A forest management decision support system for sustainable management of flammable boreal forest landscapes

An Integrated policy approach to timber harvest planning

Thèse

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RÉSUMÉ

Les feux sont un phénomène naturel dans la forêt boréale du Canada. Ils sont étroitement liés à la croissance et au développement de cet écosystème. Cependant, l'augmentation des activités anthropiques associées au changement climatique graduel peuvent provoquer un accroissement des épisodes de feux. Un tel accroissement pourrait avoir des effets indésirables sur l'industrie forestière en raison d'une rupture de l'approvisionnement en bois sur une période de planification à long terme. Cette thèse explore une approche alternative pour concevoir des stratégies qui réduiront l'impact potentiel des feux de forêt sur les revenus à long terme générés par la vente de produits forestiers ciblés, et ce, au moyen d'une politique d'aménagement forestier spécifique. L'étude est basée sur les données de trois unités d'aménagement forestier localisées dans la région boréale de la province de Québec au Canada. Les modèles de politique de planification de la récolte forestière ont été résolus en utilisant la programmation linéaire intégrée avec un taux de brûlage constant. Les options de récolte prescrites par les modèles de planification ont été évaluées à l'aide d'un modèle de simulation de paysage intégré avec un taux de brûlage stochastique.

Parmi les quatre modèles pris en compte, le modèle verticalement intégré (modèle 4) a généré les revenus les plus élevés tout en ayant les variations les moins importantes de revenu au sein et entre les périodes pour l'horizon de planification. Ce modèle a permis de maximiser la valeur actuelle nette des recettes provenant de la vente de produits de première transformation pour les deux premières périodes soumis à une récolte forestière constante et à des volumes de bois récupérés durant une période de planification complète. Les revenus plus élevés et les variations plus faibles suggèrent que le modèle peut réduire le risque des impacts des feux de forêt sur les revenus comparativement aux trois autres modèles, y compris le

modèle de rendement soutenu qui maximise le volume de la récolte soumis à des flux constants du volume de récolte durant une période de planification (modèle 1).

L'analyse des dépenses de gestion des incendies a démontré que l'augmentation de telles dépenses peut réduire le coût de lutte contre les feux et augmenter les revenus de la récolte tout en diminuant la variabilité. Cependant, il y a un niveau optimal de dépense qui dépend de la structure forestière et des régimes de feux. Par conséquent, une répartition optimale des dépenses de prévention peut réduire le risque d'impact du feu sur l'économie forestière à long terme.

La pérennité des écosystèmes est importante en gestion forestière. Par conséquent, l'intégrité écologique est de plus en plus préoccupante en ce qui concerne les forêts publiques canadiennes qui sont aménagées à des fins commerciales. La mise en œuvre d'une politique de récolte exigeant la conservation des vieilles forêts tout en tenant compte de l'impact potentiel du feu peut avoir des effets négatifs sur les revenus. Les impacts peuvent être réduits en choisissant une politique de gestion forestière alternative. La réduction des revenus à court terme peut être compensée par des retours à long terme générés par la valeur ajoutée associée à l'âge du bois en utilisant des politiques alternatives.

Finalement, les résultats démontrent que le modèle de planification de la récolte intégrée verticalement et l'optimisation des efforts de gestion du feu peuvent accroître les revenus à moyen et à long terme de l'industrie forestière. Le modèle réduit le risque de perte de revenus lié à la rupture de l'approvisionnement lorsque l'impact du feu est inclus dans le processus de planification. De plus, les solutions prescrites dans ce modèle aident à réduire le taux de récolte et à augmenter le volume des stocks qui peut être un coussin en prévision des feux qui surviennent de façon très variable au cours des périodes de l'horizon de planification.

ABSTRACT

Forest fire is a natural process in the boreal forest region of Canada and it is strongly connected to forest growth and development. Yet, increasing anthropogenic activities coupled with gradual climate change can increase fire occurrence and area burned. Such an increase may cause adverse impacts on the forest-based economy by the potential disruption of timber supply over a long-term planning horizon. This thesis explores an alternative approach to designing strategies to reduce the potential impact of fire on long-term revenues generated by the sale of prescribed harvest products using a specified forest management policy. The study is based on data from three commercially-managed forests located in the boreal forest region of the province of Quebec, Canada. The harvest planning policy models were solved using a constant average annual burn rate-embedded in a linear programming model. The harvest solutions prescribed by the planning model were evaluated by implementing them in a stochastic landscape simulation model.

Among the four policy models examined, vertically integrated model (model 4) generated the highest revenue with the least within- and among-period variation in revenue over the planning horizon. This model maximized the net present value from the sale of primary-processed wood products for the first two periods subjecting to the constant flows of harvest timber and recovered lumber volumes for an entire planning horizon. The higher revenue and lower variation suggest that the model can have lower risk of fire impacts on revenue compared with the other three models including the status quo sustained-yield policy model (model 1) that maximizes harvest timber volume subject to constant flows of the harvest volume over the planning horizon.

Analysis of fire management expenditures demonstrated that increased presuppression expenditure can reduce suppression costs and increase the revenue from the harvest while lowering the variability. However, there is an optimal level of expenditure, which depends on the structure of the forest and fire regimes. Hence, an optimal allocation of presuppression expenditure can reduce the risk of the fire on the long-term economics of the forest.

Ecosystem sustainability is important for forest management. Therefore, ecological integrity is of increasing concern with respect to commercially-managed public forests in Canada. Implementation of a harvest policy with strict requirement of old-growth forest area constraint while accounting for the possible impact of fire can have adverse impacts on revenue. The impacts can be reduced by selecting alternative forest management policies. The short-term reduction in revenue from harvests can be compensated for by long-term economic returns provided by age-related value accumulation of the harvest timber using alternative policies.

Finally, based on the results, the vertically integrated harvest planning model coupled with optimal fire management efforts can increase long-term average revenue to wood industry. The model lowers the risk of loss of revenue due to supply disruptions when the impact of fire is accounted for in the planning process. In addition, the solutions prescribed by this model help reduce the harvest rate and increase stock volume which can act as a buffer for the highly variable potential fires in the successive periods over a planning horizon.

To my parents and family

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ABBREVIATIONS AND ACRONYMS

AAC	Annual allowable cut
BCA	Benefit cost analysis
BF	Burn fraction
BFEC	Bureau de forestier en chef
BR	Burn rate
CFS	Canadian Forest Service
DSS	Decision support system
FMU	Forest management unit
ha	Hectare
HFR	Homogeneous fire region
LCL	Least-cost-plus-loss
LP	Linear programming
Mm^3	Million cubic meters
NPV	Net present value
NSERC	Natural Sciences and Engineering Research Council of Canada
QFIC	Québec Forest Industry Council
SOPFEU	Société de pprotection des forêts contre le feu

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PREFACE

I have prepared this thesis in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Sciences forestières from Université Laval, Quebec, Canada. This thesis is presented in research articles insertion mode. Among the five chapters of the thesis, Chapters Two, Three and Four are my original research, and cited references are genuinely attributed. These three chapters have been produced in the form of scientific articles that will be submitted to journals as original research articles. As the first author of these manuscripts I contributed to define problems, design research hypotheses, set objectives, design experiments and methods, compile data, prepare mathematical models, conduct simulation, analyze the simulated model outcomes and finally, write the manuscripts. Other individual co-authors contributed to the manuscripts in several ways as presented below:

1) Rijal, B., Raulier, F., and Martell, D. L. (…). Producing value-added wood products helps reduce the economic impact of fire on timber supply in Canadian boreal forests.

   Plan to submit to the Canadian Journal of Forest Research.

In this paper, my two co-authors contributed to refine the mathematical models, check errors in the results, refine the technical strength of the analyses of data. In addition, the second author contributed to restructuring the phrases of the manuscript, and the third author contributed by reviewing English. Dr. Sylvie Gauthier helped to regionalize the fire events, and provided suggestions over the manuscript as an external reviewer.

2) Rijal, B., Raulier, F., Martell, D. L., and Gauthier, S. (…). The economic impact of fire management on timber production in the boreal forest region of Quebec, Canada

Plan to submit to Forests.

In this paper, the second and third authors contributed to the refinement of the mathematical models, checked errors of the results, and refined the technical strength of the analysis process. In addition, the second author contributed to restructuring the phrases of the manuscript, and the third author contributed by reviewing the English. The fourth author contributed by reviewing the data relevancy, the technical details in the practical aspects relevant to the forest fire management in the province of Quebec.

3) Rijal, B., LeBel, L., Martell, D. L. Gauthier, S., Lussier J.-M., and Raulier, F. (…). An assessment of the potential economic impact of preserving old-growth forest using different strategic forest management policies in the fire-prone boreal forest region of Quebec, Canada.

   Plan to submit to Forest Ecology and Management.

In this paper, the second author contributed to shaping and rephrasing the manuscript, and the third author contributed by reviewing the results, technical strength and English revision. The fourth and fifth authors contributed towards the technical details in the practical aspects relevant to the commercial forest management in the face of increasing management concerns related to the conservation of natural ecosystem of fire-prone commercially-managed forests in the province of Quebec. The sixth -author helped conceptualize the problem and initialize the research procedure.

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CHAPTER 1. GENERAL INTRODUCTION

1.1. BACKGROUND AND KEY DESCRIPTIONS

1.1.1. The Canadian boreal forest

The boreal biome accounts for one third of the total forest area on earth (Schlesinger and Bernhardt, 2013). Forming a northern circumpolar band, it runs through most of Canada, Russia and Scandinavia. In North America, it extends from Alaska to Newfoundland, bordering the tundra to the north and the temperate hardwood forest to the south. The weather in the region is characterized by long and often severe winters, short summers and hence a short annual growing season. The mean annual temperature ranges from -5^{0}C to 5^{0}C and min-max temperature varies from -67^{0}C in the winter to 33^{0}C in the summer with regional variations. Likewise, the mean annual precipitation varies from 20 cm to 200 cm, mostly in the form of snow. The soil is mostly a podzol type because of the acidic soil produced under conifer canopies. The soil is often wet because of reduced evaporation under the canopy and/or a high albedo on a mostly snow-capped landscape. Organic decomposition, mineralization and soil chemistry processes are slow or often limited due to long periods of cold temperatures.

Forest vegetation is a mosaic of various seral, but mostly sub-climax plant communities. There are a few conifer species that are well adapted to the harsh climate and soils. Black- and white-spruces (*Picea* spp.) are characteristic species of this region but mixed with jack pine (*Pinus banksiana*) and balsam fir (*Abies balsamea)* regionally. In Canada 75% of the total, and 67% of the harvestable forest are located in this region (Canadian Wood Fibre Centre, 2010). Boreal species contribute 40% of Canada’s timber supply (Bogdanski, 2008). Approximately 21% of the Canadian boreal forest is in the province of Quebec.

1.1.2. Fire disturbance in boreal forest

Many forest ecosystems including the boreal forest, which represents the world's second largest forest biome, coevolve with natural disturbances (Kolden, 2010). Among several disturbance agents (White and Pickett, 1985), wildfire, which is defined as "an unplanned or unwanted natural or man-caused fire" (Merrill and Alexander, 1987) including uncontrolled prescribed fire, is by far the most ubiquitous agent in the region (Johnson, 1996). There can occasionally be large fires in the region, such as 7.4, 6.4 and 7.3 million ha fires that burned in Canada in 1989, 1994 and 1995, respectively. Canada has an annual average of 2.5 million ha area burned per year over the last 25 years (Natural Resources Canada, 2015a). Regional variations in Canada may be due to continental (east to west), latitudinal (south to north) and altitudinal (valley-ridge) variations (Turner and Romme, 1994).

The natural growth processes of the boreal forests of the province of Quebec are substantially influenced by frequent fires with fire cycles that vary regionally. The fire cycle is defined as the time required to burn a sum of area equal to the area of interest or "universe" (Johnson and van Wagner, 1985). Some regions, particularly towards the north and some southern high altitude areas (e.g., Côté Nord - Gaspé) often experience large fires. Historical mean annual burn rate, defined as the reciprocal of fire cycle or fraction of total area expressed in percentage, in Quebec varies between 0.32 and 0.78% y^{-1} (Bergeron et al., 2006; Gauthier et al., 2015a). It is forecasted to increase up to seven-fold by the end of this century (Gauthier et al., 2015b).

Changes in fire frequency can have important consequences on the resulting forest mosaic, age-class distribution and forest composition. In the boreal region of Quebec, short fire cycles create shade-intolerant short-lived and even-aged stands such as aspen (*Populus sps.*), paper birch (*Betula papyrifera*), or jack pine, whereas long fire cycles enhance shade tolerant slow-growing and uneven-aged mixed species such as balsam fir, black spruce (*Picea mariana*), white cedar (*Thuja occidentalis*), etc. (Bergeron, 2000; Gauthier et al., 2009). With respect to fire frequency, species are fire adapted (e.g., jack pine and black spruce) or fire maladapted (e.g., balsam fir, white spruce (*Picea glauca*)) (Bouchard et al., 2008). Although black spruce dominates the boreal landscape, jack pine is more abundant in the central part where the historical burn rate was the highest (0.65% y^{-1}, Irulappa et al., 2015) and balsam fir abundance increases in the eastern part, where the historical burn rate was the lowest (0.2% y^{-1}, Bouchard et al., 2008). There is a positive impact of fire to the forest ecosystem (Powers et al., 2013). However, increased disturbances (Powers et al., 2013) and climate change (Gauthier et al.,2015b; Wotton et al., 2010) can increase the fires.

1.1.3. Fire management

Fire management is defined as “a process of planning, preventing and fighting fires to protect people, property and forest resources” (Natural Resource Canada, 2016). Acknowledging both positive and negative impacts of fires, managers administer either prescribed burning or suppression activities in attempts to control fires to the level that it does not harm resources and property. The efforts are distributed by zoning the forest into intensive and/or extensive protection zones depending on the possible impacts on land management objectives (e.g., in Ontario - Martell, 1994, in Quebec - SOPFEU, 2014). Forest fire management processes include prevention of fire occurrence, establishment and spread, and suppression to control the fire (Martell, 2001). Most fires are contained by initial attack, which is defined as the first response of fire fighting force at the fire arrival site to stop the (potential) spread of the fire (Merrill and Alexander, 1987). Yet about the fires escape initial attack, defined as a fire that cannot be controlled by the initial attack force including one that burns out of control during prescribed burning (Merrill and Alexander, 1987), cause large fires that contribute about 97% of the annual area burned (Natural Resources Canada 2015a; Stocks et al., 2002).

Fire management requires a large amount of expenditure annually (up to $1 and $2 billion yearly in Canada and the USA, respectively), and a large portion of the amount is invested in suppressing large fires (Sanchez et al., 2013). The mean annual fire management costs between 1970 and 2013 in Canada regionally varied from $0.12 million (Prince Edward Island) to $106 million (Alberta), and $46 million in Quebec (Stocks and Martell, 2016). Fire management expenditures can often be a subject of political debates (Calkin et al., 2005) or become difficult to justify (Amstrong and Cumming, 2003). McCarney et al. (2008) and Martell and Sun (2008) suggest the costs should be justified trading-off co-benefits from multiple ecosystem services. Fire management and timber production have direct economic consequences for forest and wood industry. Therefore, consideration of potential of such value-added returns may help fire management of commercial forests. There are two approaches to measuring the economic efficiency of fire management (George and Storey 1979). One is least-cost-plus-loss, which gives the optimal point of investment, where the sum of fire management cost and revenue loss is the lowest (e.g., Martell and Boychuk, 1997 - Fig. 10). Another is the benefit-to-cost ratio analysis, which gives the efficiency of every unit change in the investment (Cellini and Kee, 2010). Potential increase in area burned shows that fire suppression alone is not enough (Flannigan et al., 2009). Integrated fire management planning requires different types of actions - e.g., precaution (campaign, education, fuel management, etc.) (Finney, 2005; Martell and Boychuk, 1997), prevention (detection and initial attack) and suppression (Martell, 2001), and post-fire management (Lindenmayer et al., 2004).

1.1.4. Forest planning and timber supply

A forest management plan is a set of qualitative and quantitative descriptions of activities that are to be implemented over time to meet the objectives of the landowner (Bettinger et. al, 2009). The planning process consists of three hierarchical steps: strategic, tactical and operational with varying temporal and spatial scales and activities (D'Amours and Rönnqvist, 2008). The planning provides guidelines for: i) optimal use of limited resources, ii) implementing forest management activities, iii) predicting future harvest levels, and iv) maintaining habitat and ecosystem (Bettinger et al., 2009). Current planning processes for public forests for commercial management are bound by government policies to ensure long-term ecological and social values in addition to maximizing commercial product supplies. Strategic planning is the first step of the planning process, which is usually carried out for a time-period of one and a half rotation cycles - up to 200 years (Baskent and Keles, 2005). On the other hand, the temporal scale of wood industry management planning is shorter (e.g., 10-20 years; Gunn, 2009) than that of forest management. Likewise, objectives of wood industry and forest management may be different (D'Amours and Rönnqvist, 2008; Gunn, 2007) with respect to their long-term planning horizon. These can be the sources of conflict between the producers of commodities and ecological services and can threaten the sustainability of both. Such conflicts are not new in public forest management (Mönkkönen et al., 2014; Nalle et al., 2004; Shan et al., 2009).

Timber supply planning is an important element of commercial forest management and wood industry. Timber supply is defined as an amount of timber that is available by period over a planning horizon subject to land management objectives and constraints. Traditional forest management, which is the most common approach to date, is mainly guided by a volume-maximized sustained-yield harvest policy that maintains a constant level of harvest volume for a planning horizon (Davis et al., 2001; Gunn, 2007). This policy from the perspective of this research can therefore be considered a status quo policy because of its wide uses including forest management in Canada. The harvest policy explains the objective of land management subject to specified constraints, while determining annual allowable cut (AAC) (Davis et al., 2001). Harvest policy model presents the policy in mathematical form for its implementation. Faustman's 1849 classical model, which maximizes the stand-level net present value (NPV), is also used for supply planning. Both the volume and the NPV maximized sustained-yield policies account for the growth processes but these policies account for neither the long-term industrial requirement (Gunn and Rai, 1987) nor ecosystem conservation. In Canada, despite a constant AAC over the last few years (e.g., 2001-2011), only a part of the AAC was harvested (Natural Resource Canada, 2013). The focus of the forest management is shifting from commodity to multiple value production (Lefaix-Durand et al., 2009; MacKenzie and George, 2009). It requires reengineering the harvest planning process to yield sustained supply of value-added products and ecosystem services (Didion et al, 2007).

Harvest decisions are taken by forest owners in the status quo harvest policy. On the other hand, integrated management policies account for supply chain values of the participating business units in a single management framework (Ferber and Gutknecht, 1998) and decisions are taken jointly (Gereffi, 1999). Because the forest products supply chain is often hierarchical with the forest as upper level and industry as lower level (Paradis, 2016), the integrated structure between the forest management and wood mills is often described as having a vertically-integrated structure. Although such perspectives are not new in forestry (Barros and Weintraub, 1982; Gunn and Rai, 1987), their application is still rare in strategic forest management planning (BFEC, 2013; Bouchard et. al., 2016).

1.1.5. Risk management

Forest planning calls for dealing with many risks and uncertainties (Kangas and Kangas, 2004). Pukkala and Kangas (1996) defined risk for a situation where the possible outcomes of any event or decision alternative can be expressed in terms of probability. Risk includes three components: a) likelihood (any event that exposes to probability), b) probability, and c) effects (Fairbrother and Turnley, 2005; Kaplan and Garrick, 1981). It is presented either as a sum of the product of value and the respective probability as an expected value or as a probability of receiving a specified value and/or more (Schmoldt, 2001). Fire risk in timber harvest planning is an expected outcome (e.g., harvest volume, revenue) when a harvesting plan is implemented accounting for fire. It is often expressed in terms of the probability of obtaining at least some specified amount of a harvest attribute subject to uncertain fire hazards (Savage et al., 2010).

Risk management consists of four steps, a) risk identification, b) risk impact assessment, c) risk priority analysis, and d) risk mitigation (Garvey, 2009). According to Garvey (2009), the first step - risk identification, is the process of finding and probabilistically characterizing the hazardous events that may be the source of adverse impacts on the management objective. The probability distribution of the occurrence, escape, annual area burned, etc. may be some examples related to fire. The impact assessment consists of qualifying and quantifying the possible losses of objective outputs (e.g., harvest area and volume, revenue). The priority analysis consists of ranking the severity ("most to least critical") so that the limited resources can be managed effectively. The fourth step is risk mitigation, which is a process of selecting an alternative decision tool, event or action that reduces the potential adverse impacts on objective of management. It implies that the alternative system when implemented generates higher expected value than that of original situation exposing with the hazardous event (e.g., fire). Implementation of the alternative mitigation measure can have direct or indirect costs, which may or may not be offset. “No-regret” mitigation is an approach, where there is no extra cost of introducing the mitigation measure or there is no adverse impact when it is implemented even if the hazard event does not occur (UNISDR-UNDP, 2012). The Intergovernmental Panel on Climate Change has categorized any event that has probability of occurrence of 0.90 or more as very likely (least risky), a probability between 0.67 and 0.90 as likely (risky) and 0.33 - 0.66 as unlikely (very risky) (Mastrandrea et al., 2010). Corresponding to the probability of occurrence of any event and risk-receptive capacity of management, there are three types of risk mitigation strategies, namely: to a) accept, b) avoid or transfer, and c) stay neutral (Weber and Milliman, 1997). Pukkala and Kangas (1996) point out that risk management strategies may be different for risk-avoiders, risk-seekers and risk-neutral stakeholders. Usually public property stakeholders (including public forest managers) prefer risk-avoidance strategies (e.g., probability of success ≥0.90). Such risk avoidance approaches in forest management also help protect against supply disruptions to industries that are dependent on the forest for their input.

The integration of fire risk in forest management has been investigated since the 1980s (e.g., Martell, 1980; van Wagner 1979; 1983). Deterministic approaches such as the use of a mean annual burn rate (Martell 1994; Reed and Errico, 1986) were used in management for contingency planning (Twomyanski, 1987 - adapted from Martell, 1994). The use of buffer stocks is another approach to risk management (Boychuk and Martell, 1996). Recourse decision-making (Jensen and Bard, 2003) such as periodic replanning is in practice to update the planning when changes in forest resources or policies are identified. The impacts of fire in preceding periods can be addressed by such replanning processes while updating the resource condition for the following periods. However, such posteriori measures cannot help manage the adverse impact on the objective when fire destroys the resources, except using contingency or available buffer stocks. The stochastic approach with a priori accounting for the possible impact of fire in the long-term planning process in forest fire management has recently gained momentum (e.g., Miller and Ager, 2013; Savage et al., 2010, 2011). This is due to the fact that a deterministic approach, which has been in practice since the 1980s, cannot account for the variability of the random events (Boychuk et al., 2009) and subsequently cannot always deal with the range of possible outcomes.

1.1.6. Decision support system

A decision support system (DSS) is a computer-aided procedure that processes information and provides results that help users select a policy/action plan (Sage, 1991). Using such a system, resource managers make decisions they believe will maximize management objectives by increasing effectiveness and efficiency in terms of time and resources. The development and use of linear programming (LP) (Dantzig, 1949) changed many facets of DSS use. The DSS based on LP models were implemented in forestry to determine timber harvest in the mid-1960s (Garcia, 1990). A number of forest planning models such as Timber RAM (Navon 1971), MAXMILLION (Ware and Clutter, 1971) and FORPLAN (Hoekstra et al., 1987) were developed to support timber harvest planning based on LP models. The LP solutions have been extensively implemented in forest management, usually using harvest planning models characterized as having Models I or II structure as described by Johnson and Scheurman (1977). Model I tracks all the forest management activities by period throughout the planning horizon at the individual stand level for any silviculture treatment (for example, a harvest) that takes place in the course of forest management. Aggregation by period is possible for the same treatments through rotation cycle. Model II collapses the prior information of management into single-cohort stand once harvesting has been completed (details can be found in Davis et al., 2001; Gunn, 2007). The third formulation is a network model named Model III (Garcia, 1984; Gunn and Rai, 1987), which has explicit presentation of the age-classes movement by period through a network structure. Working with Model III, one can easily monitor any activity implemented in each age-class, especially disturbances (e.g., harvesting and fire). In addition, it is relatively easy to truncate later age-classes into an aggregate age class to reduce problem size in Model III formulations. However, because of the large matrix needed to explicitly account for all age-classes for each silvicultural treatment, this may be suitable to the management situation when there are limited activities.

The solution space of an LP model is deterministic with respect to deterministic parameters or fixed number of scenarios. When we consider stochastic parameters, such deterministic solutions cannot represent the entire range of possible outcomes. It may give rise to less precise decision solutions, especially when the hazard event yields skewed distributions of the outcomes. Heuristic simulation, an alternative procedure of finding solution when exact LP solution is either not possible (e.g., does not exist or difficult to find due to nonlinearity or other complexities of objective function and constraints) or not required (Bettinger, 2009), may yield sub-optimal solutions. A possible solution may be to embed an optimization problem in a stochastic simulation framework taking the fire parameters as a random variable and presenting the outcomes in terms of probability distribution and hence risk (e.g., Savage et al., 2010). This helps identify the better policy options that may provide less risky alternative policies, plans and/or events.

1.2. PROBLEM STATEMENT AND RATIONALE

The potential impact of fire on timber supply has been investigated since the 1980s (e.g., Martell, 1980; van Wagner 1979; 1983). Contingency planning, buffer stocking, recourses-based posteriori planning including periodic replanning are some of the deterministic approaches to minimizing losses due to fire that have been explored. Contingency planning is realistic to apply in the situation when the supplies are flexible (Tomlin, 2006). There is often no buffer stock available following large disturbances (Peter and Nelson, 2005). It is now widely accepted that fire regimes are a stochastic and that their impacts should therefore be treated as a random variable (Armstrong, 2004). Because deterministic approaches cannot account for the stochastic variability of random events (Boychuk et al., 2009), risk analysis as a decision support tool in strategic planning has been growing (Gauthier et al., 2014; Miller and Ager 2013; Savage et al., 2010; 2011). Changing from a posteriori mitigation measure, a priori risk mitigation planning is suggested to keep the supply chain protected from potential supply disruptions and losses (BFEC, 2013; Savage et al., 2010). Most of the previous studies focused on risk mitigation measures for harvest volume disruptions (e.g., Gauthier et al., 2014; 2015a; Raulier et al., 2014; Savage et al., 2010; 2011) or adverse impacts on the revenue of harvested timber volume sales (e.g., Boychuk and Martell, 1996; Spring and Kennedy, 2005).

