.

The first major limitation is that it uses the Dynamap/Transportation U.S street data that only includes public roads. For most forest products companies, the majority of the roads in their transportation networks are privately owned and will not be included in the Dynamap/Transportation U.S street data. Although it is possible to add roads to this database, the process seems to involve some advanced GIS skills and expenses of further data capture. In this case study the location of the landings in the forest had to be placed on public roads, which were included in the Dynamap/Transportation US street data. This is far from the reality that actually exists in the McDonald Dunn Research Forest, where many of the harvest units can only be reached using forest roads that are not included in the ArcLogistics street dataset. Another limitation of ArcLogistics is the inability

to customize the formulation of the model. The model can only minimize cost and does not allow users to define alternative objective functions containing utilization, safety and other economic variables.

Despite these limitations, the results of this research have shown that ArcLogistics could be used in the forest industry. Given the current functionality of ArcLogistics, it is hard to imagine a large forest company implementing it for their day-to-day operational scheduling and routing. However, the cost of \$US 12,000 (as of December 2003) makes ArcLogistics a very cost competitive tool for medium to small size forestry companies to plan and evaluate the cost and efficiency of different transportation and inventory management policies when customized versions can cost millions of dollars to develop and implement.

ESRI indicates that the new version of ArcLogistics, which is due to be released in a beta version sometime next year, will come in the form of an ArcGIS extension such as Spatial Analyst. This will mean that using a private road network database will be significantly easier. It will also potentially allow for more customization of objective functions, constraints and the optimization models. This means that the new version of ArcLogistics may eliminate many of the limitations of the current version of ArcLogistic that are present when trying to solve forestry transportation problems.

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USING SPATIAL INDICES TO ESTIMATE WOOD PROCUREMENT COSTS

Luc LeBel¹, Sylvain Théberge², Kim Lowell³, and Vincent McCullough⁴

ABSTRACT

In many forest regions, cutting blocks are increasingly being dispersed over large procurement areas. Basic operational analyses make it clear that spreading operations over a larger area increases costs. However, predicting operating costs is time-consuming because a precise harvesting plan has to be laid out to measure forest logistics parameters such as total road distance and cut block size. In an attempt to make the process of evaluating different management scenarios more efficient, a GIS-based method of estimating the costs of forest operations was developed. This paper considers the problems and possibilities regarding Spatial Indices (SI), and attempts to demonstrate that 1) forest mosaics can be decomposed into spatial characteristics that are quantifiable by means of SIs, 2) a combination of SIs, used at optimal conditions enables analysts to define quantitatively the spatial characteristics of a forest mosaic, and 3) relationships can be found among SIs and wood procurement parameters. The procurement model uses cost functions based on the relationship between spatial indices that quantify factors such as cut-block dispersion and landscape heterogeneity, and operational factors such as skidding and hauling distance that were developed through multiple regression analysis.

INTRODUCTION

Forest resources managers must now adapt forest practices to reflect spatial patterns from natural disturbances and natural biophysics environment (Hessburg and others 1999, Harvey and others 2002). They are also required to distribute forest interventions in space and time to accommodate different forest users. The “mosaic” management system constitutes a forestry approach that makes this possible (Quebec 2003).

The mosaic management system consists of a forestry approach that makes possible the distribution of forest interventions in space and time so that they reflect patterns from natural disturbances and natural biophysics environment. The dispersion of logged areas is increasingly required by forest users. Indeed, it is recognized that a high concen-

tration of cut blocks does not always support the preservation of diversified quality landscapes or favorable conditions for multiple land uses. The mosaic management method is expected to maintain a diversity of favorable wildlife habitats and minimize the impact of forest operations on the landscape’s aesthetic quality. It will also contribute to long-term biodiversity preservation (Quebec 2003).

On the other hand, for the companies carrying out forest operations, this type of management has, in the short term, a negative impact on their profitability. Indeed, it has already been shown that, in the short run, a substantial increase in costs can be observed. These costs are, for the most part, the consequence of a higher investment in capital and an increase in the costs of maintaining the road network (O’Hara and others 1989, Zundel 1992, Gingras 1997, Nadeau and others 2002). As a consequence of the uncertainty surrounding the breadth of additional costs associated

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with this management method and the difficulties of defining the operational details with precision, the mosaic management system has been used with caution by the forest industry.

