IMPROVING FOREST MANAGEMENT DECISIONS BY MODELING LANDSCAPE DISTURBANCE IMPACTS ON FOREST AGE STRUCTURE DYNAMICS

by

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B.Sc. Environmental Science, University of Stirling, UK 2000

RESEARCH PROJECT IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTERS OF RESOURCE MANAGEMENT
in the
School of Resource and Environmental Management

Project No. 307

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SIMON FRASER UNIVERSITY
November 2002

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Project No: 307

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Title of Project

Improving Forest Management Decisions by Modeling Landscape Disturbance Impacts on Forest Age Structure Dynamics

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ABSTRACT

The emerging paradigm of ecosystem-based management suggests taking a holistic approach to management, which requires a thorough understanding of the interactions between anthropogenic and natural disturbance processes in forest ecosystems. Most current forest management plans are based on the hypothesis that natural disturbance and forest harvesting are compensatory in their impacts on forest ecosystems. Using a spatially explicit landscape modeling tool, I investigate the hypothesis of compensatory effects between forest harvesting and fire and the alternative hypothesis of depensatory effects. I simulate several parameters regarding management (strategy, harvesting rate and cost) and fire regime (fire return interval and extent) affecting forest ecosystem age structure at a landscape scale.

Aspatial and temporal analyses of the data suggest that the interaction of harvesting and fire are depensatory. Forest ecosystem conditions are outside the historical range of variation under the Status Quo scenario, which describes current practices of clearcutting for sustained yield in Québec's boreal forest. Results indicate that under increased disturbance levels from harvesting and fire the area of re-establishing early-seral forest experiences recurring disturbance before reaching reproductive age isolating patches from seed sources. In contrast, more restrictive alternatives to the Status Quo, which limit timber yields, can maintain a forest age structure similar to historical conditions over most of the examined range of fire regime and management parameters. A sensitivity analysis on harvesting rate showed that for harvesting rates between 0.8% and 1% annually overall timber yields are similar in the case of current sustained yield management. Overall, management strategy, harvesting rate, and fire return interval are the most significant parameters in this aspatial analysis.

ACKNOWLEDGEMENTS

I thank my supervisory committee, Marie-Josée Fortin, Ken Lertzman and Andrew Fall for their generous advice. Particularly, I would like to thank my supervisor Marie-Josée Fortin for her great support throughout the work, and Andrew Fall for his help with SELES and his valuable comments. In addition thanks go to the members of the Landscape Ecology lab, and to the REM staff, Bev, Marie-Ann, Rhonda, and Laurence for making everything work out.

This research was funded by a grant from the Sustainable Forest Management Network – Integration Project, Québec to Drs. Marie-Josée Fortin and Andrew Fall, and a NSERC grant to Dr. Marie-Josée Fortin.

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1 INTRODUCTION

For much of the past century, natural forests have been increasingly converted into managed forests, and this has had a wide range of impacts such as forest fragmentation, loss of old-growth forest and a decline in biodiversity (Hansen *et al.* 1991; Spies *et al.* 1994; Wallin *et al.* 1994; Gustafson and Crow 1996). Increasing concerns about maintaining the ecological integrity of forest ecosystems and preserving biodiversity and other ecological values have generated ongoing research by both scientists and resource managers (Coates and Burton 1997; Cissel *et al.* 1999; Messier and Kneeshaw 1999; Kneeshaw *et al.* 2000). Emerging knowledge suggests taking a broader approach to management through practices that emulate natural ecosystem variability and dynamics in order to restore functions of forests (Grumbine 1994; Rogers 1996; Landres *et al.* 1999).

The growing concern about human management of renewable natural resources has initiated a rethinking of political and economic decision-making. To this end, the Brundtland commission on Environment and Development introduced the concept of sustainable development. This concept advocates resource extraction in a way as to maintain the integrity of the resource base (World Commission on Environment and Development 1987). As a new management, paradigm sustainable development is now being integrated into the management of forests (Kneeshaw *et al.* 2000).

The emerging paradigm of sustainable forest management integrates principles such as sustained timber yield and concurrent maintenance of forest ecosystem integrity while providing a variety of other services such as recreation (Christensen *et al.* 1996; Canadian Council of Forest Ministers 1997; Messier and Kneeshaw 1999). Thus, management should address the ecosystem as a whole including the processes shaping it (Grumbine 1994; Landres *et al.* 1999; Messier and Kneeshaw 1999). To aid forest managers in their task of sustainable forest management, further research on the impact of practices and their interaction with the natural environment is however required (Messier and Kneeshaw 1999). Important management considerations and research concerns include appropriate management scale, spatial and temporal management implications, as well as operational concerns of timber harvesting (Spies *et al.* 1994; Landres *et al.* 1999; Kneeshaw *et al.* 2000). Computing tools such as Geographic Information Systems (GIS) and simulation models can contribute in examining these spatio-temporal problems (Hunsaker *et al.* 1993; Gustafson and Crow 1998). Indeed, given that we cannot wait hundreds of years to find out the emergent impact of alternative forest management activities, modeling tools for simulating likely long-term effects of different scenarios can provide important insights into potential consequences for the ecosystem (Gustafson and Crow 1998).

The main component of my research is to gain a better understanding of the interactions between anthropogenic disturbance such as forest harvesting and natural disturbance dynamics and their effect on the boreal forest ecosystem sustainability at a landscape level. Because ecosystem-based forest management advocates maintaining forests within their range of historical variability (Hansen *et al.* 1991; Swanson *et al.* 1993; Landres *et al.* 1999), an analysis of ecological indicators of forest conditions and their spatial and temporal change is required (Kneeshaw *et al.* 2000). At a landscape level, parameters such as forest age structure, species composition, patch shape and size, and spatial pattern can be used as they represent important management considerations (Messier and Kneeshaw 1999; Kneeshaw *et al.* 2000).

In this research, I investigate the combined effects of natural disturbances and forest harvesting in a boreal forest ecosystem. Specifically, I examine the impact of these processes on forest age structure relative to current ecosystem conditions by using a spatially explicit model allowing the simulation of alternative management scenarios. I analyze the effects on forest age class structure at the landscape scale. Age class is a critical indicator of forest integrity at the landscape scale (Fall *et al.* Submitted; Kneeshaw *et al.* 2000), as it is modified directly by disturbance processes.

Maintenance of older forest in the landscape is critical for the maintenance of biodiversity (Hansen *et al.* 1991; Bergeron *et al.* 1999; Carey 2000) because many elements associated with this habitat type such as snags, coarse woody debris, and complex spatial structure provide important habitat (Hansen *et al.* 1991; Burton *et al.* 1999). Industrial forestry practices typically target old forest thereby eliminating virtually all stands older than rotation length (Harvey *et al.* 2002). The alternative management strategies I investigate here are designed to sustain mature and old forest in the landscape. Examining the performance of these strategies to maintain older forest forms an important aspect of my study, a concern that generally lacks attention in forest landscape planning (Lertzman *et al.* 1997).

One important aspect of my research is the analysis of the combined disturbance effects of harvesting and fire on successful forest re-establishment after forest cover loss. In particular, forest harvesting and fire remove mature trees, while a loss of trees of reproductive age can affect natural forest regeneration (Johnson *et al.* 1998; Asselin *et al.* 2001). I will therefore examine the sensitivity of various harvesting rates and fire rotation lengths and identify parameter combinations at which broad scale boreal forest patterns, and hence many ecosystem processes, are maintained within the historical range of variation. This will contribute to a better understanding of the potential impacts of forest management on the forest ecosystem and to the development of indicators of sustainable forest management (see Kneeshaw *et al.* 2000; Yamasaki *et al.* Submitted).

Wildlife ecology and fisheries research literature describes, among others, two types of mortality effects (*e.g.*, Solari *et al.* 1997). Compensatory effects refer to a case when one source of mortality decreases mortality from other sources (Singer *et al.* 1997). This may result in an underestimation of the effect of the alternative source(s) of mortality. For example, tree mortality from fire may be attributed to the compensatory effect of harvesting potentially resulting in an underestimation of the true effect of fire. If the total combined impact of two or more causes of mortality is higher than predicted from these two sources separately, then the effect is depensatory (Solari *et al.* 1997). Hence, I investigate the hypotheses of compensatory and depensatory effects of the disturbance from harvesting in addition to fire.

1.1 Objectives

In order to investigate the relationships and feedback mechanisms between processes governing forest structure as a consequence of different fire and harvesting regimes, I focus on:

- Evaluating the impact of individual management strategies on the development of forest age structure over time;

- Evaluating the combined impacts of forest harvesting in addition to natural disturbance, *i.e.*, fire, as constraints to age structure and harvestable timber;
- Investigating disturbance effects from harvesting and fire on the occurrence and aerial extent of re-burning incidents of sexually immature early-seral forest after initial forest cover removal due to either harvesting or fire.

Industrial forestry has ignored the effect of natural disturbance (MacLean 1990) and has assumed that the effects of clear-cut harvesting and fire are compensatory (Carleton and MacLellan 1994; Aber *et al.* 2000). In this perspective harvesting replaces fire (Carleton and MacLellan 1994; Bergeron *et al.* 1998; Harvey *et al.* 2002), and maintains the ecological value of the forest ecosystem (Aber *et al.* 2000). However, Bergeron and Harvey (1997) found that forest harvesting results in a change in forest structure from an initially diverse mix of different stand ages and domination of conifers to mainly younger, deciduous stands. In contrast to the prevalent view of compensatory effects, I hypothesize that forest harvesting cannot replace fire as a disturbance, and hence creates additional impacts on the forest ecosystem. This depensatory effect will exacerbate the structural transition and the loss of old-growth forests.

2 EVALUATING FOREST MANAGEMENT DECISIONS – A SIMULATION APPROACH

Natural ecosystems worldwide are under threat as a consequence of anthropogenic activities and resource exploitation (Forman 1995; Morrison 1995). In particular, the continued decline in old-growth forests due to extensive harvesting of this resource has been recognized as a high risk to biodiversity (Carey 2000). The majority of current management strategies prescribe rigid annual forest harvesting rates based on the premise of maximizing timber yields (Messier and Kneeshaw 1999) resulting in a uniform forest age structure of young stands, and decreased species diversity (Coates and Burton 1997; Crow and Gustafson 1997; Bergeron *et al.* 1998). Older forests decline in abundance, and ecological functions associated with these mature stands, such as important habitat can be lost (Bergeron *et al.* 1999).

In the boreal forest of Québec, fire is the main disturbance type and is responsible for maintaining a heterogeneous habitat mosaic (Bergeron and Dansereau 1993; Bergeron *et al.* 1998) with forest patches of different age and composition (Bergeron and Dansereau 1993; Gauthier *et al.* 1996). Although wildfires are often stand-replacing, they rarely kill all the trees, leaving patches of undisturbed forest within the burned area (DeLong and Tanner 1996). However, where mortality does occur within burns, young forest regenerates (Bergeron and Dansereau 1993), resulting in a landscape mosaic composed of large areas of young forest interspersed with smaller patches of older forest (Johnson *et al.* 1998).

In contrast to this heterogeneous forest ecosystem structure shaped by natural disturbance, industrial maximum yield forestry strives to create an even-aged, homogenous structure whereby rotation length determines maximum tree age (Johnson *et al.* 1998). Forest management for timber production also affects species composition, which may result in loss of diversity. Plantations of desired timber species and harvesting interrupt natural succession patterns. In the mixed boreal forest of Québec, silvicultural prescriptions replace the complex succession pattern from hardwood to mixedwood to softwood stands with a cyclical rotation of similarly composed stands (Bergeron *et al.* 1998).

One important effect of natural and anthropogenic disturbance is mortality of mature trees, and hence seed sources, over large areas, *i.e.*, increasing the colonization distance (the distance seed must travel from living sources, Greene *et al.* 1999). While natural disturbance is inherent to the forest ecosystem, harvesting in addition to fire exacerbates this effect removing even more trees of reproductive age. This can have a significant impact on the success of natural regeneration of the forest (Johnson *et al.* 1998; Asselin *et al.* 2001).

Successful natural regeneration requires sexually mature trees for seed production. After the loss of sexually mature forest through either harvesting or natural disturbance, new forest regenerates from local seed. In a case where regenerating early-seral forest below sexually reproductive age is removed through further disturbance events, natural regeneration may be delayed because the seed sources are unavailable on site. Regeneration would then depend on seed dispersal and need to slowly be regenerated from the potentially remote fire/forest boundaries (Johnson *et al.* 1998; Greene *et al.* 1998; Asselin *et al.* 2001).

Among the dominant goals of ecosystem-based forest management is the maintenance of evolutionary and ecological processes (Grumbine 1994; Christensen *et al.* 1996). Natural regeneration rather than planting should therefore be the preferred method of forest re-establishment after disturbance (Silva Forest Foundation 1996; Burda *et al.* 1997). Forest management should ensure harvesting levels and practices that maintain sufficiently large areas of mature stands within the forested landscape, and minimize the number of early-seral stands that might burn before reaching sexual maturity.

To simulate the effects of different harvesting scenarios and natural disturbance (here fire) on age structure, I used a spatially explicit forest landscape model developed by Fall *et al.* (Submitted) (hereafter the Mauricie Model). This model was developed using the Spatially Explicit Landscape Event Simulator (SELES) language (Fall and Fall 2001). SELES produces numerical (*i.e.*, time series) and graphical (*i.e.*, map outputs) information for each simulation describing forest age structure. I used the time series outputs of age class summaries for investigating the effect of disturbance on structural forest descriptors by aspatial analysis of frequency distribution over time.

2.1 Forest Ecology Background

Timber harvesting (Gustafson and Crow 1994, 1998) and natural disturbances such as fire, wind, and pests (Franklin and Forman 1987; Lertzman and Fall 1998) affect forest structure. Alterations of forest ecosystems as a result of anthropogenic management can have significant effects on the development of these systems by changing the trajectory of dynamics that have shaped them over history (Gardner *et al.* 1987; Kaufmann and Regan 1995).

As a result of industrial forestry, managed naturally heterogeneous forest ecosystems have lost much of their diverse age structure, species composition and spatial patterning (Coates and Burton 1997; Crow and Gustafson 1997; Bergeron *et al.* 1998). In contrast, ecosystem-based management that maintains the natural spatial heterogeneity and temporal variability of forest structures and processes has been advocated over current practices (Coates and Steventon 1995; Galindo-Leal and Bunnell 1995; Christensen *et al.* 1996; Coates 1997; Bergeron *et al.* 1999; Burton *et al.* 1999; Cissel *et al.* 1999).

Among the components of ecosystem-based forest management is the principle of acknowledging natural disturbance regimes characteristic for a particular forest region (Attiwill 1994; MacDonald 1995; Christensen *et al.* 1996; Lieffers *et al.* 1996). In a given forest region, these parameters are affected by variables such as climate, soil, and topography (Gardner *et al.* 1987). With recognition of the significance of these disturbance dynamics for a particular forest, ecologists are also gaining an understanding of their impact on forest ecosystems; natural disturbances significantly affect the structure of most ecosystems (Gauthier *et al.* 1996; Perry and Amaranthus 1997; Lertzman and Fall 1998). Thus, one approach to mitigate some of the effects of industrial forestry involves restoring and maintaining the natural state of forests by emulating the dynamics that have shaped these systems over time (Swanson *et al.* 1993; Galindo-Leal and Bunnell 1995; Bergeron *et al.* 1999).

A number of researchers have studied the impact of natural disturbance processes (*e.g.*, Coates and Burton 1997; Crow and Gustafson 1997; Wimberly *et al.* 2000) and management practices (*e.g.*, Bergeron and Dansereau 1993; Wallin *et al.* 1994; Bergeron *et al.* 1998; Bergeron *et al.* 2001) on forest ecosystems, which has improved the understanding of ecosystem dynamics. Successful forest management that is based on ecological principles requires a thorough understanding of natural dynamics and the interactions with anthropogenic disturbance (Rogers 1996; Burton *et al.* 1999). Hence, a study on integrating ecological knowledge and management objectives to provide management guidelines is an important contribution to sustainable forest practices (Bergeron *et al.* 1999).

The management approaches proposed by Bergeron *et al.* (1999) and Burton *et al.* (1999) are examples of alternatives to industrial forestry that permit emulation of natural fire dynamics at both the stand and landscape scales. In the boreal forest, fires are often assumed to result in a negative exponential age distribution (Van Wagner 1978; Johnson and Van Wagner 1985), which provides the rationale for both management proposals for maintaining a mix of early and late successional stands, and hence species and spatial heterogeneity (Bergeron *et al.* 1999; Burton *et al.* 1999). This can be achieved through variable rotation lengths and dispersing harvesting units within the landscape (Bergeron *et al.* 1999; Burton *et al.* 1999).

Extending rotation length for parts of the landscape retains stands of various ages. Harvesting techniques can be altered to emulate natural disturbance typical for different successional stages. Mature stands of rotation age may be clearcut; variable retention could be applied to stands of intermediate age; and gap dynamics in old-growth would be mimicked through single tree selection (Bergeron *et al.* 1999).

2.2 Alternative Forest Management Strategies

I used the Mauricie Model to evaluate five management strategies (Table 1). All strategies aggregate cutblocks within distinct operating areas leaving the remaining landscape intact as much as possible to maintain connectivity within the landscape. Only when all designated cutting units within one operating area have been harvested, logging continues in the next area.

The first management strategy reflects the current management practices in Québec (*i.e.*, constant annual rate of cut; hereafter "Status Quo"; see Table 1). Harvesting rate in the Status Quo strategy was based on maximum sustained yield, limited by minimum harvest age (*i.e.*, the maximum rate of cut for a minimum harvest age of 100 years is 1% per year), and the harvesting method is assumed to be clearcutting.

I call the ecosystem-based management alternatives the "Strict Local Burton" and the "Strict Reserve Old Burton" strategies, which are adapted from the age class dependent management approach suggested by Burton *et al.* (1999) (see Table 1). The approach by Burton *et al.* (1999) maintains a proportion (35%) of forest older than 101 years, based in part on the expected fire cycle of 150-160 years for the region (Figure 1 and Table 2). This is justified by the significance of older forests for maintaining biodiversity and providing essential habitat (*e.g.,* Hansen *et al.* 1991; Bergeron *et al.* 1999; Burton *et al.* 1999; Carey 2000).

The design of the two Burton strategies, Strict Local and Strict Reserve Old, differ regarding the restriction to set aside areas to maintain older forest beyond rotation age. The strict local rule reserves forest from harvesting in any age class that does not meet its target area. Strict Reserve Old increases effort to achieve the target age-class by reserving the forest in deficient age classes as well as enough forest in older age classes to fill the deficit (*i.e.*, it is more constraining).

Both strategies were simulated using a hard and soft constraint. The hard constraint restricts harvesting of older forest by maintaining, as a priority, this forest type over satisfying the annual timber yield in a case when not enough rotation-aged wood is available. The soft constraint prioritizes timber yield by making age class structure an objective rather than a constraint.

3 METHODS

3.1 Study Area

The study area (Figure 2) is located within the Mauricie Region in south-central Québec (47° 57' N, 74° 52' W to 49° 08' N, 73° 45' W) with an extent of approximately 3.5 million hectares. Boreal conifer stands with black spruce (*Picea mariana*) and to a lesser extent jack pine (*Pinus banksiana*) and balsam fir (*Abies balsamea*) dominate the forest vegetation. Interspersed are mixed stands of softwood and hardwood species, and pure deciduous stands with trembling aspen (*Populus tremulus*) and white birch (*Betula papyfera*). The majority of stands consist of younger forest of less than 150 years, and isolated stands of mature and old forest between 150 and 300 years. Figure 2 shows the initial forest age class structure in the study area. The current forest species composition and age structure is mostly the result of natural disturbances and past management. The area has a history of natural disturbances, predominantly stand replacing fires with a mean return interval of around 150 to 160 years (Lefort *et al.* 2000). The forests within the study area have been intensively managed for timber extraction with clearcutting as the preferred harvesting technique in the southern part (Fall *et al.* Submitted). Approximately one third of the area is covered by lakes, wetlands, and bogs making harvesting in these locations difficult and costly. As a surrogate for harvesting costs (*i.e.*, road building and maintenance, transport), a cost function is considered in the model that is proportional to the distance to the local mill, which is located to the southeast, outside of the study area (Fall *et al.* Submitted).