The focus of Canadian forest management has been gradually shifting from managing for commodities to multiple value products (Dhital et al., 2013; Lefaix-Durand et al., 2009). Therefore, research is needed to explore the alternative measures to mitigate the risk or reduce the adverse impact of fire on the product values while designing long-term forest management plan. Reflecting such required policy changes in mitigation measures, this study focuses on exploring alternative mitigation measure for the economic value of timber. I considered forest products as “values” when they can be sold to primary-processing sawmill that help identify the economic impacts of fires on the value-centered production market. Therefore, I focused on reducing the potential adverse impacts or risk of economic damage (Graham et al., 2004) to industrial wood production due to fire-related supply disruptions. This study examines whether an alternative forest management policy, when implemented, can reduce the adverse economic impacts or serve as a risk mitigation measure and increase the ecological and economic values of flammable and commercially-managed public forests.

Ecosystem integrity in commercially-managed public forests is now of increasing concern in forest management in Canada. From an ecosystem point of view, old-growth forest stands have higher structural and functional diversities than younger stands (Chambers and Beckley, 2003). Therefore, the proportion of old-growth forest area is often considered as an indicator of natural forest ecosystem and biodiversity (Seymour and Hunter, 1999). The proportion of the total area of the old-growth stands can be considered as an indicator of the structural diversity at the scale of landscape or forest (Fall et al., 2004; Powelson and Martin, 2001).

Aforementioned contingency planning methods may threaten old-growth forests because it is usually applied beginning with the oldest stands and moves down until the target is fulfilled (Peter and Nelson, 2005; Savage et al., 2010). The classical sustained-yield harvest policy that maximizes either harvest timber volume or its net present value (NPV) does not help retain the old-growth forest area. In such policy harvesting starts when any stand’s biological growth (rate) culminates (volume-maximizing) or stand reaches its financial maturity (NPV-maximizing) depending on the discount rate used (Burton et al., 1999; Clark, 2005; van Wagner, 1983) or initiates harvesting when the stand attains a specified minimum harvest age (Savage et al., 2010). Due to the short rotation, it depreciates age-related wood quality (e.g., lumber recovery) (Aubry et al., 1998). When the impact of fire is accounted for, the volume-maximized rotation age further decreases (Martell, 1980). It again threatens the quality of industrial wood supply along with reducing quantitative harvest flows. The policy model prescribes the harvest of higher values in the earlier periods and lower values in the future despite an even-flow of harvest volume. Strict protection of old-growth forest without considering economic consequences can create industrial wood shortfalls. Therefore, the classical policy cannot take into consideration the long-term value pertinent to the industry. Some studies (e.g., Attiwill, 1994; Didion et al., 2007) reinforce that the commercial forest management practice should be revised in order to maintain the old-growth forest in an integrated framework with economic production.

Understanding the linkages between natural events and their ecological and economic consequences is of fundamental importance in designing risk management strategies. Because complete exclusion of fire is neither possible nor desirable (van Wagner, 1983), a planning process is required to find optimal solutions that account for both the economic potential of harvest and fire role in the ecosystem. However, fire management has not been integrated in forest management planning for most commercial forest management (Palma et al., 2007). Rather than fire prevention, large amounts of financial resources are invested in suppressing large fires, which has the potential to destroy land management objectives. Although approaches of measuring economic efficiency of fire management were developed in the early 20th century (Headley, 1916; Sparhawk, 1925: adapted from Simard 1976), these are still largely limited to theoretical uses. Application of these methods can help allocate fire management resources in commercial forests trading off the benefit of value-added forest management.

1.3. RESEARCH OBJECTIVES AND METHODS

1.3.1. Goal and objectives

This thesis addresses the sustainability of long-term forest values in terms of timber harvest revenue when the harvested timber is transformed into primary-process products at sawmill including the potential impact of fire on the planning process. My research goal was to explore forest and fire management planning processes that would lower the potential adverse impacts on revenue due to potential timber supply disruptions caused by fire and timber quality degradation over a long-term planning horizon. In order to achieve that goal, the following three main objectives were established:

Objective 1: Explore alternative forest management policies to reduce the potential adverse economic impact due to supply disruption when the impact of fire is considered in the long-term strategic harvest planning process.

Objective 2: Evaluate the impact of fire management expenditures on increasing forest values in terms of financial efficiency of the revenues from the potentially increased harvest timber and decreased fire suppression costs.

Objective 3: Examine the impact of implementing different harvest planning policies on preserving old-growth forest area, and the impact of those policies on revenue generated by timber harvest.

1.3.2. An overview of the method used

My research is based on empirical data for three commercially-managed forests located in the fire-prone boreal region of the province of Quebec (Canada). In order to represent regional variations of forest fires and harvest practices, I selected three forest management units. I used provincial forest-inventory data (2002-2004), fire data (1971-2014), various spatial maps and data, and financial data. The study covers an area of about 2.5 million ha total for the three forests and the mean annual burn rates vary between 0.06% and 0.48% per year (1971-2014). The emergence of harvesting in the eastern forest is relatively new compared to the western and central forests. I used the NATURA model (Pothier and Auger, 2011) to construct merchantable volume yield tables. I considered three primary-processed wood products (lumber, chips and sawdust) at a sawmill as the value-added products. The product yield tables were constructed using empirical models developed by Zhang and Tong (2005), Liu and Zhang (2006), and Liu et al. (2009) for black spruce, jack pine and balsam fir, respectively.

I considered four different forest management policies and constructed corresponding harvest policy models in LP framework for simulated implementation. Potential impacts of stochastic fire were evaluated using landscape simulation model. Simulation experiments were performed with periodic replanning over a planning horizon and repeated a number of times to achieve consistent mean and cover a range of variabilities. I used AMPL (Fourer et al., 2003) for programing and simulation, and Gurobi solver (Gurobi Optimization Inc., Houston, TX) linked to AMPL to solve the optimization problems and R (R Core Team, 2014) to analyze the outcomes obtained using the AMPL simulation. Statistical measures such as central tendency (mean and/or median), variability (percentiles, coefficient of variations), empirical probability distributions, and test statistics were used for analyzing and making inferences of the results.

1.4. THESIS STRUCTURE

This thesis consists of five chapters. Chapter One introduces the context of the research, general literature descriptions of the relevant topics, definitions of key terms that are relevant to this document, a brief problem statement, research objectives, an overview of method, and a brief synopsis of the thesis structure. Chapters Two through Four form the main body of my original research. These three chapters are related to the aforementioned three objectives in such a way that each chapter represents one research objective.

Chapter Two examines the potential impacts on revenues and other harvest attributes: volume and area when the random behaviour of forest fire is accounted for in strategic timber harvest planning. The quality and quantity of prescribed harvest volumes vary with varying harvest policies, and the revenue generated by the respective prescriptions. This chapter also explores the possible impacts of fire on forest-based employment, particularly the number of jobs in timber harvest and timber processing in sawmills. It further explores how the change in policy can affect harvest rates, which is an important element of forest disturbance.

Chapter Three describes a sensitivity analysis of fire management expenditures to examine how much such investments can increase value by helping reduce the area burned (burn rate). It examines whether increasing investment in fire management can serve as a risk mitigation measure against the potential impact of fire on revenue.

Preservation of old-growth forest is an indicator of biodiversity conservation and natural ecosystem function. However, consideration of old-growth forest in harvest planning may reduce harvest levels and thereby have an adverse impact on revenue. My fourth chapter examines how the preservation of old-growth forest can contribute to increasing the economic values of the forest harvest over a planning horizon in a fire-prone commercial forest.

The combined results from the three objective chapters explain how the fire and forest management policy can jointly enhance the forest ecosystem and economic values over a planning horizon and help sustain the wood industry. Chapters 2, 3, and 4 have been prepared as three independent manuscripts that are designed to submit to scientific journals. Each chapter is therefore self-contained. However, there are linkages between the chapters since the results from the first chapter feed into the second and third chapters.

A general conclusion is presented in Chapter Five. It summarizes the results pertaining to each of the three objectives and highlights their potential implications. Originality, limitations and suggestions for future research and practices are also presented. Finally, the complete bibliographic list has been presented for all the cited literature in all of my thesis chapters.

CHAPTER 2. PRODUCING VALUE-ADDED WOOD PRODUCTS HELPS REDUCE THE ECONOMIC IMPACT OF FIRE ON TIMBER SUPPLY IN CANADIAN BOREAL FORESTS

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2.0. ABSTRACT

Many forest ecosystems, including boreal forests, have coevolved with natural disturbances such as fire. When fire rates are sufficiently high, fire disturbances can have a significant negative impact on industrial timber supplies and disrupt production. One can mitigate such problems by accounting for potential fire losses in the timber supply planning process by reducing harvest levels to create and maintain a buffer stock of timber. With a forest harvest policy model based on timber volume, reducing the harvest level implies a reduction of the harvested timber volume and therefore, of revenues. A possible solution of such reduction in revenue is to change the policy to increase the value of the wood to be harvested that permits a harvest reduction with less loss of revenue. We have evaluated alternate policies for three commercially-managed forests that have different burn rates in the boreal region of the province of Quebec, Canada. When compared with a volume-maximization strategy, a revenue-maximization strategy that considers the production and selling of sawmilling wood products (lumber, chips and sawdust) substantially decreased the area and volume harvested by 27% (11-38%) and 28% (14 -36%), respectively. Mean revenues were increased with 90% probability by 130% (36 - 770%). By reducing the harvest volume flow, the total number of jobs associated with forest operations decreased by 20% (10 - 27%). The policy also increased the harvest age, and thereby enhanced the retention of greater proportions of old-growth stands.

Keywords: boreal forest, fire, revenue, risk management, strategic planning, value recovery

2.1. INTRODUCTION

Many forest ecosystems, including the boreal forest, which represents the world's second-largest forest biome, coevolve with natural disturbances. Natural disturbance history, together with climate, surficial deposits, drainage and forest successional dynamics, generate a complex mosaic of ecosystems. As a result, the boreal forest is rich in economic (e.g., both timber and non-timber resources), environmental (carbon sequestration, water regulation, wild flora and fauna) and social resources (e.g., employment and recreation) (Brandt et al., 2013). The Canadian boreal forest represents 32 % of forests worldwide and encompasses half of the forests of North America (Schlesinger and Bernhardt, 2013). It also contributes to 40 % of Canada's wood supply. Commercial exploitation of wood in Canada increased by 70% from 1970 to 2004 (Bogdanski, 2008). Though harvest levels began to decrease in 2005 and reached the 1970 level (≈120 $Mm^3\ y^{-1}$) in 2009, they resumed their increase and reached 148 $Mm^3\ y^{-1}$ in 2013 (Natural Resources Canada, 2015c). Consequently, over time harvesting activities have expanded northwards into less productive and fire-susceptible boreal regions (Powers et al., 2013). Harvesting and transportation costs in remote northern forests make the forest products industry less profitable and more vulnerable to timber supply disruptions caused by natural disturbances (Gauthier et al., 2014).

Fire is a stochastic process that can cause highly variable and uncertain losses of timber, and may trigger the need to implement unanticipated responses (such as recourse decision-making). Therefore, fire effects should be included in timber supply planning if the fire rate is high (Savage et al., 2010). Forest planning consists of a three-step hierarchical procedure with an increasing level of detail and a decreasing time horizon at each step (D'Amours et al., 2008).

The first step, strategic planning, is designed to assess the sustainability of harvesting and silviculture policies and practices over periods up to 200 years in time-horizon (Baskent and Keles, 2005) by forecasting wood supply based on data, models, and assumptions concerning forest growth, harvest and regeneration. The objective of such analyses is to devise a forest management strategy that is designed to reduce the likelihood that forest ecological, social and economic resources are not depleted by harvesting activities (Bettinger et al., 2009). Therefore, changes in the assumptions, data and models used for forecasts may increase or decrease the wood supply. Inclusion of fire effects in the planning process results in a reduction of harvest level (Armstrong, 2004; Boychuk and Martell, 1996; Savage et al., 2010).

The integration of fire risk in strategic planning has been investigated since the 1980s (van Wagner, 1983), but its inclusion in strategic planning still remains uncommon (Carlsson et al., 2009). One of the problems is the resulting size and complexity of the planning problems that need to be solved (Bettinger et al., 2009). Another is the reluctance of forest managers to reduce harvest levels to account for the potential impact of natural disturbances (Martell, 1994; Raulier et al., 2013) because such reductions immediately affect potential income and regional economic activity. Nevertheless, for the last 10 years, interest in applying risk analysis as a decision-support tool in forest fire management and strategic planning has been steadily growing (Gauthier et al., 2014; Miller and Ager 2013; Savage et al., 2010; 2011).

The main objective of our study was to explore an alternative means of reducing the impact of fire risk on timber supply though strategic planning. At this step, specific requirements of the forest industry are coarsely and conventionally described by maximizing the harvest of timber volume (Gunn, 2007; Weintraub and Romero, 2006). We hypothesized that one possible solution was to deal with this by focusing on timber that can be used to produce high-value-added products. Increasing the value of the wood that is harvested is not by itself, a mitigation strategy against fire loss, but it may indirectly contribute as product value is positively related to log size and therefore to tree diameter and height (Liu and Zhang, 2005). The harvested tree size depends on rotation age and longer rotation ages will decrease the harvest flow at the forest scale (Cissel et al., 1999). Decreasing the harvest flow will reduce the variability of the amount of timber supply available for harvest caused by fire risk (Leduc et al., 2015). A change of forest policy from maximizing timber volume to maximizing product value during strategic planning should therefore indirectly help mitigate the impact of fire. In order to demonstrate this, we considered four policy models (Davis et al., 2001, pp 577-579) developed in a linear programming simulation framework. Of the four models we considered, the first maximized timber harvest volume - a commonly used planning model (Davis et al., 2001; Gunn, 2007) in many countries including in Canada (BFEC, 2013; Natural Resource Canada 2007). The second model maximized net present values from the harvest timber directly sold to the mills (Boychuk and Martell, 1996) and third and fourth models maximized the net present values of primary-processed wood products - a vertically integrated model (Gunn and Rai, 1987). Models 3 and 4 had a different set of constraints. These four models included periodic replanning and the explicit inclusion of potential burned area in the planning process. We simulated the application of these policy models in three forest management units with different burn rates that are located in the boreal forest of the province of Quebec (Canada).

2.2. METHODS

2.2.1. Study area

In order to examine the effects of different fire regimes on timber supply and forest sustainability, we selected three forest management units (FMU) that are located in the northern part of the commercially-managed forest in the province of Quebec (Canada) (Fig. 2.1). These three management units are within the closed black spruce-moss bioclimatic domain (Robitaille and Saucier, 1998), but each is distinguished by a particular fire regime (Chabot et al., 2009; Mansuy et al., 2014), management history, species composition, and age structure. Even though black spruce dominates the forest landscape, jack pine (*Pinus banksiana* Lamb.) is more abundant in the central part of the study area (FMU 026-65), where the annual burn rate during the 20th century was the highest (0.65 % y^{-1}, Irulappa Pillai Vijayakumar et al., 2015; Le Goff et al., 2008). Balsam fir (*Abies balsamea* [L.] Mill.) abundance increases considerably in the eastern part (FMU 094-52), where the historical burn rate was the lowest (0.2 % y^{-1}, Bouchard et al., 2008). Old-growth forest (> 100-years-old) dominates stand age structure (73 % of forest area) and harvest activities are recent (< 30-years-old, Bouchard and Pothier, 2011). The western management unit (FMU 085-51) is located in the Clay Belt, where forests are often interspersed with forested peatlands because of dominant clay and organic deposits. The historical burn rate is intermediate (0.45% y^{-1}, Bergeron et al., 2006). This management unit has been intensively harvested since the 1970's (Belleau and Légaré, 2009) and is characterized by a dominance of young and immature stands (< 50-years-old, 57%). For all three management units, black spruce, jack pine and balsam fir are used to produce lumber, and pulp and paper (Liu et al. 2007).

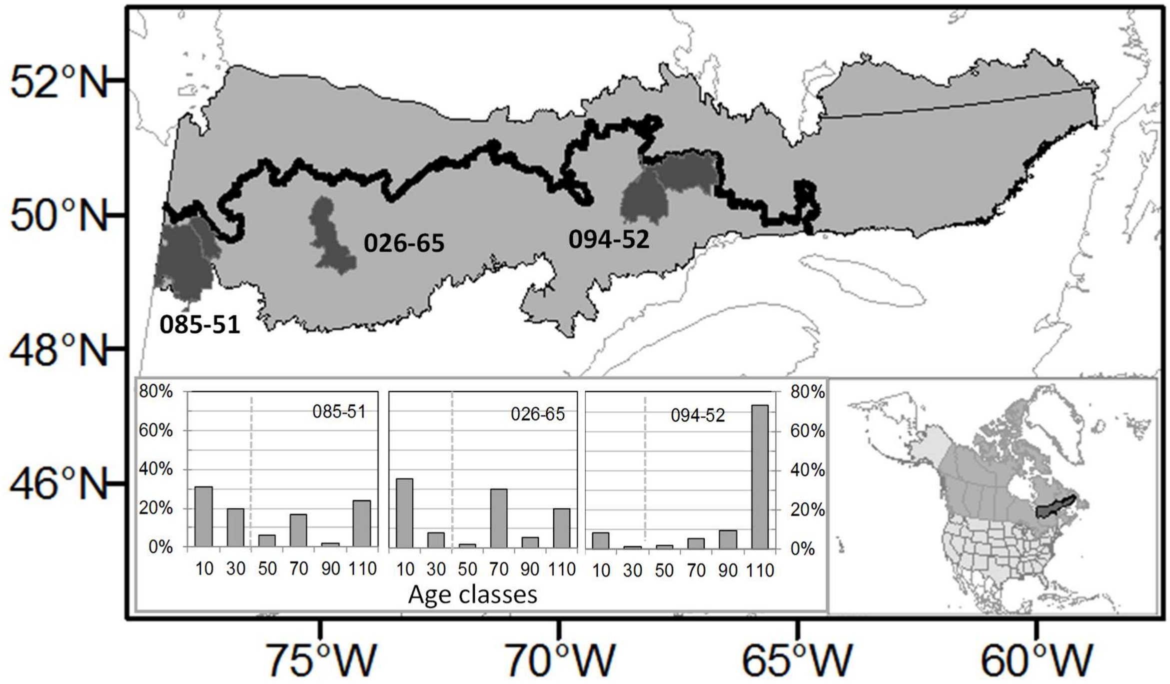

Figure 2.1. Study area, showing the spruce-moss forest (light grey), and three forest management units (FMUs, dark grey). The bold continuous line shows the northern limit of commercially-managed forests in the province of Quebec (MRNFQ, 2000). The bar plots are the distribution of age classes of the initial forest condition in three FMUs (2002 - 2004).

2.2.2. Forest and timber processing data

Four sources of data have been used to characterize forest stands in the timber production area of each forest management unit: landscape units, forest stand maps, temporary sample plots, and a growth and yield model. Landscape units and forest stand maps were used to stratify the forest. Landscape units are spatial units that were used to locate approximately, where harvesting occurs in the forest management units, allowing for the estimation of harvesting costs. A landscape unis (of a mean size of 6,300 km^2 in the black spruce-moss domain; Gauthier et al., 2015a) is defined as "a portion of landscape characterized by a recurrence of environmental attributes (i.e., relief, average altitude, nature and proportion of the main surficial deposits, hydrography) and vegetation factors (nature and distribution of species)" (Robitaille and Saucier, 1998). They are part of the ecological classification system that is used by the Ministère des Forêts, de la Faune et des Parcs, Québec (MFFP). Forest stand maps were prepared by the MFFP from the interpretation of aerial photographs taken at the scale of 1:15,000 between 1991 and 2003 during its third regular forest inventory program. We then regrouped forest stands into aspatial strata as a function of landscape unit and cartographic species composition by considering the two most important softwood species in each stand. In total, there were 39, 52 and 72 strata in FMUs 026-65, 085-51 and 094-52 respectively. Their size varied between 2 and 68 km^2 (interquartile range), with a median size of 12.5 km^2. Hardwood species were not considered, as they represent only a minor fraction of the forest area in any of the three forest management units (Table 2.1).

The stand growth model NATURA-2009 (Pothier and Auger, 2011), which is currently being used by the MFFP, was employed to construct yield curves for each stratum for a 150-year planning horizon in five-year intervals. This model consists of three sets of five equations that predict for a sample plot, the periodic evolution of stem density, basal area and merchantable timber volume per species group (shade-intolerant or tolerant softwoods, balsam fir) as a function of age and other stand variables dynamically. In addition, one more equation to predict the evolution of the dominant height as a function of age. Temporary sample plots that were located within each stratum were used to estimate the individual density, basal area and volume yield per species group curves. The species group wise yields were summed for each stratum and constructed a single yield table for each stratum using non-parametric smoothing (function *lowess* in R; R Development Core Team, 2014).

Table 2.1. Total and productive forest area, mean annual burn rates in three forest management units (FMU), and driving distance between forest stands in each FMU and the sawmills.

FMU	Total Area (km^2)	Productive Area (km^2)[1]	SPF abundance (%)[2]	Mean burn rate (% y^{-1}) (1971-2012)	Mean distance from sawmill (Range, km)
Western (085-51)	9,857	5,734	80	0.137	65 (31 – 120)
Central (026-65)	4,572	3,188	92	0.483	162 (131 – 230)
Eastern (094-52)	9,095	6,954	96	0.062	196 (140 – 255)

[1] Area that is producing at least 50 m^3/ha of merchantable timber (diameter at breast height ≥ 9 cm) over a planning horizon of 150 years, with a mean timber stem volume ≥ 50 dm^3 /tree

[2] SPF denotes spruce, pine and fir cover.

We considered lumber, chips and sawdust as the products that are produced by primary processing sawmills. Product yield curves (tables) were derived from the yield curves that are produced by NATURA with the empirical models developed by Zhang and Tong (2005), Liu and Zhang (2006), and Liu et al. (2009) for black spruce (tolerant softwood), jack pine (intolerant softwood) and balsam fir, respectively.

We used costs data provided by Tembec for FMU 085-51 in 2007 (Pasturel, 2013) to estimate all types of costs: forest management, harvest and transportation from stump to mill gate. First, we assigned the closest sawmill to each forest management unit from a publicly available list of mills that were active in 2009 (MRNFQ, 2009). We then estimated the transportation distance between each landscape unit centroid and the assigned mill with a network analysis conducted in ArcGIS 10.2 (ESRI, Redlands, CA, USA) using forest road network data (Adresses Québec, 2015). Pasturel (2013) has provided these costs at the level of harvest operating areas.

We regrouped these operating areas per landscape unit as a means of obtaining an average cost per landscape unit. The same analysis procedure was used to estimate harvesting and transportation costs for FMUs 026-65 and 094-52 based on distance from the stump to the closest mill. Harvest cost including loading was kept constant by taking the average cost of FMU 085-51 (\$39.7 m^{-3}). Transportation costs were estimated using the linear relationship between cost and distance as provided by Pasturel (2013: Fig. H-1), which varied between \$9 and \$25 m^{-3} assuming same road, speed and maintenance conditions. We have used a mean selling price of softwood logs at the mill gate of \$58.7 m^{-3} (expressed in merchantable volume, including bark) provided by Pasturel (2013), as the sawmill did not buy timber but subcontracted harvest and transportation operations. We assumed that the sawmill transformed the harvested volume into lumber, chips and sawdust and sold each product separately. The processing cost was estimated as \$24 m^{-3} of merchantable volume assuming an average conversion factor of 4.4 from merchantable volume (m^{-3}) to lumber thousand board feet (MBF) (Del Degan Massé, 2010). Ten years (2004-2013) selling price data for primary-processed products were obtained from the Quebec Forest Industry Council for lumber, MFFP for wood chips (Del Degan Massé, 2010) and Tembec (Pasturel, 2013) for sawdust. Lumber, wood chips and sawdust are shipped to different locations. We referenced Montreal as being the closest market to which lumber products can be shipped to national and international destinations. We assumed that wood chips and sawdust are shipped to the closest pulp and paper or panel mill respectively. Transportation mode can vary (truck or rail) depending on mill and market locations and has an impact on the processed-product transportation cost (\$0.02 km^{-1} m^{-3} for truck and \$0.002 km^{-1} m^{-3} for train transportation, CPCS, 2013; Laurent et al., 2013). The 10-year mean delivered product prices for lumber, chips and sawdust were \$155 m^{-3}, \$52 m^{-3} and \$9 m^{-3}, respectively (values standardized to the year 2010). We used a constant discount rate of 4% y^{-1} (BFEC, 2013) to discount for future costs and revenues, and applied it to the middle of each period.

Apart from costs and revenues, we also focused on the number of jobs related to forest management and timber processing activities. The three forest management units considered in this study are located on public land and the design of forest management strategies on public land also aims to maintain the regional employment rate (MRNFQ, 2009). The expected decrease of harvest flow caused by changing the objective to maximizing the net present value of primary-processed wood products may have a negative impact on some forest-dependent communities (Patriquin et al., 2008). For example, forest management, harvest and transportation costs are expressed per unit of harvest volume and are related to the regional employment rate (MRNFQ, 2009). We have therefore used the average number of jobs provided by provincial forest statistics (MFFPQ, 2015) for the year 2010 as: 4.84 (forest harvesting), 4.11 (lumber processing), 2.23 (chip or sawdust processing) jobs per million dollars of gross revenues (sale of timber or of a processed product). The total number of jobs in a single mill was equated to the sum of the numbers of jobs required to process the three products, assuming that a single mill would process all three products in independent processing units.

The fire burn rate was estimated for each forest management unit from past fire events that occurred between 1971 and 2014. The fire data were provided by the Quebec forest fire management agency (SOPFEU). Given that forest management units were too small to characterize a fire burn rate (Boulanger et al., 2012; 2013), we used the fire zones delimited by Chabot et al. (2009), which included the management units in our study area. The area of these fire zones varied between 48,500 and 51,000 km^2.

2.2.3. Simulation framework

We developed and used a simulation framework to compare the efficiency of four policies in reducing the economic impact of considering fire risk in the corresponding strategic planning models. For each policy model, we developed a timber harvest optimization model to design a harvesting plan congruent with the chosen policies, and a landscape simulation model to simulate the implementation of those plans in interaction with fire with a replanning process. Model components and procedures are described below. This simulation framework provided us with planned values and frequency distributions of simulated harvest volumes (m^3 ha^{-1} y^{-1}), numbers of jobs related to forest harvesting and wood processing (number of jobs (100,000 ha^{-1}) y^{-1}), net revenues for timber and for primary-processed wood products (\$ ha^{-1} y^{-1}) and harvest rates (% of terrestrial area y^{-1}) by period. Planned values were produced by solving the optimization models and the simulated realized values were produced by the simulated implementation of the optimal solutions in the landscape simulation model for the first period. Timber supplies, harvest volumes and revenues were expressed per unit of timber productive area and per year to facilitate comparison among the forest management units and harvest scenarios. The harvest area was expressed as a disturbance rate per unit of terrestrial area to allow for burn rate comparisons. Frequency distributions of simulated attributes were used to build risk curves, which correspond to the probability that a realized harvest attribute is greater than or equal to specified values (Savage et al., 2010).