Each territory is characterized by a mosaic that is unique. In order to evaluate management strategies and compare future forest states, the characterization of the initial spatial structure of the forest is necessary (Baskent 1998). Moreover, a forest land manager should be able to characterize the initial ("natural") mosaic in order to overlay an operational mosaic that reflects local objectives: forest yield, timber supply harmonization and security, wildlife habitat quality, other forest users, and timber supply costs. From an operational point of view, the characterizing approach must correspond to a rapid and simple analytical method that allows for binding the characteristics of intervention mosaics with certain parameters that influence the timber supply cost. The operational parameters to consider are the harvesting and skidding costs, transportation cost, and road network construction and maintenance costs. All of these parameters can be related to certain spatial variables such as shape, size and dispersion of cut-blocks.

In land management, the use of spatial analysis tools such as spatial indices (SIs) should facilitate the application of new spatial and time standards for forest operations and minimize the management of land with human perception (D'Eon and Glenn 2000). For example, rather than defining (qualitatively) a mosaic as fragmented with small, simply shaped polygons, one could say (quantitatively) that the mosaic has a fragmentation of 85.5%, a shape complexity of 27.0, and that the polygons have an average size of 12.6 ha.

The field of Landscape Ecology has described many SIs that allow for the quantification of landscape structure (Mladenoff and others 1993, Gustafson 1998, Tischendorf 2001) and can be used to characterize forest mosaics. The science of Landscape Ecology examines, among other things, the development and the dynamics of spatial heterogeneity, spatial heterogeneity management, and the influences of spatial heterogeneity on biotic and abiotic processes (Domont and Leduc 1994).

The definition of a landscape in the discipline of Landscape Ecology can be very diversified but, simply put, a landscape can be regarded as a spatially heterogeneous area (Turner 1989). The description of a forest mosaic corresponds to this definition. Effectively, a forest landscape consists of a mosaic of various stands that are homogeneous

relatively to their dendrometric and ecological characteristics.

The forest mosaic can be characterized according to the variation of size and shape, spatial distribution, density, and stand characteristics (species, age, height, crown closure) (Ripple and others 1991, Mladenoff and others 1993, Baskent and Jordan 1995, Kleinn 2000). SIs take into account individual patches (size, number, form or density) or their vicinity. They study the landscape's (or map's) composition and spatial pattern (Gustafson 1998). As for composition, they examine the number of classes on the map and/or the proportion and the diversity of certain classes according to the whole landscape. Alternatively, the spatial pattern is analyzed according to the average, the median, the variance or the frequency distribution of a patch's surface or linear measurements, their juxtapositions (He and others 1999). SIs can be categorized according to the following categories (this list is not exhaustive but shows the main uses for SIs):

- **Patch Size:** The size is the simplest measurement of the spatial character of a patch. The majority of SIs incorporate directly or indirectly the patch size (McGarigal and Marks 1995, Gustafson 1998).

- **Patch Shape Complexity:** Shape complexity refers to the geometry of a patch; this can be simple and compact or irregular and large. Shape is a spatial attribute that is very difficult to define with SIs because there is an infinite number of patch shapes possible. This spatial aspect is usually summarized or generalized by a shape complexity index taking into account the complexity of a whole mosaic. The measurement of shape complexity is usually based on the ratio perimeter-surface relationships between landcover proportion and indices of landscape spatial pattern (Forman and Godron 1986, Gustafson and Parker 1992, Baskent and Jordan 1995, McGarigal and Marks 1995, Gustafson 1998).

- **Core Area:** As indicated by its name, Core Area represents the inside area of a patch, after a buffer zone is specified by the analyst; it is the patch area not affected by the edge. This edge distance is defined by the investigator according to the organism or phenomenon observed and it can be fixed or variable, according to the edge types. Core Area integrates, in a single measurement, the size, the shape and the edge effect distance (Ripple and others 1991, Baskent and Jordan 1995, McGarigal and Marks 1995, Gustafson 1998, Potvin 1998).

- **Isolation/Proximity:** Isolation/proximity refers to the tendency of patches to be relatively isolated from other

patches of same or similar classes. Isolation can be calculated in terms of size and proximity to the neighboring patches, and this for each patch in the mosaic (Gustafson and Parker 1992, McGarigal and Marks 1995, Gustafson 1998).

- **Contrast:** Contrast refers to the relative difference between adjacent patch types. For example, mature forest, adjacent to immature forest will have an edge contrast that is weaker than mature forest adjacent to a field in culture. This type of SI can be calculated by assigning a contrast weight to each type (McGarigal and Marks 1995, Gustafson 1998)

- **Dispersion:** Dispersion refers to the tendency for the patches to be regularly dispersed, non-random (D'Eon and Glenn 2000) or aggregated. This index is often calculated as a function of the variability of nearest neighbor distance measures. A small standard deviation relative to the mean implies a fairly uniform or regular distribution of patches across landscapes, whereas a large standard deviation relative to the mean implies a more irregular or uneven distribution of patches (McGarigal and Marks 1995, Baskent 1998, Trani and Giles 1999).