3.2 Spatially Explicit Model at the Landscape Level

3.2.1 Model Description

To simulate the effects of different harvesting scenarios and natural disturbance (here fire), I used the Spatially Explicit Landscape Event Simulator (SELES, Fall and Fall 2001). SELES is a modeling tool addressing spatial and temporal components of change within a landscape (Fall and Fall 2001). The user specifies the initial condition of a landscape (*e.g.*, vegetation structure and composition, topography, or geology), and the parameters of change (*e.g.*, harvesting, natural disturbance, or climate), which are implemented as sub-models (Fall and Fall 2001). The user also sets the temporal extent by the desired simulation length. In addition, SELES allows the user to determine the number of replicates for each simulation.

The variables describing the initial conditions of the study area, and parameters of change (*i.e.*, succession, fire, and harvesting) were already incorporated in the Mauricie Model; these are described in Fall *et al.* (Submitted). Initially, a forest inventory database ($\text{SIFORT}_{\text{MRN-DCF, SOPFEU, SOPFIN}}$, see Fortin *et al.* 2002) using a cell resolution of 14 hectares (375×375 meters) for a total of 3.5 million hectares was used to establish the initial conditions of the forest composition (dominant and subdominant species) and forest age defined by 20-year age class intervals.

3.2.2 Model Design

As opposed to many similar landscape level studies that either examined the impact of human induced changes in landscape structure (*e.g.*, Franklin and Forman 1987; Mladenoff *et al.* 1993; Gustafson and Crow 1994; Wallin *et al.* 1994; Gustafson and Crow 1996) or those of natural disturbance (*e.g.*, Turner *et al.* 1989; Gauthier *et al.* 1996; He and Mladenoff 1999), very few have studied anthropogenic and natural disturbance effects simultaneously (*e.g.*, Gustafson *et al.* 2000; Fall *et al.* Submitted). Because complete suppression of natural disturbance events such as wildfire, windthrow, and insect outbreaks is not realistic (Van Wagner 1978), forest management should be adaptive to accommodate uncertainty associated with such events into management strategies.

In my research, I address the impact of timber harvesting in addition to natural disturbance dynamics that affect the ecosystem. The results provide clues of the disturbance impact on temporal and aspatial age class distribution. This is particularly important because of increasing fragmentation especially of old-growth stands, as well as homogeneity of forest structure due to even-aged and single species management (Franklin and Forman 1987; Mladenoff *et al.* 1993; Spies *et al.* 1994; Gustafson and Crow 1996; Coates and Burton 1997; Crow and Gustafson 1997; Bergeron *et al.* 1998). In order to achieve my objectives, I performed a sensitivity analysis with varying parameter combinations for each of the five management strategies as defined in section 2.2 and Table 1. Current sub-models of the Mauricie Model enable me to simulate landscape processes at different harvesting rates, fire return interval and extent, as well as varying harvesting costs associated with timber harvesting.

I run simulations to address three different questions. First, I performed a detailed analysis of the effect of harvesting rate in addition to management strategy (two-factor analysis) because harvesting rate is of significant interest to forest managers and the effect of different harvesting rates becomes apparent only after at least one rotation. All strategies were simulated for 500 years (*i.e.*, 5 rotations of 100 years) in the presence and absence of fire at eight levels of harvesting rate ranging from moderate 0.65% to the maximum rate allowed in Québec, 1%. Harvesting rate simply defines the portion of the productive forest that can be harvested each year. To describe the fire regime in this part of my analysis I used a stochastic model (hereafter "complex fire model") in which fire size is an emergent property that is based on fuel load and expected time until fire stopping weather (Pennanen 2002). Forest age and stand type as well as environmental variables such as soil moisture further determine fire size. This fire model provides a good approximation of historical conditions because processes that often confound historical fire cycle estimation (Lertzman *et al.* 1998) are less important in the study area, *i.e.*, fire suppression efforts have been low and are likely to be ineffective particularly for large fires (Lefort *et al.* 2000).

The complex fire sub-model is an empirical model driven by parameters that specify the mean number of fires per decade and mean fire burn duration. The model uses current fuel load information to simulate fire behaviour for any given year incorporating stochastic processes. The mean annual number of fires is determined from the relationship: mean number of fires = landscape size / (fire return interval × mean fire size). The number of fires each year and the size of each fire opening are selected from an exponential distribution. Fire ignition locations are selected from random forest cells.

In a second set of simulations, I aimed to analyze the effect of changes of several factors (five-factor analysis) such as management strategy, harvesting rate, harvesting costs and fire regime (*i.e.*, fire return interval and fire extent). Two harvesting cost functions were included to examine changes in allocation of harvesting units due to this important management factor. Harvesting cost was estimated as a relative cost for each grid cell, based on distance from the nearest mill, with increasing costs across water and bogs. The linear cost surface represented a linear increase in cost with distance from the mill, and a 10-fold increase across water and bogs (Fall *et al.* Submitted). The linear+step cost surface was similar to the linear cost surface for the first 100 kilometers distance from the mill. Cost increased exponentially after this arbitrary threshold staggered by 15-kilometer units.

One important goal of this part of the analysis was to look at a range of possible fire regimes in the region because the hypothesized historical fire cycle is associated with uncertainty (Gauthier *et al.* 1996; Bergeron *et al.* 1998) regarding, for example, climate change, the effect of fire suppression, and changes in fuel load and patterns due to harvesting (Lertzman *et al.* 1998). Also, research on the potential influence of global warming on future wildfire patterns suggests significant regional variability (Flannigan *et al.* 2001). Therefore I used a second stochastic empirical fire model (hereafter "simple fire model") driven by fire return interval and mean fire size, which allowed above described changes in fire regime but that did not consider the effect of fuel load as in the complex fire model. I also used the data obtained through these simulations to address my third research question, which examined the impact of disturbance from harvesting and fire on early-seral forest (*i.e.*, forest stands that have not reached sexual maturity) and re-burning incidents of forest before reaching reproductive age.

I used the Mauricie Model to simulate various combinations of the different harvesting and fire parameters (where hereafter a given combination will be referred as a "scenario"). For each scenario, the simulation was run for 500 years and replicated 30 times following the experimental design presented in Table 3. In total, 80 scenarios were run to address the first question and 160 for the second and third ones.

3.2.3 Model Assumptions

The implemented management strategies and stochastic fire sub-models in the Mauricie Model used a number of assumptions and generalizations about the described system:

A. The two sub-models used in the simulations to describe the fire regime are based on fire history information for this area (Lefort *et al.* 2000). Fire size in the complex fire model is dependent on forest age, stand type and land unit type. The simple fire model is a stochastic empirical model with the base fire cycle from fire history information. To address uncertainty associated with fire return interval and fire extent (Gauthier *et al.* 1996; Bergeron *et al.* 1998), a sensitivity analysis on these variables is required.

B. Forest regeneration and succession is simplified in the model. Stands are assumed to start regrowing (no replanting) immediately after disturbance based on the pre-disturbance species mix. Environmental limits such as soil nutrients are not included in the model and tree growth is unconstrained. Trees are assumed to reach sexual maturity at the age of 40 years. During succession, trees age until they reach 300 years which corresponds mostly to the mortality age of the longest-lived species mortality age, and at which point I assume stands enter a gap-phase dynamics mode with no further aging of trees within the stand.

C. A separate sub-model describes forest harvesting. Cutblock size ranges from 60 to 250 ha and they are spatially aggregated within operating areas for a total of five concurrent areas per year. Because timber-yield-curves existed only for pure stands, harvesting rate considers percentage area of the productive forest rather than wood volume. Hence, harvesting rates are based on multiples of 14 hectares (*i.e.*, cell size).

D. The rotation length of 100 years and the maximum harvesting rate of 1% with the associated timber yield in the case of the Status Quo management strategy were intended to capture current forest management practices in Québec averaged over the entire landscape.

E. The harvesting model does not include salvage logging in burnt stands. Thus, harvested area in the simulation may in effect be less than in the case where salvaged timber is included in the annual yield. Because of decay in burnt stands, achieving the annual yield may, however, require additional harvesting of living stands. Therefore, the overall impact from fire and harvesting on the forest ecosystem may be more than in the simulations.

F. Access to harvesting units anywhere in the study area is possible with only the cost of access as a constraint. Cost of access is described by the two surrogate cost surfaces, linear and linear+step, which are simplistic. Road construction and maintenance costs were not included in the harvesting model given the cell resolution.

3.3 Statistical Analysis

I performed two main types of analyses: 1) a detailed investigation of the effect of eight harvesting rate levels in addition to management strategy (two-factor analysis) and 2) a five-factor analysis including: a) five management strategies b) two harvesting rate levels, c) five (three for linear+step cost surface) fire regime lengths; d) two fire extent sizes; and e) two harvesting cost surfaces (Figure 3). I examined forest age class profiles through the 500 simulated years using four age classes: 1) early-seral forest (0 to 40 years); 2) immature forest (41 to 100 years); 3) mature forest (101 to 200 years); and 4) old forest (201+ years).

To perform ANOVA the data need to follow a normal distribution. The data on age-class frequency distribution obtained from the SELES simulations were significantly skewed (Kolmogorov-Smirnoff test: $P < 0.0001$). I applied a natural log transformation and a constant to normalize the data and eliminate the skewness (Legendre and Legendre 1998). In some cases the transformation did not achieve a normal distribution. A visual examination of the frequency distribution and residuals in those cases indicated that the use of ANOVA was acceptable given that ANOVAs are robust to some departure from normality (Kenny and Judd 1986).

For 50-year intervals, I performed ANOVAs using Proc GLM in SAS (SAS Institute 1999) to examine differences in the four age classes resulting from the interactions of different factors. I limited the analysis to test for first- and second-order interactions only. To further analyze the statistically significant results obtained through ANOVA, I performed Bonferroni-adjusted post hoc tests of the differences between the Least-Square means to examine which means contributed to the effect. Because I only performed an aspatial analysis, the effect of fire extent was evaluated as the total area of individual burns within the entire landscape.

I examined the occurrence and aerial extent of early-seral forest re-burning incidents by assessing the disturbance effects from different fire and management regimes on the amount of early-seral forest burnt. Here, age of sexual maturity was assumed to be 40 years. Hence, I performed ANOVAs as well, using Proc GLM in SAS (SAS Institute 1999), but only on the first fifty years of the simulations for multiple variables using 5-year intervals. Indeed, given that sexual maturity was set to 40 years, the effect of fire on immature forest can only be assessed for this period without being confounded with the effect of harvesting.

4 RESULTS

One common result to all analyses was that the initial age structure experienced large changes over various time lengths. The magnitude of the fluctuations and the temporal extent differed according to the combination of the harvesting and fire parameters before reaching steady state dynamics. In most cases, large-scale fluctuation stabilized between 100 and 150 years after the beginning of the simulation (see Figure 4). Depending on the combination of management and fire regimes, the steady state conditions differ in magnitude of their departure from initial condition (see Appendix A and B).

The age class structure in natural forests that are dominated by extensive, stand-replacing fires, such as the boreal forest, tends to follow a negative exponential distribution (Van Wagner 1978; Johnson and Van Wagner 1985). Figure 5 shows the emerging age class structure in the case of the Strict Local strategy using a hard constraint and the Status Quo strategy in the presence of fire using the complex fire model for a harvesting rate of 0.75% after 300 years of simulations. For comparison Figure 5 also shows initial conditions and conditions after 300 years in the case of simulating fire only.

Initially the forest is dominated by immature forest (approx. 60%) with some early-seral (approx. 20%), and mature and old (approx. 20%) forest (see Figure 5). The initial age class distribution is the result of a combination of several natural disturbance agents, fire, spruce budworm, and windthrow. Although fire is the dominant disturbance type in the study region, the effect of spruce budworm, which affects particularly old softwood stands (Bergeron and Harvey 1997), and also other agents such as windthrow may have caused a lack of forest older than 200 years in the present landscape. Due to the impact of spruce budworm and other natural disturbance processes, the age class distribution under natural conditions may actually be curtailed compared to the results from the simulation of fire only without harvesting.

Sustainable forest management should at least maintain an age structure similar to initial conditions. I examined the distributions resulting from different scenarios after age class distribution reached steady state, which occurred after 100 to 150 years of the simulations. Age class structure after 300 years of fire only follows a negative exponential distribution with forest older than 300 years represented as one class (see Figure 5). Only the two Burton approaches using a hard constraint produce a declining age class structure as natural boreal forests do (Van Wagner 1978; Johnson and Van Wagner 1985), because they are designed to do so (see Figure 5 for the case of the Strict Local strategy using a hard constraint). The Status Quo and Burton strategies using a soft constraint produce a homogenous age class distribution typical for industrial forestry defined by harvesting rotation length (see Figure 5 for the case of the Status Quo strategy). Only at harvesting rate levels lower than 0.75% can these strategies maintain forest older than 100 years, *i.e.*, the harvesting rotation length. Although the Burton strategies target an age class distribution that maintains forest up to a maximum age of 220 years, this target is not maintained using a soft constraint and performance is similar to the Status Quo strategy.

4.1 Two-Factor Analysis: Harvesting Rate Levels

This analysis addressed the effect of harvesting rate on age class distribution and the performance of alternatives to Status Quo management. Harvesting rate [after 200 years of simulation: $F = 75.06, p = <0.0001$ (0-40 years); $F = 682.59, p = <0.0001$ (41-100 years); $F = 71.30, p = <0.0001$ (101-200 years); $F = 583.86, p = <0.0001$ (201+ years)] as well as management strategy [after 200 years of simulation: $F = 1061.61, p = <0.0001$ (0-40 years); $F = 5782.90, p = <0.0001$ (41-100 years); $F = 201.16, p = <0.0001$ (101-200 years); $F = 2257.42, p = <0.0001$ (201+ years)] are statistically significant overall variables. Important, however, is the effect of the interaction between individual variables, particularly in the presence of fire, and the impact on the area of mature and old forest, *i.e.,* age classes 101 to 200 years, and 201 years and older.

The effect of harvesting rate is highly significant. In the cases of the Status Quo and Burton strategies (Strict Local and Strict Reserve Old) using a soft constraint already small changes of 0.05% in annual harvest can cause significant changes in forest age structure, particularly in the case of early-seral and old forest. The post hoc test results are significant for most harvesting rate combinations in the case of early-seral forest (see Table 4 for the case of the Status Quo strategy). Bonferroni-adjusted post hoc tests for old forest (201+ years) are significantly different for harvesting rate combinations of 0.65%

to 1% and 0.70% to 1% (see Table 5 for the case of the Status Quo strategy). For combinations of harvesting rates of 0.75% and higher, results for small changes of 0.05% are often not significantly different (see Table 5 for the case of the Status Quo strategy) because the area of old forest is too far reduced to producing significant effects. The two Burton strategies using a hard constraint perform better and maintain a similar age class structure for all eight harvesting rates with significant proportions of older forest as compared to initial conditions. The post hoc tests show no significant differences in the areas of the four age classes for the eight levels of harvesting rate in the case of the Strict Local and Strict Reserve Old Burton strategies with a hard constraint (see Table 6 for forest older than 201 years in the case of the Strict Local strategy). These two strategies prioritize maintaining mature and old forest over satisfying timber yields. Hence, their improved performance compared to using a soft constraint in maintaining an age class structure more similar to initial conditions and within the simulated natural conditions comes at the cost of reducing harvested area. Harvested area in the case of the two Burton strategies using a hard constraint is significantly different from the area harvested in the case of the two Burton strategies using a soft constraint for corresponding harvesting rates (see Table 7). In particular, given the age class target (see Figure 1 and Table 2), the maximum long-term harvest level allowable is 0.65% per year, so an increase in the harvest target over 0.65% cannot be met using the hard constraint.

Compared to initial conditions, the area of early-seral forest increases significantly in all cases of management. The area of early-seral forest increases on average by approximately 20-25% in the case of the Status Quo, Strict Local and Strict Reserve Old using a soft constraint, and by approximately 10% in the case of the two Burton strategies using a hard constraint (see Figure 6 for Strict Local and Strict Reserve Old using a hard constraint). Whereas for the Status Quo and the two Burton strategies using a soft constraint this increase is largely in favour of a decrease in area of mature and old forest, in the hard constraint situation the increase is in favour of early-seral and immature forest between 0 and 40 years, and 41 and 100 years respectively. This demonstrates the better performance of the hard constraint approaches in maintaining older forest. Here, the area of forest older than 101 years increases compared to initial conditions by approximately 10% to about 30% over the entire landscape. Hardly any older forest remains in the case of the Status Quo and the two Burton strategies using a soft constraint, where the fraction of this forest age class declines from 13% to between 1% and 5% after only half a rotation (50 years) for a maximum harvesting rate of 1%.

Post-hoc tests show that the Strict Local and Strict Reserve Old strategies using a hard constraint are not statistically different for age classes 101 to 200 years and 201 years and older. However, Bonferroni-adjusted post hoc tests for age classes 0 to 40 years and 41 to 100 years are statistically significantly different (see Table 8). Figure 6 shows the age class distribution in the case of the Strict Local and Strict Reserve Old using a hard constraint for four harvesting rates and in the presence and absence of fire after 200 years. The superior performance to maintaining mature and old forest of the Strict Reserve Old strategy compared to the Strict Local strategy becomes particularly apparent in relation to harvesting rate. In many cases, harvesting rates in the case of Strict Reserve Old are not significantly different from 10 to 20% higher harvesting rates in the case of Strict Local. Because satisfying timber yield is prioritized over maintaining older forest when using a soft constraint, the differences between the two strategies disappear.

One important aspect of my research was to examine the hypothesis of compensatory effects where harvesting replaces mortality from natural disturbance (MacLean 1990; Carleton and MacLellan 1994; Bergeron *et al.* 1998; Aber *et al.* 2000; Harvey *et al.* 2002). Figure 7 contrasts the effects of harvesting in the presence and absence of natural disturbance for four of the eight harvesting rates simulated in the case of the Status Quo strategy. The interaction of harvesting and fire leads to significant changes in age structure. The two-way ANOVA indicated that the results are statistically significantly different (see Table 9). In particular, the cumulative effect of harvesting and fire results in changes to the percentage of mean area of mature and old forest relative to initial conditions.

The age class structure, emerging from simulating harvesting only without disturbance from fire, represents conditions in the case of the null-hypothesis. The time series graphs in Figure 7 demonstrate the changes in forest age class structure from simulations of harvesting only and from harvesting in the presence of fire. With the exception of harvesting at the maximum level of 1% in the case of harvesting and no fire, mature forest between 101 and 200 years, as well as forest older than 201 years, cover a substantial area similar to initial conditions (see Figure 7). However, these forest types almost entirely disappear in the case of harvesting in the presence of fire (see Figure 7). Figure 7 also shows that in the presence of fire timber yields cannot be maintained at the simulated rates.

In order to represent natural conditions I simulated forest development in the case of fire only using the complex fire model. The minimum and maximum area per age class obtained through simulating fire without additional harvesting for 500 years and 30 replicates are shown in Figure 7. With the exception of age class 41 to 100 years, values for Status Quo management in the presence of fire are outside this range indicating unsustainable conditions.