The four policy models were compared with a set of performance metrics based upon the statistics of the possible outcomes from the simulations. We have used six performance metrics, namely, (a) harvest volume, (b) harvest rate, (c) net revenue from the sale of harvest volume (d) net revenue from the sale of processed wood products, (e) number of jobs related to forest operations, and (f) number of jobs related to wood processing. For harvest volume and number of jobs, we compared the different scenarios with the medians of the values over a planning horizon, but with annualized amounts presented in terms of per year basis. We presented interquartile ranges, which provided a measure of the fluctuation of those metrics by period through the planning horizon. For revenues, we have used the discounted sum of periodic net revenues (net present value - NPV) and its interquartile range. We have compared undiscounted periodic net revenues between scenarios as a measure of revenue variability through the planning horizon. In addition to these six performance metrics, we have used other indicators that helped us interpret the simulation results, namely, harvest age, lumber recovery factor, and surplus area available for harvest (Boyland et al., 2006). It provided the area still available for harvest, and it is related to the size of the available buffer stock of timber.

2.2.4. Timber harvest scheduling optimization models

We developed four optimization models based upon different sets of policies. The first model maximized timber harvest volume over a 150-year planning horizon subject to even-flow of the harvest volume. The second model differed from the first by maximizing the net present value (NPV) of timber harvested with the same set of constraints. The third and fourth models maximized the NPV of primary-processed wood products produced and sold, but did so with different sets of constraints. They were constructed using a Model III structure (Garcia, 1984; Gunn and Rai, 1987; Reed and Errico, 1986) because of the ease of including fire disturbances in such models (Savage et al., 2010). We used the AMPL modeling language (Fourer et al., 2003) to model the optimization problems and Gurobi 5.6.0 (Gurobi Optimization Inc., Houston, TX) to solve them.

Model 1: Timber volume maximization

The first model aims to maximize the timber volume harvested over the planning horizon subject to even-flow constraints. Let,

s	stratum (1...S; S = 39, 52 and 72 in FMUs 026-65, 085-51 and 094-52)
a	age class (1...30, five year intervals)
t	period (1...30, each five-year period)

Decision variables:

h_{sat}	area planned to be harvested in age-class *a* of stratum *s* period *t* ∀ *s*, *a and t*
x_{sat}	area of age class *a* of stratum *s* at start of period *t* (ha), ∀ *s*, *a* and *t.* With respect to LP model, this is defined as a decision variable. However, values are generated by age class movements by period from the initial age classes in each stratum ($x_{sa0)}$ using Model III network structure (Eqs. 2.4 - 2.6).

Parameters:

v_{sa}	merchantable volume per hectare of stratum *s* in age class *a* (m^3 ha^{-1}), ∀ *s* and *a*,
$a_{min.s}$	minimum harvest age (periods) ∀ *s*

The objective function of model 1 maximizes the harvest volume over the planning horizon:

$$Z = \max \sum_{s=1}^{S} \sum_{a=a_{min.s}}^{30} \sum_{t=1}^{30} v_{sa}\, h_{sat} \qquad [2.1]$$

Constrained to:

Even-flow of harvest volume:

$$\sum_{s=1}^{S} \sum_{a=a_{min.s}}^{30} v_{sa}\, h_{sa(t-1)} = \sum_{s=1}^{S} \sum_{a=a_{min.s}}^{30} v_{sa}\, h_{sat}\,, \quad \forall\ t \in \{2...30\} \qquad [2.2]$$

The planned harvest area is limited to less than or equal to the area that is available in each stratum, age class and period, after accounting for the effect of fire in a given period:

$$h_{sat} \leq (1 - b_f)x_{sat}, \quad \forall \text{ s, a and t} \qquad [2.3]$$

where b_f is a constant burn rate (fraction of the forest burned during each period) in each forest management unit (FMU). If fire burns age classes indiscriminately, as assumed by Reed and Errico (1986) in the deterministic mean value version of their optimization model, b_f does not vary by age, stratum or period within the FMU.

Area accounting constraints:

in the youngest age class

$$x_{s1t} = \sum_{a=1}^{30} h_{sa(t-1)} + b_f \sum_{a=1}^{30} x_{sa(t-1)}, \quad \forall \text{ s, a and t} \in \{2...30\} \qquad [2.4]$$

in the oldest age class (sink)

$$x_{s30t} = (1 - b_f) \sum_{a=29}^{30} x_{sa(t-1)} - \sum_{a=29}^{30} h_{sa(t-1)}, \quad \forall\, s \text{ and } t \in \{2...30\} \qquad [2.5]$$

in intermediate age classes

$$x_{sat} = (1 - b_f)\, x_{s(a-1)(t-1)} - h_{s(a-1)(t-1)}, \quad \forall\, s, a \in \{2...29\} \text{ and } t \in \{2...30\} \qquad [2.6]$$

Model 2: Timber revenue (net present value) maximization

Model 1 maximizes the timber harvest volume and therefore does not address the real impact of fire risk on economic values explicitly (Gunn, 2007). Model 2 was designed to address this issue by maximizing the expected NPV of forest management activities. To estimate periodic net revenue, different costs need to be subtracted from the selling price to account for typical activities that occur in the forest (e.g., harvest, transportation from the harvest site to the processing mill gate, management costs and indirect costs such as road construction and maintenance). Optimal solutions from model 2 should therefore avoid planning the harvesting of the stands that would generate negative revenue, which should reduce the planned harvest area and indirectly serve as a mitigation strategy against fire risk on supply disruption. Let, parameters:

$r_{timber.m}$	timber selling price at mill (*m*) gate (\$ m^{-3}),
c_f	cost of forest management and harvesting including loading (\$ m^{-3} timber volume; fixed for all forest management units),
$c_{tr.sm}$	Transportation cost between stand (*s*; at the spatial scale of landscape centroid and mill (\$ m^{-3} timber volume),
γ_t	periodic discount factor ($(\frac{1}{1+r/100})^{5t-2.5}$) assumed to be applied in the middle of the 5-year period, *r* being a discount rate (4% y^{-1}, BFEC, 2013).

Maximize:

$$NPV_{timber} = \sum_{t=1}^{30} \left[\gamma_t \sum_{s=1}^{S} \left[\left(r_{timber.m} - c_f - c_{tr.sm} \right) \sum_{\mathrm{a=mi\ \ .s}}^{30} v_{sa}\, h_{sat} \right] \right] \qquad [2.7]$$

Subject to even-flow constraint (Eq. 2.2), availability of harvestable area (Eq. 2.3) and area accounting constraints, as in model 1 (Eqs. 2.4 – 2.6).

Models 3 and 4: Maximization of the total revenue from primary-processed wood products

With model 2, we have assumed that the price paid for timber delivered to the mill gate is constant. It is expressed in terms of \$ m^{-3} and does not vary by log dimensions. Therefore, model 2 is insensitive to the potential of increasing the value derived from harvesting timber by producing a higher proportion of high-value wood products in the primary transformation.

Models 3 and 4 therefore aim to maximize net present value of primary-processed wood products. As a vertically integrated forest management policy (Barros and Weintraub, 1982; Gunn and Rai, 1987), the sawmill is responsible for all types of costs, i.e., forest management, harvesting, transportation, and maximize the revenue (NPV) from the primary-processed products. In the same time, the integrated structure respects sustainable management of forest, which is reflected by an even-flow of harvest timber volume over a planning horizon. We developed two variants of the integrated policies and represented by models 3 and 4.

Model 3 maximizes the net present values constrained by an even-flow of harvest volume over the planning horizon.

Let, additionally

p	product (1...3, for lumber, chips and sawdust)

Parameters:

r_{pm}	product selling price at delivery sites of the products *p* (\$ m^{-3}), ∀ *p,*
v_{psa}	product volume per hectare (m^3 ha^{-1}), ∀ *p*, *s* and *a*,
$c_{pr.m}$	product processing (*pr*) cost at mill m per unit of timber volume (\$ m^{-3} merchantable volume),
$c_{tr.pm}$	product transportation (*tr*) cost from the mill m to the delivery site (\$ m^{-3}),
$d_{s.m}$	distance between the centroid of landscape unit to which stratum *s* belongs and the closest mill (*m*) ∀ *s*

The model 3 formulation to implement the first variant of integrated policy is given as:

$$NPV_{Products} = \sum_{t=1}^{30}\left[\gamma_t \sum_{p=1}^{3}\sum_{s=1}^{S}\left[\left(r_{pm} - c_f - c_{tr.sm} - c_{pr.m} - c_{tr.pm}\right)\sum_{a=a_{min.s}}^{30} v_{psa}\, h_{sat}\right]\right] \quad [2.8]$$

Constrained by even-flow of volume (Eq. 2.2), availability of harvestable area (Eq. 2.3) and area accounting constraints (Eqs. 2.4 - 2.6).

The second variant of the integrated model (model 4) maximizes the objective function (Eq. 2.8) only the first two periods because we want to maximize the short- and medium-term economic values (González-Cabán, 2008; Szaraz, 2014, *unpublished*), but ensure the even-flow of harvest volume over a planning horizon.

Since lumber has the highest value, maximizing the net present value of primary-processed wood products over the entire planning horizon will deplete the timber that can be used to produce lumber in the early periods, preferably from stands located near the processing mill. The fourth model addresses these problems by considering two more constraints of even-flows harvested lumber and distance-weighted harvested lumber in addition to the constraints of model 3. The three forest management units considered in this study are located on public land and in addition to economic benefits to the forest industry, the design of forest management strategies on public land aim at maintaining regional employment (MRNFQ, 2009). An even flow of net revenue for a mill across the planning horizon will not necessarily produce an even flow of timber harvest volume, and fluctuations of volume flow can have a negative impact on forest-dependent communities (Patriquin et al., 2008). For example, forest management, harvest and transportation costs can be expressed per unit of harvest volume and are related to the regional employment rate (MRNFQ, 2009).

Therefore, model 4 has the same objective function (Eq. 2.8) but maximizes only for the first two periods. In addition to the same constraints as in model 3, model 4 has two more constraints to a) ensure even-flow of lumber volume, and b) penalize harvest from the closer stands from the mill with the reciprocal of the distance between the stand and the mill.

Even-flow of lumber volume produced by the mills:

$$\sum_{s=1}^{S} \sum_{a=a_{min.s}}^{30} v_{psa}\, h_{sa(t-1)} = \sum_{s=1}^{S} \sum_{a=a_{min.s}}^{30} v_{psa}\, h_{sat},\ p = \text{lumber}\ \forall\ t \in \{2\ldots30\} \qquad [2.9]$$

Even flow of distance-weighted lumber volume:

$$\sum_{s=1}^{S} \frac{1}{d_{sm}} \sum_{a=a_{min.s}}^{30} v_{psa}\, h_{sa(t-1)} = \sum_{s=1}^{S} \frac{1}{d_{sm}} \sum_{a_{min.s}}^{30} v_{psa}\, h_{sat}\ , p = \text{lumber}\ \forall\ t \in \{2\ldots30\} \qquad [2.10]$$

2.2.5. Landscape simulation model

The landscape simulation model projects the dynamics of forest age structure over time by accounting for fire and harvesting. It uses the same equations as those of the area accounting constraints incorporating the effects of fire (Eq. 2.4-2.6), with some differences. First, the periodic burn rate, b_t, varies from period to period and is generated from random draws ($\boldsymbol{b_i}$) of annual burn rates that were observed between 1971 and 2014 in the fire zone corresponding to the forest management units under study.

Assuming that annual burn rates are independently distributed through time and that annual burn rates are equivalent to annual fire probabilities (van Wagner, 1978), the burn rate that is observed over a given period of time (e.g., 5 years) is equal to the complementary value of the probability of observing no fire during that period. Under these assumptions, this probability is equal to the product of annual probabilities that are associated with observing no fire. Therefore, the burn rate over a period of five years is equal to:

$$b_t = 1 - \prod_{i=1}^{5} (1 - \beta_i) \qquad [2.11]$$

The second difference relates to realized harvest, $\tilde{h}_{sat}$, which corresponds to the minimum of the planned harvest h_{sat} and area that is available in the same age class (a) in the same stratum (s) during period (t) $(\tilde{x}_{sat})$:

$$\tilde{h}_{sat} = \min(\tilde{x}_{sat}, h_{sat}) \qquad [2.12]$$

Harvesting occurs after the fire. These changes lead to the following simulation model:

$$\tilde{x}_{sa} \ = (1 - b_t)x_{sa1}, \ \forall \text{ s and a} \qquad [2.13]$$

$$\tilde{x}_{s1t} = \sum_{a=1}^{30} \tilde{h}_{sa(t-1)} + b_{(t-1)} \sum_{a=1}^{30} \ \tilde{x}_{sa(t-1)}, \ \forall \ s, a \text{ and } t \in \{2..30\} \qquad [2.14]$$

$$\tilde{x}_{s30t} = (1 - b_t) \sum_{a=29}^{30} \tilde{x}_{\mathrm{sa}(t-1)} - \sum_{a=29}^{30} \tilde{h}_{\mathrm{sa}(t-1)}, \ \forall \ s \text{ and } t \in \{2..30\} \qquad [2.15]$$

$$\tilde{x}_{sat} = (1 - b_t) \ \tilde{x}_{s(a-1)(t-1)} - \tilde{h}_{s(a-1)(t-1)}, \ \forall \ s, a \in \{2...29\} \text{ and } t \in \{2..30\} \qquad [2.16]$$

We used AMPL for landscape simulation modeling (Eqs. 2.12 - 2.16), and R (R Development Core Team, 2014) for further analyses of the simulated outputs using AMPL. AMPL was used for both timber supply optimization and landscape simulation, for the ease of data exchange between both models through iterative loops.

2.2.6. Replanning process

Periodic replanning requires a process of data exchange between a timber harvest optimization model and the landscape simulation model. With replanning, the optimized solution (i.e., harvest plan) of a timber supply model is provided at the start of each period to the landscape simulation model. Only one period is simulated and two outputs are provided, viz., the starting forest age structure of the next period, which is used as the initial state for a new replanning, and the realized harvest simulated with the landscape simulation model for that period.

This process was repeated 50 times to build empirical probability distributions of realized attributes (area, timber and forest product volumes and revenues, number of jobs). To decide upon the number of simulations required for a reliable distribution, we first generated 1,500 simulations of model 1 for the most flammable forest. We then performed random draws with replacement from an array of 1,500 simulated revenues, with a number of draws corresponding to a chosen number of simulation (25, 50, 100, ..., 1500). This process was repeated 1,000 times to have 1,000 estimations of empirical probability distributions. These 1,000 estimates then served to estimate coefficients of variation of the 5th, 50th and 95th percentiles of the distributions of revenues as a function of the number of simulations. We found for this forest that 50 repetitions were sufficient to obtain coefficients of variation of the 5th, 50th and 95th percentiles of the probability distributions of harvest revenues below ± 5% of their median values (Supplementary Fig. 2.1). The distributions of the possible outcomes were then used to generate risk curves, which correspond to the frequency distribution for which a realized harvest attribute is greater than or equal to a specified value (Savage et al., 2010). These risk curves served to define a risk zone, where specified values of a realized attribute have a probability of occurrence greater than zero and less than one.

2.3. RESULTS

2.3.1. Basis for comparison: harvest volume maximization

The simulated implementation of the optimized harvest plans generated by all four optimizations models was successful (median rate of success of 100%), despite the simulated random fire events. This success was evaluated as the differences between the planned and the realized harvest attributes. The success rate decreased at most to 83% (minimum periodic median value) for model 1 in the forest management unit with the highest burn rate (FMU 026-65).

When the optimal harvest plans produced by model 1 were implemented in the landscape simulation model in interaction with fire, the median realized harvest volumes over the planning horizon varied between 0.80 and 1.02 $m^3 ha^{-1} y^{-1}$, the median numbers of jobs, between 54 and 64 jobs $(100,000 ha)^{-1} y^{-1}$, and the NPV between 533 and 624 \$ ha^{-1}. The number of jobs remained fairly uniformly distributed between forest operations (42 to 45%) and wood processing (55 and 58%) (Table 2.2). Eighty-seven percent of the jobs dedicated to wood processing was related to lumber processing. The median NPV from forest operations (13.6 - 125.4 \$ ha^{-1}) represented between 3 and 20% of the total NPV. The highest NPV for forest operations (125.4 \$$ha^{-1}$ for FMU 085-51) was associated with the shortest average distance between harvesting sites and sawmill (65 km; 31 - 105 km). The lowest NPV for forest operations (13.6 \$$ha^{-1}$) was associated with the longest distance (196 km; 140 - 225 km).

As a measure of the variability of the performance metrics over the planning horizon, the interquartile range of the harvest volume (0.006 to 0.034 $m^3 ha^{-1} y^{-1}$) remained low relative to its associated median harvest volume (0.8 to 3.3%), contrary to the total number of jobs (5 and 10 jobs $(100,000 ha)^{-1} y^{-1}$, 9 to 18% of the median values) and to the undiscounted periodic net revenues (8.2 and 14.5 $\$\ \text{ha}^{-1}\text{y}^{-1}$, 49 to 236% - Table 2.3). The variability of the performance metrics was the lowest for the FMU 085-51, which showed the lowest proportion of premature, mature and old stands (ages greater than 40 years, 49%, vs 57% for 026-65 and 90% for 094-52) (Fig. 2.1). Revenues and number of jobs from wood processing are associated with lumber recovery and lumber recovery proportions are declining through time in FMUs 026-65 and 094-52 (Fig. 2.2), which indicates to a shift in the proportions of wood products processed through time with model 1. This shift in wood product proportions with model 1 is related to the occurrence of negative revenues from period 15 (75 years from now) for forest management unit 026-65 (Fig. 2.3). The initial lumber recovery proportion was also the lowest for forest management unit 085-51 (Fig. 2.2). The interquartile ranges for the number of jobs for forest operations were very small (0.2 - 1.0 jobs (100,000 ha)$^{-1}$ y^{-1} - Table 2.2), in correlation with the low interquartile ranges of harvest volume.

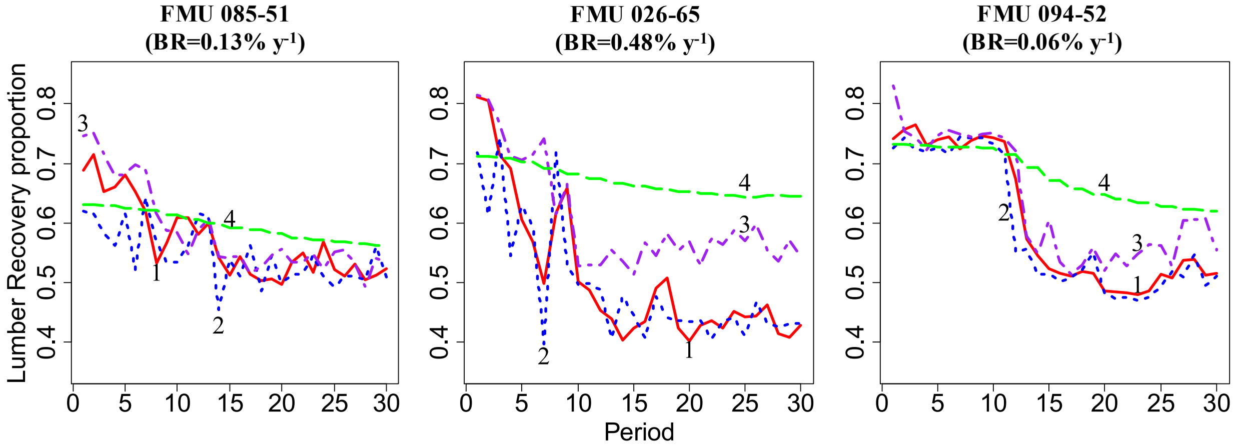

Figure 2.2. Lumber recovery proportion from harvested flows by period (5-year) in three forest management units (FMUs). The numbers refer to timber harvest optimization models 1- 4.

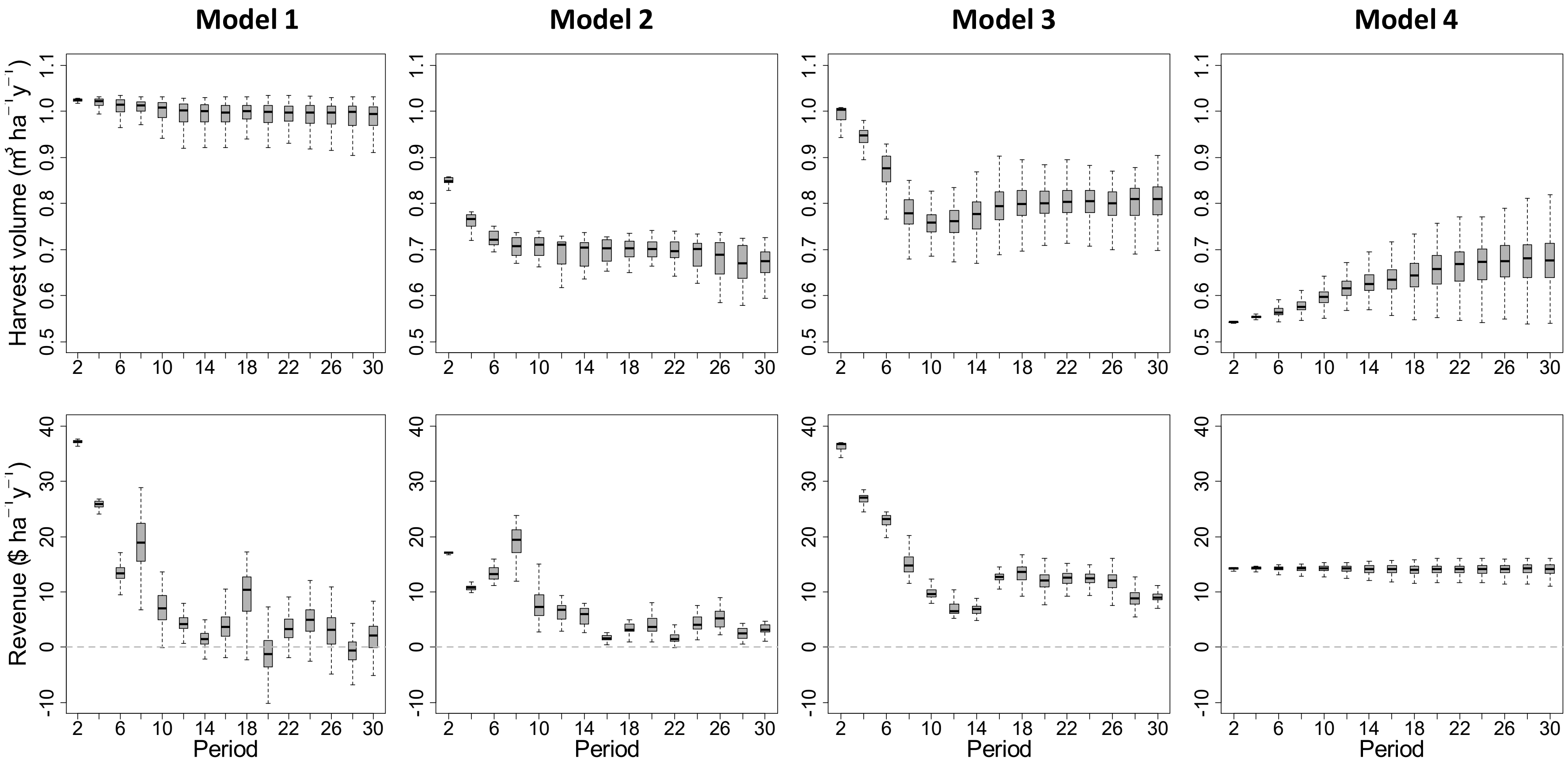

Figure 2.3. Boxplot showing the distribution of timber harvest volume and net revenue (undiscounted) by period using four harvest planning models for most flammable forest management unit 026-65 (burn rate 0.48% y^{-1}) using 50 times repeated simulations.

Some performance metrics therefore varied through the planning horizon and the implementation of optimized solutions with the landscape simulation model was not always successful in terms of reducing the differences between planned and realized solutions because of fire occurrence. As a consequence, we were able to define a risk zone corresponding to the range of outputs with a probability of occurrence greater than zero but less than one (Fig. 2.4). This risk zone was estimated with the complementary cumulative distribution functions (1-CDF) of the realized performance metrics. Risk zones for the harvest volume were narrow with model 1 for all three forest management units (Fig 2.4). Risk zones were wider for undiscounted revenues, especially in the forest management unit with the highest burn rate (FMU 026-65) (Fig. 2.4). Globally, these risk zones provide information similar to interquartile ranges, but they can also be used to estimate the value (harvest volume, revenue or number of jobs) that can be sustained at a chosen risk level. For instance, the maximum realized harvest volume very likely to occur (with probability = 90%) with model 1 was on average of 0.89 m^3 $ha^{-1}y^{-1}$ and varied among the management units between 0.79 and 0.96 m^3 ha^{-1} y^{-1} (Fig. 2.4). The maximum undiscounted revenue very likely to occur with model 1 was $ 6.1 $ha^{-1}y^{-1}$ ($-0.7 - 13.5 $ha^{-1}y^{-1}$) (Fig. 2.4). The negative value of $-0.7 $ha^{-1}y^{-1}$ was observed for the forest management unit with the highest burn rate (026-65, Fig. 2.4).

2.3.2. Long-term stabilization of net revenues

When we maximized timber sale revenues (model 2), the NPV from forest operations was increased between 8 to 73%, the planned harvest volume was reduced on average by 15% (1 - 30%) and median NPV from wood processing was substantially lower than those of model 1 (-26% on average - Table 2.2). Conversely, when we maximized the revenues from processed wood products (model 3), NPV from wood processing was increased by 4 to 11%, the total NPV was increased by 4 to 9%, and harvest volume was reduced by 3 to 21%. Again, the lowest increase in NPV and the lowest decrease in harvest volume was observed for the forest management unit with the lowest amounts of premature and mature forest (085-51). When in addition to maximizing the revenue of processed wood products, we considered even-flows of lumber volumes and of distance-weighted lumber volumes (model 4), realized median NPV values from both forest operation and wood processing were lower than those of the first three models (Table 2.2). The lumber recovery proportion remained however more stable through time for model 4 (Fig. 2.2), and consequently, average undiscounted revenues were substantially higher for this model (between 7 and 184%, when compared with model 1 - Table 2.3). Planned undiscounted revenues using models 1 and 2 were not stable through the planning horizon. Rather, they were very high during the earlier periods, decreased, and then reached low or negative values as early as the 10th 5-year period. These low or negative values are explained by a progressive decrease in the lumber yield (Fig. 2.3), which is related to a decrease in harvesting ages from 125-150 years to 50-60 years for all three forest management units. In addition, model 4 provided the smallest interquartile ranges for undiscounted revenues ($0.86 ha^{-1} y^{-1} compared to $11.53 ha^{-1} y^{-1} (8.24 - 14.55 ha^{-1} y^{-1}) for model 1 and $8.66 ha^{-1} y^{-1} ($5.04 - 13.52 ha^{-1} y^{-1}) for model 2). Model 4 further scheduled smaller harvest volume (Fig. 2.3), especially in the earlier periods, which resulted in lower total NPV. As a consequence, and contrary to undiscounted net revenues, the volume harvested decreased when changing the objective to maximizing the net present value of wood products (models 3 and 4), at most between 13 and 39 % (models 1 vs 4, Table 2.2).