- **Contagion/Interspersion:** The contagion refers to the tendency of patches of the same type to be spatially aggregated. Contagion does not take the patch into account as such, but rather the extent to which cells of similar classes are aggregated. There are several ways of calculating these indices but in general, an algorithm determines the probability of finding cells or adjacent patches of the same types (McGarigal and Marks 1995, Gustafson 1998, Hargis and others 1998, He and others 1999). The lacunarity is also a measurement used for the calculation of contagion and interspersion. It is a measurement borrowed from fractal geometry which calculates landscape contagion at several scales (McGarigal and Marks 1995, Gustafson 1998).

- **Subdivision:** Subdivision refers to the scattering of patches. This SI category does not refer to the size, form, relative position or spatial arrangement of patches as such. However, since the subdivision generally affects patch spatial organization, it is difficult to isolate subdivision as an independent measurement. This index can be evaluated according to the number or density of patches, average patch size, aggregation or patch size distribution (McGarigal and Marks 1995, Gustafson 1998, Jeager 2000). When applied to the class level, these SIs can be used to determine the fragmentation of a patch type. Moreover, applied to a whole landscape, they can be used to quantify landscape texture

(granulation). A landscape with a fine texture is characterized by its many small patches while a landscape with a coarse texture shows some large patches (McGarigal and Marks 1995, Trani and Giles 1999). It can be based on strict adjacency, a threshold of distance or a specific function of the distance between patches. Several SIs can be derived from patch connections (McGarigal and Marks 1995).

Since the beginning of the 1980s, several SIs were introduced for various uses (Turner 1989, McGarigal and Marks 1995, Jeager 2000). In spite of a significant interest in the use of SIs, there is still some uncertainty as to their effectiveness for quantifying the characteristics of "real" landscapes. Indeed, SIs have mainly been examined in relation to simulated (computer generated) landscapes and their behavior on real landscapes is not well understood. Therefore, the behavior and sensitivity of SIs relative to different spatial patterns of "real" landscapes are obscure. The knowledge of SIs' behavior and sensitivity in relation to different area sizes of "real" landscapes is also sparse. Furthermore, while characterizing a landscape, particular care must be taken in regard to scale, resolution and landscape extent (McGarigal and Marks 1995)

Since each SI has a theoretical extent and a frequency distribution that has been analyzed using simulated landscapes (Gustafson 1998, Hargis and others 1998, He and others 1999), it is difficult to determine which SIs are the most valuable on real landscapes. The empirical analysis of "natural" variations of SIs remains one of the greatest challenges confronting landscape pattern analysis (McGarigal and Marks 1995).

The lack of knowledge of SIs and the difficulties associated with the interpretation of their responses to spatial pattern is a significant obstacle to the goal of defining landscapes objectively and using SIs for other forestry applications such as evaluating wood procurement costs. Indeed, these problems have caused an incomplete integration of the principles of landscape ecology in resources management (Davidson 1998, Gustafson 1998, Tischendorf 2001, Plante 2002).

If several SIs are correlated, show interactions among themselves, and measure multiple components of spatial patterns, analysis is difficult (Hargis and others 1998, Tischendorf 2001). Consequently, consideration of several SIs measurements, individual and specific to one heterogeneity variable, can be very instructive (Li and Reynolds 1995). Thus, the use of SIs is effective for the comparison of different landscapes, the same landscape at different