The Burton strategies using a soft constraint produce a similar age class structure to the Status Quo. Fluctuations in area per age class increase with rising harvesting rate indicating that the disturbance changes the forest ecosystem state so that recovery to historical conditions may be delayed or impossible. The results of the age class profiles and ANOVAs suggest the rejection of the null-hypothesis of the compensatory effect of harvesting. The mean, minimum and maximum values for the four main age classes resulting from the interaction between fire and harvesting for all five management strategies are included in Appendices A and B.

Creating conditions where the forest ecosystem's ability to recover from disturbance is lost also affects timber supply (see Figure 8). In the case of the Status Quo only at a harvesting rate of 0.65% is timber supply continuous at a constant rate over 500 years of simulation with 30 replicates. The higher the harvesting rate, the larger the fluctuations of timber yield become relative to their particular maximum yield. Although fluctuations are the highest for a harvesting rate of 1%, timber yield is maximized at this level over 500 years. However, timber yields for harvesting rates higher than 0.80% are within 3% of each other for these strategies (see Tables 10 and 11).

Harvesting rates can be expressed in area of forest that is targeted for harvest. For an annual harvesting rate of 1% an area the size of the entire forested landscape under management is expected to be harvested over a 100-year period. Table 10 shows the total timber yield after 500 years for each of the eight harvesting rates and the respective target yield for Status Quo, and Strict Local and Strict Reserve Old strategies using a soft constraint. Timber yields for harvesting rates between 0.80% and 1% are similar because fire limits the harvestable area causing increasing reductions in the expected timber yield with increasing harvesting rate.

The simulation results illustrate that yield targets cannot be met for harvesting rates of 0.70% and higher in the long-term. The percentage of yield target relative to the maximum obtained yield and the percentage yield achieved at each harvesting rate are presented in Table 11. Total yield is similar over a range of harvesting rates from 0.80% to 1%. The observed pattern holds true for Status Quo as well as Strict Local and Strict Reserve Old using a soft constraint. The Burton strategies using a hard constraint behave differently as timber yields are secondary to maintaining forest age class structure. In the case of these strategies using a hard constraint, timber yields drop to similar levels for all eight harvesting rates as area is set aside for maintaining older forest. Total yields after 500 years are within 2.5% for all levels of cut.

The depensatory effect of both harvesting and fire results in more area of early-seral forest. Figure 9 shows the effect of fire using the Status Quo and the Strict Reserve Old strategy with a hard constraint for four of the eight levels of harvesting rates. This effect is more pronounced in the Status Quo and Burton strategies using a soft constraint and hereby reducing the area of mature and old forest statistically significantly (see Table 12). Figure 9 also demonstrates the effect of changes in harvesting rate. Because the hard constraint requires setting aside area of older forest for recovery, the Burton strategies using a hard constraint are able to maintain a more or less constant area of mature and old forest (101 to 200 years, 201+ years) for all harvesting rates.

The two-way ANOVA also confirms that the Burton approaches using a soft constraint perform very similar to the Status Quo; Bonferroni-adjusted post hoc tests for these strategies are not significantly different for three of the four age classes examined (0 to 40, 41 to 100, and 101 to 200 years; see Table 13). Results for forest older than 201 years are significantly different for the Strict Reserve Old strategy, and the Status Quo and Strict Local strategy (see Table 13), because a) due to the nature of the Burton strategy, forest older than the target age, *i.e.*, 220 years, slowly disappears, and b) Strict Reserve Old is more restrictive in maintaining old forest than Strict Local.

A slightly different situation exists when the two-way ANOVA is limited to simulation results for harvesting in the presence of fire (*i.e.*, excluding results from scenarios run in the absence of fire). The fire regime affects whether levels of harvesting rate become significantly different; in most cases though, harvesting rates of less than 0.80% are not significantly different for the same strategy. At levels larger than 0.80%, results for harvesting rates that lie within 0.15% from each other are not significantly different.

4.2 Five-Factor Analysis

Results of the two-factor analysis have indicated that the effect of harvesting in addition to fire increases the disturbance impact on the forest ecosystem. The five-factor analysis presents a sensitivity analysis of three management factors, management strategy, harvesting rate, and harvesting cost, and two factors describing fire regime, fire return interval and fire extent.

As can be expected, at higher fire frequency (shorter fire return interval) the disturbance effect increases. The two Burton strategies using a soft constraint maintain a forest age structure similar to initial conditions and a constant timber yield only at long fire return intervals of 250 years and a harvesting rate of 0.65%. An increase in fire frequency leads to a decrease in mature and old forest in favour of early-seral forest and then to a decrease in timber yield. At a harvesting rate of 0.65%, a change in fire return interval mainly affects results for the area of early-seral, mature and old forest whereas immature forest between 41 and 100 years is less affected. This can be explained by the higher fire probability of older forest, which is replaced by younger forest. The forest ecosystem's ability to recover from the combined effects of harvesting and fire is maintained at this low harvesting rate of 0.65%. However, at a harvesting rate of 1% the area of early-seral forest and forest between 41 and 100 years increases at the expense of forest older than 101 years, and, in the case of the Status Quo, virtually eliminating this forest type (see Figure 10). Figure 10 shows the fraction of total area for each of the four age classes (0 to 40 years, 41 to 100 years, 101 to 200 years, 201+ years) after 200 years of simulation for the Status Quo and Strict Reserve Old strategy using a hard constraint at harvesting rates 0.65% and 1% in relation to changes in fire return interval. As fire frequency increases the area per age class experiences non-linear changes conforming to the alternative hypothesis of depensatory effects.

The forest ecosystem loses its ability to recover from disturbance at high harvesting rates for all examined combinations of fire return interval and fire extent. The graphs in Figure 10 indicate that Status Quo results in a decrease in landscape heterogeneity where the forest is dominated by young stands below rotation age. The Burton strategies using a soft constraint show similar patterns. Compared to initial conditions, the Burton strategies using a hard constraint maintain a substantial area of forest of all age classes over all fire regimes regardless of harvesting rate. Areas for age classes 101 to 200 years and 201 years and older are similar at both harvesting rates of 0.65% and 1% (see Figure 10). Forest older than rotation age almost entirely disappears under Status Quo at the same time as area of immature forests increases with shorter fire returns to a maximum of 60% of the forested area at a return interval of 50 years.

The effect of fire return interval (FRI) on forest age class structure is overall statistically significant (Table 14). However, post-hoc tests reveal that for mature and old forest, fire return time is of no significance in the case of the Burton strategies using a hard constraint [after 200 years of simulation: $t = 0.0268, p = 1.000$ (mature forest, SLBurton); $t = 0.1216, p = 1.000$ (old forest, SLBurton); $t = 0.0690, p = 1.000$ (mature forest, SROBurton); $t = 0.1169, p = 1.000$ (old forest, SROBurton)]. These management strategies are able to maintain similar areas of mature and old forest regardless of fire frequency.

In this analysis, a change in fire extent results in statistically significant effects for the forest age class 101 to 200 years only [after 200 years of simulation: $F = 8.12, p =$ 0.0044 (0-40 years); $F = 1.13, p = 0.2874$ (41-100 years); $F = 28.13, p = <0.0001$ (101-200 years); $F = 9.45, p = 0.0021$ (201+ years)]. Post-hoc tests show that fire extent is not a highly significant variable and produces significant results only in combination with other significant variables such as fire return interval and harvesting rate. Map outputs (not shown) suggest that changes in fire extent will result in important changes in the spatial distribution of forest stands of different age classes in the landscape.

The Factorial ANOVA results for testing fixed effects show that a change in harvesting cost does not cause statistically significant changes in the area of any of the four age classes [after 200 years of simulation: $F = 0.01, p = 0.9130$ (0-40 years); $F = 5.91, p = 0.0151$ (41-100 years); $F = 8.31, p = 0.0040$ (101-200 years); $F = 2.21, p = 0.1368$ (201+ years)]. However, examining the results of the Bonferroni-adjusted post hoc tests indicates that harvesting cost produces statistically significant effects on the area early-seral, immature, and mature forest in a number of cases (see Table 15). This should be expected because a change from the linear cost function to the linear+step cost function will lead to a concentration of operating areas and harvesting cutblocks at close proximity to the mill, while forest beyond a threshold distance will experience primarily natural disturbance effects. This hypothesis is supported by the simulation results. At a harvesting rate of 0.65% the Status Quo and the two Burton strategies using a soft constraint maintain more old forest than the two Burton strategies using a hard constraint, although at the cost of more early-seral and immature forest (see Appendix B). Hence, for larger fire return interval and for increased harvesting costs, forest within the distance threshold range will be of more less uniform age based on rotation length whereas the average age of forest beyond the distance threshold will increase.

4.3 Re-burning Incidents of Early-Seral Forest

I used the proportion of early-seral forest below sexually reproductive age as an indicator of ecosystem conditions. Because both, anthropogenic and natural disturbance compete for the same resource, trees, the combined impact may become too large pushing ecosystem conditions outside of the historical range of variability.

Two components of the fire regime, fire return interval and extent, are the most significant factors producing significantly different results (see Table 16). The effects of the management strategy, harvesting rate, and harvesting cost, are not significant (see Table 16). However, the Bonferroni-adjusted post hoc tests suggest that the three management factors (strategy, harvesting rate and cost), in combination with fire return interval and extent produce significantly different results (Table 17) providing further reason to reject the null-hypothesis of the compensatory effect of forest harvesting in the presence of natural disturbance from fire.

The total mean percentage of forest area with re-burning incidents of sexually immature forest is a small but stable forest area, on average between 1% and 3% of early-seral forest annually, as we should expect from an empirical fire model. However, in some cases more than 15% of early-seral forest can be affected (in particular the long upper tails of the distribution, see Figure 11). Because the amount of early-seral forest increases significantly over time, particularly under the Status Quo and the two Burton strategies using a soft constraint, as much as 10% of the entire landscape, or an area of more than 200,000 hectares, can be affected by re-burning incidents (see Figure 11).

Harvesting has a significant effect on the fraction of early-seral forest. For comparison, Figure 11 also shows the area of re-burning incidents of early-seral forest in the case of fire only without harvesting representing natural conditions. In this case, especially for the short fire return interval of 50 years, the area of re-burning incidents of early-seral forest relative to the total area of this forest type is similar to the area affected from a combination of fire and harvesting (see Figure 11). However, a highly significant difference exists in the area of re-burning incidents of early-seral forest relative to the total forested area. Only as much as 5% but more generally approximately 1% of the total forested area is affected by re-burning incidents compared to as much as 10 % in the case of harvesting and fire (Figure 11). This is because harvesting creates more early-seral forest in the landscape, which could potentially be subject to re-burning incidents.

These findings highlight several important aspects of ecosystem-based forest management. Although I did not examine the spatial configuration of re-burning incidents of early-seral forest, the aspatial analyses (time series and ANOVA) indicate that the area of re-burning incidents is sufficiently large that patches may become isolated from seed sources leading to undesired changes in succession (Hansen *et al.* 1991; Bergeron and Harvey 1997).

4.4 Summary of Findings

To examine my initial hypothesis concerning the combined effect of harvesting and fire on the forest age class structure, I performed three sets of analyses that addressed important management concerns. The hypothesis of compensatory effects, where harvesting replaces the effect of fire, is not supported by the data and the statistical analyses. We can thus reject the null-hypothesis in favour of the alternative hypothesis of depensatory effects. One important aspect of all three analyses was to examine the performance of five management strategies in maintaining forest older than rotation length. The Status Quo and two alternatives, the Strict Local and Strict Reserve Old strategies using a soft constraint, produced similar, results that did not differ statistically. These strategies did not maintain a comparable area of older forest as the one observed in the initial conditions, even at moderate harvesting rates (see Appendix A and B). The two alternative strategies, Strict Local and Strict Reserve Old using a hard constraint, performed well and maintained more than 20% of forest older than rotation length regardless of disturbance levels from harvesting and fire, with the exception when fire return intervals were very short (see Appendix A and B).

The analyses also showed the effect of introducing harvesting to a forest ecosystem previously shaped primarily by natural disturbance agents. The age structure initially experiences large fluctuations until the forest ecosystem reaches a new steady state after approximately 100 to 150 years. In the absence of fire, the age class distribution remains constant after the new steady state has established, while fire introduces fluctuations to the otherwise stable age class distribution (see Figure 4).

My first research question addressed the disturbance impact from forest management and fire through a detailed analysis of harvesting rate. Harvesting rate is a statistically significant factor leading to changes in forest age class distribution. The sensitivity analysis of harvesting rate showed that at high harvesting rates the forest ecosystem loses its ability to recover from the disturbance effects, resulting in a decline in area of mature and old forest in favour of early-seral and immature forest. This is exacerbated when harvesting occurs in the presence of fire; harvesting at the same rate in the presence of fire pushes the forest ecosystem far outside the simulated range of natural variability (see Figure 7).

Harvesting and fire compete for the same resource, trees, while the ecosystem's productivity is limited. Total harvesting yields after 500 years of simulation for harvesting rates of 0.80% to 1% in the case of the Status Quo and the two Burton strategies using a soft constraint are within 3% of each other (see Table 10). Harvesting at the maximum rate of 1% achieves only 76% of the projected yield (see Table 11). Hence, based on timber yield no significant difference exists between harvesting at rates from 0.80% to 1%, while the impact on age structure differs greatly. For a harvesting rate of

0.80% in the case of Status Quo, and Strict Local and Strict Reserve Old using a soft constraint, the area of mature and old forest decreases to a similar extent as for a harvesting rate of 1% (see Figure 7). However, the impact on the overall forest ecosystem is less, as evidenced by a more stable timber yield over time and less fluctuation in the area per age class (see Figure 7).

The second research question addressed a broader set of management factors and fire regimes to examine their effect on age class distribution, and to analyze the occurrence and aerial extent of early-seral forest re-burning incidents. Fire return interval is a statistically significant factor (see Table 14), and the impact of disturbance from both, harvesting and fire, on the forest ecosystem increases with higher fire frequency (see Figure 10). The effect of fire return interval on age class distribution is coupled with harvesting rate. At a harvesting rate of 0.65%, mature and old forest is replaced by early-seral forest while the area of immature forest is less affected. Mature and old forests, as well as immature forests are replaced by early-seral forest at a harvesting rate of 1% (see Figure 10). The effect of a change in fire return interval is statistically not significant in the case of the two Burton strategies using a hard constraint for fire return intervals of more than 50 years. Here, the effect of fire is compensated for by a decrease in harvesting yield.

In this aspatial analysis, the effect of a change in fire extent as expressed in the total area burned per year is statistically significant for mature forest only. Spatially, however, changes in fire extent affect the spatial distribution of forest in a particular age class in the landscape with consequences on connectivity of old-growth stands. The effect of harvesting cost is similar. Fixed effects ANOVA are statistically not significant while Bonferroni-adjusted post hoc tests indicate that a change in harvesting cost produces statistically significant results (see Table 15) as can be expected considering the allocation of harvesting blocks in the landscape as a function of the cost to accessing.

Fire return interval and extent are the most significant factors producing statistically differently results in the analysis of the occurrence and aerial extent of early-seral forest re-burning incidents (see Table 16). The effects of the management strategy and harvesting rate are not significant (see Table 16). However, they do produce significant results in combination with fire return interval in the Bonferroni-adjusted post hoc tests (see Table 17). The total area with re-burning incidents is generally between 1% and 3% of early-seral forest. However, maximum values can reach more than 15%, affecting as much as 10% of the entire landscape, or more than 200,000 hectares (see Figure 11).

One of the goals of ecosystem-based management is to maintain the forest within the historical range of variability. Using the range for the area of each age class obtained through the simulation of fire only, I examined the results of each scenario for parameter combinations that maintain an age class structure within this range. Status Quo and the two Burton strategies using a soft constraint produced an age class distribution within the apparent natural range only in the case of a fire return interval of 250 years and a harvest rate of 0.65%. The area of immature forest (41 to 100 years) generally falls within the natural range. Early-seral forest (0 to 40 years) well exceeds the maximum area under apparent natural conditions at the cost of mature and old forest. The area for these two forest types lies far below the simulated values.

The two Burton strategies using a hard constraint for most parameter combinations maintain an age class distribution that falls well within the simulated natural range, with the exception of old forest (201+ years), which, as a consequence of the age class target, covers less area than under historical condition. Because the Burton strategies using a hard constraint perform similarly for the studied range of eight harvesting rates, the dominant factor is fire return interval. Only for a short return interval of 50 years can these strategies not maintain an age class distribution that is within the historical range.

The analysis of the occurrence and aerial extent of early-seral forest re-burning incidents did not indicate a parameter combination for which the area of burned early-seral forest was minimized. Fire regime was identified as the most important factor in this case. Due to the stochastic behaviour of this disturbance type, the affected area can reach extremes regardless of existing forest conditions.

5 DISCUSSION

Natural disturbance processes are inherent to forest ecosystems and will persist despite suppression efforts. The results of this research suggest rejecting the null-hypothesis of the compensatory effect of forest harvesting in the presence of natural disturbance from fire. Hence, we need to reduce the impact of our management in order to maintain the forest ecosystem within its historical range of variability. This requires a change in management practices away from traditional sustained yield, even-aged systems (Kneeshaw *et al.* 2000) to ecosystem-based alternatives such as the Burton strategies examined in this research. In addition, expanding the management scale from the stand level to regions and improving the understanding of the forest ecosystem and associated ecological processes are necessary to achieve sustainable forestry practices.

Because natural disturbance is an important ecological process and cannot be substituted by forest harvesting in the context of ecosystem-based management (Christensen *et al.* 1996), forest management has to adjust harvest levels accordingly (Aber *et al.* 2000). If, as is often the case in industrial forestry, the allowable cut is determined without acknowledging the depensatory effect of harvesting and natural disturbance (MacLean 1990; Carleton and MacLellan 1994; Aber *et al.* 2000), forest ecosystem integrity is jeopardized as the ecosystems' ability to buffer against disturbance diminishes as a function of increasing harvesting rate levels.

The results of my research highlight the need for a good understanding of the forest ecosystem and natural disturbance processes (Franklin *et al.* 2000) in order to practice ecosystem-based forest management successfully. The sensitivity analysis on fire regime showed that changes in this parameter can have significant effects on forest age structure and on timber yield. Particularly in light of potential changes in future climate, forest management needs to study the effects of natural disturbance and manage the forest accordingly. The significance of management at a landscape scale is also emphasized as setting aside other areas may compensate for forest losses to natural disturbance events. This requires flexible management particularly regarding timber yields.

5.1 Alternative Management Strategies

The simulated management strategies based on the proposal by Burton *et al.* (1999) were developed as sustainable alternatives to the Status Quo. The results showed that in the case of the alternative hypothesis of depensatory effects of harvesting, the Burton strategies perform better than the Status Quo in maintaining old forest, however conditional on the harvesting constraint.

The constraint to harvesting old forest presented the most significant difference in the simulated alternative management strategies. Using a soft constraint, the Strict Local and the Strict Reserve Old strategies produce an age class structure similar to the Status Quo strategy. As such these management strategies do not present sustainable alternatives to the Status Quo because the area of old forest is significantly reduced compared to initial conditions. Although these management strategies are based on extending rotation length for parts of the landscape in order to preserve old forest, the targeted age class distribution (see Figure 1 and Table 2) is not realized because old forest is harvested to achieve timber yield targets.

The two Burton strategies using a hard constraint maintain a steady area of old forest over time that is similar to initial conditions. The hard constraint limits harvesting in order to maintain the targeted age class structure (see Figure 1 and Table 2). Because the maintenance of old forest is achieved at the cost of a decrease in timber yield, annual yields can fluctuate significantly depending on the extent of natural disturbances. However, the magnitude of timber yield fluctuations may not be as large as found in the simulations because salvage logging, which was not included, can contribute to the yield of harvested green wood.