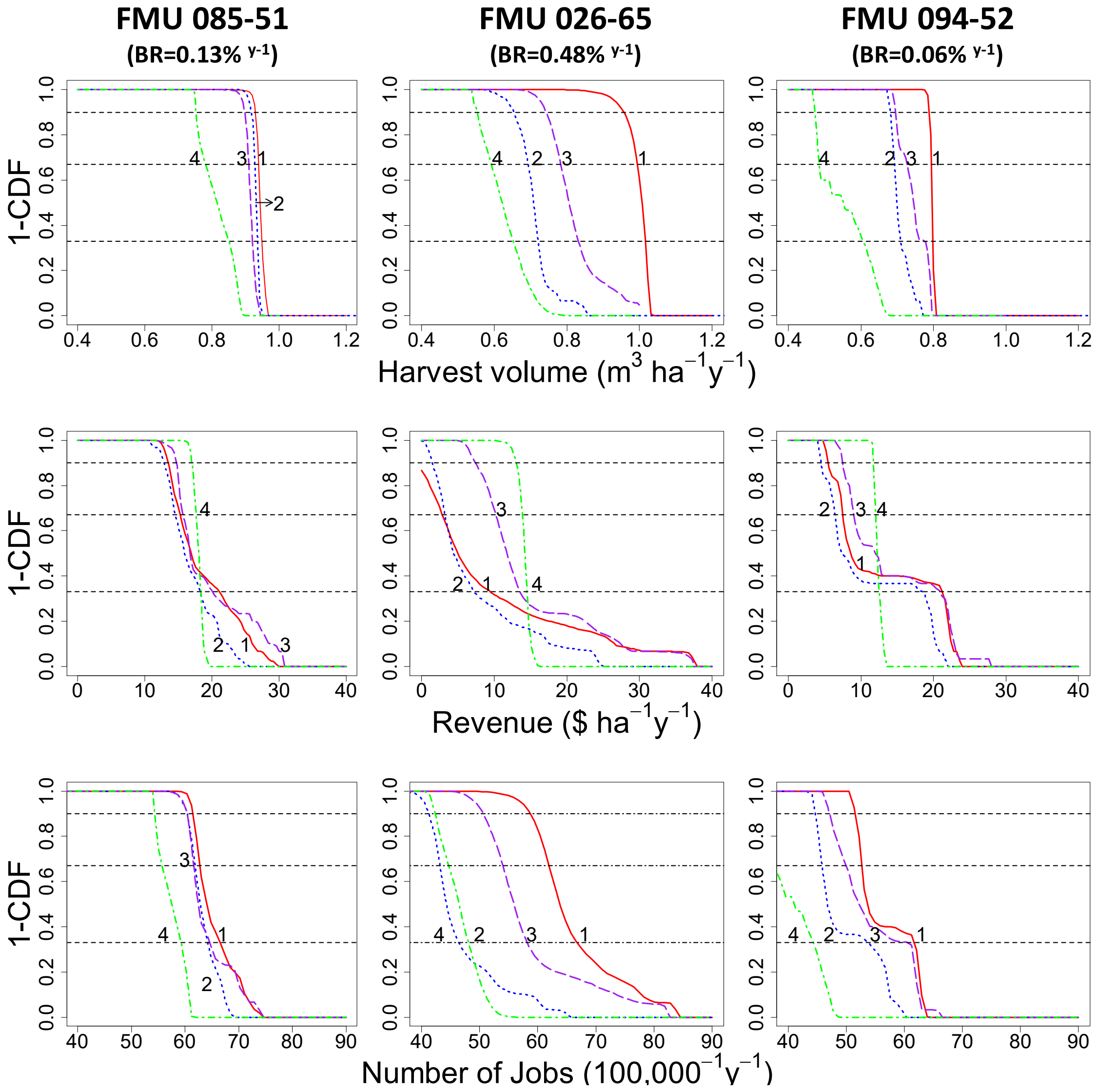

Figure 2.4. Risk analysis. Complementary cumulative density function (1-CDF) for the realized harvest volume (top), revenue (middle) and number of jobs (bottom) using four timber harvest optimization models in three forest management units (FMUs) of varying burn rates (BR). Numbers 1 to 4 correspond to timber harvest optimization models. The dotted horizontal lines represent the probability values 0.33, 0.67, and 0.90 associated to not likely, likely and very likely events, respectively (Mastrandrea et al., 2010). The distributions are produced using the output data from 30 periods and 50 repeated simulations.

Table 2.2. Performance metrics of median of the outcomes obtained using four harvest policy models in three forest management units (FMUs). The numbers in the parentheses are inter-quartile ranges. The Forest and Mill in the table are the respective attributes that occurred in forest harvesting and wood mill processing, respectively.

FMU	**Attributes**		**Model 1**	**Model 2**	**Model 3**	**Model 4**
Western (085-51)	Harvest volume (m^{3}ha^{-1}y^{-1})		0.94 (0.015)	0.93 (0.01)	0.91 (0.018)	0.82 (0.098)
	Harvest rate (%y^{-1})		0.82 (0.175)	0.84 (0.146)	0.79 (0.177)	0.76 (0.132)
	NPV ($\$$ ha^{-1})	Forest	125.4 (0.3)	135.4 (0. 9)	119.6 (0.1)	104.3 (0.4)
		Mill	498.9 (5.4)	384.8 (1.0)	552.2 (4.8)	369. 9 (3.6)
		Total	624.3 (5.4)	520.16 (1.5)	671.8 (3.2)	474.2 (3.1)
	Job (# y^{-1}/ 100,000 ha)	Forest	26.8 (0.4)	26.5 (0.3)	26.0 (0.5)	23.2 (2.8)
		Mill	37.2 (5.2)	36.4 (3.3)	36.35 (4.4)	34.3 (2.1)
		Total	64.0 (5.6)	62.9 (3.9)	62.31(4.9)	57.5 (5.0)
Central (026-65)	Harvest volume (m^{3}ha^{-1}y^{-1})		1.01 (0.034)	0.71 (0.042)	0.80(0.076)	0.62 (0.092)
	Harvest rate (%y^{-1})		1.03 (0.178)	0.74 (0.079)	0.73 (0.135)	0.59 (0.094)
	NPV ($\$$ ha^{-1})	Forest	25.8 (2.4)	44.7 (1.1)	23.4 (0.8)	1.4 (0.8)
		Mill	571.9 (29.5)	343.2 (6.9)	627.5 (26.0)	361.0 (10.8)
		Total	597.8 (32.0)	387.7 (8.0)	651.1 (26.5)	362.4 (9.9)
	Job (# y^{-1}/ 100,000 ha)	Forest	28.6 (1.0)	20.1 (1.2)	22.9 (2.2)	17.7 (2.6)
		Mill	35.2 (7.8)	24.4 (5.3)	32.89 (5.2)	28.8 (2.6)
		Total	63.8 (8.4)	44.4 (5.9)	55.9 (7.1)	46.4 (5.3)
Eastern (094-52)	Harvest volume (m^{3}ha^{-1}y^{-1})		0.8 (0.006)	0.7 (0.035)	0.75 (0.081)	0.55 (0.144)
	Harvest rate (%y^{-1})		1.27 (0.254)	1.17 (0.31)	1.13 (0.31)	0. 94 (0.162)
	NPV ($\$$ ha^{-1})	Forest	13.6 (0.4)	22.4 (0.1)	17.5 (0.1)	12.8 (0.1)
		Mill	519. 6 (2.3)	455.3 (1.7)	540.7 (0.6)	315.3 (0.6)
		Total	533.2 (2.1)	477.7 (1.8)	558.3 (1.7)	328.2 (0.6)
	Job (# y^{-1}/ 100,000 ha)	Forest	22.6 (0.2)	19.8 (1.0)	21.16 (2.6)	15.7 (4.1)
		Mill	31.0 (9.9)	26.9 (9.8)	31.00 (10.8)	25.4 (4.2)
		Total	53.6 (9.9)	46.7 (10.9)	52.24 (12.6)	41.1 (8.3)

2.3.3. Decrease in the total number of jobs but increase in the number of jobs per unit of volume harvested

The number of jobs for forest harvest remains constant when expressed in terms of units of harvest volume (28.4 jobs (100,000 m^3)$^{-1}$ y^{-1}) and was therefore related to the volume harvested. As the harvest volume decreased on average for models 2 to 4 by 15 to 28%, so did the number of jobs for forest operations (Table 2.2, Fig. 2.5). The numbers of jobs also decreased for wood processing for models 2 to 4 in all three forest management units, but less (on average between 3 and 15%, Fig. 2.5, Table 2.2). Because the number of jobs is higher for lumber than for chips or sawdust, the higher lumber recovery factor maintained with models 3 and 4 was associated with more jobs per unit of harvested volume (40 to 47 jobs (100,000 m^3)$^{-1}$ for models 3 and 4 *vs* 35 to 40 jobs (100,000 m^3)$^{-1}$ for model 1).

Table 2.3. Median annual revenue ($ $ha^{-1}y^{-1}$) obtained by forest harvesting and wood processing (sawmill) through a 150-year planning horizon using four timber harvest policy models in three forest management units (FMUs). The numbers in the parentheses are interquartile ranges of an array of 1,500 outcomes (30 periods and 50 repeated simulations).

FMU		Model 1	Model 2	Model 3	Model 4
Western (085-51)	Forest harvesting	5.0 (0.5)	5.1 (0.6)	4.9 (0.5)	4.4 (0.5)
	Wood processing	11.7 (7.9)	11.1 (5.0)	11.8 (7.0)	13.6 (1.5)
	Total	16.9 (8.2)	16.0 (5.0)	16.7 (8.2)	18.2 (1.0)
Central (026-65)	Forest harvesting	0.5 (2.2)	1.6 (0.1)	0.6 (2.4)	0.1 (0.1)
	Wood processing	4.9 (11.9)	2.8 (7.3)	11.2 (7.8)	14.2 (1.0)
	Total	5.0 (11.8)	4.4 (7.4)	11.8 (6.5)	14.2 (0.9)
Eastern (094-52)	Forest harvesting	0.6 (0.3)	0.7 (0.2)	0.6 (0.3)	0.5 (0.1)
	Wood processing	8.3 (14.7)	6.7 (13.6)	11.3 (13.3)	11. 8 (0.8)
	Total	8.6 (14.6)	7.4 (13.5)	11.9 (13.3)	12.2 (0.7)

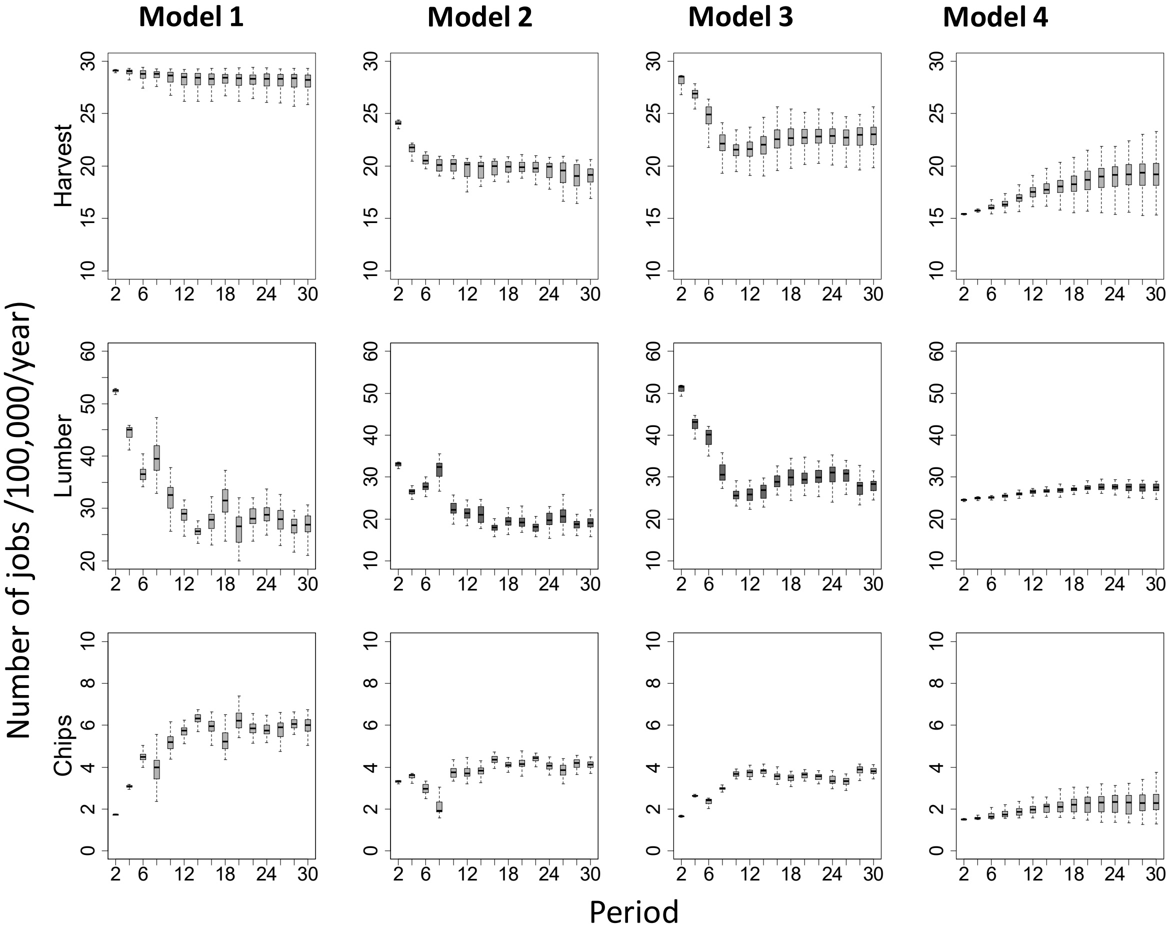

Figure 2.5. Boxplots showing the distribution of number of jobs- lumber and chips flows by period **w**hen four harvest planning models are implemented in the most flammable forest (forest management unit 026-65, annual burn rate 0.48% y^{-1}).

2.3.4. Decrease in the harvest rate and increase in buffer stock size

The median harvest rates varied between 0.82 and 1.27 % y^{-1} with model 1. Harvest rates decreased with models 2 and 3 on average by 11 to 15% (up to 29 %), when compared with model 1. The greatest decreases in the harvest rate were however, observed with model 4 (on average 26%, between 10 and 43%). In the case of model 4, harvest rates were reduced to values between 0.59 and 0.94 % y^{-1} (Fig. 2.6) A reduction of periodically harvested area implies an increased surplus area available for harvest in successive periods. There were substantial differences in surplus areas among the models (Fig. 2.7). Proportion of terrestrial area available as a buffer stock was substantially higher using model 4 (4.8%; 1.3 - 14.4%) compared with models 1 (2.3%; 1.0 - 14.4%), 2 (1.7%; 0.1 - 14.4%), or 3 (3.21%; 0.1 - 14.4%).

As a consequence of its higher harvest rate, model 1 scheduled clearcut harvest mostly in young stands (< 75-years-old) from the 7th-10th 5-year period, whereas harvest with model 4 included more mature stands (75- to 100-years-old) and old stands (≥ 100-years-old) throughout the planning horizon (Figs. 2.2, 2.7). Age at harvest is related to the proportion of lumber recovery, because the mean lumber recovery increases from 0.47-0.50 for young stands to 0.71-0.76 for old forests in the three FMUs (Fig. 2.3).

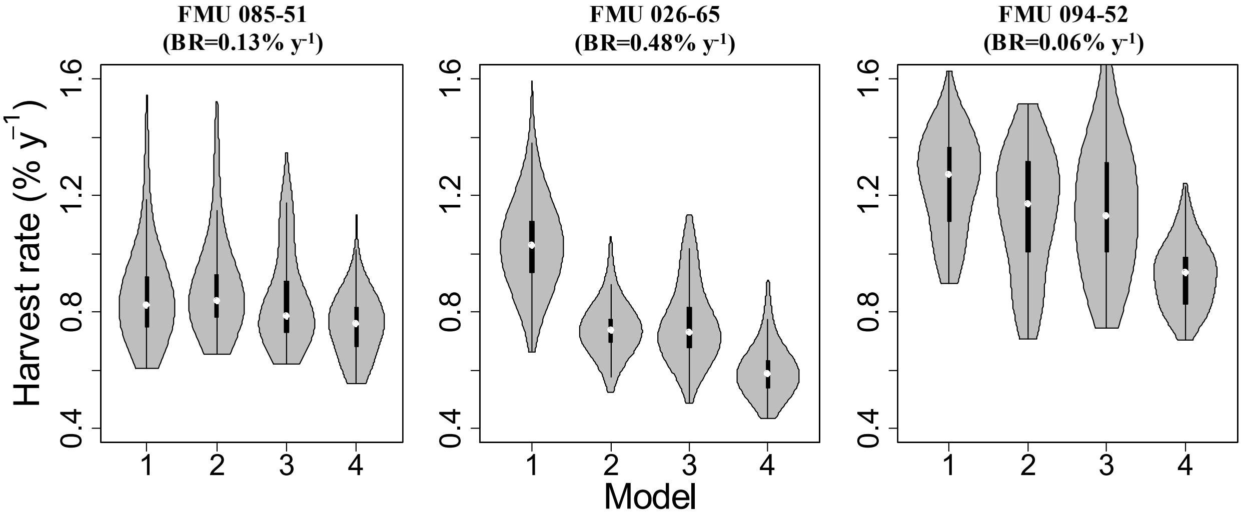

Figure 2.6. Violin plot showing the harvest rate (% of terrestrial area) when models 1 to 4 are applied in three forest management units (FMUs) of varying burn rates (BR). The plots are produced with the output data of 30 periods and 50 repeated simulations.

2.3.5. Higher net revenues at a chosen risk level

The width of the risk zone for realized harvest volumes was most often larger for models 2 to 4 when compared to model 1 (Fig. 2.4). The widest risk zone for harvest volume was observed with model 4 in the forest management unit 026-65 (0.52 - 0.82 m^{-3} ha^{-1} y^{-1}). As a consequence, harvest volumes implemented with model 4 with a high probability (p=0.90) were substantially lower than those of model 1 (0.55 - 0.75 *vs* 0.79 - 0.96 m^{-3} ha^{-1} y^{-1}). The width of the risk zone for undiscounted revenues was narrower with model 2, helping avoid negative revenues observed during the planning horizon with model 1 (-\$0.1 - 25.1 ha^{-1} y^{-1} for model 2 vs -\$10.2 to 37.9 ha^{-1} y^{-1} for model 1; Fig. 2.4). Similar patterns were observed with models 3 and 4 for all three FMUs, which had differing fire regimes. The narrowest risk zone and the highest revenues likely or very likely to occur were provided with model 4, independently of the BR.

2.4. DISCUSSION

Savage et al. (2010) have shown that incorporation of fire in the timber harvest model, in addition to periodic replanning, alleviates the variability and reductions in harvest volume caused by fire over the planning horizon. This is what we have observed with model 1 for harvest volume (Figs. 2.3 and 2.4). Conversely, a revenue maximization strategy (models 2 to 4) increased revenue and reduced its variability, but slightly increased variation in harvested timber volume (compared to model 1; Figs. 2.3 and 2.4), as already noted by Boychuk and Martell (1996). Some variability in realized harvest volumes, revenues or number of jobs occurred across the planning horizon for all four timber supply models (Figs. 2.3 and 2.4). It occurred despite the incorporation of fire and even-flow constraints in all four optimization models with replanning. These systematic differences observed between the levels of periodic planned and realized attributes among multiple iterations through the planning horizon are due to planning within a rolling planning horizon framework. In this instance, the planning horizon is extended by one period at each periodic iteration. Different reasons can explain these drifts despite the requirement of sustainability that is explicitly formulated in timber supply models (Armstrong, 2004; McQuillan, 1986; Paradis et al., 2013).

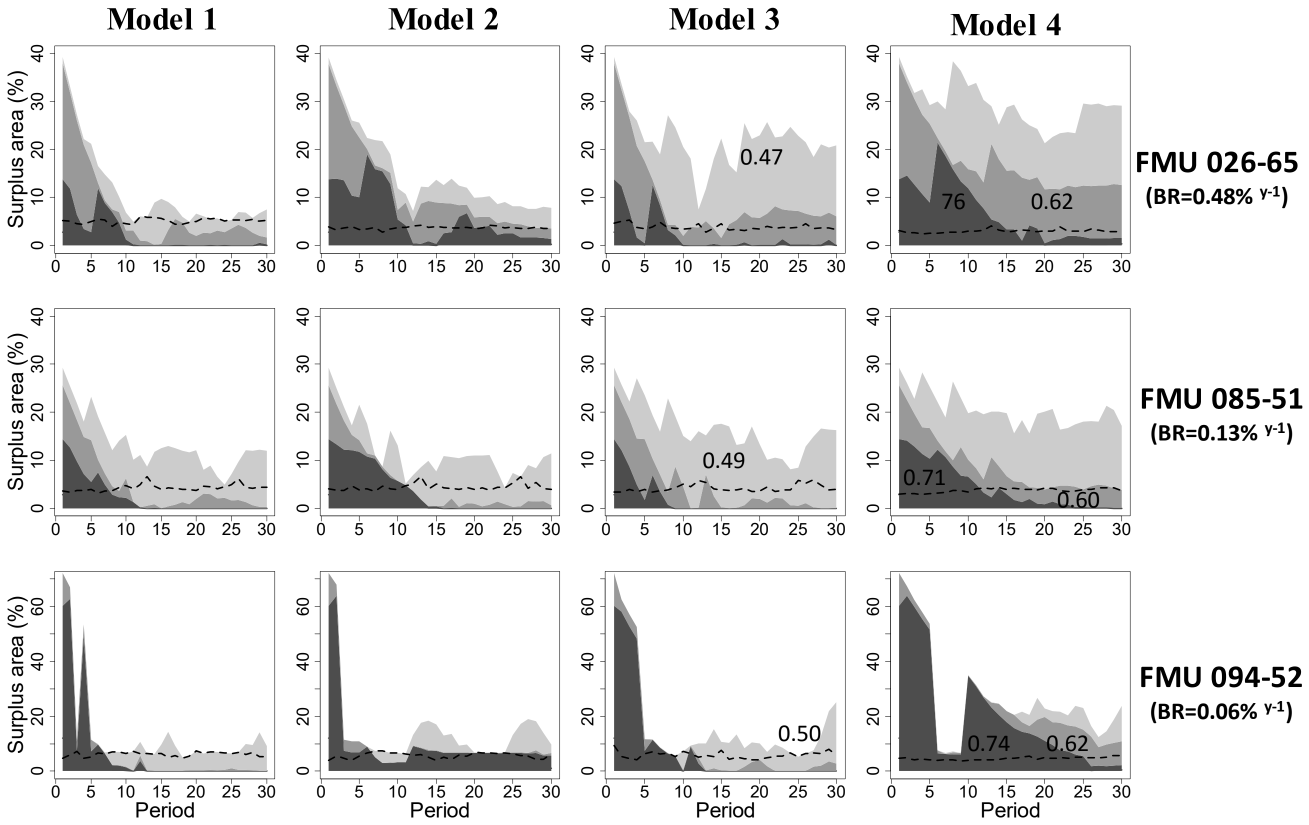

Figure 2.7. The median surplus area (% per period) and realized harvest rate (% per period) in three FMUs with varying burn rates (BR) using four models. Light, medium and dark grey shades show the median values of the available area for three age classes (50 to 74 years old; 75 to 99 years old; ≥ 100 years old). Numbers in the shaded areas are the median lumber recovery proportions for a corresponding age class. Dotted lines are the median of realized periodic harvest rates of 50-time repeated simulations.

In the present case, we saw at least two sources of drift occurring: one was due to the lack of complete effectiveness of the mitigation measures that were taken to protect the harvest volume against fire risk (e.g., Savage et al., 2010: their Fig. 5), while the second resulted from progressive conversion of the actual forest age structure of the forest management units to an age structure that was in balance with the cumulated natural and anthropogenic disturbances (model 2) (Armstrong, 2004). Drift size varied from one forest management unit to the next, depending upon the initial age structure and speed of depletion of standing stock (Fig. 2.7), but we noticed that in any case the drift importance was more related to the initial forest structure. Even flow constraints of lumber volume and distance weighted lumber volumes used in model 4 helped reduce this drift (Figs. 2.2 and 2.3). We explain this drift reduction by a lower harvest rate and the consequent building of a buffer stock of timber (Fig. 2.7). The build-up of a buffer stock of timber (Fig. 2.7) results in less frequent harvest flow shortfalls (Leduc et al., 2015) and, therefore, provides more resilience to risk (Boychuk and Martell, 1996) and less impact due to fire (Savage et al., 2010; van Wagner, 1983).

Two important facts led to substantially lower harvest rates with revenue maximization compared to a volume maximization strategy when considering fire effects. First, costs of managing the forest, harvesting, and processing of timber were minimized by avoiding unprofitable timber harvests (models 2- 4). Second, an increased proportion of high-value lumber was recovered with models 3 - 4 (Fig. 2.3). Models 3 and 4 therefore required a lower quantity of harvest volume to yield substantially higher revenues with a higher probability. At the level of strategic planning, economic objectives are a function of harvestable volume flows over time. Optimal solutions found when maximizing harvest volume tend to decrease harvest age and hence lumber recovery (Liu et al., 2007; Zhang and Tong, 2005). This leads to economically distorted solutions over short and also long terms when the objective is to maximize harvest volume (model 1, Fig. 2.3). Such distortions can be avoided by maximizing the net present value of primary-processed wood products (models 3 and 4). Lumber resources were also depleted through time with the first three models in the forest management units that still had such resources (026-65 and 094-52). Inclusion of sustained lumber volume flow and distance-weighed lumber flow with model 4 helped control this depletion but induced an abrupt reduction of harvest volume, net revenue and number of jobs in the early periods of the planning horizon. Assuming model 1 represents business as usual, such a reduction would be difficult to justify for decision makers and it would be necessary to find a model representing a compromise between models 3 and 4.

Increased value recovery was also associated with an increase in the mean age at harvest from about 70 to 100 years. Deferring harvest age increases the probability of a stand being burned before it reaches maturity (Gauthier et al. 2015a; Martell, 1980; Reed, 1984). In our case, such a probability increased between 31 and 50 % (model 1 vs model 3), depending upon the forest management unit and its associated burn rate. Still, at the level of one stand in any of our forest management units, deferred harvesting also decreased its land expectation value at rotation start (Davis et al., 2001) by 2 to 7 %, with a discount rate of 4 % y^{-1}. In our case, these negative impacts of harvest deferral at the level of stands seemed to be largely offset at the scale of forest management units with a revenue maximization strategy (Table 2.2).