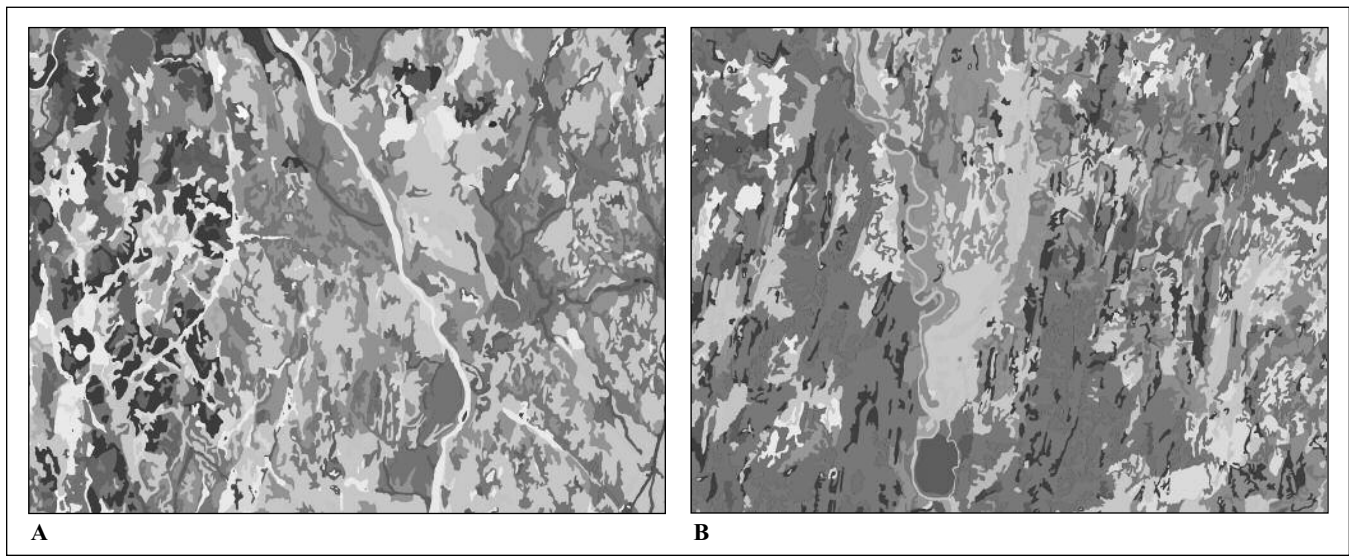


Figure 1—Raster forest cover maps (after generalization) from one of the three participating forest companies.

times or the same landscape under different management strategies (Gustafson 1998).

Considering the problems and possibilities regarding SIs, this study will demonstrate that 1) forest mosaics can be decomposed into spatial characteristics that are quantifiable by means of SIs, 2) using a combination of SIs at optimal conditions should enable us to define quantitatively the spatial characteristics of a forest mosaic, and 3) relationships can be found among SIs and wood procurement parameters.

METHODS

Study Area and Data

To determine the behavior and the sensitivity of SIs on real forest mosaics, a sample of forest cover maps with different spatial configurations was needed. Knowing that spatial patterns of forest mosaics vary from one geographical area to another, we asked for, and received, the collaboration of three forest companies: Abitibi-Consolidated, Bowater and Smurfit-Stone. These companies' lands are located in distinct areas of Quebec's (Canada) public forest. By each providing two maps that they judged different in respect to spatial configuration of forest types (for example, patch diversity, patch geometry, patch size, etc.), these companies' representatives provided six forest mosaics that had different structures. These differences were the consequence of factors such as topography, fire regime, latitude, or disturbances caused by spruce budworm (*Choristoneura fumiferana* (Clem.)). In addition, the companies provided

digital map layers containing historical dispersion patterns of forest operation layouts: roads, harvested blocks, wood yards, camp locations, etc. These map layers provided essential information to establish relations between forest mosaic spatial characteristics and wood procurement costs.

These datasets, used for forest management, include a geometrical and descriptive database with common elements. The maps are based on the geodetic reference NAD 83, cartographic projection MTM and a scale of 1/20 000.

Data

The forest cover maps described previously are vectorial categorical cartographic documents. They consist of discrete polygons that represent homogeneous forest vegetation zones (vegetation types). In order to convert the map from vectorial format to raster format, the software *ArcView* 3.2 (*ArcView* GIS 3.2 is a software produced by the company Environmental Systems Research Institute, Inc. Copyright ©1995, 2003 ESRI) was used. The images for one of the three companies are presented in Figure 1. The raster format of 10m X 10m resolution used to perform the analysis does not significantly affect the precision of the forest cover map, however it does simplify SI programming.

Quantitative Characterization of Forest Mosaics

Window Size for the Calculation of SIs—The spatial pattern detected in an ecological mosaic is related to the scale (Forman and Godron 1986, Turner 1989, McGarigal and Marks 1995); the ecological concept of scale includes

extent and grain. The extent and grain define a resolution's higher and lower limits and any inference relating to the dependence of a system on a given scale is driven by the extent and grain. Consequently, it is essential that the extent and grain represent accurately the ecological phenomenon or organism under investigation. Otherwise, the landscape patterns detected will have little significance and will probably result in erroneous conclusions. Unfortunately, this ideal manner of defining scale is not very realistic. In practice, extent and grain size are often dictated by the scale of the image used (for example, the resolution of remotely sensed image) or data-processing capabilities. For this study, the SIs were tested empirically using different scales. This was done by keeping the grain (pixel) size constant and applying each SI in a moving window; an area unit defining a specific landscape extent and moving in regular intervals across the forest mosaics.