The Strict Local strategy and the Strict Reserve Old strategy produce no significant differences in the simulated age class structure in the case of the soft constraint. This can be expected because harvesting of old forest is unconstrained. The Strict Reserve Old strategy is designed to be more restrictive than the Strict Local strategy in preserving old forest and, hence, may produce significantly different results when harvesting of old forest is limited. The difference between these strategies becomes significant particularly when the extent of the disturbance from fire is high with short fire return times. At long fire return intervals the level of disturbance is reduced and constraining harvest of old forest is less significant because more old forest is available.

5.2 Forest Management Implications

The traditional approach in forestry to sustained timber yields (Kneeshaw *et al.* 2000) is challenged by the paradigm of ecosystem-based forest management. One of the goals of ecosystem-based forest management is to take a long-term approach to forest management (Grumbine 1994; Galindo-Leal and Bunnel 1995). In order to maintain the ecological basis that supports forest resources into the future, a reduction of timber yields may be required. For example, Burda *et al.* (1997) advocate determining cutting rates by ecological rather than economic factors.

My research showed that timber yields for annual harvesting rates of 0.80% to 1% are similar. Thus, harvesting at the maximum harvesting rate produces no economic gain. However, at a harvesting rate of 0.80%, ecosystem conditions are better maintained than at the maximum level of 1%. Managers should therefore reduce harvesting rates in order to meet the goals of ecosystem-based management.

A reduction of harvesting rate will provide an initial relief on harvesting of forest beyond rotation age. However, my results showed that only under a hard harvesting constraint that prioritizes the maintenance of forest older than rotation length can the goal of sustaining this forest type be achieved. Forest management institutions have in part recognized this. For example, the Forest Practices Code of British Columbia contains targets for the retention of old-growth forest (B.C. Ministry of Forests 1995). Because using a hard constraint on harvesting this forest type implies reduced timber yields, effective implementation of such a measure requires a shift in forest management from a constant yield policy to a more flexible approach toward harvesting yield.

One potential alternative to a constant yield policy is an adjustment of timber yield based on natural disturbance losses, which could mean low yields for several years after disturbance followed by higher yields until the next disturbance event. However, such an approach requires flexibility in management when, for example, harvesting units must be re-allocated in response to a natural disturbance event. As well, economic difficulties may arise for mills due to fluctuations in timber supply.

A second alternative may be to reduce or minimize the area under management by having intensively managed zones, similar to tree farms, and other zones with limited forestry or none at all (Hunter and Calhoun 1996). This would result in reduced operational costs as harvesting could be carried out in proximity to a mill. Accessing a smaller area would also reduce the ecological damage of forestry operations such as fragmentation and spread of disease, and damage associated with, roads (Aber *et al.* 2000).

As our understanding of forest ecosystems improves, ecosystem-based forest management implies developing silvicultural practices reflecting this knowledge (Aber *et al.* 2000). For example, silvicultural methods such as thinning and variable retention could be used to direct forest succession and to select higher quality trees for future harvesting (Coates 1997; DeBell *et al.* 1997; Franklin *et al.* 1997). One aim may be to maintain a continuous forest cover unless a natural disturbance event occurs. Such measures may ensure a steady source of quality seeds (Coates and Burton 1997), maintain the basis for non-timber forest products (Aber *et al.* 2000), and increase the resilience of the forest ecosystem against insect outbreaks (Perry and Amaranthus 1997; Aber *et al.* 2000). Also, associated ecological functions such as carbon sequestration, and maintenance of soil and water quality would benefit from alternative forestry practices (Aber *et al.* 2000).

Intensive harvesting at high levels of cut without harvesting constraints to maintain mature and old forest leads to a uniform age structure dominated by forest of less than rotation age. The forest ecosystem experiences a shift toward shade-intolerant early successional hardwoods (Bergeron and Harvey 1997). Such simplified forests have lost much of their biodiversity (Aber *et al.* 2000). These effects are not desirable and managers should implement binding harvesting constraints and decrease harvesting rates accordingly.

Harvesting in addition to fire significantly increases the potential for re-burning incidents of early-seral forest because it creates more of this forest type than under historical conditions. Reducing the rate of harvesting and careful planning of the allocation of areas to be harvested in space and time can help minimizing the occurrence and spatial extent of early-seral forest re-burning incidents, and hence the failure of natural regeneration. This may be achieved by maintaining connectivity between older forest stands.

Natural regeneration creates diverse forest conditions (MacDonald 1995) while artificial replanting of clearcuts may promote homogeneity (Hansen *et al.* 1991), often favours commercial softwood species over hardwoods (Bergeron and Harvey 1997; Kneeshaw *et al.* 2000), can be costly (MacDonald 1995; Messier and Kneeshaw 1999), and may not be as efficient as natural regeneration (Messier and Kneeshaw 1999). Some proponents of ecosystem-based forest management therefore endorse natural regeneration from local seed sources (Silva Forest Foundation 1996; Burda *et al.* 1997).

While I simulated fire as the main natural disturbance type, windthrow and insect attacks are also important disturbances in a boreal system. They also need be addressed appropriately in management. Hence, maintaining diversity of the forest ecosystem through ecosystem-based forest management with moderate harvesting levels and appropriate management may reduce the risk of large-scale disturbance from these disturbance types (Christensen *et al.* 1996; Aber *et al.* 2000).

5.3 Future Research Needs

Because I only examined aspatial and temporal trends, a spatial analysis could provide additional insights into several problems associated with forest management practices such as fragmentation, and the shape and size of patches (*e.g.*, Wallin *et al.* 1994; Gustafson and Crow 1996; Crow and Gustafson 1997; Gustafson 1999). Examination of shifts in species composition as a result of shorter growing cycles due to more intense and frequent disturbance would be useful to support the findings of my analysis.

Research using similar strategies (*e.g.*, Bergeron *et al.* 1999) that target different age class distributions may reveal better alternatives. Harvesting sub-models that simulate alternative treatments such as thinning and variable retention rather than clearcutting can be used to find further alternatives (Coates 1997; Franklin *et al.* 1997).

Because the annual allowable cut is generally calculated by volume (Natural Resources Canada 2001), using a volume-based unit to express timber yield may be more appropriate, and could improve the relevance of my model to forest management. Further improvements that would benefit the model's utility include sub-models that simulate road construction in order to show its effect on fragmentation. A sub-model to represent succession processes could improve the model's capability to estimate changes in species composition.

Some of these improvements to the model, such as simulating road construction and variable retention, would require a higher cell resolution. However, finer resolution requires more computer resources and slows down the simulations. The user therefore must decide on the required detail accordingly. One possible alternative to increasing the details of the sub-models in SELES would be to combine stand-scale models such as SORTIE (Harvey *et al.* 2002) with landscape models.

5.4 Strength and Limitations

My research shows the utility of simulation modeling for examining potential outcomes of management actions. I conducted an extensive sensitivity analysis of five important management and fire regime factors affecting the forest ecosystem, explicitly addressing uncertainties associated with natural systems. The results are in a format suitable to be integrated into a decision analysis process. This may be useful for managers to select from several alternatives based on a range of relevant criteria.

My research improves upon previous studies, *e.g.*, Franklin and Forman (1987), Turner *et al.* (1989), Mladenoff *et al.* (1993), Gustafson and Crow (1994), Wallin *et al.* (1994), Gustafson and Crow (1996), Gauthier *et al.* (1996), He and Mladenoff (1999), by addressing concurrently natural and human disturbance impacts on the forest ecosystem. This allowed me to examine the characteristics of the interactions between these disturbance types and to assess their combined effect. Because most current forest management assumes these interactions cause no adverse effects (Carleton and MacLellan 1994; Aber *et al.* 2000), my results provide important information to improve management practices.

In my research, I examined the effect of natural and human disturbance on the age class structure of a forest. Because forest age structure is an important indicator for assessing forest practices in relation to ecosystem integrity (Kneeshaw *at al.* 2000; Fall *et al.* Submitted), the results can contribute to better-informed management decisions. For example, the finding that timber yields for harvesting rates of 0.80% to 1% are very similar can be used to support a reduction of harvesting rates within the boreal forest.

While I addressed a number of uncertainties in the sensitivity analysis, natural processes cannot be forecasted with complete confidence. Variables such as climate will significantly affect ecosystem processes (Flannigan *et al.* 2001). Also, the model did not include natural disturbance agents other than fire, such as windthrow and insect outbreaks. However, a balance exists between the number of variables and detail of their interactions included in the model, *i.e.*, the complexity of the model, and the need for simplification in order to produce results that can be understood and interpreted.

Because of the coarse cell resolution of the input data, the model did not capture processes at scales smaller than forest stands. This affected the modeled size of harvesting units, *i.e.*, cutblocks had to be multiples of 14 hectares. Even though I used a spatially explicit model, I did not analyze the data spatially. The spatial analysis of the map outputs should be the next step of this research.

Missing information to calculate timber yield by volume was a limitation to the suitability of the results within the management realm. The results may be further confounded by the simplistic representation of regeneration and succession processes. This may affect the economic domain because of the distinct qualities of different tree species, as well as the ecological domain because of the potential changes in species composition.

6 CONCLUSION

Several decades of industrial forestry have adversely affected forest ecosystem conditions in North America (Hansen *et al.* 1991; Carey 2000). The alternative paradigm of ecosystem-based forest management has challenged inherent assumptions of conventional forestry (Messier and Kneeshaw 1999; Kneeshaw *et al.* 2000). With my research, I intended to explore the implications of the hypothesis that the disturbance effect from harvesting in the presence of fire is compensatory (Carleton and MacLellan 1994; Aber *et al.* 2000).

The results showed that harvesting exacerbates the effect of fire, increasing the possibility of pushing the ecosystem outside its historical range of variability. In fact, the Status Quo and the Strict Local and Strict Reserve Old Burton strategies using a soft constraint cannot maintain an age class distribution within the bounds of the simulated natural range. The two Burton strategies using a hard constraint perform well, and with the exception of a very short fire return interval of 50 years sustain a forest age structure within its historical range, however at the cost of timber yield. This highlights the fact that setting an explicit target for the age class structure can be a key component of ecosystem-based management, as it would ensure the maintenance of mature and old forest that is important for biodiversity (Burton *et al.* 1999; Carey 2000). In order to achieve the desired age class target distribution it may be necessary that the maintenance of this target take precedence over the harvesting target.

Ecosystem-based forest management endorses forest management that sustains the ability of the forest to maintain its ecological functions while providing timber and other non-timber forest products (Messier and Kneeshaw 1999). Performance of forestry practices toward obtaining the objectives of ecosystem-based management is measured through indicators such as age class structure (Messier and Kneeshaw 1999; Kneeshaw *et al.* 2000). The loss of older forest is among the major concerns (Carey 2000). As my results showed, continuing with the Status Quo approach of industrial forestry will decrease the portion of older forest with time.

One of the objectives of my research was to examine the performance of the Status Quo and alternative forest management strategies to achieving ecosystem-based management objectives. I used age class structure as an indicator toward this goal. I showed that although the alternative management strategy proposed by Burton *et al.* (1999) can maintain a heterogeneous age structure in my study system, this objective can only be achieved by concurrently lowering harvesting yield targets and imposing constraints on harvesting old forest.

The ecosystem-based management principle of incorporating natural disturbance regimes into management (Attiwill 1994) and maintaining the forest ecosystem within its range of historical variability (Swanson *et al.* 1993; Galindo-Leal and Bunnell 1995) is based on a thorough understanding of natural disturbance processes and the additional impact of management. As such, ecosystem-based management requires a shift from the traditionally short-term planning approach in forest management (Galindo-Leal and Bunnell 1995). My research was directed at the landscape scale over a long time frame, and the results emphasize the importance of managing forest ecosystems at large temporal and spatial scales.

It is impossible to eliminate natural disturbances. Because industrial forest management has generally ignored the consequences of interactions between natural disturbance and harvesting, harvesting levels exceeded maximum sustainable yield. Older forest was reduced in abundance on the landscape and concurrently important features associated with it such as snags and coarse woody debris (Burton *et al.* 1999). With the prospect of climate change-related increasing pressure on forest ecosystems (Aber *et al.* 2000), forest management must explore new avenues such as reducing harvesting rates (Aber *et al.* 2000), extending rotations (Bergeron *et al.* 1999; Burton *et al.* 1999; Aber *et al.* 2000), and creating distinct management zones with intensive to no management (Hunter and Calhoun 1996) in order to sustain forest ecosystems into the future. For example, the analysis of the effect of harvesting rate showed that rates of 0.80% to 1% lead to very similar results in the case of the Status Quo and the two Burton strategies using a soft constraint. Considering that harvesting at the maximum yield of 1% only achieves about 80% of the targeted yield, a reduction in harvesting rate without a parallel reduction in timber yield is possible, but with reduced impact on the forest ecosystem.

My analysis of the occurrence and aerial extent of early-seral forest re-burning incidents emphasizes the need for sustainable forestry practices, which include maintaining natural processes such as regeneration from seed and traditional successional pathways (*e.g.* Burda *et al.* 1997). However, if the area of re-burning incident of early-seral forest exceeds a distance threshold at which the seed source is too remote, natural regeneration and successional processes may be interrupted, leading to changes in species composition (Hansen *et al.* 1991; Bergeron and Harvey 1997). This is possible for any of the management strategies and parameter combinations I examined where more than 10% of the entire landscape was affected by re-burning incident of early-seral forest.

Much ongoing research addresses operational issues (*e.g.*, Vyse 1999; Mitchell 2001; Abetz and Kladtke 2002) and current harvesting experiments produce new insights into the performance of different methods (*e.g.*, Graham and Jain 1998; Beese and Arnott 1999; Harvey 1999; Harvey *et al.* 2002). However, it would be folly to expect definitive answers from these studies regarding the management of forest ecosystems. While modeling exercises such as this can provide general guidance they do not capture the complexity of a forest ecosystem, and hence we are confronted with uncertainty.

Ecosystem-based management addresses uncertainty through adaptive management (Christensen *et al.* 1996) by incorporating past experiences into future management and thereby improving management over time (Wilhere 2002). The ability to change management activities in light of new knowledge provides flexibility to adapt to, for example, impacts of climate change. My research showed that timber yields from harvesting in the presence of fire are similar for annual harvesting rates of 0.80% to 1%. Hence, initial steps of adaptive management could be to reduce harvesting rates, extend rotations, and create zones of different management intensities. Such measures may move forest management closer to the goals of ecosystem-based management and ensure a smoother transition from high intensity industrial forestry to sustainable practices without jeopardizing the economic basis of forestry.

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TABLE 1. FIVE MANAGEMENT STRATEGIES DESCRIBING IMPLEMENTATION OF TIMBER HARVESTING WITHIN THE LANDSCAPE.

Management strategies	**Main Characteristics**	**References**
1) Status Quo	• Currently prescribed management plan in Québec • Targets annual percentage of the landscape for harvesting[2]	• Fall *et al.* (Submitted)
2 and 3) Strict Local Burton[1] • *Hard and soft constraint*	• Based on extended rotation • Targets particular age distribution • Restricts harvesting forest in any age classes that are in deficit	• Burton *et al.* (1999) • Fall *et al.* (Submitted)
4 and 5) Strict Reserve Old Burton[1] • *Hard and soft constraint*	• Based on extended rotation • Targets particular age distribution • Restricts harvesting forest in any age classes that are in deficit *plus* reserving forest in younger age classes for an older age class that is in deficit.	• Burton *et al.* (1999) • Fall *et al.* (Submitted)

[1] Simulated using a hard constraint (reaching desired age distribution supersedes obtaining prescribed yield) and a soft constraint (obtaining prescribed yield supersedes age class distribution constraint).

[2] Constant rate harvesting is usually specified as a constant volume per year, where I model a constant area per year to minimize model complexity and avoid the need to compute volumes.

TABLE 2. PERCENTAGE TARGETED DISTRIBUTION FOR REMAINING FOREST PER AGE CLASS (8) IN THE BURTON MANAGEMENT STRATEGY.

Age Class (years)	**% target of forest remaining**
0 – 100	65.0
101-120	11.75
121-140	9.25
141-160	6.75
161-180	4.25
181-200	1.75
201-220	1.25
> 221	0

TABLE 3. EXPERIMENTAL DESIGN OF MY RESEARCH CONSISTING OF COMBINATIONS OF DIFFERENT HARVESTING RATES, FIRE RETURN INTERVAL AND EXTENT, AS WELL AS VARYING HARVESTING COSTS ASSOCIATED WITH TIMBER HARVESTING THAT WILL FORM A SERIES OF SIMULATIONS PREDICTING RESPECTIVE OUTCOMES.

Scenarios					
Management Strategies	***Question 1*** (Total of 80 scenarios) **Two-Factor Analysis**	***Questions 2 and 3*** (Total of 160 scenarios) **Five-factor Analysis**			
	Harvesting Rate[1]	*Fire Regime*[2]		*Harvesting Rate*	*Harvesting cost*
		Return Interval (years)	*Mean Size (ha)*		
• *Status Quo* • *Strict Local Burton hard* • *Strict Local Burton soft* • *Strict Reserve Old Burton hard* • *Strict Reserve Old Burton hard*	• 0.65% • 0.70% • 0.75% • 0.80% • 0.85% • 0.90% • 0.95% • 1%	• 50 • 100[3] • 150 • 200[3] • 250	• 1500 • 6500	• 0.65% • 1%	• <u>Linear:</u> Gradually increasing cost with distance from mill located in southeast part • <u>Linear+Step:</u> As above but high increase in cost further than 100 km distance from mill

[1] Simulated in the presence and absence of fire; fire behaviour is modelled using the complex fire model

[2] As described by extent and number of fires using the simple fire model; two combinations (i.e., small mean extent/high number of fires and large mean extent/low number of fires) will be simulated for each fire regime scenario

[3] Fire return intervals of 100 and 200 years in combination with linear cost surface only

TABLE 4. BONFERRONI-ADJUSTED T AND P VALUES FOR THE INTERACTION BETWEEN EIGHT HARVESTING RATES (0.65%, 0.70%, 0.75%, 0.80%, 0.85%, 0.90%, 0.95%, 1%) IN THE CASE OF THE STATUS QUO STRATEGY AFTER 200 YEARS OF SIMULATION FOR EARLY-SERAL FOREST (0 TO 40 YEARS).

Harvesting Rate		**0.70%**	**0.75%**	**0.80%**	**0.85%**	**0.90%**	**0.95%**	**1.00%**
0.65%	*t*	-6.41	-8.84	-13.39	-16.52	-20.7	-22.72	-25.9
	p	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
0.70%	*t*		-2.43	-6.98	-10.11	-14.29	-16.31	-19.49
	p		1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
0.75%	*t*			-4.55	-7.68	-11.86	-13.88	-17.06
	p			0.0062	<0.0001	<0.0001	<0.0001	<0.0001
0.80%	*t*				-3.13	-7.3	-9.33	-12.51
	p				1	<0.0001	<0.0001	<0.0001
0.85%	*t*					-4.17	-6.2	-9.38
	p					0.0347	<0.0001	<0.0001
0.90%	*t*						-2.02	-5.21
	p						1	0.0002
0.95%	*t*							-3.18
	p							1

TABLE 5. BONFERRONI-ADJUSTED T AND P VALUES FOR THE INTERACTION BETWEEN EIGHT HARVESTING RATES (0.65%, 0.70%, 0.75%, 0.80%, 0.85%, 0.90%, 0.95%, 1%) IN THE CASE OF THE STATUS QUO STRATEGY AFTER 200 YEARS OF SIMULATION FOR OLD FOREST (201+ YEARS).