Deferral of the minimum age at harvest not only provided an economic opportunity that would counteract the negative effects of fire on timber supplies, but would also provide better trade-offs for retaining higher proportions of mature and old-growth stands (Fig. 2.7). Retaining these stand stages through volume maximization is difficult when the annual burn rate is greater than 0.45 % y^{-1} (Savage et al., 2011). In our case, a revenue maximization strategy enhanced the retention of greater proportions of old-growth stands. Therefore, it would be seen as a strategy for intensifying lumber production. Also, reductions in harvest area with lowing the reduction on revenues may serve as a provision for complementing the losses of stock due to fire, thereby increasing the likelihood of cumulative natural and anthropogenic disturbances remaining below specified thresholds.

2.5. CONCLUSION

Maximizing net present values from the sale of processed wood products helped design forest management strategies that increased the proportion of the harvest that could be used to produce high value lumber. It also decreased the timber volume flows since many costs (harvest, transportation, processing) were expressed per units of harvested volume. As a consequence, harvest rates and volumes harvested were reduced, which helped maintain over time the presence of a buffer stock of timber with a higher potential of lumber recovery proportion and therefore of maintaining greater value harvest in the successive periods. This buffer then served as a risk mitigation measure against fire risk. Harvest age was also deferred because log size is related to a greater lumber recovery per unit of merchantable volume. Decrease of harvest volume and harvest age deferral also helped maintain a greater proportion of old-growth forest. Our study therefore provided the indication that a tighter link between strategic forest management planning and the chain of processes existing between timber harvest and selling of processed wood products, which helps reduce the harvest rate, offers the opportunity of finding better compromises between harvest activities and other ecosystem services, despite the occurrence of natural disturbances.

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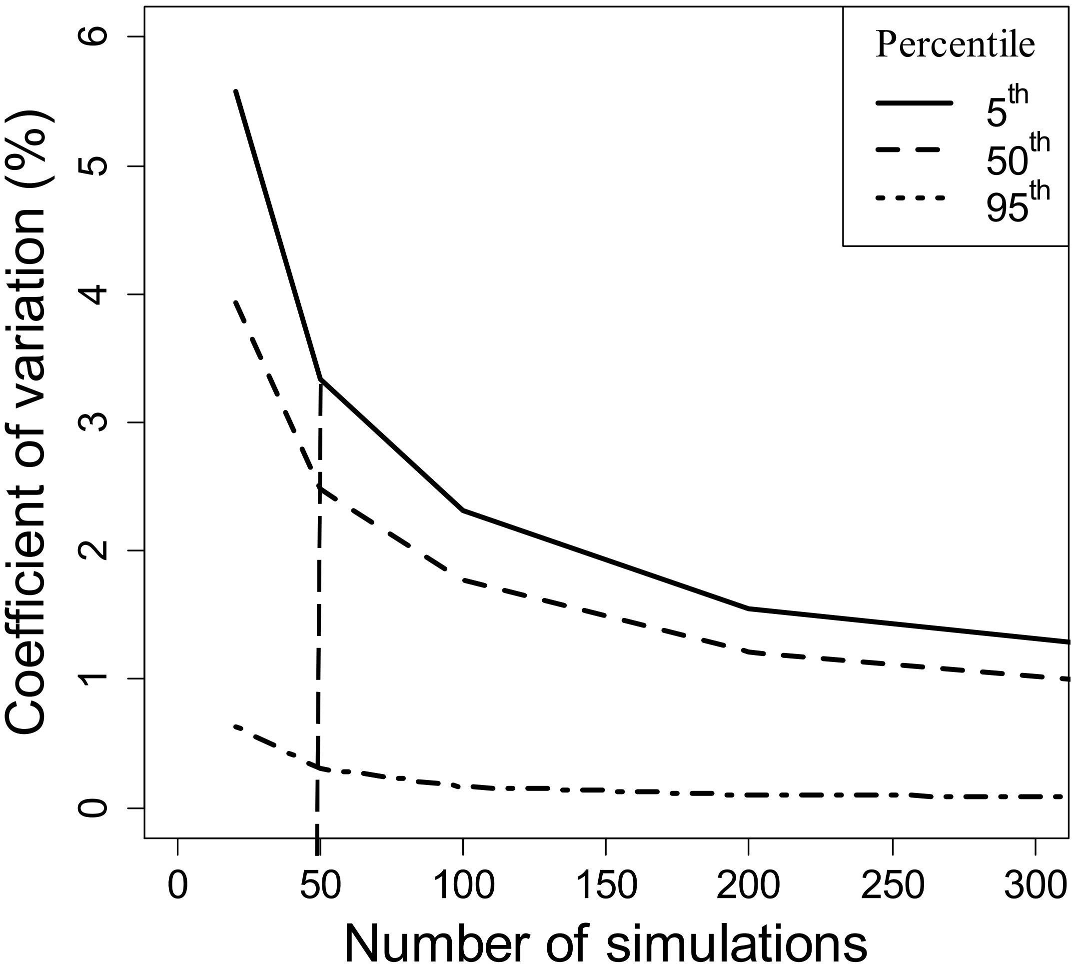

Supplementary Figure 2.1. Determination of the required number of simulations: coefficient of variation of the 5th, 50th and 95th percentiles of realized revenue using timber harvest planning model 1. The percentiles are constructed for each number of simulation by 1,000 times random draws from a pool of 1,500 simulations.

CHAPTER 3. THE ECONOMIC IMPACT OF FIRE MANAGEMENT ON TIMBER PRODUCTION IN THE BOREAL FOREST REGION OF QUEBEC

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3.0. ABSTRACT

Although wildfire is an important component of the dynamics of boreal forest ecosystems, it often threatens public safety and infrastructure and contributes to the loss of forest resources, especially when fires escape and become large. Fire management costs represent substantial amounts incurred annually in Canada, especially when large fires occur. The main objective of this study was to evaluate the financial impact of fire management on forest management. Our experiment consisted of sensitivity analyses among nine selected presuppression cost scenarios using forest and fire data for three commercially-managed forest management units with varying annual burn rates (0.06 - 0.56%y^{-1}) in the boreal forest region of Quebec. The results showed that an increase in presuppression expenditures reduced the burn rate. For example, presuppression expenditures of \$0.40 and \$1.00 $ha^{-1}y^{-1}$ led to burn rates of 1.48% y^{-1} (0.0 - 7.3% y^{-1}) and 0.29% (0.0 - 1.4% y^{-1}), respectively in the most flammable forest. The reduction in burn rate increased revenue from value-added timber sales and reduced fire suppression costs. Such decreases in burn rates caused decreases in the net present value losses from 3 - 34% to 1 - 7% for the respective presuppression scenarios as compared with the respective values for the "no-fire" situation depending on the flammability of the three forests. We confirm our hypotheses that reduced suppression cost and increased revenue from value-added timber harvest with a lower risk compensate for increased presuppression costs. However, compensation is possible up to an optimal point, where benefit-to-cost ratio equals one. The optimal points of expenditure for fire management vary depending on the fire regime and forest productivity.

Keyword: *Benefit-cost, boreal forest, fire, fire suppression forest management unit, presuppression, risk, timber harvest, value-added*

3.1. INTRODUCTION

Although wildfire is an important component of the dynamics of boreal forest ecosystems (Johnson, 1996), it threatens public safety and infrastructure and contributes to the loss of forest resources. Total economic impacts due to timber and property losses, fire management cost and post-fire consequences represent between 0.8 and 2.0% of the gross domestic product in developed countries (Ashe and McAneney, 2012). In Canada, annual losses due to wildfire have been estimated to be around $1 billion, which include 70 Mm^3 of burned timber and $8 million equivalent of property damages (de Groot et al., 2003; Natural Resources Canada 2015a). This demonstrates the importance of fire management, especially in areas where there is a high risk of fire that poses threats to public safety, insfrastructure and forests managed for timber production.

When the burn rate is large enough, the potential impact of fire on sustained timber harvest should be accounted for to avoid the risk of supply disruptions (Boychuk and Martell, 1996; Savage et al., 2010), which reduces the short-term harvest level (Boychuk and Martell, 1996). Accounting for the potential impact of fire on supply in the planning model may have direct adverse impact on revenue. Fire management can reduce such losses by increasing supply. Therefore, there may be a possibility of finding a better compromise between increasing the resilience of long-term timber supply and increasing fire management costs to reduce fire risk. For example, one possible solution to maintaining the harvest volume and revenue to the levels estimated without fire risk is to reduce the area burned by investing in fire management (Martell, 1994). Another solution is to design forest management strategies that help reduce the harvest volume and harvest rate, thereby reducing the risk of supply disruptions, while maintaining or minimizing the losses in the revenues (Rijal et al., Chapter 1).

Fire management includes prevention, detection, initial attack, and suppression (Martell, 2001). Fire management success depends on the success of detection and initial attack (Cumming, 2005; Martell and Sun, 2008). Most forest fires in Canada are contained by the initial attack force, which is the first intervention to stop fire spread (Merrill and Alexander, 1987). An escaped fire is defined as a fire that is not controlled by the initial attack force and it includes those that burn out of control during prescribed burning (Merrill and Alexander, 1987) if the escaped fire surpasses the planned or acceptable limit. About 3% fires become large (area > 200 ha) (Cumming 2005; Natural Resources Canada, 2015a) and are responsible for about 97% of the area burned annually (Stocks et al., 2002).

Fire management costs are often classified into two categories: presuppression and suppression (Bellinger et al., 1983; Simard, 1976). According to Martell (2001, p. 535), presuppression costs include administrative costs such as regular salaries of fire fighters, infrastructure developed and maintained for prevention and early detection and education, patrol, campaign, and investment in new facilities. Presuppression expenditures help reduce the area burned by reducing the proportion of escaped fires through rapid detection and rapid deployment of the initial attack force. Suppression costs include any extra costs incurred fighting fires once a fire has been detected. Suppression costs need to be further categorized into two components: suppression during initial attack and suppression of escaped fires, because a high portion of suppression costs are incurred fighting escaped fires (González-Cabán, 2008). The total area of fires controlled by an initial attack has almost no impact on the annual burn rate (Cummings 2005; Johnson et al. 2001). When a fire escapes, the area burned can be assumed a random process, i.e., independent of initial attack (Cumming, 2005) or the presuppression budget (Martell and Boychuk, 1997).

Fire management overwhelmingly focuses on suppression (e.g., 94% in the US, Wildland Leadership Council, 2004). Fire management costs are often subject to political debates or are difficult to justify (Armstrong and Cumming, 2003; Calkin et al., 2005). When managing fire-prone commercial forests, the fire managers are required to protect an area that would otherwise have burned. Concerns regarding the economic efficiency of fire management lead to the development of two strategic models to measure the economic efficiency of fire management (George and Storey, 1979). The first one is the "least-cost-plus-loss" (LCL), which is the sum of fire management costs and net value change due to fire management (Sparhawk, 1925: adapted from Simard 1976). The LCL minimum point corresponds to the optimum amount of presuppression budget to spend on fire management (Martell and Boychuk, 1997). Another is benefit-to-cost ratio (Simard, 1976), which is one step further than the LCL (Cellini and Kee, 2010). This approach quantifies the benefit or loss if investment runs sub-optimally and it explains marginal gain for one added unit of investment. These models do not consider tactical or even detailed operational activities of fire management but only inform on budget allocation for optimal presuppression cost (Martell and Boychuk, 1997; Rodríguez y Silva and González-Cabán, 2010). Although the concerns about the financial impact of fire management on timber supply are not new (e.g., Martell, 1994), we are still lacking empirical studies evaluating the impact of fire management on the annual area burned and therefore on timber supply (Johnson et al., 2001) and subsequently on revenue. However, Cumming (2005) showed that such impacts could be estimated indirectly by modeling escaped fires. The probability of fire escape may be related to the number of fires that occur on the previous three days (Podur and Martell, 2007) or yearly (Cumming, 2005), and to the response time between fire detection and initial attack (Martell and Sun, 2008).

The main objective of this study was to evaluate the impact of presuppression expenditures on the sum of revenues from the sale of primary-processed wood and fire suppression costs. Accounting for the impact of fire in the harvest planning model reduces the harvest level, but the amount and variability depend upon the annual burn rate (Savage et al., 2010). On the other hand, reducing the area burned through fire management may increase the harvest and reduce variability. Hence, fire management may reduce the negative effect of harvest reduction and variations by period over a planning horizon. We hypothesize that such an impact should be positive up to the certain extent where the added value of fire management as a sum of increase in revenues from the increased timber harvesting and a decrease in suppression costs can offset the increased presuppression expenditures. The specific objectives were to: a) model the fire escape process with respect to fire management costs and estimate the resulting annual burn rate, and b) carry out a sensitivity analysis of the impact of varying burn rates with respect to varying presuppression costs on timber harvesting and revenues. We treated presuppression expenditures as a fire management input that can impact the area burned directly and hence the revenues from primary-processed wood products (lumber, chips and sawdust). Our experiment consisted of sensitivity analyses of benefit-to-cost ratio as a measure of financial efficiency among nine selected input scenarios. In the sensitivity analyses, we examined the extent to which an increase in presuppression expenditures would be offset by a) an increase in revenues from primary-processed wood products, and b) a reduction in fire suppression costs. We carried out this simulation experiment using data from three commercially-managed forests with different burn rates that are located in the boreal forest region of the province of Quebec (Canada).

3.2. METHODS

3.2.1. Study area

We selected three forest management units (FMU) located in the northern part of the commercially-managed forest in the province of Quebec (Canada) (Fig. 3.1) for our study. This provided variation in mean burn rates (0.06 - 0.56 % y^{-1}). These management units are located within the boreal black spruce-moss bioclimatic domain (Robitaille and Saucier, 1998), which covers an area about 160,000 km^2, between 48^0-51^0 N latitude and 65^0-79^0 W longitude (Fig. 3.1). Forest composition is shaped by fires with burn rates that vary across the region. An increase in the burn rate is observed from east to west and from south to north (Bergeron et al., 2006; Bouchard et al., 2008). Tree species in the north-west region, where the fire cycle (the time required to burn an entire area of interest) is short (< 100 up to 500 years), are fire-adapted softwood mainly black spruce (*Picea mariana* [Mill.]) and jack pine (*Pinus banksiana* Lamb.), accompanied by some intolerant hardwood. In the eastern part, where the fire cycle is relatively longer (> 500 years), fire-averse balsam fir (*Abies balsamea* [L] Mill.) substantially increases in proportion (Bouchard et al., 2008). Black spruce, jack pine and balsam fir are commercially important species in the region (Liu et al., 2007).

3.2.2. Data sources and processing

We used three types of data: a) forest fire event data and fire management costs from the Société de Protection des forêts contre le feu (SOPFEU) and annual reports published since its creation (SOPFEU, 1994 - 2014) to manage wildfire in the region, b) forest inventory data and forest maps provided by the Ministère des Forêts, de la Faune et des Parcs, and c) financial data compiled from various sources. In addition, we used spatial data such as maps of landscape units, forest management units and road network. Details are provided below.

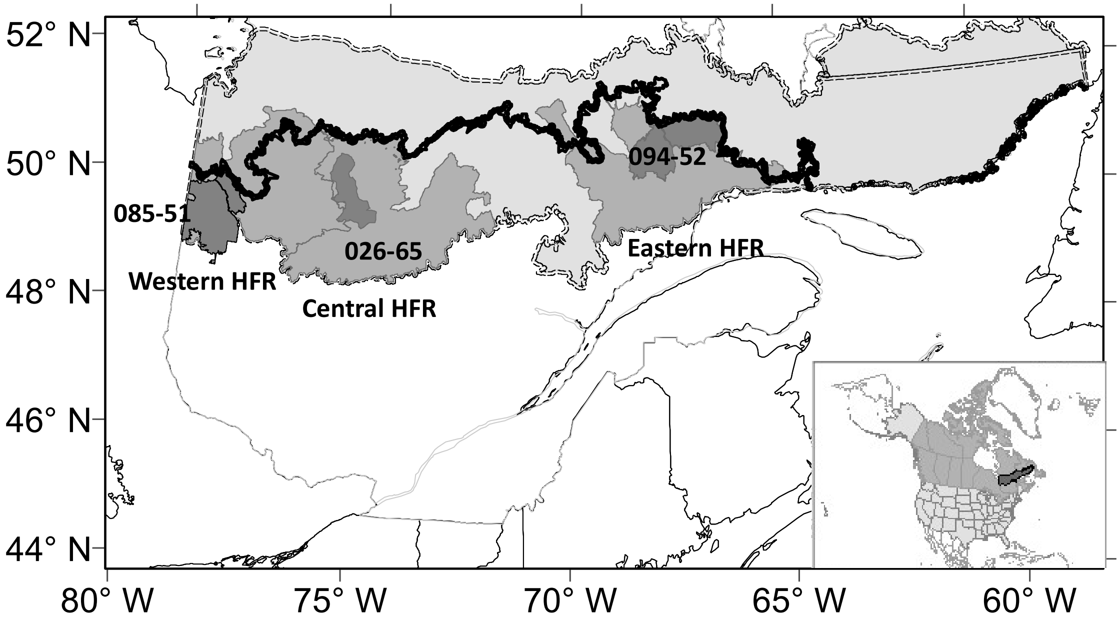

Figure 3.1. Study area, showing three forest management units (dark gray) and three homogeneous fire zones (HFR - medium gray) within the spruce-moss bioclimatic domain (light gray) in Quebec Province. The bold line is the northern limit of commercial forest and fire intensive protection zone (MRNFQ, 2000).

Fire data and suppression costs were provided at the scale of individual fires. Annual presuppression costs were given at the scale of the entire fire intensive protection zone of the province of Quebec. Comprising all commercially-managed forests of the province of Quebec in this zone, the intensive protection zone is the area where fire management activities are intensive to protect any kind of potential losses (for details about the definition in the context of Ontario, Martell, 1994). We have used three homogeneous fire regions (HFR) in association with the three FMU's chosen for our study (Fig. 3.1). Each HFR corresponds to a spatially contiguous area of similar fire-fuel environment (homogeneous weather, topography, soil and fuel combustibility - Chabot et al., 2009). Burn rates for each unit were estimated using fire data for the 1994-2014 in order to correspond with available fire management costs observed at the scale of these fire regions (Table 3.1). All reported fire management costs were expressed in constant dollars (base year of 2010) using the inflation calculator of the Bank of Canada (2015).

We regrouped the forest stands of each management unit into aspatial strata based on their membership in a landscape unit and their species composition. Landscape units are "a portion of landscape characterized by a recurrence of environmental attributes (i.e., relief, average altitude, nature and proportion of the main surficial deposits, hydrography) and vegetation (nature and distribution of species)" (Robitaille and Saucier, 1998). The stands of each landscape unit were regrouped according to their two most abundant species groups (shade intolerant or tolerant softwood, and balsam fir – hardwood was not considered), to render the forest stratification consistent with the NATURA-2009 growth and yield model (Pothier and Auger, 2011). In total, there were 52, 38 and 70 strata in western (085-51), central (026-65) and eastern (094-52) forest management units, respectively. We considered lumber, chips and sawdust as the primary-processed products at a sawmill. The product-wise yield curves were constructed using the models developed by Zhang et al. (2006), Zhang and Tong (2005) and Liu et al. (2009) for black spruce, jack pine and balsam fir, respectively. Species group-wise yield curves were then summed to construct the stratum-level single yield curve for the timber and the three products using non-parametric smoothing (function *lowess* in R; R Development Core Team 2014). We fixed the stand minimum harvesting age when total standing timber volume exceeds 50 m^3 ha^{-1}, with a mean stem volume ≥50 dm^3 $tree^{-1}$ (Raulier et al. 2013) in a 150-year planning horizon.

Table 3.1. Summary statistics (median, minimum and maximum values) of the recorded annual fire and fire management cost data (1994 - 2014) for three homogeneous fire regions (Chabot et al., 2009). Costs have been standardized to constant dollars at the base year 2010 (Bank of Canada, 2015).

Attributes	Fire region			
	Unit	Western	Central[1]	Eastern
Homogenous fire region	Km^2	45,600	52,500	46,900
Burn rate	$\% \ y^{-1}$	0.04 (0.0 – 1.4)	0.09 (0.0 – 5.4)	0.002 (0.0 – 0.5)
Fire number	$\# \ y^{-1}$	18 (2 – 81)	32 (8 – 192)	17 (4 – 64)
Number of escaped fires	$\# \ y^{-1}$	6 (0 – 24)	9 (0 – 72)	2 (0 – 15)
Area of escaped fires	ha	12 (3 – 18,320)	30 (3 – 77,700)	15 (3 – 10,520)
Presuppression expenditures	$\$ \ ha^{-1} \ y^{-1}$	0.76 (0.62 – 0.86)	0.76 (0.62 – 0.86)	0.76 (0.62 – 0.86)
Suppression costs				
Fires controlled by initial attack	$\$ \ ha^{-1} \ y^{-1}$	0.03 (0.00 – 0.13)	0.04 (0.00 – 0.33)	0.04 (0.00 – 0.17)
Escaped fires	$\$ \ ha^{-1} \ y^{-1}$	0.18 (0.00 – 1.08)	0.37 (0.01 – 3.63)	0.18 (0.00 0 1.83)

[1] The central fire region corresponds to the two fire regions of Chabot et al. (2009) merged because central forest management unit (026-65) falls in two HFRs.

We used most of the costs related to forest management, harvesting and log transportation from Pasturel (2013) for forest management unit 085-51. The costs of forest management and harvesting included all direct and indirect costs from stand regeneration and tending, and felling up to loading. It was kept constant at \$39.7 m^{-3} (Pasturel, 2013). In order to estimate transportation costs from the harvest site to a primary processing sawmill, we used a linear regression equation developed by Pasturel (2013, appendix H) that provided costs between \$9 - \$25 m^{-3} depending on the distance between the harvest site and the mill. For simplicity, we located the closest sawmill for each management unit among the publicly available list of sawmills active in 2009 (MRNFQ, 2009), assuming that all the timber harvested from each FMU would be transformed into lumber, chips and sawdust at a single mill. We calculated the driving distance between the centroid of each landscape unit and the mill with network analyses tool in ArcGIS 10.2 (ESRI, Redlands, CA, USA) using forest road network data (Adresses Québec, 2015). This analysis procedure was extended to estimate harvesting and transportation costs for the other two forest management units. The processing cost of timber at the sawmill was estimated to be \$24 m^{-3} of merchantable volume assuming an average conversion factor of 4.4 from merchantable volume (m^{-3}) to lumber thousand board-feet (Del Degan Massé, 2010). Transportation costs from sawmill to product destinations varied as a function of transportation modes (\$ 0.02 m^{-3} km^{-1} for truck and \$0.002 m^{3} km^{-1} for train - CPCS, 2013; Laurent et al., 2013) to the Montreal market (for lumber), to the paper mill (for chips) or panel mill (for sawdust). We assumed that sawdust produced by the sawmill closed to FMU 085-51 could be transported by train (due to the availability of railroad network) and by truck in other FMUs. We used a selling price at the delivery site of \$155 m^{-3} and \$52 m^{-3} for lumber and chips, respectively. We used the ten-year mean (2004-2013) of lumber selling prices (Montreal market - Quebec Forest Industry Council) and wood chip prices (delivered to the closest paper mill - Del Degan Massé, 2012). Prices were expressed in constant dollars (base year 2010). We used a price of \$9 m^{-3} for sawdust (delivered to the closest panel mill) (Pasturel, 2013). We used an interest rate of 4% y^{-1} to discount future revenues and costs (BFEC, 2013), and applied it to the middle point of each period, assuming harvests would be scheduled at the midpoint of each period.

3.2.3. Simulation framework

We carried out a sensitivity analysis in the form of a benefit-cost analysis (BCA) to evaluate how much fire management would be able to increase the revenue from primary-processed wood products. The increase in the revenue as a result of decreasing revenue losses caused by the burning of timber suitable for harvest and processing (short-term, direct effect of fire – Zybach et al., 2009) and the losses in net present value (long-term, indirect effect of fire). We varied the level of presuppression costs (nine levels) to examine the impacts of fire management on revenues from the sales of primary-processed wood products despite the occurrence of unexpected fire events. The objective of this analysis was to find the level of fire management cost for each forest management unit beyond which the marginal gain in revenues of processed wood products between two levels of fire management costs was inferior to the marginal increase in fire management costs. To this effect, we designed a timber harvest planning framework for a 150-year planning horizon by 5-year periods, which corresponds to the planning horizon and periodic replanning of the current (2013 -2018) timber harvest planning policy of forest management in Quebec (BFEC, 2013).

The framework consisted of two model components. The first model was a timber harvest optimization model that specified, at the start of each period, a strategic forest management plan that would maximize the revenue of primary-processed wood products. The second model was an aspatial landscape dynamics model. This model simulated the implementation of the optimized harvest plan during the period in interaction with the random occurrence of fire and fire management. During each period, two models interacted together through an implementation of the harvest plan in a periodic replanning process (Savage et al., 2010). Details on these two models are provided below. Since we assumed fire is a random process in the landscape dynamics model, simulation cycles had to be repeated several times to cover the range of possible outcomes (revenue) with respect to the randomly-drawn burn rates (details below). Our simulation process therefore yielded multiple iterations of sequences of periodic revenues for primary-processed wood products as a function of the level of presuppression costs for each forest management unit. We have used a common random number approach (Schruben and Margolin, 1978) so that each iteration used exactly the same sequence of random numbers across all levels of presuppression costs. This procedure allowed us to estimate frequency distributions of periodic revenues from harvest and wood processing, fire management costs, losses from burned wood and also differences in revenues and costs (that is, marginal revenues and costs) for each iteration between consecutive levels of presuppression expenditures. Our revenue and losses analyses focused on the first ten years of the planning horizon in order to evaluate the short-term financial effects of fire management corresponding to the shorter planning horizon of sawmill (D’Amours and Rönnqvist, 2008; Gunn, 2009).

In order to obtain stable probability distributions, we first generated 1,500 simulations for the lowest two presuppression expenditure scenarios (\$0.20 and 0.40 ha^{-1}y^{-1}) in the most flammable forest, where the variability was expected to be the highest. We then performed random draws with replacement from the 1,500 simulated revenues, with a number of draws corresponding to a chosen number of simulations (25, 50, 100,…, 1,500). Corresponding to our research objective, we confined the examination only for the marginal revenue. This process was repeated 1,000 times in order to construct the frequency distributions of the 5th, 50th and 95th percentiles. We estimated the coefficients of variation of each of these percentiles. 100 repetitions were sufficient to obtain coefficients of variation of the selected percentiles distributions of marginal change of harvest revenues below ± 5% of their median values for the most flammable forest (Supplementary Fig. 3.1).