Choice and Calculation of the Selected SIs—Ten SIs were selected to quantify different spatial aspects considered to be essential for the characterization of various landscapes (Table 1). Patch Richness Density (PRD), which tallies the classes present in the landscape, and Patch Density (PD), which counts the number of patches, were used to quantify landscape composition. Regarding spatial patterns, Edge Density (ED), Landscape Shape Index (LSI), and Area-Weighted Mean Shape Index (AWMSI) provide a measurement of patch complexity in the landscape. Contagion Index (CONTAG) gives a quantitative evaluation of landscape fragmentation while Patch Cohesion Index (COHESION) measures connectivity among patches of the same class in the landscape. Regarding patch area size, Mean Patch Area Distribution (AREA_MN) indicates the average patch size in the landscape whereas Mean Core Area Distribution (CORE_MN) provides an average of the patch core area for the patches in the landscape. Finally, the Range of Euclidean Nearest Neighbor Distance (ENN_RA) quantifies the isolation/proximity of patches in the landscape, i.e., the tendency for the patches to be more or less isolated from patches of the same class. This collection of SIs shows that the forest mosaic can be broken up into characteristics that can be quantified to define its spatial patterns and composition. McGarigal and Marks (1995) detail the mathematical expressions for these and other SIs.

Each of the SIs documented in this section can be used with a vectorial or raster data format. However, since the SI's calculation is performed on raster images, the explanation and comments on SIs and their mathematical expressions (Table 1) will be done for this format of data.

Frequency Distributions and Statistics—For each of the six cartographic layers, the ten selected SIs were calculated within a moving window of 50 ha, 200 ha, and 400 ha. The SIs were calculated only for windows where each patch had an attribute and the window did not overlap the map's external limits. From the SIs results, the frequency distributions were generated. From these distributions, the basic descriptive statistics were determined.

To understand SIs' behavior and determine if they can detect visual spatial configuration differences between different landscapes, one can test if two independent empirical distributions come from two different populations. To determine this and to verify the validity of each SI, the Kolmogorov-Smirnov two-sample test (K-S) was used. The K-S test was conducted using the software *S-Plus*. (*S-Plus 6.0* is a software produced by the company *Insightful Corporation*. ©2002 Insightful Corporation.) The threshold for the rejection of the hypothesis that two distributions are identical was 99%.

Use of SIs to Predict Key Wood Procurement Parameters

Using detailed operational maps of each of the procurement areas studied, a spatial analysis was conducted. The spatial analysis of the past operation layouts helped establish which factors - road construction, harvesting, transportation, equipment displacement (moving) and planning - contributed to wood procurement cost. It also permitted determining at what scale - whole landscape, operational area, harvesting sectors, or cut blocks - the SIs should be used for effective cost quantification. Moreover, the analysis highlighted which spatial features - roads, harvesting sectors dispersion, cut block shapes, etc. - are significant for the characterization of the operational mosaic and which SIs could contribute to its quantification.

Since the cost of forest operations is usually based on the specific forest class of interest, for example, the cut blocks for the cost of harvesting, or the distance between harvesting sectors and the mill for the cost of transportation, a binary model was used to characterize the operational mosaic with SIs.

This analysis allowed the identification of SIs that are most suitable for calculation of different forest operation features costs. These are Contagion Index, Euclidean Nearest Neighbor, Edge Density, Class Area (Patch Area, but for a given class), and Patch Density. Once the SIs had been selected to quantify different spatial aspects of operational features, the multiple regression analysis technique

Table 1—Summary of the selected landscape metrics used for the analysis.