Harvesting Rate		**0.70%**	**0.75%**	**0.80%**	**0.85%**	**0.90%**	**0.95%**	**1.00%**
0.65%	*t*	10.24	18.92	19.73	20.88	22.22	24.52	42.53
	p	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
0.70%	*t*		8.68	9.49	10.64	11.98	14.28	32.29
	p		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
0.75%	*t*			0.81	1.96	3.3	5.6	23.6
	p			1	1	1	<0.0001	<0.0001
0.80%	*t*				1.15	2.49	4.79	22.79
	p				1	1	0.002	<0.0001
0.85%	*t*					1.34	3.64	21.64
	p					1	0.3124	<0.0001
0.90%	*t*						2.3	20.3
	p						1	<0.0001
0.95%	*t*							18
	p							<0.0001

Table 6. Bonferroni-adjusted t and p values for the interaction between eight harvesting rates (0.65%, 0.70%, 0.75%, 0.80%, 0.85%, 0.90%, 0.95%, 1%) in the case of the Strict Local strategy using a hard constraint after 200 years of simulation for old forest (201+ years).

Harvesting Rate		0.70%	0.75%	0.80%	0.85%	0.90%	0.95%	1.00%
0.65%	*t*	0.93	0.89	0.79	0.80	0.26	0.27	0.26
	p	1	1	1	1	1	1	1
0.70%	*t*		0.06	0.17	0.17	0.17	0.18	0.17
	p		1	1	1	1	1	1
0.75%	*t*			0.12	0.12	0.12	0.12	0.11
	p			1	1	1	1	1
0.80%	*t*				-0.00	-0.00	0.00	-0.01
	p				1	1	1	1
0.85%	*t*					0.00	0.01	-0.00
	p					1	1	1
0.90%	*t*						0.00	-0.01
	p						1	1
0.95%	*t*							-0.01
	p						1	1

Table 7. Mean harvesting yield after 500 years for 30 replicates in the case of the Strict Local and Strict Reserve Old strategies using hard and soft constraint in the presence of fire.

Harvesting Rate (%)	**Mean Harvesting Yield [area harvested in thousands of hectares]** (±1stdev)			
	SLBurton hard	*SLBurton soft*	*SROBurton hard*	*SROBurton soft*
0.65	4651 (±1.92)	7585 (±0.68)	3785 (±1.81)	7586 (±0.68)
0.70	4675 (±2.08)	8109 (±0.76)	3718 (±1.87)	8086 (±0.80)
0.75	4642 (±2.26)	8428 (±1.28)	3801 (±1.92)	8396 (±1.40)
0.80	4629 (±2.38)	8619 (±1.99)	3716 (±2.00)	8567 (±2.12)
0.85	4662 (±2.52)	8656 (±3.05)	3788 (±2.08)	8644 (±2.99)
0.90	4678 (±2.65)	8688 (±3.78)	3752 (±2.20)	8733 (±3.73)
0.95	4668 (±2.67)	8766 (±4.14)	3779 (±2.20)	8761 (±4.08)
1	4734 (±2.83)	8781 (±4.64)	3808 (±2.33)	8819 (±4.49)

TABLE 8. BONFERRONI-ADJUSTED T AND P VALUES FOR THE DIFFERENCE IN THE EFFECT OF STRICT LOCAL AND STRICT RESERVE OLD STRATEGIES USING A HARD CONSTRAINT RELATIVE TO AGE CLASSES (0 TO 40; 41 TO 100; 101 TO 200; 201+ YEARS) AFTER 50, 100, 200, 300, 400 AND 500 YEARS OF SIMULATION.

	Forest 0 to 40 years		**Forest 41 to 100 years**		**Forest 101 to 200 years**		**Forest 201+ years**	
Time (years)	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*
50	12.04	<0.0001	19.77	<0.0001	-20.55	<0.0001	-2.79	0.0789
100	-7.56	<0.0001	35.72	<0.0001	-0.25	1.0000	-0.88	1.0000
200	4.78	<0.0001	41.80	<0.0001	-0.91	1.0000	-1.00	1.0000
300	14.41	<0.0001	18.43	<0.0001	-1.36	1.0000	-0.47	1.0000
400	-2.26	0.3555	17.84	<0.0001	-2.38	0.2634	-0.42	1.0000
500	1.40	1.0000	16.71	<0.0001	-3.04	0.0357	-0.50	1.0000

TABLE 9. F AND P VALUES FOR FIXED EFFECTS ANOVA FOR THE EFFECT OF FIRE AFTER 50, 100, 200, 300, 400 AND 500 YEARS OF SIMULATION FOR FOUR AGE CLASSES (0 TO 40, 41 TO 100, 101 TO 200, 201+ YEARS). THE RESULTS ARE FOR THE EFFECT OF FIRE ONLY AND MAY BE CONFOUNDED BY THE EFFECT OF OTHER FACTORS, I.E. MANAGEMENT STRATEGY AND HARVESTING RATE.

	Forest 0 to 40 years		**Forest 41 to 100 years**		**Forest 101 to 200 years**		**Forest 201+ years**	
Time (years)	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
50	146.63	<0.0001	1.27	0.2634	51.81	<0.0001	28.20	<0.0001
100	307.19	<0.0001	217.00	<0.0001	248.58	<0.0001	198.78	<0.0001
200	295.93	<0.0001	103.80	<0.0001	19.36	<0.0001	262.42	<0.0001
300	241.14	<0.0001	115.32	<0.0001	32.88	<0.0001	258.49	<0.0001
400	309.21	<0.0001	104.84	<0.0001	78.24	<0.0001	282.02	<0.0001
500	261.08	<0.0001	135.24	<0.0001	100.75	<0.0001	284.06	<0.0001

Table 10. Mean harvesting yield after 500 years for 30 replicates in the case of the Status Quo and Strict Local and Strict Reserve Old strategies using a soft constraint in the presence of fire.

Harvesting Rate (%)	**Mean Harvesting Yield [area harvested in thousands of hectares]** (±1stdev)			**Targeted Yield (thousands of hectares)**
	SLBurton	*SROBurton*	*Status Quo*	
0.65	7585 (±0.68)	7587 (±0.68)	7586 (±0.68)	7588
0.70	8109 (±0.76)	8099 (±0.80)	8086 (±0.80)	8169
0.75	8428 (±1.28)	8393 (±1.29)	8396 (±1.40)	8750
0.80	8619 (±1.99)	8562 (±2.10)	8567 (±2.12)	9331
0.85	8656 (±3.05)	8676 (±2.95)	8644 (±2.99)	9919
0.90	8688 (±3.78)	8766 (±3.64)	8733 (±3.73)	10500
0.95	8766 (±4.14)	8784 (±4.17)	8761 (±4.08)	11081
1	8781 (±4.64)	8806 (±4.54)	8819 (±4.49)	11669

Table 11. Mean percentage harvesting yield after 500 years for 30 replicates in the case of the Status Quo and Strict Local and Strict Reserve Old strategies using a soft constraint in the presence of fire relative to maximum yield obtained in the Status Quo (i.e., 8819 ha; see Table 10) and relative to each respective harvesting rate target (see column "Targeted Yield" in Table 10).

Harvesting Rate (%)	**Mean Harvesting Yield (% yield relative to yield at a harvesting rate of 1%)**			**Mean Harvesting Yield (% yield relative to respective targeted yield)**		
	SLBurton	*SROBurton*	*Status Quo*	*SLBurton*	*SROBurton*	*Status Quo*
0.65	86	86	86	100	100	100
0.70	92	92	92	99	99	99
0.75	96	95	95	96	96	96
0.80	98	97	97	92	92	92
0.85	98	98	98	87	88	87
0.90	99	99	99	83	83	83
0.95	99	100	99	79	79	79
1	100	100	100	75	75	76

TABLE 12. BONFERRONI-ADJUSTED T AND P VALUES FOR THE EFFECT OF FIRE IN THE CASE OF STATUS QUO AND TWO BURTON STRATEGIES USING A SOFT CONSTRAINT ON OLDER FOREST (101 TO 200, 201+ YEARS) AFTER 200 YEARS OF SIMULATION.

Age Class		**Status Quo - Fire**		**Strict Local - Fire**		**Strict Reserve Old - Fire**	
		t	*p*	*t*	*p*	*t*	*p*
101 to 200 years	**Status Quo**	19.23	<0.0001				
	Strict Local			19.47	<0.0001		
	Strict Reserve Old					17.92	<0.0001
201+ years	**Status Quo**	58.47	<0.0001				
	Strict Local			64.50	<0.0001		
	Strict Reserve Old					57.22	<.0001

Table 13. Bonferroni-adjusted t and p values for the effect of Status Quo and two Burton strategies using a soft constraint on the four age classes (0 to 40, 41 to 100, 101 to 200, 201+ years) after 200 years of simulation.

Age Class		**Strict Reserve Old**		**Status Quo**	
		t	*p*	*t*	*p*
0 to 40 years	**Strict Local**	-1.54	1.0000	-0.31	1.0000
	Strict Reserve Old			0.2182	1.0000
41 to 100 years	**Strict Local**	0.31	1.0000	-0.90	1.0000
	Strict Reserve Old			-1.21	1.0000
101 to 200 years	**Strict Local**	0.44	1.0000	1.84	0.9839
	Strict Reserve Old			0.1602	1.0000
201+ years	**Strict Local**	6.54	<0.0001	1.61	1.0000
	Strict Reserve Old			-4.92	<0.0001

TABLE 14. F AND P VALUES FOR FIXED EFFECTS FOR THE EFFECT OF FIRE RETURN INTERVAL AFTER 50, 100, 200, 300, 400 AND 500 YEARS OF SIMULATION FOR FOUR AGE CLASSES (0 TO 40, 41 TO 100, 101 TO 200, 201+ YEARS). THE RESULTS ARE FOR THE EFFECT OF FIRE RETURN INTERVAL ONLY AND MAY BE CONFOUNDED BY THE EFFECT OF OTHER FACTORS, I.E. MANAGEMENT STRATEGY, HARVESTING RATE, FIRE EXTENT, AND HARVESTING COST.

	Forest 0 to 40 years		**Forest 41 to 100 years**		**Forest 101 to 200 years**		**Forest 201+ years**	
Time (years)	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
50	7146.93	<0.0001	6484.21	<0.0001	3340.13	<0.0001	2031.06	<0.0001
100	8019.29	<0.0001	2039.86	<0.0001	408.79	<0.0001	480.30	<0.0001
200	8127.03	<0.0001	1414.34	<0.0001	22.09	<0.0001	312.39	<0.0001
300	7423.98	<0.0001	1888.95	<0.0001	103.16	<0.0001	312.96	<0.0001
400	7569.24	<0.0001	1786.22	<0.0001	406.85	<0.0001	348.67	<0.0001
500	7288.23	<0.0001	1804.69	<0.0001	369.35	<0.0001	335.16	<0.0001

TABLE 15. BONFERRONI-ADJUSTED T AND P VALUES FOR THE DIFFERENCE IN THE EFFECT OF A CHANGE IN HARVESTING COST RELATIVE TO AGE CLASS AFTER 50, 100, 200, 300, 400 AND 500 YEARS OF SIMULATION FOR FOUR AGE CLASSES (0 TO 40, 41 TO 100, 101 TO 200, 201+ YEARS).

	0 to 40 years		**41 to 100 years**		**101 to 200 years**		**201+ years**	
Time (years)	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*
50	-5.66	<0.0001	-0.87	0.3867	7.65	<0.0001	-2.87	0.0041
100	-3.06	0.0022	-2.71	0.0067	2.62	0.0088	2.42	0.0156
200	-2.93	0.0034	-4.94	<0.0001	4.02	<0.0001	1.49	0.1368
300	-3.43	0.0006	-4.39	<0.0001	2.33	0.0197	1.82	0.0683
400	-4.20	<0.0001	-4.24	<0.0001	2.90	0.0038	1.66	0.0976
500	-5.35	<0.0001	-3.12	0.0019	3.48	0.0005	2.58	0.0098

TABLE 16. F AND P VALUES FOR FIXED EFFECTS FOR STRATEGY, HARVESTING RATE, FIRE RETURN INTERVAL, FIRE EXTENT, AND HARVESTING COST AFTER 5, 10, 20, 30, 40 AND 50 YEARS OF SIMULATION FOR AREA OF BURNED EARLY-SERAL FOREST. INDIVIDUAL RESULTS ARE FOR THE EFFECT OF ONE FACTOR ONLY AND MAY BE CONFOUNDED BY THE EFFECT OF THE REMAINING FACTORS..

	Management strategy		**Harvesting Rate**		**Fire Return Interval**		**Fire Extent**		**Harvesting cost**	
Time (years)	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
5	1.26	0.277	0.39	0.533	226.76	<0.0001	168.68	<0.0001	0.03	0.8717
10	1.67	0.1395	4.2	0.0406	211.83	<0.0001	204.35	<0.0001	2.43	0.1192
20	3.39	0.0046	3.74	0.0532	304.53	<0.0001	154.23	<0.0001	0	0.9653
30	1.22	0.2979	2.63	0.1048	229	<0.0001	195.92	<0.0001	0.42	0.5157
40	3.14	0.0079	1.49	0.2226	253.85	<0.0001	257.59	<0.0001	0.4	0.5277
50	0.86	0.505	3.59	0.0581	226.1	<0.0001	261.55	<0.0001	0.71	0.3981

TABLE 17. *T AND P VALUES FOR LEAST SQUARES MEANS FOR INTERACTIONS BETWEEN MANAGEMENT FACTORS (STRATEGY, HARVESTING RATE AND COST) AND FIRE RETURN INTERVAL AND EXTENT AFTER 50 YEARS OF SIMULATION FOR EARLY-SERAL FOREST.*

		Fire Return Interval (years)						Fire Extent (hectares)			
		50		150		250		1500		6500	
		t	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*
Management strategy	**Status Quo**	22.14	<0.0001	14.09	<0.0001	10.74	<0.0001	24.84	<0.0001	13.51	<0.0001
	SL Burton soft	21.68	<0.0001	15.81	<0.0001	9.81	<0.0001	24.19	<0.0001	14.43	<0.0001
	SRO Burton soft	22.96	<0.0001	15.8	<0.0001	11.71	<0.0001	25.18	<0.0001	16.02	<0.0001
	SL Burton hard	22.5	<0.0001	13.99	<0.0001	10.12	<0.0001	24.02	<0.0001	14.04	<0.0001
	SRO Burton hard	21.42	<0.0001	15.52	<0.0001	9.1	<0.0001	23.17	<0.0001	14.42	<0.0001
Harvesting Rate (%)	**0.65**	38.35	<0.0001	24.72	<0.0001	16.55	<0.0001	40.6	<0.0001	24.4	<0.0001
	1	38.96	<0.0001	26.7	<0.0001	18.6	<0.0001	42.47	<0.0001	26.33	<0.0001
Harvesting Cost	**Linear**	39.22	<0.0001	23.58	<0.0001	18.11	<0.0001	40.83	<0.0001	25.23	<0.0001
	Linear+Step	38.1	<0.0001	27.84	<0.0001	17.04	<0.0001	42.25	<0.0001	25.5	<0.0001

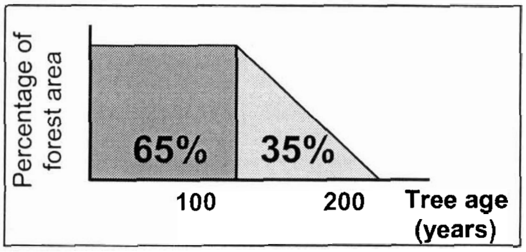


FIGURE 1. PERCENTAGE TARGETED DISTRIBUTION FOR REMAINING FOREST PER AGE CLASS (2) IN THE BURTON MANAGEMENT STRATEGY.

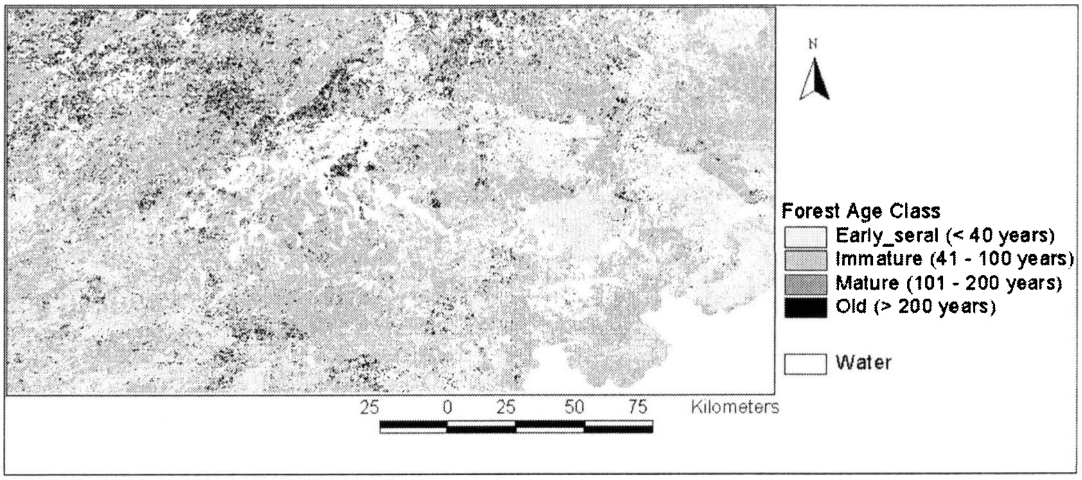
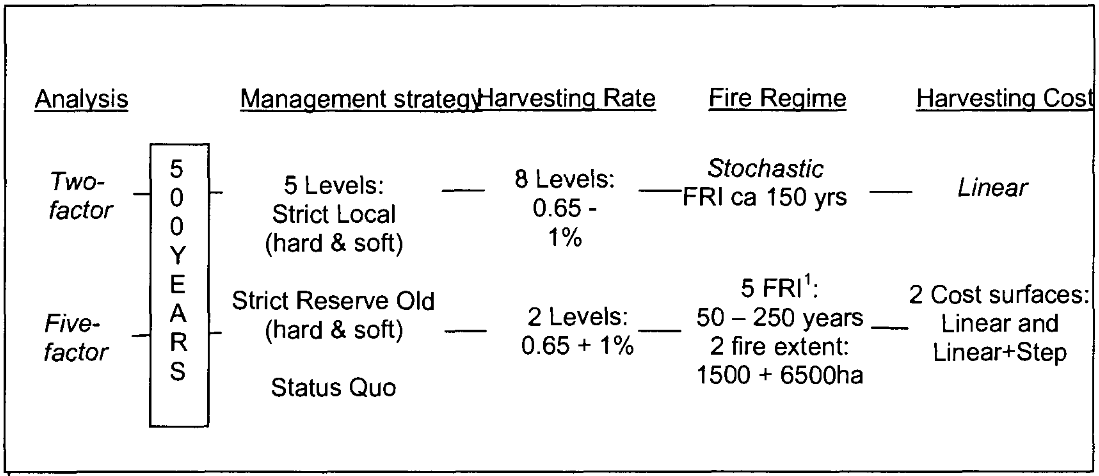


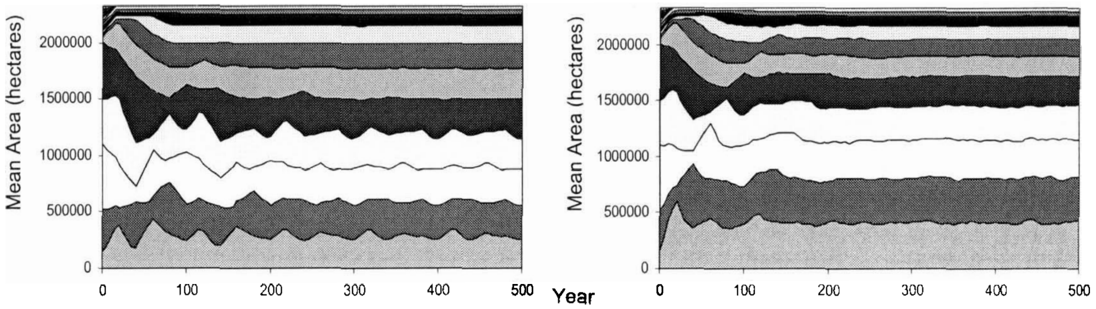
FIGURE 2. INITIAL FOREST AGE CLASS STRUCTURE (0-40, 41-100, 101-200, 201+ YEARS).