As marginal revenues and costs were not correlated, levels of presuppression costs were evaluated by testing the equality between median marginal revenues and median marginal costs with Wilcoxon ranked-sum tests (Wilcoxon, 1945). Nine presuppression expenditure scenarios were evaluated with an increment of \$0.20 ha^{-1}y^{-1} between two chosen extremes. The lowest presuppression expenditure we have examined was \$0.20 ha^{-1}y^{-1}, or about one-third of the minimum cost (\$0.60 ha^{-1}y^{-1}) observed between 1994 and 2014 in the SOPFEU annual reports. This lowest value helped assess whether we could reduce fire management costs in the forest management unit with the lowest burn rate. Because of the increasing trend of fire management costs, we evaluated up to a maximum value of \$1.80 ha^{-1}y^{-1}, roughly doubling the maximum value of observed costs for the past 21 years for the forest management unit with the highest burn rate (\$0.86 ha^{-1}y^{-1}). The following three subsections §3.2.3.1 - §3.2.3.3 explain the components of the simulation models in more detail.

3.2.3.1. Timber harvest scheduling optimization model

We designed a timber harvest scheduling model that maximized the net present values from the sale of primary-processed products by the closest sawmill for each forest management unit. Rijal et al. (Chapter 1) have shown that compared to other harvest models that maximize timber volume or timber revenue, this type of model yields the highest revenue with the least within- and among-period fluctuations over the planning horizon while substantially reducing the risk of timber supply disruptions caused by fire. This model accounts for the average impact of fire on the forest age structure (Reed and Errico, 1986). We formulated the model with a Model III structure (Garcia 1984; Gunn and Rai 1987; Reed and Errico 1986) because of the relative ease with which it accounts for fire disturbances (Savage et al., 2010).

Let,

Indices:

s	stratum (1...S; S= 38, 52, and 70 in FMUs 026-65, 085-51 and 094-52),
a	age class (1...30, 5-year intervals),
t	period (1...30, each of 5-year period),
p	product (1...3; lumber, chips and sawdust),

Decision variable:

h_{sat}	area planned to be harvested (ha) in stratum *s* and age class *a* in period *t*, ∀ *s*, *a* and *t*
x_{sat}	area of age class *a* of stratum *s* at start of period *t* (ha), ∀ *s*, *a* and *t.* With respect to LP model, this is defined as a decision variable. However, values are generated by age-class movement by period from the initial age-class distribution in each stratum ($x_{sa0)}$ using Model III network structure (Eqs. 3.4 - 3.6).

Parameters:

x_{sa0} initial condition: area (ha) in stratum *s* of an age class *a* in (ha), ∀ *s*, and *a,*

v_{sa} merchantable volume in stratum *s* in age class *a* (m^3 ha^{-1}), ∀ *s* and *a*,

v_{psa} product volume (m^3 ha^{-1}), ∀ *p*, *s* and *a*,

$a_{min.s}$ minimum harvest age (periods), ∀ *s*,

b_f constant periodic burn rate, obtained by taking the mean of 10,000 times stochastic simulation for each presuppression scenario (details below),

$d_{s.m}$ distance between the centroid of landscape unit to which a stratum belongs and the closest primary processing mill (*m*), ∀ *s,*

r_{pm} product selling price at delivery site for product *p* processed at mill *m* (\$ m^{-3}), ∀ *p,* and *m*,

$c_{fs.m}$ total costs incurred in the forest per unit of timber volume harvested (forest management, harvest, including loading timber - \$39 m^{-3}) and transportation costs up to the closest sawmill (\$ m^{-3} merchantable volume),

$c_{pr.m}$ product processing (*pr*) cost per unit of timber volume (\$ m^{-3} volume),

$c_{tr.pm}$ transportation cost (*tr*) from the processing mill to the delivery site (\$ m^{-3} merchantable volume),

γ_t periodic discount factor ($(\frac{1}{1+r/100})^{5t-2.5}$) assumed to be applied at the mid point of 5-year period, *r* being a discount rate (4 % y^{-1}, BFEC 2013).

We maximized the net present value only the first two periods to correspond with the strategic/tactical planning horizon of wood mill (D'Amours and Rönnqvist, 2008; Gunn, 2007). The short-term economic value is of growing concern as an important aspect of successful forest management (González-Cabán, 2008; Szaraz, 2014, *unpublished*) in addition to a sustainable long-term wood supply. We considered the economic value of the timber harvested when the timber is transported and processed in the primary processing mill. The objective function is structured in such a way that the policy model is vertically integrated where the wood mill affords all types of costs, i.e., forest management, harvesting, transportation and processing costs, and maximizes its net present values, but abides forest sustainability requirement by applying even flow of harvest volume.

The objective function therefore, aims to maximize the revenue from the sale of wood products processed at the closest primary processing mill as:

$$NPV_{Prod} = \max \sum_{t=1}^{2} \left[\gamma_t \sum_{p=1}^{3} \sum_{s=1}^{S} \left[\left(r_{pm} - c_f - \mathrm{c}_{tr.sm} - c_{pr.m} - c_{tr.pm} \right) \sum_{a=a_{min.s}}^{30} v_{psa}\, h_{sat} \right] \right] \quad [3.1]$$

Constrained to:

Periodic even flow of harvest volume:

$$\sum_{s=1}^{S} \sum_{a=a_{min.s}}^{30} v_{sa}\, h_{sa(t-1)} = \sum_{s=1}^{S} \sum_{a=a_{min.s}}^{30} v_{sa}\, h_{sat} \;, \quad \forall\, t \in \{2..30\} \qquad [3.2]$$

The planned harvest area is limited to less than or equal to the area available in each stratum, age class and period, after accounting for the effect of forest fire with a constant periodic average burn fraction (b_f) by period over a planning horizon:

$$h_{sat} \leq (1 - \mathrm{b}_f) x_{sat}, \quad \forall\, s, a \text{ and } t \qquad [3.3]$$

Following Reed and Errico (1986), we also assumed that fire occurred randomly, i.e., independently of the stratum or the age-class within each FMU. Accordingly, the area accounting constraints in Model III structure are given as:

in the youngest age class:

$$x_{s1t} = \sum_{a=1}^{30} h_{sa(t-1)} + b_f \sum_{a=1}^{30} x_{sa(t-1)}\ , \quad \forall\ s, a \text{ and } t \in \{2..30\} \qquad [3.4]$$

in the upper collecting age class:

$$x_{sat} = (1 - b_f) \sum_{a=29}^{30} x_{\mathrm{s}a(t-1)} - \sum_{a=29}^{30} h_{\mathrm{s}a(t-1)}, \quad \forall\ s \text{ and } t \in \{2..30\} \qquad [3.5]$$

and, in the intermediate age classes:

$$x_{sat} = \left(1 - b_f\right) x_{s(a-1)(t-1)} - h_{s(a-1)(t-1)}, \quad \forall\ s, a \in \{2..29\} \text{ and } t \in \{2..30\} \quad [3.6]$$

Lumber has the highest selling value among the three products we used here as the primary-processed products. Therefore, to avoid depleting the lumber resource with the lowest processing costs, we also considered an even-flow constraint of lumber yield and an even flow of distance-weighted lumber yield:

$$\sum_{s=1}^{S} \sum_{a=a_{min.s}}^{30} h_{sa(t-1)}\ v_{psa} = \sum_{s=1}^{S} \sum_{a=a_{min.s}}^{30} h_{sat}\ v_{psa}, \quad p = \text{lumber}, \forall\ t \in \{2..30\} \quad [3.7]$$

$$\sum_{s=1}^{S} \frac{1}{d_{sm}} \sum_{a=a_{min.s}}^{30} h_{sa(t-1)}\ v_{psa} = \sum_{s=1}^{S} \frac{1}{d_{sm}} \sum_{a_{min.s}}^{30} h_{sat}\ v_{psa}, \quad \text{p} = \text{lumber}, \forall\ t \in ..30\} \quad [3.8]$$

We used the AMPL modeling language (Fourer et al., 2003) to formulate the optimization model and Gurobi 5.6.0 (Gurobi Optimization Inc., Houston, TX) to solve it on the AMPL platform. The solution produced an optimized harvest plan by period for a planning horizon.

3.2.3.2. Landscape dynamics model

We used a landscape dynamics model to project the forest age structure over the planning horizon (150 years), accounting for harvesting, fire and fire management. It consists of modeling: a) escaped fires, b) landscape dynamics simulation, and c) suppression costs.

Fire model

We followed Cumming (2005) to model annual number of escaped fires as a function of annual fire load (density) and "presuppression preparedness", which we replaced with direct presuppression expenditures. A fire in Quebec is considered to be an escaped (fire) once its area is larger than 3 ha (Gauthier et al., 2005; SOPFEU 2014). Cumming (2005) used that value in his analysis of fire data of Alberta. Contrary to Cumming (2005), we calibrated our fire escape model at the scale of homogeneous fire regions, since probability of fire detection may vary regionally (Wotton and Martell, 2005). Annual fire occurrence ($N_{h.f.tot}$, number per year, h being a homogeneous fire region) as well as the individual fire size of escaped fires are assumed to be independent of presuppression efforts (Cumming, 2005; Martell and Boychuk, 1997). Therefore, the total area burned annually in a fire region essentially equals the number of escaped fires ($N_{h.f.esc}$) time the mean escaped fire size ($\bar{A}_{h.f.esc}$, ha). We used the fire data from the SOPFEU fire database to estimate a mean fire size by fire region. We estimated the parameters of a relationship explaining the number of escaped fires as a function of presuppression expenditures and annual fire load, corresponding to number of fire occurrence per year (Cumming, 2005) using a generalized linear model. We selected a negative binomial (log) link function because $N_{h.f.esc}$ frequency distributions were overly dispersed (variance is larger than mean) (Venables and Ripley, 2013) (Table 1).

$$N_{h.f.esc} \sim g\left(\beta_{\mathrm{h.0}} + \beta_{\mathrm{h.1}} \log\left(N_{h.f.tot}\right) + \beta_{\mathrm{h.2}}\, \mathrm{C}_{presup}\, A_h\right) \qquad [3.9]$$

where C_{presup} is an annual presuppression expenditure ($ ha^{-1} y^{-1}), A_h is the terrestrial area of an homogeneous fire region, $g(.)$ is a link function and $\beta_{\mathrm{h.i}}$ are model parameters. Although the annual area burned in the north is larger than that of the south, the number of fire arrivals exhibits no spatial pattern within the entire intensive protection zone (details of data at the Quebec scale are beyond the scope of this paper). The objective of the presuppression program is to prevent fire establishment, spread and escape by managing fuel or early detection to facilitate suppression as well as for an education campaign and patrolling. It implies that it is reasonable to assume that the presuppression cost has been distributed uniformly across the zone (Table 3.1). Cumming (2005) has shown that the probability of fire escape and therefore the number of escaped fires may be nonlinearly related to the annual fire load. Preliminary analyses showed that a log transformation provided a better fit when compared to the polynomial approach used by Cumming (2005). We also scaled annual presuppression costs to the fire region level as a function of their terrestrial area.

b) Landscape dynamics

Landscape dynamics are simulated with the same equations as those of the area accounting constraints in the timber harvest model (Eq. 3.4 - 3.6), with two differences. The first difference relates to the periodic burn rate. Periodic burn rates were generated from random draws of annual number of fires and annual mean fire sizes observed between 1994 and 2014. Equation 3.9 was used with the annual number of fires to estimate the annual number of escaped fires: assuming that annual burn rates are independently distributed over time and that burn rates are equivalent to annual burn probabilities (van Wagner 1978), the periodic burn rate is equal to the complementary probability of observing no fire during that period. A periodic burn rate can therefore be estimated with:

$$b_t = 1 - \prod_{i=1}^{5}(1 - \frac{N_{(h.f.esc)i}\,\bar{A}_{(h.f.esc)i}}{A_F}) \qquad [3.10]$$

where A_h is the terrestrial area of the homogeneous fire region that includes the forest management unit (Table 3.1). The b_t was updated by simulating for every period and repetition before its uses in the landscape simulation model.

We used the mean of b_t as the constant b_f required for our optimization model (Eq. 3.3 – 3.6) for each presuppression scenario. Although, there were only 441 possible cases for random draws of two independent variables from a pool of 21 years of observations, 10,000 random draws were conducted for each presuppression scenario to evaluate the probability distribution function of b_f and achieve consistent estimations of the mean values (b_f).

The second difference relates to realized harvest $\tilde{h}_{sat}$ that may be lower than the area planned to be harvested due to the simulated occurrence of fire events (b_t). We took the minimum value between planned harvest area (h_{sat}) and area available in the same stratum and age class at that period ($\tilde{x}_{sat}$):

$$\tilde{h}_{sat} = \min(\tilde{x}_{sat}, h_{sat}) \qquad [3.11]$$

Harvest occurs after the impact of fire is accounted for:

$$\tilde{x}_{sa1} = (1 - b_t)x_{sa1}\text{ , } \forall\ s \text{ and } a \qquad [3.12]$$

$$\tilde{x}_{s1t} = \sum_{a=1}^{30} \tilde{h}_{sa(t-1)} + b_{(t-1)} \sum_{a=1}^{30} \tilde{x}_{sa(t-1)}\text{ , } \forall\ s, a \text{ and } t \in \{2...30\} \qquad [3.13]$$

$$\tilde{x}_{s30t} = (1 - b_t) \sum_{a=29}^{30} \tilde{x}_{sa(t-1)} - \sum_{a=29}^{30} \tilde{h}_{sa(t-1)},\ \forall\ s \text{ and } t \in \{2...30\} \qquad [3.14]$$

$$\tilde{x}_{sat} = (1 - b_t)\, \tilde{x}_{s(a-1)(t-1)} - \tilde{h}_{s(a-1)(t-1)}, \forall\ s, a \in \{2...29\} \text{ and } t \in \{2...30\} \quad [3.15]$$

We estimated the value of the timber burned by fire, accounting for a minimum age of harvest below which forest management, harvesting, transportation and processing costs cannot be compensated for by the sale of wood products (Rijal et al., Chapter 1):

$$b_t \sum_{p=1}^{3} \sum_{s=1}^{S} \left[\left(r_{pm} - c_{fs.m} - c_{pr.m} - c_{tr.pm} \right) \sum_{a=a_{min.s}}^{30} v_{psa}\, \tilde{x}_{sat} \right] \text{t} \in \{1...30\} \qquad [3.16]$$

Where $\tilde{x}_{sat}$ is the simulated forest area in stratum *s*, of age class *a*, period *t,* and the burned wood volume comes to be $\tilde{x}_{sat} * v_{sa}$ m^3, which gives the equivalent burned products volumes of $\sum_{p=1}^{3} \tilde{x}_{sat} * v_{psa}$ m^3. Likewise, we estimated the realized losses of NPV for the first two periods by comparing the NPV for each presuppression scenario with the NPV obtained without the impact of fire as “no-fire” situation by simulating optimization and landscape simulations models with periodic burn rates zero (i.e., b_f, and $b_t = 0$, in all equations mentioned above).

c) Modeling suppression costs

Martell and Boychuk (1997) modeled suppression cost for individual fires as a function of number of fire occurrences, the failure rate of initial attack (escaped fires) and individual fire perimeters. We evaluated empirically their model of suppression costs for fires controlled by the initial attack force and escaped fires separately because fire numbers and burned areas varied substantially between the two with our data, indicating the bimodal nature of suppression costs. Also, contrary to Martell and Boychuk (1997) who used the square root of the burned area as a proxy of fire perimeter, we found using a stepwise variable selection method (*step* function in R - R: Core Development Team, 2014) that the total area burned was better correlated with suppression costs than the sum of fire perimeters. Annual suppression costs ($

ha^{-1} y^{-1}) for fires controlled by the initial attack force ($C_{h.sup.con}$) and escaped fires ($C_{h.sup.esc}$) were modeled with a linear regression for each fire region as:

$$C_{h.sup.con} = \alpha_{h0.con} + \alpha_{h1.con} \frac{N_{h.f.con}}{A_h} + \alpha_{h2.con} \frac{A_{h.burned.con}}{A_h} \tag{3.17}$$

$$C_{h.sup.esc} = \alpha_{h0.esc} + \alpha_{h1.esc} \frac{N_{h.f.esc}}{A_h} + \alpha_{h2.esc} \frac{A_{h.burned.esc}}{A_h} \tag{3.18}$$

where $N_{h.f.con}$ is the number of fires controlled annually (obtained from $N_{h.f.tot} - N_{h.f.esc}$), and $A_{h.burned.con}$ and $A_{h.burne\ .esc}$ are the areas (ha y^{-1}) annually burned by controlled and escaped fires, respectively. The total fire management cost is the sum of the two predicted costs and is therefore an indirect function of presuppression costs via $N_{h.f.esc}$ (Eq. 3.9).

We used AMPL to build our landscape dynamics model because of its ease in exchanging data between the timber harvest optimization and the landscape dynamics models through an automated looping process.

3.3. RESULTS

3.3.1. Modeling of fire management

Between 1994 and 2014, annual presuppression expenditures ranged between \$0.62-0.86 ha^{-1} y^{-1} and suppression costs between \$0 and 3.63 ha^{-1} y^{-1} depending on the burn rate in three regions. Eighty-nine percent of total fire management costs were allocated to the suppression of fires that escaped initial attack in the three fire regions between 1994 and 2014, with no apparent differences between the regions (Table 3.1).

3.3.1.1. Annual fire escape

The first specific objective of our study was to model the number of escaped fires as a function of presuppression expenditures and the total number of fires (eq. 3.9, Table 3.2). For two fire regions, the R^2 values were particularly high (0.93-0.94) due to the high correlation between the number of escaped fires and the total number of fires (annual fire load) (correlation coeffient varied between 0.83-0.85). For equivalent pressuppression expenditures, the number of escaped fires relative to the total number of fires is higher by 20% in the central fire region (Table 3.2), where the mean burn rate is the highest (Table 3.1). The influence of presupression expenditures on the annual number of escaped fires is significant for all three fire regions (Table 3.2), and this influence is also highest for the central fire region. The maximum temporal autocorrelation for the number of escaped fires was not significant at 5% for all three fire regions. Likewise, the variance inflation factor between the two covariates of eq. 3.9 is substantally lower than the rule of thumb value of 10 (O'Brien 2007). The models not only captured the trend observed between 1994 and 2014, but they also explained the extreme values observed in 1996 and 2005 (Fig. 3.2) well.

Table 3.2. Parameters of regression models of the number of escaped fires (Eq. 3.9) in three homogeneous fire regions (HFR). The displayed parameters are significant at 5% error level and numbers in the parentheses are standard errors.

HFR	Parameters			R^2
	Intercept ($\beta_{h.0}$)	Annual fire load ($\beta_{h.1}$) (log transformed)	Presuppression expenditures ($\beta_{h.2}$)	
Western	-	1.00 (0.10)	-0.348 (0.102)	0.94
Central	-	1.21 (0.09)	-0.531 (0.097)	0.93
Eastern	-	0.97 (0.16)	-0.396 (0.145)	0.68

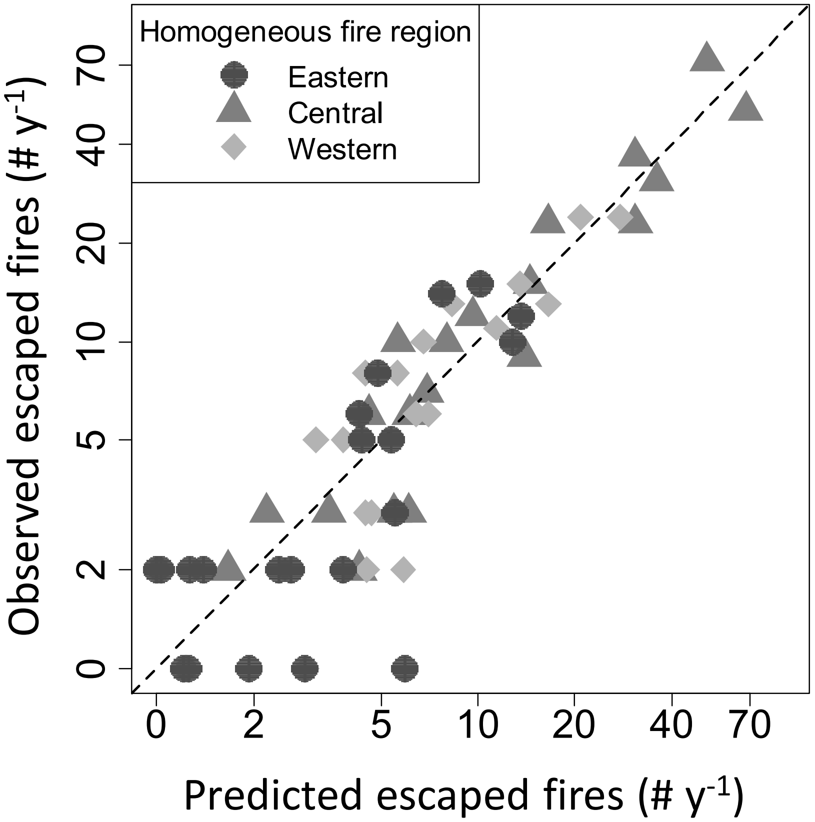

Figure 3.2. Observed and predicted numbers of escaped fires (eq. 3.9) for the three considered homogeneous fire regions.

3.3.1.2. Modeling suppression costs

The suppression costs for each fire successfully controlled by the initial attack force varied on average between \$10,000 and \$13,900 ha^{-1} of area burned in three homogeneous fire regions (Eq. 3.17, Table 3.3). Suppression costs for controlled fires are on average more expensive in the eastern and western fire regions, where they also depend on the final fire size (Table 3.3). Mean size for controlled fires (0.37 ha) is not substantially different in the three fire regions. However, there is variation in the cost, which means that suppression costs incurred in controlling those fires during the initial attack may have varied between fire regions by year and are partly influenced by fire numbers (Fig. 3.3). The cost of suppressing an escaped fire (Eq. 3.18) was sometimes proportional to its final fire size (eastern region), sometimes not (western region), where it costs on average \$155,000 (Table 3.3). Mean size of escaped fires varied between 575 ha and 1867 ha. Finally, there were no significant temporal autocorrelations for annual suppression costs for either controlled or escaped fires at any lag, and very small variance inflation factors were observed between the two covariates of both models.

Table 3.3. Parameters of the regression models of suppression costs for controlled (Eq. 3.17) and escaped fires (Eq. 18) in three homogeneous fire regions. The displayed parameters are all significant at 5% error level and numbers in the parentheses are standard errors. Intercepts of Eqs. 3.17 and 3.18 were not significant in all cases.

Fire region	Fires controlled during initial attack			Model for escaped fire		
	Number of fires ($\alpha_{1.con}$)	Fire size ($\alpha_{2.con}$)	R^2	Number of fires ($\alpha_{1.esc}$)	Fire size ($\alpha_{2.esc}$)	R^2
Western	4965 (1279)	13,403 (2660)	0.93	154,850 (26,089)	-	0.58
Central	10859 (586)	-	0.90	130,912 (49,925)	42 (17)	0.67
Eastern	5080 (1948)	23,820 (5761)	0.84	-	343 (34)	0.78

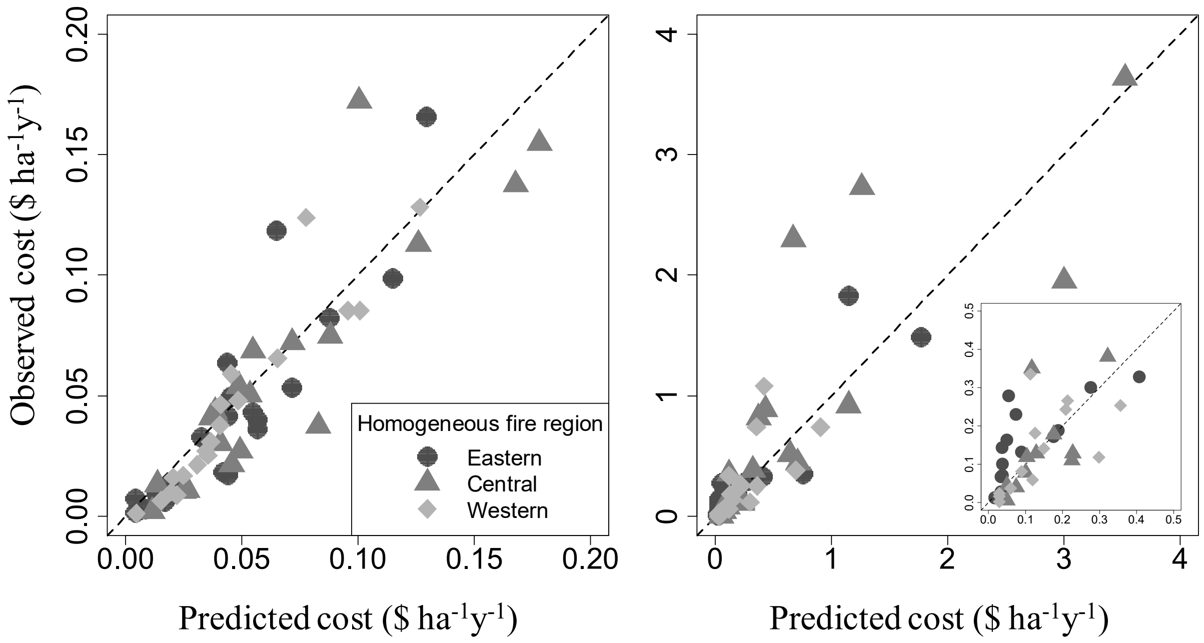

Figure 3.3. Observed and predicted annual fire suppression costs for: a) controlled fires, and b) escaped fires with an inset figure for small x-axis, in three homogenous fire regions.

3.3.1.3. Calculation of fire management costs

The annual number of escaped fires is significantly related to presuppression expenditures (Eq. 3.9, Table 3.2). Simulations with the landscape dynamics model helped visualize the impact of changing presuppression expenditures on the burn rate. There is asymptotically declining mean and median burn rates and a decreasing variability with respect to increasing presuppression expenditures (Fig. 3.4, upper panel). Above all, box plots of Figure 3.4 (upper panel) provide probabilities of occurrence of a given burn rate as a function of a level of pre-suppression expenditure: for example, the probability of observing in the central fire region an annual burn rate larger than 0.05% y^{-1} is reduced from about 66% to 50% when presuppression expenditures are increased from \$0.40 to 1.00 ha^{-1}y^{-1}.