Name	Characteristics	Mathematic expression	Units
Patch Richness Density (PRD)	Measures the number of patch classes in the landscape	$PRD = \frac{m}{A} (10\ 000)(100)$	Number / 100 ha
Patch Density (PD)	Measures the number of patches in the landscape	$PD = \frac{N}{A} (10\ 000)(100)$	Number / 100 ha
Edge Density (ED)	Measures the total length of edge segments in the landscape	$ED = \frac{E}{A} (10\ 000)$	m/ha
Landscape Shape Index (LSI)	Measure the total length of edge segments in the landscape and compares it to a square standard	$LSI = \frac{E}{\sqrt{A}}$	Without units
Area-Weighted Mean Shape Index (AWMSI)	Measures the average patch shape (in the landscape) by weighting the patch area so that larger patches have larger weight than smaller patches	$AWMSI = \sum_{i=1}^m \left[\left[\frac{p_i}{\sqrt{a_i}} \right] \cdot \left[\frac{a_i}{A} \right] \right]$	Without units
Contagion Index (CONTAG)	Measures the relative aggregation of the landscape	$CONTAG = \left[1 + \frac{\sum_{i=1}^m \sum_{j=1}^m \left[(P_i) \left\{ \frac{g_{ij}}{\sum_{j=1}^m g_{ij}} \right\} \right] \cdot \left[\ln (P_i) \left\{ \frac{g_{ij}}{\sum_{j=1}^m g_{ij}} \right\} \right]}{2 \ln (m)} \right] (100)$	Percentage (%)
Patch Cohesion Index (COHESION)	Measures the connectivity of patches of the same class in the landscape	$COHESION = \left[1 - \frac{\sum_{i=1}^m P_i^*}{\sum_{i=1}^m P_i^* \sqrt{a_i^*}} \right] \cdot \left[1 - \frac{1}{\sqrt{Z}} \right]^{-1} \times 100$	Percentage (%)
Mean of patch Area Distribution (AREA_MN)	Measures the average patch area size for the landscape	$AREA_MN = \frac{\sum_{i=1}^n \left[a_i \left\{ \frac{1}{10\ 000} \right\} \right]}{n}$	Ha
Range of Euclidean Nearest Neighbor Distance (ENN_RA)	Measures the range of the distance between patches of the same class in the landscape	$ENN_RA = h_{i\ max} - h_{i\ min}$	Meter
Mean of Core Area Distribution (CORE_MN)	Measures the average patch area size for the landscape, excluding an edge buffer (specified by the user)	$CORE_MN = \frac{\sum_{i=1}^n a_i^c \left\{ \frac{1}{10\ 000} \right\}}{n}$	Ha

m : number of patch types in the landscape
 A : landscape total area (m²)
 E : landscape total length of edge segments
 N : number of patches in the landscape
 p_i : patch perimeter (m)
 a_i : patch area (m²)
 P_i : landscape proportion occupied by patch type i
 g_{ij} : number of adjacency between pixels of type i and j

P_i^{*} : patch perimeter (in pixel)
 a_i^{*} : patch area (in pixel)
 Z : total number of pixel in the landscape
 h_i : shortest Euclidean distance from the edge of a patch and a patch of the same class
 a_i^c : patch core area (Note : a edge buffer is specified by the user, in this study : 50 meters)