[1] Six levels in combination with linear+step cost surface only, *i.e.*, without fire return intervals of 100 and 200 years

FIGURE 3. PRESENTATION OF FACTORS INCLUDED IN THE ASPATIAL AND TEMPORAL ANALYSES.

a) Strict Local hard constraint *c) Strict Local hard constraint and fire*



b) Strict Local soft constraint *d) Strict Local soft constraint and fire*

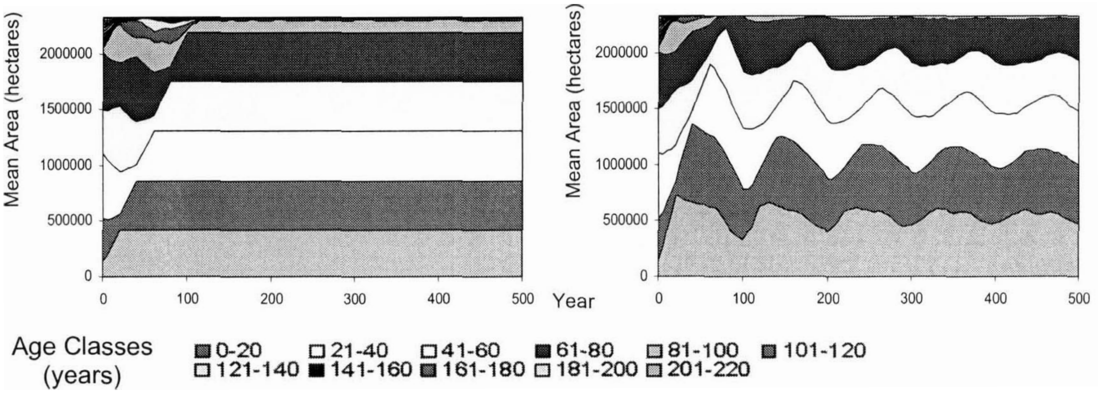
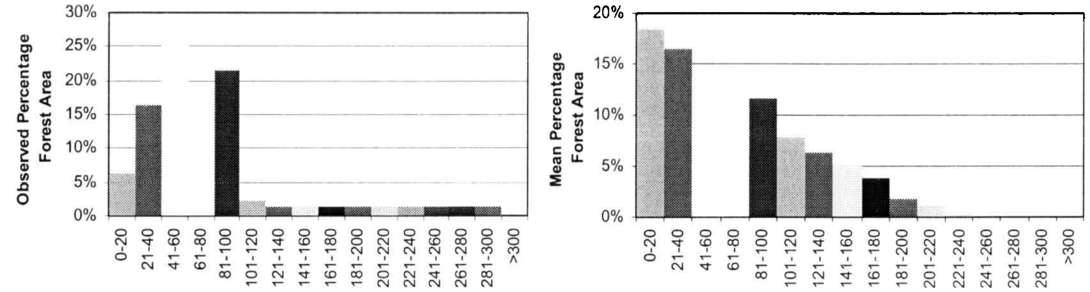
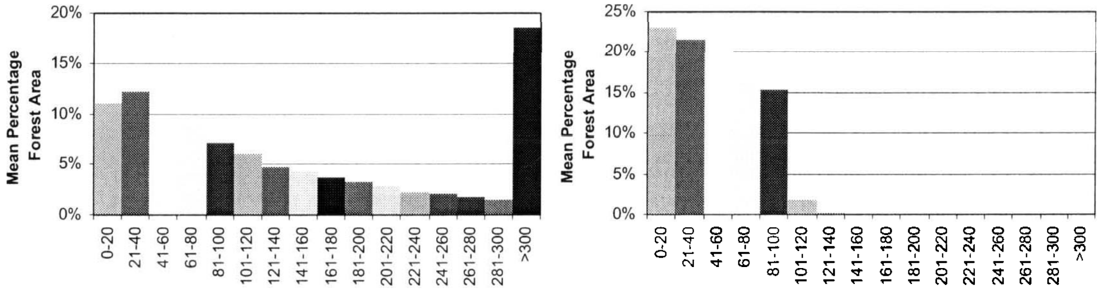


FIGURE 4. MEAN AREA AGE CLASS DISTRIBUTION (20 YEARS REPRESENTED BY ONE COLOUR) FOR 30 REPLICATES STARTING WITH THE YOUNGEST AGE CLASS AT THE BOTTOM FOR A) STRICT LOCAL HARD CONSTRAINT; B) STRICT LOCAL SOFT CONSTRAINT; C) STRICT LOCAL HARD CONSTRAINT AND FIRE; AND D) STRICT LOCAL SOFT CONSTRAINT AND FIRE. HARVESTING RATE IS 1%.



a) Initial conditions

c) Strict Local hard constraint and fire



b) Fire only

d) Status Quo and fire

FIGURE 5. AGE CLASS FREQUENCY DISTRIBUTIONS FOR A) INITIAL CONDITIONS; AND B) CONDITIONS AFTER 300 YEARS IN THE PRESENCE OF FIRE WITHOUT HARVESTING; C) CONDITIONS AFTER 300 YEARS IN THE CASE OF THE STRICT LOCAL STRATEGY USING A HARD CONSTRAINT IN THE PRESENCE OF FIRE AND A 0.75% HARVESTING RATE; AND D) CONDITIONS AFTER 300 YEARS IN THE CASE OF THE STATUS QUO IN THE PRESENCE OF FIRE AND A 0.75% HARVESTING RATE OVER 30 REPLICATES. FIRE WAS SIMULATED USING THE COMPLEX FIRE MODEL.

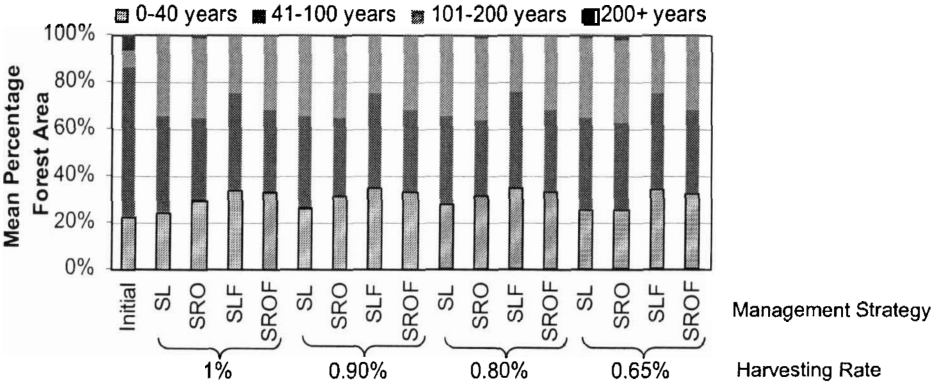
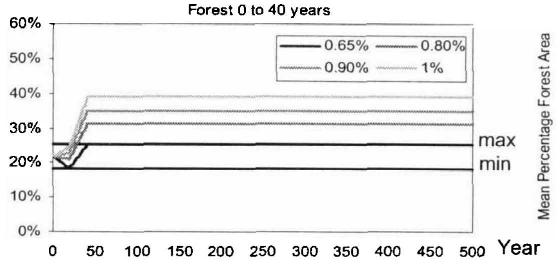


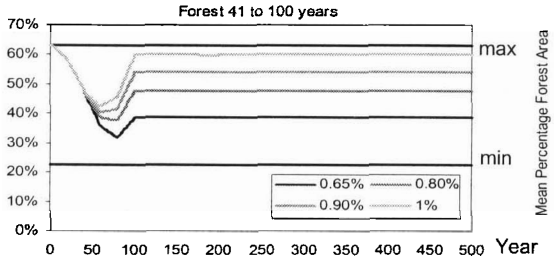
FIGURE 6. MEAN PERCENTAGE FOREST AREA OVER 30 REPLICATES FOR FOUR AGE CLASSES (0 TO 40, 41 TO 100, 101 TO 100, 201+ YEARS) IN THE CASE OF THE STRICT LOCAL AND STRICT RESERVE OLD USING A HARD CONSTRAINT FOR FOUR HARVESTING RATES (1%, 0.90%, 0.80%, AND 0.65%) IN THE ABSENCE (SL, SRO) AND PRESENCE OF FIRE (SLF, SROF) AFTER 200 YEARS OF SIMULATION.

Figure 7. Mean percentage forest area age class distribution over 30 replicates in the absence of fire for age classes a) 0 to 40 years; b) 41 to 100 years; c) 101 to 200 years; d) 201+ years; and e) area harvested; and in the presence of fire for age classes f) 0 to 40 years; g) 41 to 100 years; h) 101 to 200 years; i) 201+ years; and j) area harvested in the case of the Status Quo for harvesting rates 1%, 0.90%, 0.80%, and 0.65%. Graphs a) to d) and f) to i) also include minimum and maximum area per age class obtained through simulating fire without additional harvesting. (next page)

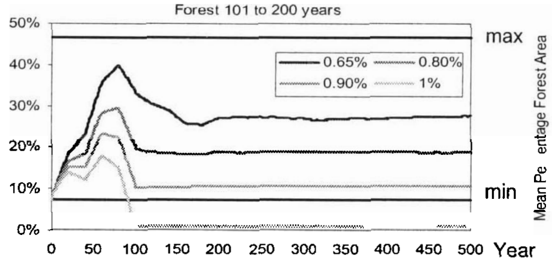
a) Age class 0 to 40 years without fire



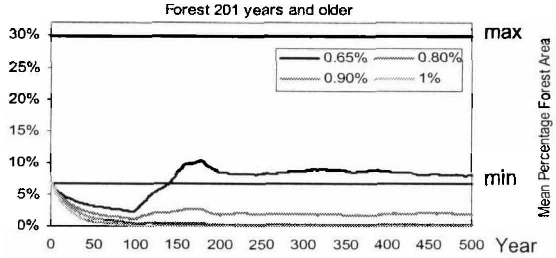
b) Age class 41 to 100 years without fire



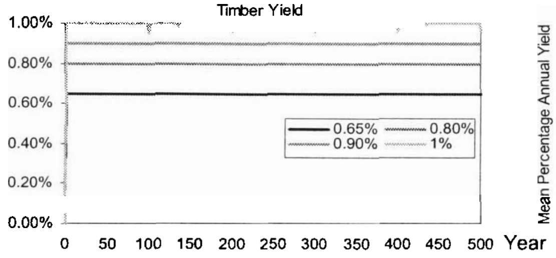
c) Age class 101 to 200 years without fire



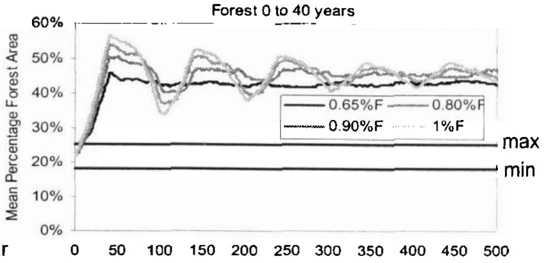
d) Age class 201+ years without fire



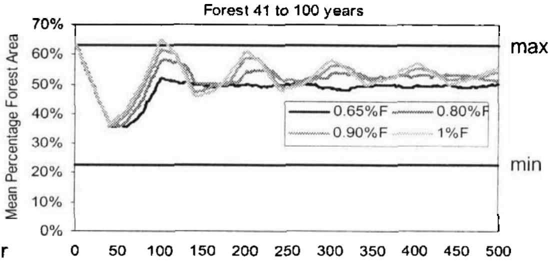
e) *Area harvested in absence of fire*



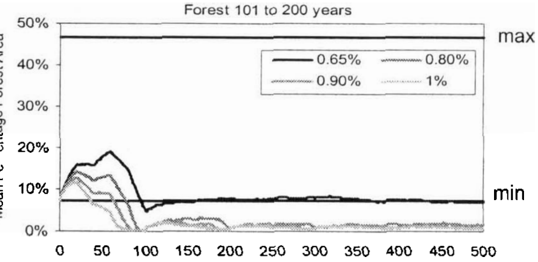
f) Age class 0 to 40 years with fire



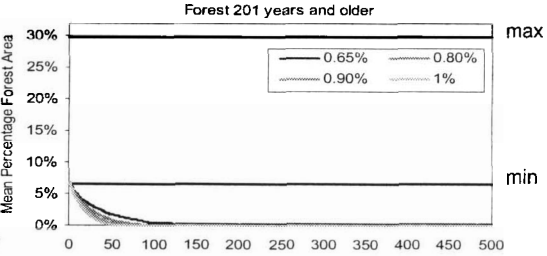
g) Age class 41 to 100 years with fire



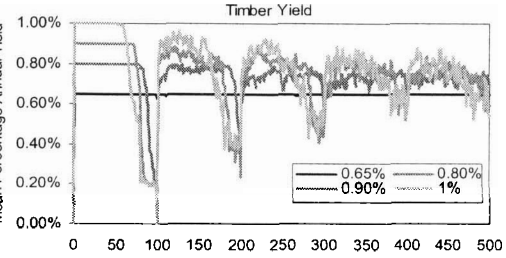
h) Age class 101 to 200 years with fire



i) Age class 201+ years with fire



j) *Area harvested in presence of fire*



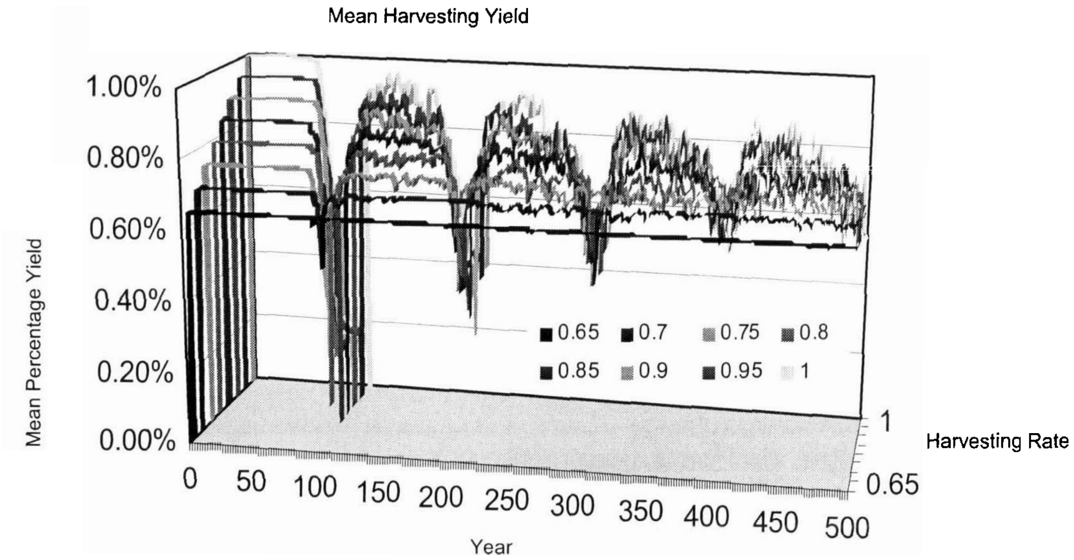


FIGURE 8. MEAN PERCENTAGE HARVESTING YIELD OVER 30 REPLICATES FOR STATUS QUO FOR EIGHT HARVESTING RATES IN THE PRESENCE OF FIRE, WHERE YIELDS ARE EXPRESSED RELATIVE TO THE MAXIMUM POSSIBLE HARVESTING RATE OF 1%.

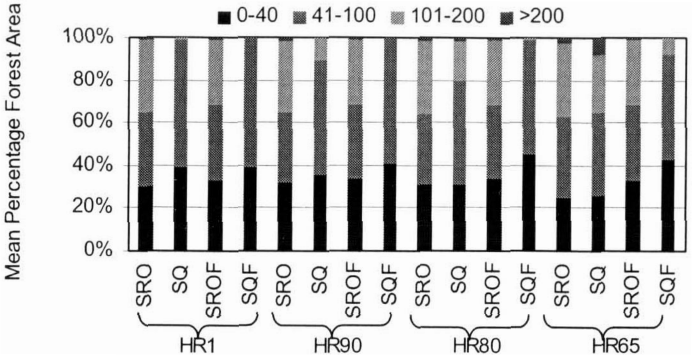
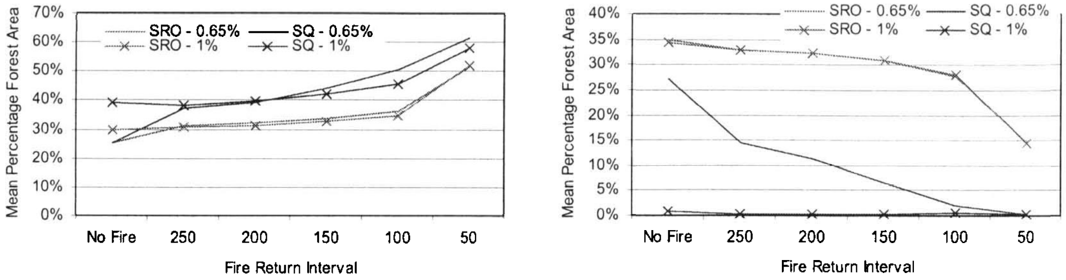


FIGURE 9. MEAN PERCENTAGE FOREST AREA OVER 30 REPLICATES FOR FOUR AGE CLASSES (0 TO 40, 41 TO 100, 101 TO 100, 201+ YEARS) IN THE CASE OF STATUS QUO AND STRICT RESERVE OLD USING A HARD CONSTRAINT FOR FOUR HARVESTING RATES (1%, 0.90%, 0.80%, AND 0.65%) IN THE ABSENCE (SRO, SQ) AND PRESENCE OF FIRE (SROF, SQF) AFTER 200 YEARS OF SIMULATION.

a) Age class 0-40 years

c) Age class 101-200 years



b) Age class 41-100 years

d) Age class 201 years and older

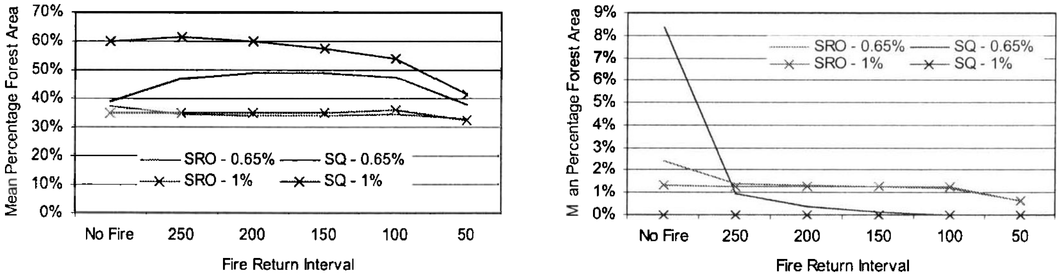
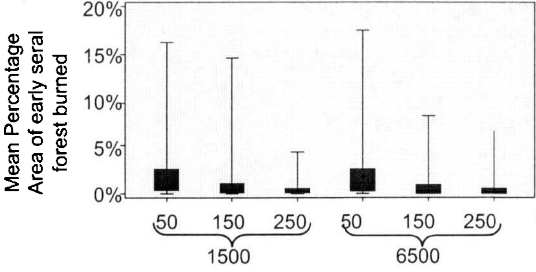
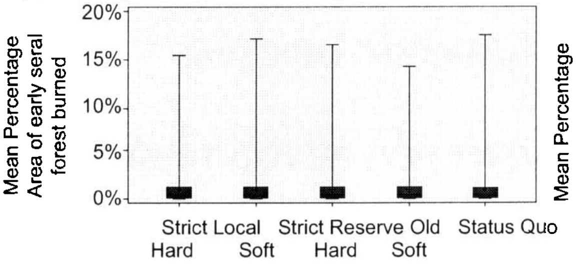


FIGURE 10. FRACTION OF TOTAL MEAN PERCENTAGE AREA OVER 30 REPLICATES FOR AGE CLASSES A) 0 TO 40 YEARS; B) 41 TO 100 YEARS; C) 101 TO 200 YEARS; AND D) 201+ YEARS IN THE CASE OF THE STATUS QUO AND STRICT RESERVE OLD STRATEGY USING A HARD CONSTRAINT AT HARVESTING RATES 0.65% AND 1% IN RELATION TO FIRE RETURN INTERVAL (250, 200, 150, 100, AND 50 YEARS) FOR SMALL FIRE EXTENT OF 1500 HECTARES AFTER 200 YEARS OF SIMULATION.