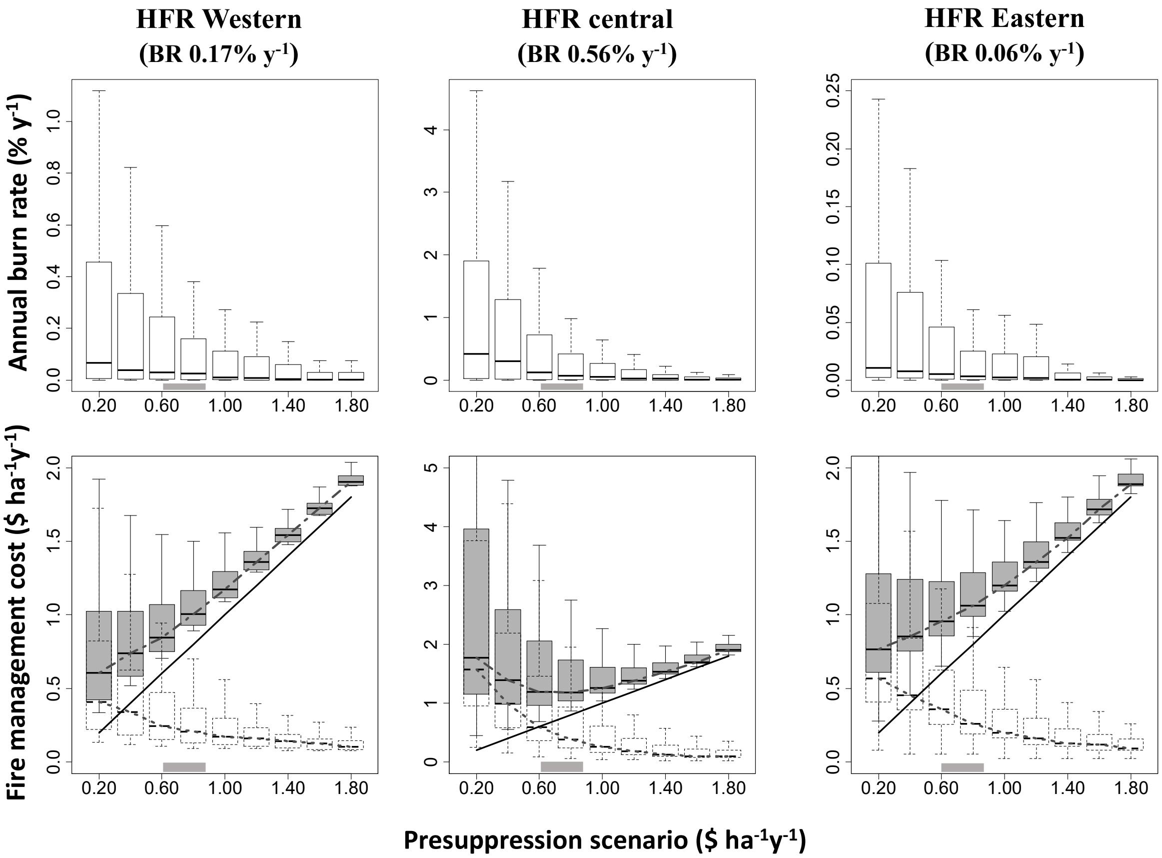

Figure 3.4. Simulated annual burn rate (BR) and fire management cost for nine presuppression cost scenarios in three homogeneous fire regions (HFR) of varying BR. Light gray with dotted boxplot is only suppression cost and dark gray with continuous line boxplot is total (presuppression + Suppression) costs. The dotted lines are median values for suppression and total costs and continuous lines are presuppression cost. Gray bars in the x axes are the approximate ranges of observed presuppression costs (1994-2014). Y-axes are presented in different scales.

Once the number of escaped fires is estimated with eq. 3.9, suppression costs can be estimated for each presuppression expenditure scenario with equations 3.17 and 3.18 (Table 3.3). Presuppression expenditures contributed to reduce the annual burn rate (Fig. 3.4, upper panel), which reduced both the inter-annual variability and the median level of suppression costs (Fig. 3.4, lower panel). For example, median suppression costs lowered in the central fire region from \$0.97 $ha^{-1}y^{-1}$ (\$0.19 - 6.54 $ha^{-1}y^{-1}$) to \$0.25 $ha^{-1}y^{-1}$ (\$0.06 - 1.62 $ha^{-1}y^{-1}$) when presuppression expenditures were increased from \$0.40 $ha^{-1}y^{-1}$ to \$1.00 $ha^{-1}y^{-1}$, respectively. When summing the two types of costs (presuppression and suppression), median values for minimum fire management costs were \$1.18, 0.77 and \$0.61 ha^{-1} y^{-1} in the central, western and eastern fire regions, respectively, for presuppression expenditures of \$0.80, 0.20 and 0.20 $ha^{-1}y^{-1}$ (Fig. 3.4, lower panel). These numbers need to be compared to median annual fire management costs spent between 1994 and 2014: \$1.16 (0.63 - 4.73), 0.95 (0.63 - 1.97) and 0.95 (0.64 -2.80) $ha^{-1}y^{-1}$, for the central, western and eastern fire regions respectively.

3.3.2. Economic value of fire management

3.3.2.1. Periodic flows of revenues

Implementation of the optimal harvest schedule with the landscape dynamics model through a replanning process provided approximately non-declining periodic revenues from primary-processed wood products, except for forest management unit 094-52, where revenue declined slightly over time (Fig. 3.5). Increasing presuppression expenditures increased the median periodic revenues and reduced periodic revenue variability (Fig. 3.5). Relative revenue differences between presuppression expenditure scenarios varied as a function of the burn rate, with the highest differences observed for the management unit 026-65 (central region – highest burn rate) and the lowest observed for the unit 094-52 (eastern region – lowest burn rate) (Fig. 3.6). For example, in the central forest management unit (026-65), the median revenue for the first two periods increased from \$15.7 to \$22.1 ha^{-1} y^{-1} when presuppression expenditures were increased from \$0.4 to \$1.0 ha^{-1} y^{-1} (Fig. 3.6 upper panel).

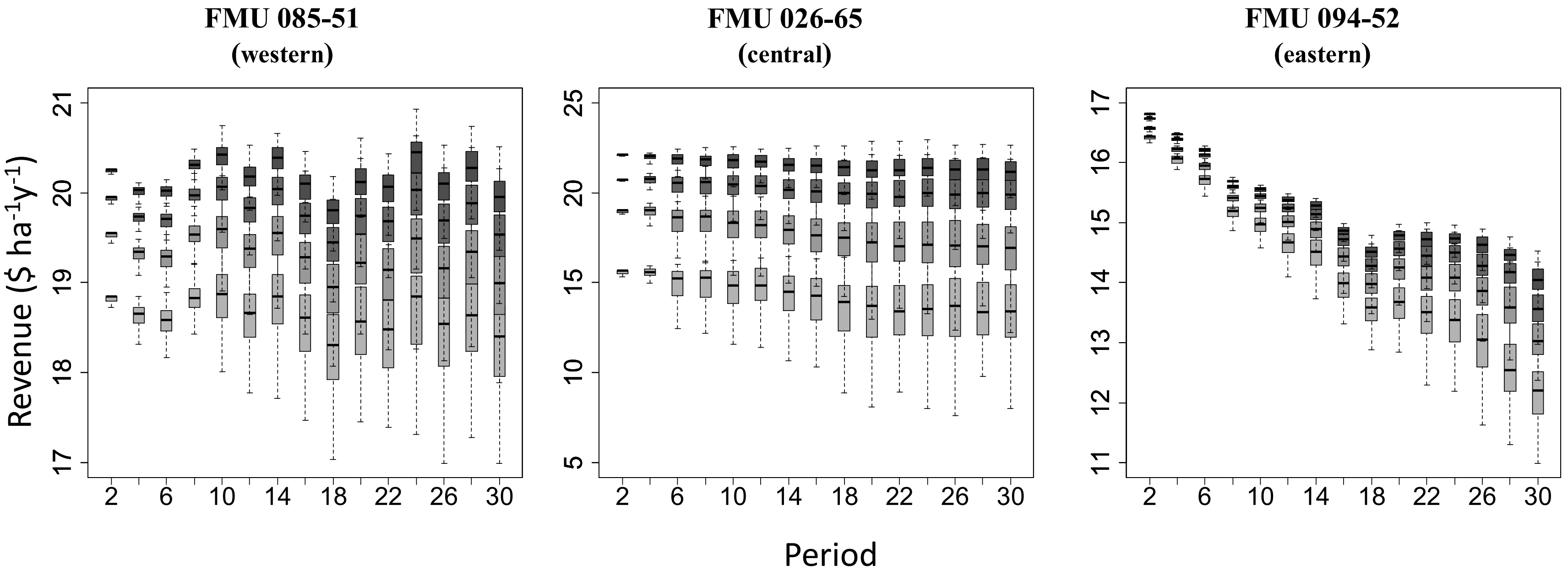

Figure 3.5. Annual revenue generated in three forest management units (FMU) by period from 100 times repeated simulation. Of the nine scenarios evaluated, only four scenarios between \$0.40 ha^{-1}y^{-1} (lower-most boxplot) and \$1.00 ha^{-1}y^{-1} (upper-most boxplot) are presented here. The presented four scenarios are for presuppression expenditure of \$0.40, \$0.60, \$0.80, and \$1.00 ha^{-1}y^{-1}. Y-axes are presented in different scales for three FMUs to compare the outcomes primarily among the scenarios within each FMU.

The values of the burned timber, which were financially beneficial to harvest (stands of age above than minimum age of harvesting), varied by the flammability of forest and annual burn rates corresponding to the presuppression scenarios. In the most flammable forest (FMU 026-65) the timber values burned were estimated to be \$7.80 ha^{-1}y^{-1} (\$2.80 - \$26.17 ha^{-1}y^{-1}) and \$0.16 ha^{-1}y^{-1} (\$0.57 - \$5.54 ha^{-1}y^{-1}) (Fig. 3.6 lower panel) when the annual burn rates vary between 0.31% y^{-1} (0.00 - 4.1%y^{-1}) and 0.05% y^{-1} (0.00 - 0.76% y^{-1}) for the presuppression scenarios of \$0.40 and \$1.00 ha^{-1}y^{-1}, respectively resulting from the first two periods NPV losses of 34% and 7% (Table 3.4).

3.3.2.2. Benefit-cost analysis

We can monitor the marginal changes in simulated realized revenues for the first two planning periods and simulated fire management costs as a function of presuppression expenditure scenarios (Fig. 3.7). Benefit-cost analyses realized with median values showed that optimal presuppression expenditures are \$1.40, \$1.80 and 0.60 ha^{-1}y^{-1} for western (085-51), central (026-65) and eastern (094-52) forests management units, respectively.

Wilcoxon ranked-sum tests showed that presuppression expenditures lower than \$1.20, \$1.60 and.0.40 ha^{-1}y^{-1} (Fig. 3.7) produced median marginal revenues significantly (5% error level) less than median marginal fire management costs in western, central and eastern forests management units, respectively.

Table 3.4. Median values of annual burn rates, timber burned values (first two periods) and net present values (NPV, first two periods) in three forest managemetn units.

Presuppression Scenario ($ $ha^{-1}y^{-1}$)	**Western FMU (085-51)**			**Central FMU (026-65)**			**Eastern FMU (094-52)**		
	Burn rate (% y^{-1})	Burned value ($ $ha^{-1}y^{-1}$)	NPV ($ ha^{-1})	Burn rate (% y^{-1})	Burned value ($ $ha^{-1}y^{-1}$)	NPV ($ ha^{-1})	Burn rate (% y^{-1})	Burned value ($ $ha^{-1}y^{-1}$)	NPV ($ ha^{-1})
No (ignored) fire	0.0000	0.00	172.4	0.0000	0.00	195.3	0.0000	0.00	139.8
1 (0.20)	0.0669	2.9	148.4	0.4195	12.8	92.2	0.0106	3.65	131.8
2 (0.40)	0.0392	2.1	154.9	0.3056	7.8	128.7	0.0076	2.45	135.0
3 (0.60)	0.0305	1.4	160.7	0.1223	4.7	156.2	0.0050	1.66	136.2
4 (0.80)	0.0247	1.0	164.0	0.0707	2.8	170.5	0.0031	1.16	137.6
5 (1.00)	0.0107	0.7	166.5	0.0501	1.6	181.6	0.0022	0.83	138.2
6 (1.20)	0.0073	0.5	168.0	0.0283	1.0	186.8	0.0017	0.49	138.9
7 (1.40)	0.0043	0.4	169.5	0.0250	0.5	190.6	0.0006	0.32	139.1
8 (1.60)	0.0023	0.3	170.4	0.0058	0.3	192.5	0.0004	0.22	139.4
9 (1.80)	0.0018	0.2	171.0	0.0033	0.2	193.7	0.0001	0.17	139.5

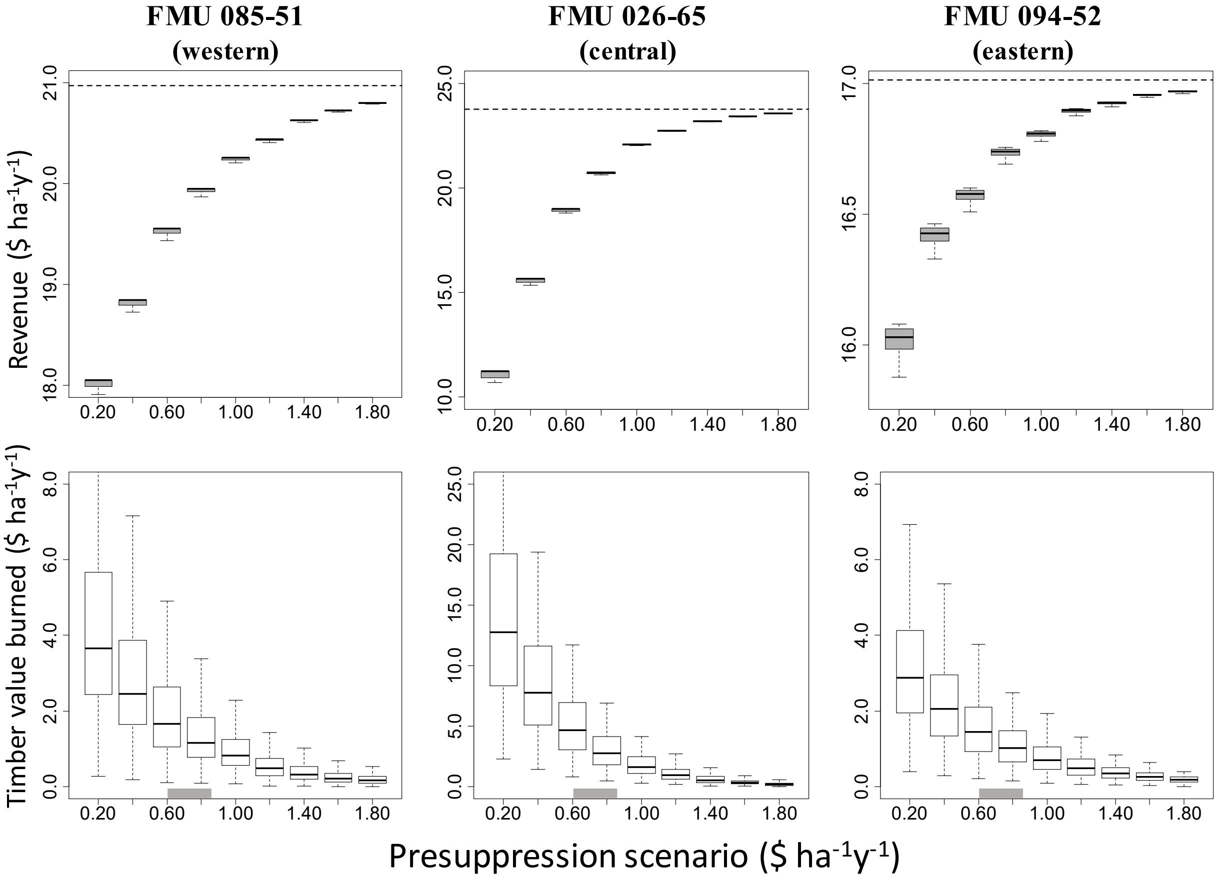

Figure 3.6. Revenue generated using timber harvest models (upper panel) and timber value burned (timber of the age above than minimum age of harvesting, lower panel) in the first two periods in three forest management units (FMU). The gray bars in the x-axis show the observed ranges of presuppression cost. The horizontal dotted lines are the revenues obtained when the impacts of fire were ignored. Y-axes are presented in different scales for three FMUs to compare the outcomes primarily among the scenarios within each FMU.

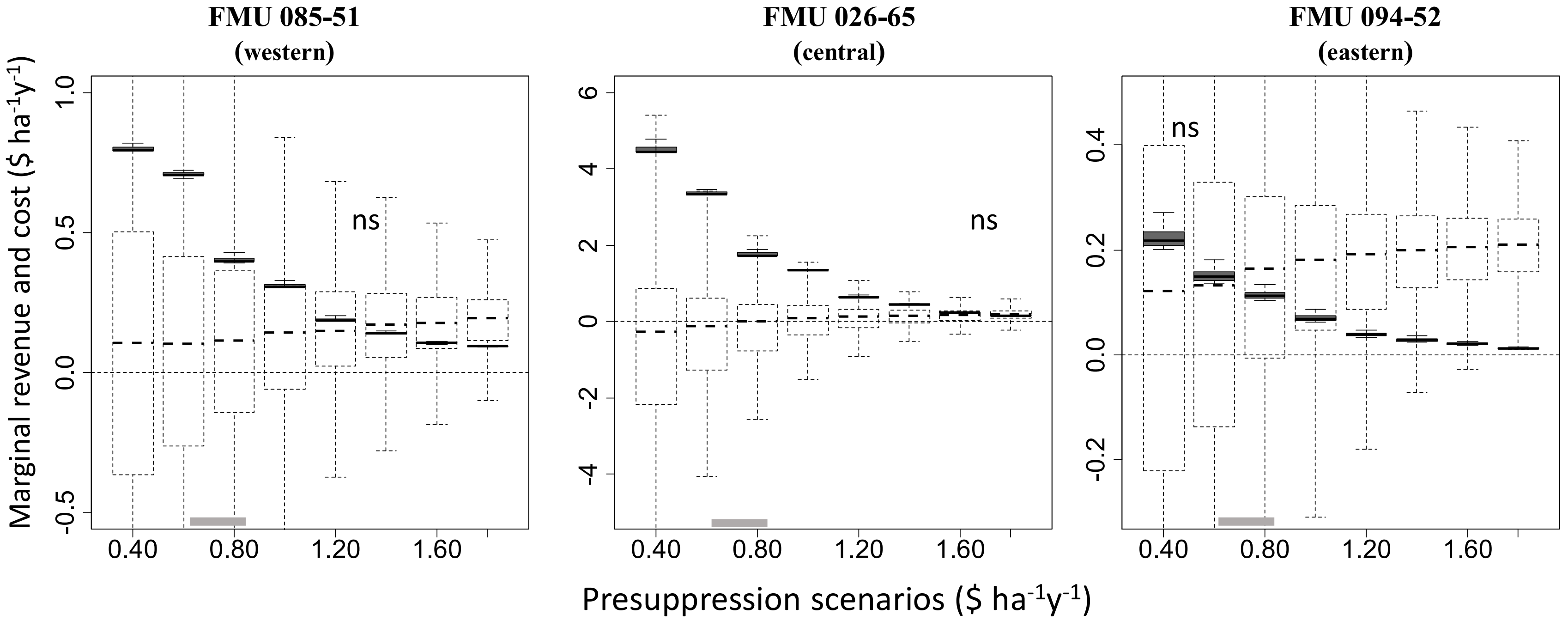

Figure 3.7. Boxplot of marginal revenue (dark with continuous lines) and marginal fire management cost (white with dotted lines) against nine presuppression scenarios in three forest management units (FMUs) for the first two periods. The Wilcoxon rank-sum test (for two sample median) shows that the presuppression scenarios left to *ns* (not significant) reject the null hypotheses implying marginal revenue is greater than marginal cost at 5%. The gray bars in the x-axis show the observed ranges of presuppression cost. Y-axes are presented in different scales for three FMUs to compare the outcomes primarily among the scenarios within each FMU.

3.4. DISCUSSION

The fire escape model, which we constructed for sensitivity analysis, was parsimonious with only two significant parameters for all three homogeneous fire regions (Table 3.2), and it explained most of the observed variability of fires. Increasing presuppression expenditures is significantly related to a decrease in the number of fires escaping initial attack (Eq. 3.9, Table 3.2, Cumming, 2005). With the data we have used, this relationship varies depending on the fire region (parameter $\beta_{h.2}$ in Table 3.2; Podur and Martell, 2007), and the annual number of fire. Moreover, we explicitly demonstrated that the trajectory of the burn rate with respect to presuppression cost converges asymptotically to zero following a roughly negative exponential (Fig.3.4, upper panel) along with a decreasing variability. Further, we corroborated empirically the theoretical model of Martell and Boychuk (1997) for estimating suppression costs but we had to parameterize this model separately for controlled and escaped fires (Table3.3) in order to better account for the bimodal nature of suppression costs.

An increase in presuppression expenditures theoretically results in a reduction of suppression costs (e.g., Bellinger et al., 1983; Simard, 1976) and our sensitivity analysis confirmed this expected relationship (Fig. 3.4, lower panel), even in a stochastic framework, which presented the opportunity of cost savings (Bratten et al., 1981-Fig. 25). Increasing presuppression expenditures not only reduced the burn rate and increased expected periodic revenues from harvest and wood processing, but it also reduced their intra- and inter- period variability over the entire planning horizon (Fig. 3.5). This is particularly important as it contributes to reducing the risk of timber supply disruptions, even when fire impact is already accounted for in the harvest planning model (Eqs. 3.4-3.6). The suppression cost tended to stabilize due to very smaller area burned for the larger amount of presuppression costs (Fig. 3.4). It indicated that beyond a certain point increasing the presuppression cost has no substantial effect on reducing the burn rate. It presents that fire managers should carefully examine the potential impacts of the investment on value added revenue while allocating the budget for fire management.

Likewise, our study is consistent with Martell (1994)'s finding that net present value increased by reducing the burn rate, but we have extended our analysis to characterize the range within which it would be valid and gradients between consecutive scenarios successesively in a stochastic framework. The negative gradient of suppression cost cannot pay off the positive gradient of presuppression cost after some cut-off point in the presuppression scenarios (Fig. 3.4, lower panel). It happens because the losses of timber value are small for the larger amount of presuppression cost (Fig. 3.6, Table 3.4) which indicated that increasing the presuppression cost might not have substantial effect in increasing the value beyond the cut-off point. The cut-off point, where the benefit to cost ratio becomes 1, is the optimal level of investment for fire management. Any amount of investment above the optimal point cannot be offset. We presented the result for the research question of how far the fire management cost had positive impact on the value addition to timber supply planning in commercially-managed forest. This empirical research demonstration helps to evaluate the trade-off between fire management costs and potential value losses due to fire in commercial forests that Podur and Martell (2007) left as an "avenue of future research" while modeling the probability of escape with respect to fire management.

Increasing the presuppression cost not only reduced the burn rate and hence reduced the suppression cost, but it also produced more value recovery by reducing the loss of revenue by period through a planning horizon (Fig. 3.5). Risk analysis as a decision support tool in wildfire management is rapidly growing in the past decades (such as, Mees et al., 1993) but limited to small fires (e.g., Fried et al., 2006) and research related to it is still sparse (Miller and Ager, 2013). We accounted for both of the suppression cost and revenue from the sale of harvest and processed wood stochastically in response to impacts on them while dealing with stochastic fire. Hence, our analyses yielded stochastic impacts of fire management on revenues and suppression costs that have been presented in terms of distribution for each examined presuppression scenario. If we are concerned about risk management for the potential impact of fire, increasing presuppression cost may be another mitigation measure up to the certain point of investment, where we can realize decreasing variability and increasing revenue. This is particularly important if we have to reduce the risk in a flammable forest, where accounting for the impact of fire in the planning model is not sufficient to reduce up to the desired level of risk (such as, Savage et al., 2010) or accounting for fire in the model hugely reduces the harvest value. Such a reduction immediately poses a crisis to the value-added industrial wood supply.

This result delivers a message that increasing presuppression cost can reduce the risk of annual timber supply disruption by reducing the variability and increasing the harvest, and hence, increase the expected values of simulated realized revenue. The relationship between risk and variability exists in such a way that the higher the variability, the higher the risk as presented by Savage et al. (2010, 2011), and Rijal et al. (Chapter 1) considered the expected values showing that in addition to reducing the variability, increasing the revenue (potent) reduces the risk. Further analysis of relative gradients of net value changes with respect to varying cost in three forest management units using benefit cost analysis shows how far the fire management cost would be cost efficient to add the revenue from the sale of primary-processed wood obtained from the harvest models simulation. There are two factors, namely, burn rate and site productivity, which determine the limit of investment up to which any investment would be financially efficient. It is rational that more flammable forest may require more investment to manage fire and increase value because the higher the burn rate, the bigger the expected loss, as presented by Rijal et al. (Chapter 1). The higher the burn rate, the more the gradient of impacts on suppression cost (Fig. 3.4) and revenue generated (Fig. 3.6) between the two consecutive presuppression scenariaos among the examined three FMUs, which shows that the impact of per unit pressuppresion cost is the highest in the most flammable forest (Fig. 3.7).

When the burn rate is sufficiently small, which is with the median and mean values of 0.005% y^{-1} and 0.03% y^{-1}, respectively in all of three FMUs, it cannot outweigh the cost incurred for fire management. When the total cost (presuppression and suppression) reaches the minimum (optimal) point then increases due to the constant increase in presuppression and relatively stabilized suppression costs (Fig. 3.4). Earlier, Savage et al. (2010) recommended that annual burn rate lower than 0.45%y^{-1} does not necessitate accounting for the fire in the harvest-volume maximized planning model. In contrast, corroborating van Wagner (1983) our analyses with revenue-maximized planning model indicated that even smaller burn rates can have impacts on revenue and justify fire management, but it is site specific. Because all the FMUs are located in the fire intensive-protection zone, fire management is inevitable for any small scale of potential fire and its impact. Therefore, a forest manager should be able to estimate the suppression cost and determine the deficit budget from the value recovery for the forecasted fire that will escape given the specified level of presuppression cost. At present, management has been working with a wide variation of annual suppression costs as we modeled (Fig. 3.4) and observed data (≈\$0.03-3.63 ha^{-1} y^{-1} (Table 3.1). The amount and variability can be reduced by increasing the presuppression cost, which can be compensated for by reduced suppression cost and value addition from timber supply with lesser risk.

As the simplest model for the strategic planning, we dealt with only the presuppression expenditures in monetary form directly using the advantage of the availability of such data although more complex models are also in existence such as SINAMI (Rodríguez y Silva and Gonzalez-Caban, 2010). As we noted earlier, the presuppression investment may imply any fire management activity at tactical and operational level planning that helps: a) prevent fire, such as fuel management (Flannigan et al., 2009), and education and awareness campaign (Martell and Boychuk, 1997). These activities protect from fires igniting, establishing and spreading b) reducing (the chance of) large fires by early detection and enacting efficient warning systems (Martell, 2001). It enhances successful control by initial attack force (Gauthier et al., 2005; Martell and Sun, 2008) and c) apriori post-fire management (Lindenmayer et al., 2004) to reduce the possible impact of fire on properties and resources. Such details would be useful to develop fire management planning at the tactical and operational levels as KITRAL model (Pedernera and Julio, 1999).