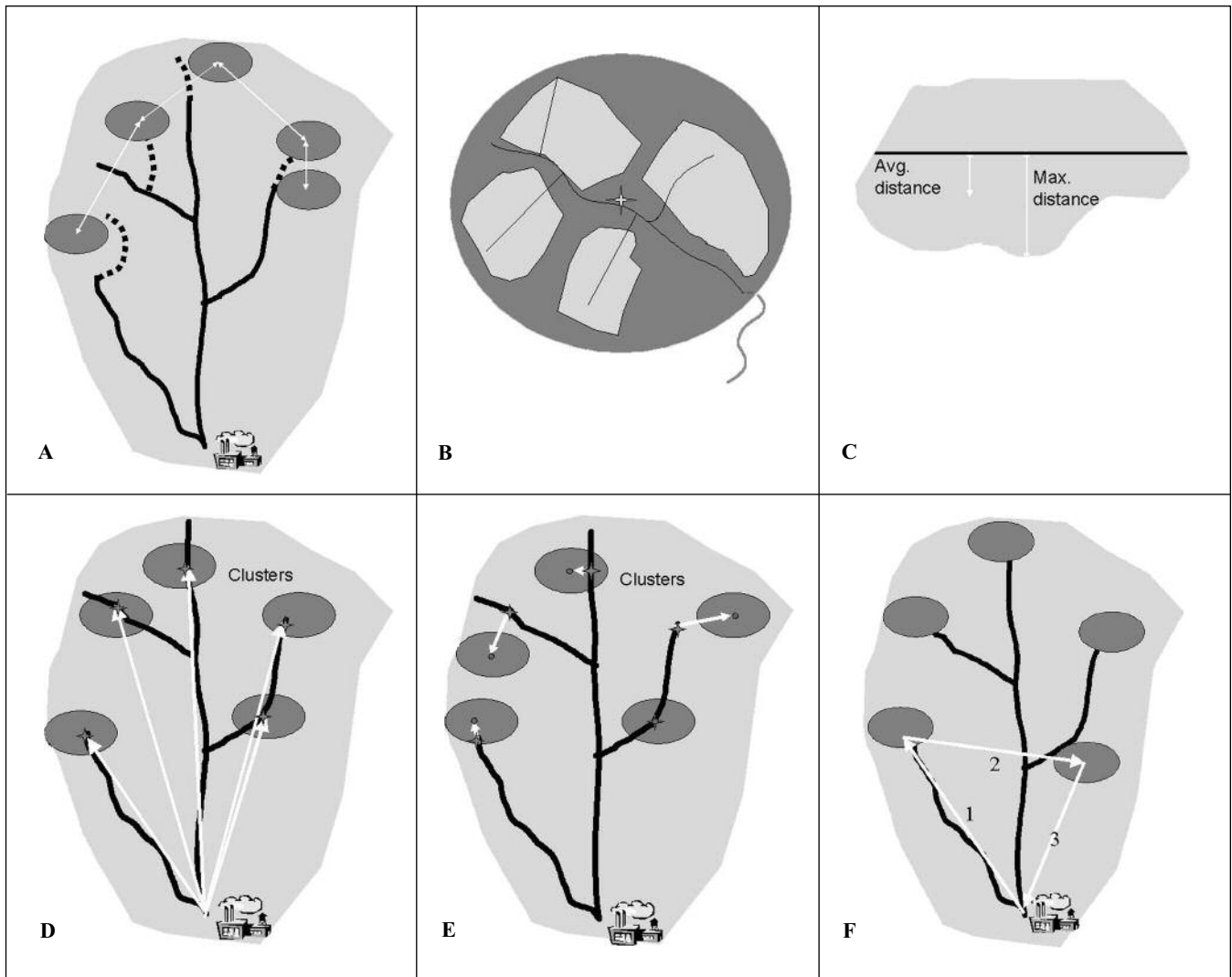


Figure 2—Spatial factors impacting wood procurement cost, A) access roads, B) extraction roads, C) skidding distances, D) access for wood transport, E) transport for extraction of wood from harvesting sectors, and F) machinery displacement between blocks.

was used to determine the correlation between the SIs and the measured operational features. Also, the multiple regression technique permitted the generation of functions using SIs to calculate the operational features. The result is a predictive model. Detailed historical data provided by the companies allowed for the comparison between actual and predicted values. Finally, the cost functions developed were constructed and tested for robustness and sensitivity.

ANALYSIS AND DISCUSSION

Quantitative Characterization of Forest Mosaics

This analysis shows that eight of the 10 SIs selected can detect differences among different forest mosaics. Patch Richness Density, Patch Density, Edge Density, Landscape

Shape Index, Area-Weighted Mean Shape Index, Patch Cohesion Index, Patch Area Density Mean, and Mean of Core Area are appropriate for characterizing different forest mosaics for at least one of the scales (window sizes) used. The determination of SIs able to effectively quantify the patch proximity and landscape fragmentation, or the optimal conditions to use them has not been attained. Nevertheless, our results show that the use of a combination of different SIs, used under optimal conditions (landscape scales), should allow the spatial and quantitative characterization of forest mosaic associated with a territory.

This study has revealed several points. 1) SIs must be used at the scale of the ecological phenomenon understudy. Empirical studies such as this one can serve as a reference

Table 2—Results for the three procurement areas and the global model, from the predictive model produced for each parameter using SIs.

Selected variables\ Territories	Bowater	Smurfit-Stone	Abitibi- Consolidated	Global (3 territories)
Construction + Access Road Maintenance	PD; AREA_MN r ² =0.52	AREA_MN; PD r ² =0.66	AREA_MN; PD r ² =0.29	PD;AREA_AM r ² =0.66
Construction + Extraction Road Maintenance	CA; PD r ² =0.92	CA; PD r ² =0.63	CA; PD r ² = 0.39	CA; PD r ² =0.741
Transport Access Road	vol_dist_acc (ENN) r ² =0.99	dist_vol_acc (ENN) r ² =0.55	dist_vol_acc (ENN) r ² =0.70	dist_vol_acc (ENN) r ² =0.82
Transport Extraction Road	dist_vol_rec (ENN) r ² =0.95	dist_vol_rec (ENN) r ² = 0.94	dist_vol_rec (ENN) r ² =0.94	dist_vol_rec (ENN) r ² =0.91
Forwarding distances	MIN; MAX; ED r ² =0.94	MIN; MAX; ED r ² =0.93	MIN; MAX; ED r ² =0.95	MAX; MIN; ED r ² =0.94

Table 3—For each factor impacting wood procurement cost, function developed with the use of SIs and the R².