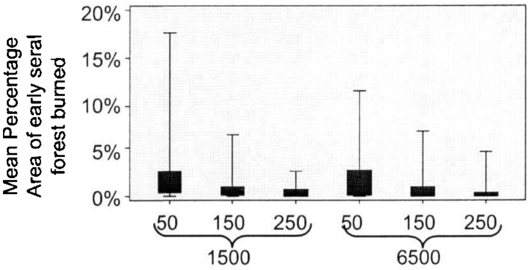
a) Area of early-seral forest re-burning incidents relative to the area of early seral forest as a function of fire regime



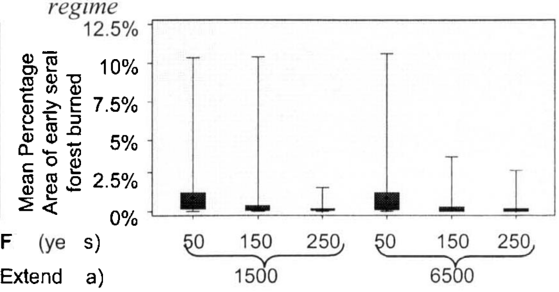
b) Area of early-seral forest re-burning incidents relative to the area of early seral forest as a function of management strategy



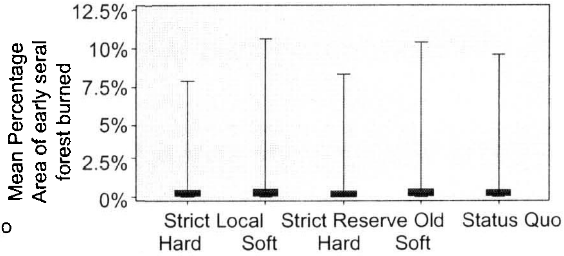
c) Area of early-seral forest re-burning incidents relative to the area of early seral forest as a function of fire regime for fire only without harvesting



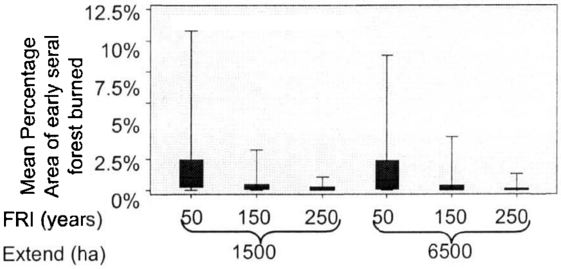
d) Area of early-seral forest re-burning incidents relative to total forested area as a function of fire regime



e) Area of early-seral forest re-burning incidents relative to total forested area as a function of management strategy



f) Area of early-seral forest re-burning incidents relative to total forested area as a function of fire regime for fire only without harvesting



APPENDIX A

MINIMUM, MAXIMUM AND MEAN PERCENTAGE FOREST COVER FOR TWO-FACTOR ANALYSIS SCENARIOS

Two-factor analysis: Minimum, maximum, and mean values (%) of area covered by four main age classes (0-40, 41-100, 101-200, 201+ years) averaged over the 500-year simulation period as result of the interaction between management strategy, harvesting rate, and fire.

Forest 0 to 40 years: Initial value 22.65% (Fire only: min 18.13%; max 25.33%; mean 23.42%)

Management Strategy		*Harvest Rate*							
		0.65%	*0.70%*	*0.75%*	*0.80%*	*0.85%*	*0.90%*	*0.95%*	*1%*
Strict Local - hard constraint	*min*	21.81	21.81	21.81	21.81	21.81	21.81	21.81	21.81
	max	39.70	39.37	39.19	39.16	39.48	39.44	39.72	40.06
	mean	34.22	34.17	34.41	34.49	34.48	34.50	34.54	34.37
Strict Local - soft constraint	*min*	21.81	21.81	21.81	21.81	21.81	21.81	21.81	21.81
	max	45.99	46.53	48.69	49.85	54.04	54.83	55.67	58.51
	mean	42.23	43.47	44.26	44.51	44.97	45.26	45.37	45.52
Strict Reserve Old - hard constraint	*min*	21.81	21.81	21.81	21.81	21.81	21.81	21.81	21.81
	max	36.71	36.74	37.19	37.51	36.74	36.64	37.32	36.37
	mean	32.35	32.51	32.31	32.51	32.23	32.43	32.39	32.24
Strict Reserve Old - soft constraint	*min*	21.81	21.81	21.81	21.81	21.81	21.81	21.81	21.81
	max	45.89	47.10	48.46	51.19	52.51	54.17	55.45	57.91
	mean	42.03	43.44	44.33	44.78	44.88	45.06	45.25	45.41
Status Quo	*min*	21.81	21.81	21.81	21.81	21.81	21.81	21.81	21.81
	max	45.89	46.96	50.03	50.56	53.16	54.42	55.81	56.71
	mean	42.02	43.47	44.37	44.70	45.01	45.12	45.36	45.41

Forest 41 to 100 years: Initial value 63.34% (Fire only: min 22.68%; max 63.34%; mean 27.27%)

Management Strategy		*Harvest Rate*							
		0.65%	*0.70%*	*0.75%*	*0.80%*	*0.85%*	*0.90%*	*0.95%*	*1%*
Strict Local - hard constraint	*min*	34.52	34.71	34.33	34.99	34.86	35.30	35.13	35.45
	max	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34
	mean	39.70	39.75	39.70	39.74	39.74	39.81	39.82	39.85
Strict Local - soft constraint	*min*	35.37	35.78	36.20	36.27	34.90	35.62	36.08	35.45
	max	63.34	63.34	63.34	63.34	63.34	63.34	63.78	66.14
	mean	48.60	50.17	51.16	51.67	51.92	52.06	52.28	52.39
Strict Reserve Old - hard constraint	*min*	30.21	29.97	29.80	29.82	30.53	30.27	29.25	30.62
	max	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34
	mean	37.48	37.43	37.47	37.42	37.49	37.48	37.47	37.52
Strict Reserve Old - soft constraint	*min*	35.40	35.14	36.15	35.78	35.86	35.92	36.48	35.82
	max	63.34	63.34	63.34	63.34	63.34	63.34	64.47	66.45
	mean	48.52	50.24	51.13	51.56	51.89	52.18	52.26	52.40
Status Quo	*min*	35.48	34.73	35.05	35.65	35.53	35.80	36.05	36.66
	max	63.34	63.34	63.34	63.34	63.34	63.34	63.34	65.24
	mean	48.53	50.17	51.13	51.55	51.88	52.18	52.29	52.48

Forest 101 to 200 years: Initial value 7.39% (Fire only: min 7.39%; max 46.59%; mean 25.95%)

Management Strategy		Harvest Rate							
		0.65%	*0.70%*	*0.75%*	*0.80%*	*0.85%*	*0.90%*	*0.95%*	*1%*
Strict Local - hard constraint	*min*	7.39	7.39	7.39	7.39	7.39	7.39	7.39	7.39
	max	29.51	29.72	29.50	29.93	29.71	29.89	29.85	29.75
	mean	24.70	24.71	24.56	24.44	24.47	24.39	24.35	24.54
Strict Local - soft constraint	*min*	5.14	2.48	0.41	0.05	0.00	0.00	0.00	0.00
	max	20.16	18.98	16.37	15.97	15.07	14.44	14.01	13.15
	mean	8.83	6.10	4.36	3.63	2.93	2.52	2.20	1.95
Strict Reserve Old - hard constraint	*min*	7.39	7.39	7.39	7.39	7.39	7.39	7.39	7.39
	max	32.91	32.86	32.89	32.47	32.66	32.79	32.92	32.98
	mean	28.83	28.73	28.90	28.76	28.97	28.80	28.84	28.94
Strict Reserve Old - soft constraint	*min*	5.22	1.80	0.29	0.00	0.00	0.00	0.00	0.00
	max	20.41	18.02	16.55	15.88	15.29	14.64	13.94	13.16
	mean	9.04	5.99	4.25	3.40	2.97	2.53	2.26	1.97
Status Quo	*min*	4.94	2.19	0.23	0.00	0.00	0.00	0.00	0.00
	max	19.12	17.56	14.73	14.23	13.32	12.86	12.26	11.74
	mean	8.87	5.92	4.12	3.42	2.82	2.44	2.12	1.90

Forest 201+ years: Initial value 6.63% (Fire only: min 6.63%; max 29.82%; mean 23.35%)

Management Strategy		Harvest Rate							
		0.65%	*0.70%*	*0.75%*	*0.80%*	*0.85%*	*0.90%*	*0.95%*	*1%*
Strict Local - hard constraint	*min*	0.79	0.78	0.78	0.79	0.79	0.78	0.79	0.79
	max	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68
	mean	1.38	1.36	1.34	1.33	1.31	1.30	1.30	1.29
Strict Local - soft constraint	*min*	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	max	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68
	mean	0.34	0.25	0.21	0.19	0.17	0.16	0.15	0.14
Strict Reserve Old - hard constraint	*min*	0.79	0.78	0.80	0.76	0.78	0.77	0.79	0.81
	max	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68
	mean	1.33	1.32	1.32	1.31	1.30	1.30	1.30	1.30
Strict Reserve Old - soft constraint	*min*	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	max	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68
	mean	0.34	0.25	0.21	0.19	0.18	0.16	0.15	0.14
Status Quo	*min*	0.09	0.01	0.00	0.00	0.00	0.00	0.00	0.00
	max	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68
	mean	0.59	0.45	0.37	0.33	0.30	0.26	0.24	0.22

APPENDIX B

MINIMUM, MAXIMUM AND MEAN PERCENTAGE FOREST COVER FOR FIVE-FACTOR ANALYSIS SCENARIOS

Five-factor analysis: Minimum, maximum, and mean values (%) of area covered by four main age classes (0-40, 41-100, 101-200, 200+ years) averaged over the 500-year simulation period as result of the interaction between management strategy, harvesting rate, harvesting cost, and fire regime.

Linear Harvesting cost:

<u>Forest 0 to 40 years</u>: Initial value 22.65%

Harvest rate 0.65%

Fire Extent (hectares)		***1500***					***6500***				
Fire Return Interval (years)		***50***	***100***	***150***	***200***	***250***	***50***	***100***	***150***	***200***	***250***
Fire Only	min	20.95	19.94	16.42	13.60	12.06	20.95	20.32	15.97	13.72	11.78
	max	51.41	31.86	22.93	22.65	22.65	50.60	30.93	22.65	22.65	22.65
	mean	48.89	29.51	21.41	16.27	13.42	47.80	28.69	20.14	16.03	13.12
Strict Local - hard constraint	min	21.60	21.60	21.60	21.60	21.60	21.60	21.60	21.60	21.60	21.60
	max	58.26	43.07	38.22	35.26	34.10	57.10	43.17	38.12	35.64	33.24
	mean	52.19	38.47	34.05	31.81	30.30	51.74	38.96	34.40	32.05	30.51
Strict Local - soft constraint	min	21.60	21.60	21.60	21.60	21.60	21.60	21.60	21.60	21.60	21.60
	max	69.64	51.57	44.79	40.80	38.45	67.93	50.95	44.63	40.41	37.95
	mean	59.70	48.47	42.85	38.78	36.22	59.06	48.01	42.32	38.71	35.92
Strict Reserve Old - hard constraint	min	21.60	21.60	21.60	20.54	19.12	21.60	21.60	21.60	20.09	19.58
	max	55.48	41.04	37.60	36.05	36.14	53.50	40.06	37.80	36.51	34.93
	mean	51.22	36.59	31.95	30.02	29.03	50.12	36.10	31.93	30.03	28.89
Strict Reserve Old - soft constraint	min	21.60	21.60	21.60	21.60	21.60	21.60	21.60	21.60	21.60	21.60
	max	68.29	52.32	45.30	40.40	37.71	68.82	52.68	44.70	40.27	37.88
	mean	59.80	48.68	43.10	38.64	36.23	59.59	48.02	42.19	38.41	35.97
Status Quo	min	21.60	21.60	21.60	21.60	21.60	21.60	21.60	21.60	21.60	21.60
	max	69.77	51.62	44.65	40.31	37.49	68.87	51.75	45.36	39.98	37.63
	mean	59.64	48.45	42.65	38.69	36.12	59.10	48.17	42.17	38.16	35.93

Forest 0 to 40 years: Initial value 22.65%

Harvest rate 1%

Fire Extent (hectares)		*1500*					*6500*				
Fire Return Interval (years)		*50*	*100*	*150*	*200*	*250*	*50*	*100*	*150*	*200*	*250*
Fire Only	min	20.95	19.94	16.42	13.60	12.06	20.95	20.32	15.97	13.72	11.78
	max	51.41	31.86	22.93	22.65	22.65	50.60	30.93	22.65	22.65	22.65
	mean	48.89	29.51	21.41	16.27	13.42	47.80	28.69	20.14	16.03	13.12
Strict Local - hard constraint	min	21.81	21.81	21.81	21.81	21.81	21.81	21.81	21.81	21.81	21.81
	max	58.03	43.06	37.79	34.98	33.72	57.99	43.35	38.39	35.02	33.33
	mean	52.33	38.76	34.36	31.96	30.65	52.04	39.17	34.63	32.21	30.88
Strict Local - soft constraint	min	21.81	21.81	21.81	21.81	21.81	21.81	21.81	21.81	21.81	21.81
	max	76.03	63.64	56.32	52.57	50.15	75.57	63.77	55.96	51.98	50.40
	mean	60.44	49.86	45.97	44.02	42.82	59.94	49.70	45.74	43.73	42.61
Strict Reserve Old - hard constraint	min	21.81	21.81	21.81	19.81	19.45	21.81	21.81	21.81	19.80	19.35
	max	54.16	40.45	36.87	36.30	35.64	53.58	40.70	37.02	36.54	36.18
	mean	51.07	36.57	32.03	30.02	28.92	50.16	36.40	32.02	29.90	29.02
Strict Reserve Old - soft constraint	min	21.81	21.81	21.81	21.81	21.81	21.81	21.81	21.81	21.81	21.81
	max	76.78	61.76	56.67	52.49	50.60	76.87	62.32	56.37	53.17	49.60
	mean	60.18	49.65	45.97	43.95	42.78	59.82	49.42	45.59	43.75	42.61
Status Quo	min	21.81	21.81	21.81	21.81	21.81	21.81	21.81	21.81	21.81	21.81
	max	75.78	63.15	56.90	52.25	50.88	76.94	62.70	56.56	52.38	49.78
	mean	60.31	49.84	46.03	43.99	42.96	60.22	49.30	45.72	43.82	42.66

***Forest 41 to 100 years*: Initial value 63.34%**

Harvest rate 0.65%

Fire Extent (hectares)		*1500*					*6500*				
Fire Return Interval (years)		*50*	*100*	*150*	*200*	*250*	*50*	*100*	*150*	*200*	*250*
Fire Only	min	21.53	23.25	21.15	17.66	15.71	20.99	23.28	19.78	17.61	14.93
	max	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34
	mean	30.12	29.65	26.10	22.74	20.52	29.42	28.79	25.14	22.37	20.07
Strict Local - hard constraint	min	22.57	31.60	33.77	34.06	34.22	23.27	32.08	33.44	33.96	33.77
	max	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34
	mean	33.00	38.45	39.59	39.94	40.09	33.22	38.78	40.03	40.36	40.49
Strict Local - soft constraint	min	22.85	31.95	34.00	34.07	34.80	23.34	32.99	33.86	34.44	34.81
	max	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34
	mean	38.53	47.44	48.58	47.70	46.88	39.05	47.51	48.45	47.72	46.80
Strict Reserve Old - hard constraint	min	22.18	27.88	29.06	29.33	28.70	23.71	29.10	28.90	28.83	29.43
	max	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34
	mean	32.12	36.31	37.47	38.07	38.44	32.15	36.49	37.52	38.24	38.60
Strict Reserve Old - soft constraint	min	23.16	31.39	33.78	34.34	34.77	23.00	31.27	34.50	35.27	34.16
	max	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34
	mean	38.35	47.36	48.61	47.66	46.84	38.55	47.54	48.37	47.54	46.77
Status Quo	min	23.00	32.16	33.54	34.37	34.38	23.55	32.27	33.49	34.58	34.55
	max	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34
	mean	38.53	47.39	48.50	47.63	46.85	38.94	47.39	48.41	47.53	46.69

Forest 41 to 100 years: Initial value 63.34%

Harvest rate 1%

Fire Extent (hectares)		*1500*					*6500*				
Fire Return Interval (years)		*50*	*100*	*150*	*200*	*250*	*50*	*100*	*150*	*200*	*250*
Fire Only	min	21.53	23.25	21.15	17.66	15.71	20.99	23.28	19.78	17.61	14.93
	max	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34
	mean	30.12	29.65	26.10	22.74	20.52	29.42	28.79	25.14	22.37	20.07
Strict Local - hard constraint	min	23.09	33.03	33.20	33.80	33.14	22.86	32.73	33.91	33.51	33.98
	max	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34
	mean	33.00	38.50	39.69	40.20	40.40	33.18	38.94	40.21	40.66	40.88
Strict Local - soft constraint	min	23.29	32.67	37.08	39.27	40.25	23.70	32.51	37.18	39.82	39.97
	max	63.34	63.34	64.29	64.33	64.49	63.34	63.34	63.83	63.34	65.56
	mean	38.52	48.50	51.96	53.62	54.55	38.99	48.62	52.06	53.67	54.52
Strict Reserve Old - hard constraint	min	23.16	28.25	29.22	29.18	29.34	23.79	28.39	29.49	29.02	28.86
	max	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34	63.34
	mean	32.16	36.36	37.47	38.14	38.58	32.18	36.38	37.58	38.30	38.70
Strict Reserve Old - soft constraint	min	22.59	33.86	36.75	39.32	39.86	22.53	33.36	36.87	38.87	40.48
	max	63.34	63.34	64.32	64.43	65.06	63.34	63.34	63.98	65.24	63.34
	mean	38.78	48.66	51.98	53.62	54.60	39.13	48.84	52.21	53.68	54.56
Status Quo	min	23.49	33.04	36.95	39.39	40.13	22.45	33.02	37.30	39.17	40.60
	max	63.34	63.34	63.34	64.35	65.00	63.34	63.34	64.02	64.41	64.48
	mean	38.66	48.52	51.92	53.61	54.48	38.75	48.98	52.07	53.64	54.57