Factor impacting wood procurement cost	Function developed with the use of SIs	R ² (%)
Access roads (figure 2-A)	Total Distance (TD) TD = 1.300*10 ⁸ PD ¹ + 3.06 *10 ⁵	52
Extraction roads (figure 2-B)	Extraction Road Distance (ERD) ERD = 2.294*10 CA ² + 2.434*10 ⁷ PD ³ + 3.377*10 ²	91
Forwarding distances (figure 2-C)	Average Distance (AD) AD = AD = 0.410 MAX ⁴ +0.660 MIN ⁵ - 2.068*10 ⁴ ED ⁶ + 4.875	99
Wood transport (access) (figure 2-D)	Wood Transport Access (WTA) WTA = 1.163* ENN ⁷ -6.001*10 ³	95
Wood transport (extraction) (figure 2-E)	Wood Transport Extraction (WTE) WTE = 1.267*ENN ⁸ -3.891*10 ²	94

¹ Patch Density of the harvesting area

² Core Area of the cut blocks

³ Patch Density of the cut blocks

⁴ Maximum distance between a line crossing the cut block major axis and the cut block edge

⁵ Minimum distance between a line crossing the cut block major axis and the cut block edge

⁶ Edge Density of the cut blocks

⁷ Euclidean Nearest Neighbor between the harvesting sectors' centroide and the mill

⁸ Euclidean Nearest Neighbor between the harvesting sectors' centroide and the access road

for determining it. 2) The scale must be constant when using SIs to compare landscapes. This implies that the landscapes must have the same cartographic scale, as well as the same resolution and extent. Moreover the landscapes should be generated according to the same standards. 3) SIs are not effective at all scales to detect different landscapes. In fact, they must be used under conditions (scales) that give them the most sensitivity. And 4), if in doubt, it is preferable to test SIs empirically in order to know their behavior.

Application: Use of SIs to Predict Key Wood Procurement Parameters

The analysis of the use of SIs to predict key wood procurement parameters showed that SIs could be used to predict procurement cost at a strategic level of planning. However, SIs do not provide an advantage over a more traditional method using GIS and road planning at the operational level.

Hence, at the strategic planning level, access roads, extraction roads, skidding distances, access for wood transport, transport for extraction of wood from harvesting sectors, and machinery displacement between blocks have been identified as the main spatial factors impacting the wood procurement cost (Figure 2). Of these factors, the regression analysis revealed that all but the displacement of machinery could use SIs to evaluate procurement cost. For the displacement of machinery, the SIs selected were not reliable to provide a robust evaluation.

A predictive model was produced for each parameter in each of the three procurement areas (Table 2). In all cases, the same SIs were identified as the most statistically significant. The predictive value is optimum when region specific models are used to predict the dependent variable. However, for all key parameters except “access road”, the global model can provide useful estimates to decision makers.

The function developed (using SIs) to quantify the key wood procurement parameters are presented in Table 3. This table also shows the R^2 value.

Hence, to determine wood procurement cost of the different factors impacting it, one can apply widely used cost functions and provide the estimated spatial parameter (Table 3).

CONCLUSION

In Quebec (Canada), the appearance of the “mosaic” forest management method, which aims at conciliating needs of different forest users by maintaining forest land integrity, imposes new spatio-temporal standards on forest resources managers. This trend of adapting forest operations to imitate the spatial pattern generated by the regime of natural disturbances and natural environment is increasingly popular in Quebec and elsewhere.

SIs are mathematical expressions having the goal of objectively quantifying aspects of landscapes’ spatial composition and configuration on categorical maps. Consequently, a combination of different SIs should enable the definition of forest mosaics’ spatial characteristics. It is from this premise that this study originated.

In this context, SIs can thus be used as a tool for forest planning in order to determine which management scenario will minimize the forest operation effects on a landscape’s structure. Moreover, they could be used, at a strategic resource management level, to evaluate wood procurement cost of a scenario or management method.

This study demonstrated that SIs could be part of a simple and robust methodology to spatially characterize forest mosaics and call attention to their possibilities for uses in forest resources management. It also showed the utilization potential of SIs to predict key wood procurement parameters and help evaluate wood procurement costs. Although preliminary results demonstrate that procurement cost predicted using an SI-based equation would only apply at a strategic planning level, and that results would be less accurate than those obtained with a more exact approach, significant time savings are possible nonetheless. Moreover, an SI-based approach may provide new methodological possibilities for advanced harvesting modeling.

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