Forest 101 to 200 years: Initial value 7.39%

Harvest rate 0.65%

Fire Extent (hectares)		*1500*					*6500*				
Fire Return Interval (years)		*50*	*100*	*150*	*200*	*250*	*50*	*100*	*150*	*200*	*250*
Fire Only	min	7.39	7.39	7.39	7.39	7.39	7.39	7.39	7.39	7.39	7.39
	max	23.78	40.87	50.67	58.10	61.94	25.69	41.58	51.34	57.65	62.73
	mean	14.11	24.35	27.24	27.88	27.56	14.28	24.15	27.16	27.60	27.32
Strict Local - hard constraint	min	7.39	7.39	7.39	7.39	7.39	7.39	7.39	7.39	7.39	7.39
	max	21.37	27.78	30.46	31.76	32.21	21.99	27.47	30.50	31.65	32.35
	mean	13.85	21.79	24.99	26.82	28.16	14.04	20.98	24.19	26.14	27.51
Strict Local - soft constraint	min	0.00	0.63	5.36	7.39	7.39	0.00	1.24	5.79	7.39	7.39
	max	13.87	16.92	21.85	25.44	27.09	13.99	16.85	21.61	25.36	27.41
	mean	1.58	3.85	8.23	12.94	16.09	1.71	4.24	8.87	13.00	16.40
Strict Reserve Old - hard constraint	min	7.39	7.39	7.39	7.39	7.39	7.39	7.39	7.39	7.39	7.39
	max	23.24	32.05	33.22	33.65	34.67	24.93	32.24	33.03	33.80	35.28
	mean	15.61	25.85	29.24	30.53	31.10	16.65	26.16	29.21	30.34	31.05
Strict Reserve Old - soft constraint	min	0.00	0.51	5.18	7.39	7.39	0.00	0.41	5.92	7.39	7.39
	max	14.23	16.95	21.62	25.27	27.19	13.97	16.81	21.94	25.17	27.45
	mean	1.66	3.72	7.95	13.12	16.10	1.67	4.20	9.08	13.46	16.41
Status Quo	min	0.00	0.57	5.72	7.39	7.39	0.00	0.73	5.57	7.39	7.39
	max	12.86	15.54	21.01	23.81	26.12	13.06	15.42	21.52	23.94	26.00
	mean	1.55	3.75	8.22	12.71	15.55	1.67	4.03	8.79	13.23	15.81

Forest 101 to 200 years: Initial value 7.39%

Harvest rate 1%

Fire Extent (hectares)		*1500*					*6500*				
Fire Return Interval (years)		*50*	*100*	*150*	*200*	*250*	*50*	*100*	*150*	*200*	*250*
Fire Only	min	7.39	7.39	7.39	7.39	7.39	7.39	7.39	7.39	7.39	7.39
	max	23.78	40.87	50.67	58.10	61.94	25.69	41.58	51.34	57.65	62.73
	mean	14.11	24.35	27.24	27.88	27.56	14.28	24.15	27.16	27.60	27.32
Strict Local - hard constraint	min	7.39	7.39	7.39	7.39	7.39	7.39	7.39	7.39	7.39	7.39
	max	21.32	27.83	30.21	31.71	32.14	20.96	27.38	30.45	31.61	32.17
	mean	13.76	21.54	24.68	26.53	27.62	13.84	20.71	23.88	25.81	26.91
Strict Local - soft constraint	min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	max	10.95	12.83	13.53	14.01	14.40	11.09	12.49	13.62	14.04	14.46
	mean	0.92	1.50	1.93	2.21	2.47	0.95	1.54	2.06	2.45	2.71
Strict Reserve Old - hard constraint	min	7.39	7.39	7.39	7.39	7.39	7.39	7.39	7.39	7.39	7.39
	max	24.47	32.08	33.21	33.65	33.97	25.60	32.31	33.08	33.54	33.89
	mean	15.72	25.84	29.20	30.52	31.16	16.60	26.00	29.11	30.48	30.94
Strict Reserve Old - soft constraint	min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	max	11.06	12.79	13.54	14.24	14.48	10.83	12.95	13.74	14.19	14.53
	mean	0.92	1.55	1.91	2.28	2.48	0.93	1.61	2.05	2.42	2.67
Status Quo	min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	max	9.77	11.25	11.98	12.33	12.61	9.87	11.23	12.24	12.45	12.72
	mean	0.87	1.43	1.83	2.16	2.32	0.87	1.52	1.99	2.30	2.53

Forest 201+ years: Initial value 6.63%

Harvest rate 0.65%

Fire Extent (hectares)		*1500*					*6500*				
Fire Return Interval (years)		*50*	*100*	*150*	*200*	*250*	*50*	*100*	*150*	*200*	*250*
Fire Only	min	2.84	5.80	6.63	6.63	6.63	3.30	5.89	6.63	6.63	6.63
	max	8.24	21.50	32.72	43.28	50.06	10.14	23.31	35.65	44.25	51.88
	mean	6.87	16.49	25.25	33.11	38.50	8.50	18.37	27.56	34.00	39.49
Strict Local - hard constraint	min	0.30	0.60	0.77	0.89	0.95	0.35	0.61	0.77	0.89	0.97
	max	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68
	mean	0.97	1.28	1.37	1.42	1.45	1.01	1.28	1.38	1.44	1.50
Strict Local - soft constraint	min	0.00	0.00	0.02	0.09	0.13	0.00	0.00	0.03	0.09	0.14
	max	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68
	mean	0.18	0.24	0.34	0.58	0.81	0.19	0.24	0.35	0.57	0.87
Strict Reserve Old - hard constraint	min	0.29	0.59	0.80	0.95	1.04	0.34	0.64	0.82	0.96	1.09
	max	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68
	mean	1.06	1.25	1.33	1.39	1.44	1.09	1.25	1.33	1.39	1.46
Strict Reserve Old - soft constraint	min	0.00	0.00	0.02	0.09	0.13	0.00	0.00	0.03	0.09	0.14
	max	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68
	mean	0.19	0.24	0.33	0.58	0.84	0.19	0.24	0.36	0.60	0.84
Status Quo	min	0.00	0.00	0.08	0.36	0.88	0.00	0.00	0.10	0.47	0.98
	max	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68
	mean	0.28	0.42	0.63	0.97	1.48	0.29	0.41	0.63	1.08	1.57

Forest 201+ years: Initial value 6.63%

Harvest rate 1%

Fire Extent (hectares)		*1500*					*6500*				
Fire Return Interval (years)		*50*	*100*	*150*	*200*	*250*	*50*	*100*	*150*	*200*	*250*
Fire Only	min	2.84	5.80	6.63	6.63	6.63	3.30	5.89	6.63	6.63	6.63
	max	8.24	21.50	32.72	43.28	50.06	10.14	23.31	35.65	44.25	51.88
	mean	6.87	16.49	25.25	33.11	38.50	8.50	18.37	27.56	34.00	39.49
Strict Local - hard constraint	min	0.31	0.59	0.76	0.90	0.96	0.34	0.62	0.78	0.90	0.96
	max	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68
	mean	0.91	1.20	1.27	1.31	1.33	0.94	1.19	1.28	1.32	1.33
Strict Local - soft constraint	min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	max	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68
	mean	0.12	0.14	0.14	0.15	0.15	0.12	0.14	0.14	0.15	0.15
Strict Reserve Old - hard constraint	min	0.31	0.59	0.78	0.91	0.99	0.35	0.63	0.78	0.93	1.00
	max	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68
	mean	1.05	1.23	1.30	1.32	1.34	1.06	1.22	1.29	1.33	1.35
Strict Reserve Old - soft constraint	min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	max	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68
	mean	0.12	0.14	0.14	0.15	0.15	0.12	0.14	0.14	0.15	0.15
Status Quo	min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	max	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68
	mean	0.17	0.20	0.23	0.24	0.24	0.17	0.20	0.22	0.24	0.24

Linear + Step Harvesting cost

***Forest 0 to 40 years*: Initial value 22.65%**

Harvest rate 0.65%

Fire Extent (hectares)		*1500*			*6500*		
Fire Return Interval (years)		*50*	*150*	*250*	*50*	*150*	*250*
Fire Only	min	20.95	16.42	12.06	20.95	15.97	11.78
	max	51.41	22.93	22.65	50.60	22.65	22.65
	mean	48.89	21.41	13.42	47.80	20.14	13.12
Strict Local - hard constraint	min	21.60	21.60	21.60	21.60	21.60	21.60
	max	57.30	38.16	33.88	57.45	38.00	33.69
	mean	52.31	33.95	30.33	52.09	34.47	30.54
Strict Local - soft constraint	min	21.60	21.60	21.60	21.60	21.60	21.60
	max	68.46	45.07	37.57	69.38	44.67	37.65
	mean	59.64	42.82	36.16	59.92	42.35	35.89
Strict Reserve Old - hard constraint	min	21.60	21.60	19.06	21.60	21.60	18.84
	max	55.83	37.26	35.06	56.52	37.63	34.41
	mean	50.96	31.99	28.86	51.09	31.97	28.84
Strict Reserve Old - soft constraint	min	21.60	21.60	21.60	21.60	21.60	21.60
	max	68.83	44.95	37.74	70.17	44.57	37.65
	mean	59.84	42.83	36.14	59.96	42.15	35.90
Status Quo	min	21.60	21.60	21.60	21.60	21.60	21.60
	max	68.71	45.81	37.94	70.79	45.23	37.82
	mean	60.06	43.01	36.26	59.84	42.38	35.84

Forest 0 to 40 years: Initial value 22.65%

Harvest rate 1%

Fire Extent (hectares)		*1500*			*6500*		
Fire Return Interval (years)		*50*	*150*	*250*	*50*	*150*	*250*
Fire Only	min	20.95	16.42	12.06	20.95	15.97	11.78
	max	51.41	22.93	22.65	50.60	22.65	22.65
	mean	48.89	21.41	13.42	47.80	20.14	13.12
Strict Local - hard constraint	min	21.81	21.81	21.81	21.81	21.81	21.81
	max	58.99	37.83	33.23	58.61	37.52	33.29
	mean	52.51	34.27	30.53	52.11	34.44	30.96
Strict Local - soft constraint	min	21.81	21.81	21.81	21.81	21.81	21.81
	max	75.56	56.32	50.38	76.27	56.45	49.62
	mean	60.32	46.05	42.80	59.96	45.81	42.67
Strict Reserve Old - hard constraint	min	21.81	21.69	19.02	21.81	21.69	18.77
	max	54.40	37.49	36.09	53.80	37.49	36.02
	mean	51.08	32.00	28.99	50.76	32.00	28.95
Strict Reserve Old - soft constraint	min	21.81	21.81	21.81	21.81	21.81	21.81
	max	76.26	56.86	50.21	75.99	55.80	49.50
	mean	60.22	45.91	42.86	60.20	45.74	42.57
Status Quo	min	21.60	21.81	21.81	21.81	21.81	21.81
	max	68.71	56.43	50.46	76.02	55.89	50.20
	mean	60.06	46.00	42.89	59.55	45.81	42.63

<u>Forest 41 to 100 years</u>: Initial value 63.34%

Harvest rate 0.65%

Fire Extent (hectares)		*1500*			*6500*		
Fire Return Interval (years)		*50*	*150*	*250*	*50*	*150*	*250*
Fire Only	min	21.53	21.15	15.71	20.99	19.78	14.93
	max	63.34	63.34	63.34	63.34	63.34	63.34
	mean	30.12	26.10	20.52	29.42	25.14	20.07
Strict Local - hard constraint	min	23.41	33.45	33.59	23.34	33.69	33.04
	max	63.34	63.34	63.34	63.34	63.34	63.34
	mean	32.88	39.57	40.05	33.07	39.96	40.42
Strict Local - soft constraint	min	24.81	34.07	34.93	23.10	34.01	34.92
	max	63.34	63.34	63.34	63.34	63.34	63.34
	mean	38.41	48.58	46.87	38.28	48.38	46.77
Strict Reserve Old - hard constraint	min	22.15	29.15	28.75	21.69	28.76	29.02
	max	63.34	63.34	63.34	63.34	63.34	63.34
	mean	32.26	37.42	38.29	32.17	37.53	38.46
Strict Reserve Old - soft constraint	min	23.06	33.53	34.94	22.09	33.51	35.39
	max	63.34	63.34	63.34	63.34	63.34	63.34
	mean	38.34	48.63	46.86	38.29	48.38	46.67
Status Quo	min	23.28	33.73	34.75	22.50	33.91	34.75
	max	63.34	63.34	63.34	63.34	63.34	63.34
	mean	38.21	48.56	46.87	38.38	48.44	46.67

Forest 41 to 100 years: Initial value 63.34%

Harvest rate 1%

Fire Extent (hectares)		*1500*			*6500*		
Fire Return Interval (years)		*50*	*150*	*250*	*50*	*150*	*250*
Fire Only	min	21.53	21.15	15.71	20.99	19.78	14.93
	max	63.34	63.34	63.34	63.34	63.34	63.34
	mean	30.12	26.10	20.52	29.42	25.14	20.07
Strict Local - hard constraint	min	22.59	33.52	33.58	22.49	33.91	33.58
	max	63.34	63.34	63.34	63.34	63.34	63.34
	mean	32.90	39.72	40.42	33.12	40.31	40.81
Strict Local - soft constraint	min	23.66	36.91	39.94	23.10	36.80	40.39
	max	63.34	63.47	64.24	63.34	64.31	63.71
	mean	38.64	51.87	54.55	38.98	52.03	54.55
Strict Reserve Old - hard constraint	min	22.93	28.83	28.79	23.00	28.83	28.75
	max	63.34	63.34	63.34	63.34	63.34	63.34
	mean	32.14	37.58	38.51	31.90	37.58	38.74
Strict Reserve Old - soft constraint	min	23.08	36.91	40.44	23.29	37.27	40.64
	max	63.34	63.62	64.20	63.34	63.34	64.41
	mean	38.74	52.03	54.55	38.74	52.07	54.60
Status Quo	min	23.28	37.34	40.15	23.25	37.26	40.30
	max	63.34	64.11	64.27	63.34	63.45	63.95
	mean	38.21	51.93	54.53	39.36	52.00	54.57

Forest 101 to 200 years: Initial value 7.39%

Harvest rate 0.65%

Fire Extent (hectares)		*1500*			*6500*		
Fire Return Interval (years)		*50*	*150*	*250*	*50*	*150*	*250*
Fire Only	min	7.39	7.39	7.39	7.39	7.39	7.39
	max	23.78	50.67	61.94	25.69	51.34	62.73
	mean	14.11	27.24	27.56	14.28	27.16	27.32
Strict Local - hard constraint	min	7.39	7.39	7.39	7.39	7.39	7.39
	max	21.77	30.55	32.12	20.75	30.26	32.01
	mean	13.83	25.08	28.11	13.85	24.17	27.50
Strict Local - soft constraint	min	0.00	5.24	7.39	0.00	5.99	7.39
	max	13.98	21.20	25.76	13.41	21.21	26.20
	mean	1.71	8.01	15.17	1.57	8.61	15.52
Strict Reserve Old - hard constraint	min	7.39	7.39	7.39	7.39	7.39	7.39
	max	24.13	33.26	34.72	23.34	33.21	35.21
	mean	15.72	29.21	31.15	15.67	29.12	31.01
Strict Reserve Old - soft constraint	min	0.00	5.24	7.39	0.00	5.91	7.39
	max	13.42	21.00	25.85	13.08	21.86	26.38
	mean	1.59	7.95	15.22	1.51	8.78	15.58
Status Quo	min	0.00	4.70	7.39	0.00	4.50	7.39
	max	11.49	18.95	24.31	11.97	19.92	24.83
	mean	1.40	7.30	12.91	1.42	7.92	13.29

***Forest 101 to 200 years*: Initial value 7.39%**

Harvest rate 1%

Fire Extent (hectares)		*1500*			*6500*		
Fire Return Interval (years)		*50*	*150*	*250*	*50*	*150*	*250*
Fire Only	min	7.39	7.39	7.39	7.39	7.39	7.39
	max	23.78	50.67	61.94	25.69	51.34	62.73
	mean	14.11	27.24	27.56	14.28	27.16	27.32
Strict Local - hard constraint	min	7.39	7.39	33.58	7.39	7.39	7.39
	max	20.59	30.35	63.34	20.98	30.69	32.11
	mean	13.67	24.73	40.42	13.83	23.98	26.89
Strict Local - soft constraint	min	0.00	0.00	39.94	0.00	0.00	0.00
	max	10.29	12.51	64.24	10.45	12.49	13.41
	mean	0.89	1.89	54.55	0.92	1.98	2.58
Strict Reserve Old - hard constraint	min	7.39	7.39	7.39	7.39	7.39	7.39
	max	23.65	33.12	34.02	24.63	33.12	34.04
	mean	15.73	29.12	31.11	16.28	29.12	30.92
Strict Reserve Old - soft constraint	min	0.00	0.00	40.44	0.00	0.00	0.00
	max	10.48	12.59	64.20	10.38	12.63	13.33
	mean	0.90	1.88	54.55	0.92	2.00	2.63
Status Quo	min	0.00	0.00	40.15	0.00	0.00	0.00
	max	11.49	11.01	64.27	9.56	11.04	11.68
	mean	1.40	1.77	54.53	0.89	1.89	2.45

***Forest 201+ years*: Initial value 6.63%**

Harvest rate 0.65%

Fire Extent (hectares)		*1500*			*6500*		
Fire Return Interval (years)		*50*	*150*	*250*	*50*	*150*	*250*
Fire Only	min	2.84	6.63	6.63	3.30	6.63	6.63
	max	8.24	32.72	50.06	10.14	35.65	51.88
	mean	6.87	25.25	38.50	8.50	27.56	39.49
Strict Local - hard constraint	min	0.31	0.78	0.95	0.31	0.78	0.98
	max	6.68	6.68	6.68	6.68	6.68	6.68
	mean	0.98	1.40	1.50	0.98	1.40	1.53
Strict Local - soft constraint	min	0.00	0.09	0.54	0.00	0.10	0.58
	max	6.68	6.68	6.68	6.68	6.68	6.68
	mean	0.24	0.59	1.79	0.23	0.66	1.82
Strict Reserve Old - hard constraint	min	0.30	0.81	1.30	0.29	0.84	1.31
	max	6.68	6.68	6.68	6.68	6.68	6.68
	mean	1.07	1.37	1.70	1.06	1.38	1.69
Strict Reserve Old - soft constraint	min	0.00	0.06	0.54	0.00	0.12	0.65
	max	6.68	6.68	6.68	6.68	6.68	6.68
	mean	0.24	0.59	1.78	0.23	0.69	1.86
Status Quo	min	0.00	0.23	2.88	0.00	0.27	2.86
	max	6.68	6.68	6.68	6.68	6.68	6.68
	mean	0.34	1.13	3.96	0.35	1.26	4.20

Forest 201+ years: Initial value 6.63%

Harvest rate 1%

Fire Extent (hectares)		*1500*			*6500*		
Fire Return Interval (years)		*50*	*150*	*250*	*50*	*150*	*250*
Fire Only	min	2.84	6.63	6.63	3.30	6.63	6.63
	max	8.24	32.72	50.06	10.14	35.65	51.88
	mean	6.87	25.25	38.50	8.50	27.56	39.49
Strict Local - hard constraint	min	0.29	0.77	0.96	0.33	0.79	0.98
	max	6.68	6.68	6.68	6.68	6.68	6.68
	mean	0.92	1.28	1.33	0.94	1.28	1.34
Strict Local - soft constraint	min	0.00	0.00	0.00	0.00	0.00	0.00
	max	6.68	6.68	6.68	6.68	6.68	6.68
	mean	0.15	0.19	0.20	0.15	0.19	0.20
Strict Reserve Old - hard constraint	min	0.30	0.83	1.01	0.33	0.83	1.03
	max	6.68	6.68	6.68	6.68	6.68	6.68
	mean	1.05	1.30	1.39	1.06	1.30	1.39
Strict Reserve Old - soft constraint	min	0.00	0.00	0.00	0.00	0.00	0.00
	max	6.68	6.68	6.68	6.68	6.68	6.68
	mean	0.15	0.19	0.20	0.15	0.19	0.20
Status Quo	min	0.00	0.00	0.00	0.00	0.00	0.00
	max	6.68	6.68	6.68	6.68	6.68	6.68
	mean	0.34	0.30	0.36	0.21	0.30	0.35