We acknowledge the limitations of our work. In order to simplify our model with the best uses of the data we had, we constructed disintegrated forest and fire management models while calculating annual burn rates and their subsequent impacts on revenue. We were aware that harvest and silviculture activities may act as fuel management and hence help change the fire regime, which ultimately affects the harvest amount and revenue (Hirsch et al., 2001). Empirical evidence presented by Acuna et al. (2011) using integrated FireSmart model (Hirsch et al., 2001) presented the revenue gain by 8.1% compared to disintegrated model, which reduced the mean burn rate from 6% to 3.9% with the simulated harvest rate of about 1% y^{-1}. It has facilitated examining the error rate in our study to be less than 5% because the mean annual burn rate in the most flammable homogeneous fire region of our study area ranged between

2.5% y^{-1} and less than 0.02% y^{-1} in our nine scenarios and lower harvest rate (about 0.60 -0.75 % y^{-1}, Rijal et al., Chapter 1). Furthermore, our study areas belong to the natural forests that have received minimal silviculture treatments including any tending operations. Likewise, although there are several studies that assume that burn rate is independent of species composition and age structure (e.g., Armstrong, 2004; Martell 1994; Reed and Errico 1986; Savage et al. 2010; 2011), we acknowledge the use of such unproved assumptions in our study. Bernier et al. (2016) has shown that the burn rates are selective according to species composition and age structure. Nevertheless, its impact might have been minimal because our study areas belong to fire-tolerant conifer forests, and we regionalized the burn rate using homogenous fire regions, which account for landscape, forest cover and flammability (Chabot et al. 2009). These are the spatial determinant attributes of fire regimes.

3.4. CONCLUSION

Despite increasing concerns over the financial efficiency of fire management costs or setting an objective to reduce the costs in response to political debates over ever-increasing investment, substantial studies about the financial impact of fire management at the commercial forest management strategic planning do not exist. Our study can be helpful in this respect. We found that the burn rate decreases asymptotically to zero against increasing presuppression cost, but it is financially efficient within a specified limit of investment, and the gradients and the limits varied, based on forest and fire regime. The presuppression cost can be paid off by reducing the suppression cost and by increasing the sale value of products, and hence positive efficiency is achieved within the specified range. Moreover, increasing presuppression reduces the variability of suppression costs and revenues from harvest timber, and hence reduces the risk of industrial supply disruption due to fire. We confirm our hypotheses that: a) we can obtain financial efficiency (positive benefit) up to a certain level of presuppression cost, and b) increasing costs reduce the risks of timber sale values and suppression costs. We show that when the timber harvest planning requires reducing the risk due to forest fire, it is suggested that the presuppression cost be increased in addition to accounting for the fire in the planning model. It will help to evaluate the trade-off between increased cost and correspondingly decreased net value loss, and how far the protected timber can compensate the cost of fire management as well as increase the value of timber harvest. Our analysis procedure may be a useful tool in allocating fire management fund to increase value of investment in commercial forest management.

ACKNOWLEDGEMENTS

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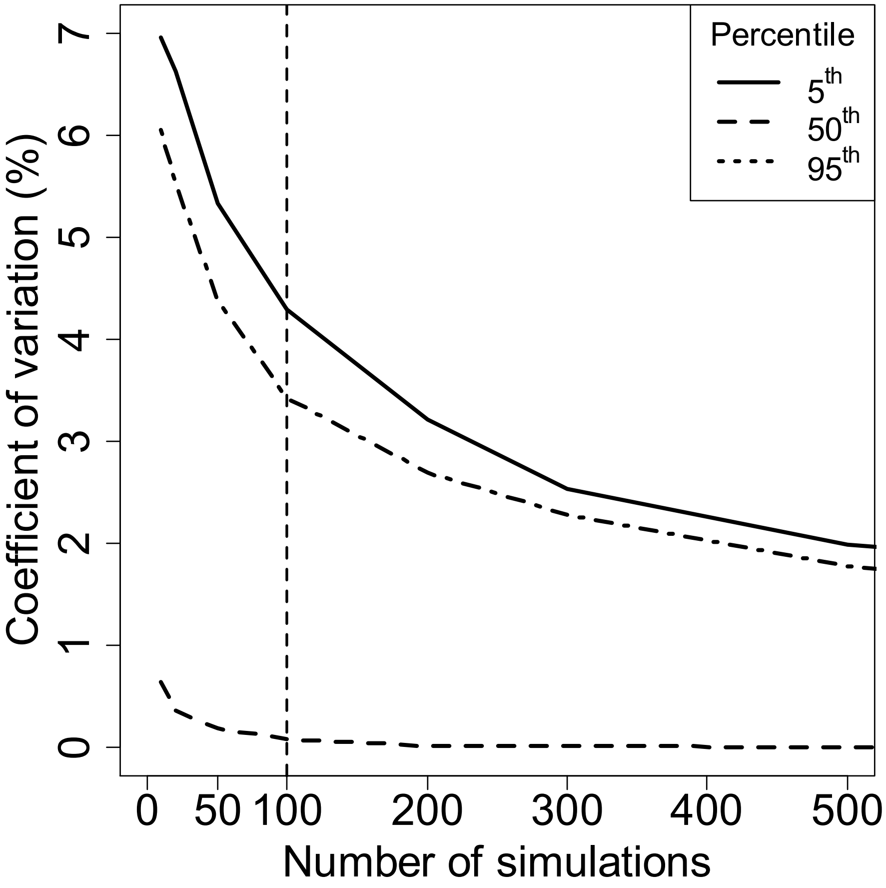

Supplementary Figure 3.1. Determination of the required number of simulations: coefficient of variation of the 5th, 50th and 95th percentiles of marginal difference of revenues between two lower most scenarios (\$0.20 and \$0.40 ha^{-1}y^{-1}) in the most flammable forest using timber harvest model. The percentiles are constructed for each number of simulation by 1,000 times random draws from a pool of 1,000 simulations.

CHAPTER 4. AN ASSESSMENT OF THE POTENTIAL ECONOMIC IMPACT OF PRESERVING OLD-GROWTH FOREST USING DIFFERENT STRATEGIC FOREST MANAGEMENT POLICIES IN THE FIRE-PRONE BOREAL FOREST REGION OF QUEBEC, CANADA

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4.0. ABSTRACT

Old-growth forest is important for sustaining both biodiversity and the bio-economy but, fire disturbances and commonly-used harvest practices can have adverse impacts on old-growth forests, and gradually depreciate forest values over time. It is well documented that different harvest planning policies, when implemented, prescribe various harvest levels. However, the impacts of the planning on the preservation of old-growth forest are less documented. The objective of this study was to examine the capacity of three harvest policies to lower the risk of adverse impacts on revenues when implementing the policies with a constraint of preserving a minimum of 20% old-growth area. We constructed three strategic timber harvest-scheduling models to implement the policies. The models were simulated using data obtained for three forests with different fire regimes. The model solutions without the constraint did not help retain at least 20% old-growth area over the 150-year planning horizon. However, the proportions were slightly higher using model 3 (maximized revenue of processed timber) than in model 1 (maximized timber volume). Model 2 (maximized revenue of timber) behaved similarly to model 1 except it did not prescribe harvesting in the distant strata. When we implemented the constraint, model 3 yielded the highest revenue with the least variation as in most flammable forest, where model 3 yielded the revenue of \$11.7 $ha^{-1}y^{-1}$ (\$0 - 12.8 $ha^{-1}y^{-1}$) compared with model 1 (\$6.4; 0 - 21.6 $ha^{-1}y^{-1}$) and model 2 (\$6.3; 0.0 - 19.5 $ha^{-1}y^{-1}$). Model 3 also increased the probability of realizing feasible solutions to 0.87 - 1.0 compared to the probability of 0.71 -0.83 using model 1 with the constraint. Hence, the third policy facilitated the retention of old-growth forest with the least impacts on revenue, and helped preserve value of forest with less risk.

Keyword: *fire, harvest policy, old-growth forest, optimization, simulation, timber supply*

4.1. INTRODUCTION

Timber supply, defined as an amount of timber available for harvest from a specific forest over time, is an important aspect of commercial forest management. The supply during any period depends on the management (e.g., silviculture treatments and harvest schedule), the disturbance regime experienced during the preceding periods and the long-term site productivity. Long-term timber supply is routinely projected using simulation or optimization models, which specify the optimal harvest and silviculture schedule in interaction with forest structure, growth dynamics and forest management objectives. Such long-term harvest plans are periodically revised to consider unpredictable changes in forest structure and production or to accommodate the impacts of disturbance events on the supply. Typically, only the planned activities for the first period are implemented ensuring the long-term even-flows of harvest in the current forest management policy and practices. Traditional forest management is guided by sustained-yield harvest policies that maximize a constant harvest volume throughout a planning horizon (Davis et al., 2001; Gunn, 2007). They respect the sustainability (non-declining) of forest timber supply but have received increasing criticism due to lack of consideration of ecological sustainability (Millennium Ecosystem Assessment, 2005). In some cases, it may also prescribe uneconomic harvest flows (Gunn, 2007). In addition, Faustman's 1849 classical model, which maximizes the stand-level net present value (NPV), is also used for forest harvest planning, but the rotation age is sensitive to the discount rate (Clark, 2005) and it does not respond to industrial requirements (Gunn and Rai, 1987). There are many studies dating back to the 1980s that show the necessity of including economic factors in strategic forest management planning to account for the value of harvest. Alternative forest harvest policies and modeling frameworks were also suggested based on explicit economic principles in an integrated framework with wood industry (e.g., Barros and Weintraub, 1982; Gunn and Rai, 1987). However, the policy of maximizing volume production with a non-declining flow over time is still a deeply-rooted guiding principle in timber harvest planning in many countries including Canada (Natural Resource Canada, 2007). Both harvest policies (harvest volume or NPV maximization) account for forest growth process but neither account for ecological sustainability while designing strategic planning. The conflicts between the production of commodity and ecological service are not new (Mönkkönen et al., 2014; Nalle et al., 2004). Sustained timber volume-based harvest plans of natural forest rapidly depreciate economic values and accelerate harvest rates over the planning horizon that threaten the economic success of forest management (Rijal et al., Chapter 1).

Conservation of the ecological integrity of managed forests is an important aspect of sustainable forest management. Ecosystem-based forest management has been introduced to maintain the natural ecosystem integrity by narrowing the gap between the natural processes of forest growth, e.g., (re-)initiation and establishment, and commercial forest management (Gauthier et al., 2009). The natural process of Canadian boreal forest growth and development is influenced by fire disturbances (Johnson, 1996). The forests in some regions are characterized by the existence of a high proportion of old-growth forest area (e.g., 47 -74% in Quebec, Bouchard et al., 2015). Old-growth forests have been defined in many ways (Wirth et al., 2009). In this paper, we considered the old-growth stand when it enters re-initiation phase (Oliver, 1980) or when post-disturbance cohorts start dying (Franklin et al., 2002; Kneeshaw and Gauthier, 2003). This consideration matches forest harvesting activities with forest gap (shape, size and frequency) dynamics of natural disturbance and is a key attribute of ecosystem-based forest management (Hunter, 1993). From an ecological point of view, old-growth forest stands have higher structural and functional diversity than younger stands (Chambers and Beckley, 2003). Therefore, the total area of old-growth stands on the landscape scale is one of the indicators of structural diversity (Fall et al., 2004; Powelson and Martin, 2001). The preservation of old-growth forest is also a concern of industrial forest management of matured timber supply for better wood quality (e.g., British Columbia, Burton et al., 1999). Moreover, when the impact of fire is accounted for in the volume-maximized model, the rotation cycle and old-growth forest area decrease (Martell, 1980; Savage et al., 2011).

Many management solutions can be considered to improve the proportions of old-growth forest area and economic productions. Several studies have shown that harvest activities affect age structure (e.g., Barclay et al., 2006; Didion et al., 2007; Fall et al, 2004) and not surprisingly, have economic consequences (Binkley et al., 1994; Horne et al., 1991). Harvest disturbances to forest ecosystems can be reduced by retaining a portion of the old-growth stands (Seymour and Hunter, 1999), or by lengthening the rotation cycle (Koskela et al., 2007). In order to conserve forest ecosystems, revised forest management policies that ensure the preservation of at least some specified proportion of old-growth forest area is recommended (e.g., in Quebec, Bouchard et al., 2015; Jetté et al., 2013). However, the adoption of such policies may reduce harvest volume allocations and increase the variability of harvest volume. In some cases, the optimization problems do not have feasible solutions, which results in zero (no) harvest volume during some periods (Conrod, 2010; Savage et. al, 2011). Such fluctuation or zero-harvest situations jeopardize economic opportunities. We suggest that harvest planning policies should aim to minimize the potential adverse impacts on the economic opportunities when we implement old-growth forest area constraint to meet its strict requirement in forest management. A possible option may be to employ alternative harvest policies that increase efficiency on revenue production, which implies high-value harvest prescriptions rather than maximizing volume production in a sustainable way. On another hand, reductions of harvest area (rate) lower the impact of fire on harvest flows (van Wagner 1983, Fig. 2). Rijal et al. (Chapter 1) demonstrated that primary-processed wood value embedded in a planning model can reduce the harvest rate and at the same time increase the economic value of the forest by deferring the harvest age until trees gain more processing value. Age deferral also enhances the proportion of old-growth stands in the forest. In this study, we attempt to examine whether such value-embedded model would be an alternative method of lowering the adverse impact on economic production when minimal proportion of old-growth forest area requirements are implemented.

The primary objectives of this study are to examine: a) the impacts of implementing different harvest planning policies on preserving old-growth forest area and b) the impact of those policies on timber harvest revenue while meeting the strict requirements of the old-growth forest levels. Three harvest planning policies were evaluated. The first policy maximizes the harvest volume subjecting to long-term even-flow of harvest volume over the planning horizon. The second policy maximizes the net present value (NPV) from the sale of harvest volume with the same constraint. The third policy maximizes the NPV for the first two periods from the sale of primary-processed products subjecting to even-flow of high-value products over the planning horizon. We constructed three harvest scheduling optimization models, one for each policy and with or without retaining the minimum target level of the old-growth forest. We inferred the results by comparing medians and fluctuations of three model-outcomes: a) proportion of preserved old-growth forest, b) revenue generated by harvesting, and c) harvest area. We used the data taken for three commercially-managed boreal forests in the province of Quebec in Canada.

4.2. METHODS

4.2.1. Study area

The boreal forest region is the most fire-prone commercial forest in the Province of Quebec. It has been subjected to increased anthropogenic disturbances as timber harvesting activities gradually extended towards the north (Powers et al., 2013). We selected three forest management units (FMUs), each of which represents a distinct provincial forest administrative jurisdiction located in the boreal region (Fig. 4.1). We attempted to cover varying initial age structure (dominated by the immature and the old-growth stands) as an indicator of varying previous harvest and fire regimes. These three management units are in the spruce-moss bioclimatic domain within the continuous boreal forest subzone (Robitaille and Saucier, 1998). Although black spruce (*Picea mariana* [Mill.]) dominates the region, jack pine (*Pinus banksiana* Lamb.), a species well adapted to fire, is abundant in the central part of the study area (FMU 026-65). It represents the most flammable forest in the boreal region (with the mean annual burn rate of 0.48% y^{-1}, as we estimated using empirical data for the period 1971-2014, detail follows) and relatively longer history of harvesting activities. The forest is dominated by immature (≤50 years old) stands (43% of total area) and lower proportion (21%) of old-growth (≥100 years old, Jetté et al., 2013) compared to the historical proportion of old-growth forest area (mean = 47%; range = 30 - 65%: Bouchard et al., 2015 -Annex c). Balsam fir (*Abies balsamea* [L] Mill.), a species that is less well adapted to fire, increases considerably in the eastern part (FMU 094-52). The eastern forest is dominated by old-growth forest (73%) having the least immature (10%) stands (Fig. 4.1), which may be due to newly introduced harvest activities (<30 years; Bouchard and Pothier, 2011) and a low annual burn rate (0.06%y^{-1}) compared with other two FMUs. The western management unit (FMU 085-51) is located in the Clay Belt area where forests are often interspersed with forested peatlands because of dominant clay and organic deposits (Robitaille and Saucier, 1998). This management unit has been intensively harvested since the 1970s (Belleau and Légaré, 2009) and is characterized by a dominance of immature (51%) and fewer (24%) old-growth stands. The forest has an intermediate mean annual burn rate of 0.13% y^{-1} that represents the average fire regime in the commercial forest of Quebec. Black spruce, jack pine and balsam fir are harvested for lumber and pulp (Liu et al., 2007).

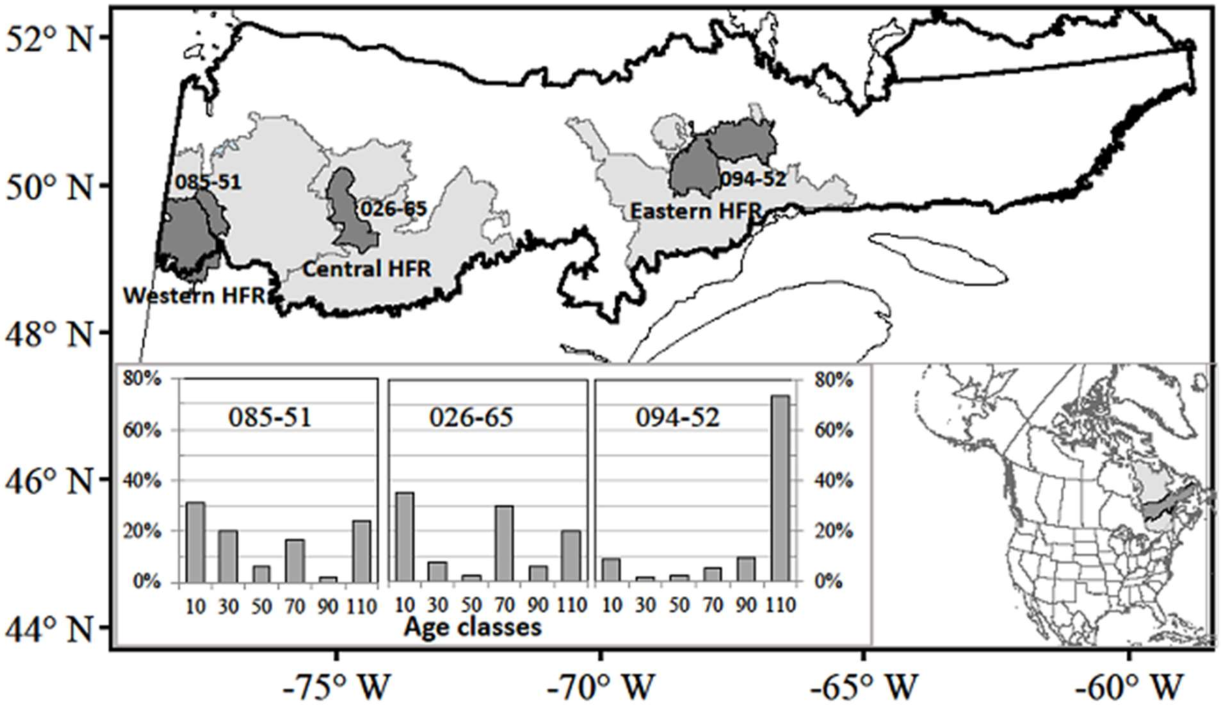

Figure 4.1. Study area showing the boundary of spruce-moss forest, three homogeneous fire regions (HFR-Chabot et al., 2009, light gray) that encompass three forest management units (FMUs, dark gray). The bar plots show the age-class distribution of each FMU based on 2002-2004 inventory data.

4.2.2. Forest and timber processing data

We used four types of data, namely: a) forest inventory data, b) financial data, c) fire data, and d) spatial data. Forest inventory (2002-2004) data was obtained from Ministère des Forêts, de la Faune et des Parcs, Québec (MFFPQ). We constructed strata-based yield tables by dividing each FMU into aspatial strata based on landscape unit and cover type to better represent biogeography specific growth potentials. A landscape unit is defined as "a portion of landscape characterized by a recurrence of environmental attributes (type of relief, average altitude, nature and proportion of the main surficial deposits, hydrography) and vegetation factors" (Robitaille and Saucier, 1998). Cover types were obtained from forest stand maps prepared by the MFFPQ from the interpretation of aerial photographs taken at the scale of 1:15,000. We then aggregated the forest stands into strata as a function of landscape unit and cartographic species composition by considering the two most important softwood species in each stand. Each stratum was an aspatial collection of stands of relatively homogenous forest-cover type within the spatially mapped landscape unit belonging to the same forest and hence the stratum consisted of a mixture of species and age classes (Table 4.1).

The merchantable volume (diameter at breast height ≥ 9 cm.) yield tables were generated using a growth model NATURA-2009 (Pothier and Auger, 2011) based on forest inventory (temporary sample plots) data available from the MFFPQ. It is a stand-level dynamics model that consists of three sets of five equations. They predict the periodic progression of stem density, basal area and timber volume per species group (shade-intolerant or tolerant softwoods, balsam fir) as a function of age and other stand variables iteratively. In this study, we considered only three softwood species groups (spruce, pine and fir) because of their dominance in the area (Table 4.1). We considered lumber, chips and sawdust as primary processed forest products. The products yield tables were derived from the empirical models developed by Liu and Zhang (2006), Zhang and Tong (2005) and Liu et al. (2009) for black spruce (tolerant softwood), jack pine (intolerant softwood) and balsam fir, respectively, using the outputs from NATURA model. The volume and transformed product yield tables for all species groups were summed for each stratum and smoothened to construct a single yield table using a non-parametric smoothing (*lowess* in R; R Core Team, 2014).

We used the data provided by Tembec Inc. (a forest company) in 2007 for the western forest (FMU 085-51), to estimate the costs of forest management, harvesting and transportation from stump to mill gate (Pasturel, 2013). To estimate transportation costs from the forest to the mill we assumed all harvested timber would be taken to the closest primary processing mill for each FMU from a publicly available list of mills active in 2009 (MRNFQ, 2009). We assumed the designated softwood sawmill would convert the timber into lumber, chips and sawdust. We then used a network analysis in ArcGIS 10.2 (ESRI, Redlands, USA) to estimate the driving distance between each landscape unit centroid and the assigned mill with using forest road network data (Adresses Québec, 2015). The transportation cost was estimated using a linear relationship between cost and distance using Pasturel (2013: Fig. H-1) assuming a constant road and driving condition. The same analysis procedure was used to estimate transportation costs for central and eastern forests. The selling price of timber at stump site was kept constant for all three forests by using the average from the western forest (Pasturel, 2013).

Table 4.1. Summary statistics of the spatial data for the three forest management units (FMU).

FMU	Total area (km^2)	Productive area (km^2)[1]	SPF[2] abundance (%)	Number of strata	Area of strata, mean (min – max), ha.	Transportation distance, mean (min – max), Km.	Initial state of old-growth forest (% of productive area)	Mean annual burn rate (% y^{-1}; 1971 -2014)
Western (085-51)	9,857	5,734	80	52	14,335 (39 – 138,552)	65 (31 – 120)	24	0.13
Central (026-65)	4,572	3,188	92	38	11,384 (5- 72,960)	162 (131 – 230)	21	0.48
Eastern (094-52)	9,095	6,954	96	70	10,399 (8 – 247,645)	196 (140 – 255)	73	0.06

[1] Forest area that is producing at least 50 m^3/ha of merchantable timber (diameter at breast height ≥ 9 cm) over a 150 year planning horizon of, with a mean timber stem volume greater than 50 dm^3 /tree.

[2] SPF denotes the spruce, pine and fir species cover type.

The transformed products from the mills were delivered to product specific delivery sites. We used the 10-year (2004-2013) average lumber selling prices delivered to Montreal market. Likewise, the 10-year average price for wood chips (Del Degan Massé, 2012) at the closest paper mill was used. The price for sawdust was taken from Pasturel (2013) and it was applied to the panel mill closest to each forest. All prices were standardized to constant 2010 dollars using the inflation calculator of the Bank of Canada (2015). Transportation cost from sawmill to product destinations varied as a function of transportation modes for truck or train (CPCS, 2013; Laurent et al., 2013) to the Montreal market (for lumber), the closest papermill (for chips) or panel mill (for sawdust). Mill capacities for processing timber were assumed to be non-limiting because these are considered as tactical level parameters (Bouchard et al., 2016; D'Amours and Rönnqvist, 2008). The details of the parameter are provided in Table 4.2.

Table 4.2. Indices, variables and parameters used in the three harvest planning models. The terms used in the table are described in the text.

Notation	Description	Value	Reference
Indices			
s	stratum (1...S; S = 38, 52 and 70 in FMUs 026-65, 085-51 and 094-52 respectively)	-	-
a	age class (1...30), 5-year interval	-	-
t	period (1...30), 5-year interval)	-	-
p	product (1...3, lumber, chips, sawdust)	-	-
Decision variables (Equations 4.1, 4.8, 4.9)			
h_{sat}	planned harvest area (ha) in stratum *s,* of age class *a,* in period *t* (obtained from optimization model), ∀ *s*, *a* and *t*	-	-

x_{sat}	[1]area of stratum s, age class a, at the start of period t (ha) obtained from optimization model, ∀ s, a and t,	-	-
Model parameters (Equations 4.2 -4.7, 4.10-4.11)			
A_f	Total forest area in FMU f	-	-
x_{sa0}	Initial area of stratum s, age class a, (ha) l, ∀ s, and a		
v_{sa}	merchantable volume of stratum s, in age class a (m^3 ha^{-1}), ∀ s and a	-	-
$a_{min.s}$	minimum harvest age (periods), ∀ s	stand volume ≥50 $m^{-3}ha^{-1}$ and individual tree volume ≥50 dcm^{-3}	Raulier et al. 2013
v_{psa}	transformed product volume (m^3 ha^{-1}), ∀ p, s and a,	-	-
$r_{timber.sm}$	revenue: merchantable timber volume selling price to mill	\$58.7 m^{-3}	Tembec 2007 (Pasturel 2013)
$r_{p.m}$	revenue: transformed product selling price at their product wise destinations (\$ m^{-3})	lumber \$155.0 m^{-3} chips \$52.0 m^{-3} sawdust \$9.0 m^{-3}	QFIC[2], 2014 Del Degan Massé 2012
c_{fs}	forest management costs (\$ m^{-3} merchantable volume)	\$39.7 m^{-3}	Pasturel 2013
$c_{pr.m}$	product processing cost at primary processing mill (\$ m^{-3} merchantable volume)	\$24.0 m^{-3}	Del Degan Massé, 2010
$c_{tr.f}$	transportation cost for harvest volume between the harvest site and the mill	\$9.0 – 25.0 m^{-3}	Pasturel (2013: Fig. H-1)

$c_{tr.pm}$	transportation cost for processed wood between mill and delivery site	lumber \$0.02 $m^{-3}km^{-1}$; chips 0.02 $m^{-3}km^{-1}$; sawdust: 0.02 $m^{-3}km^{-1}$(truck) or 0.002 $m^{-3}km^{-1}$ (train)	CPCS 2013; Laurent et al. 2013
$c_{timber.sm}$	sum of forest management and harvest and transportation costs (c_s+$c_{tr.f}$)	\$48.7 – 64.7 m^{-3}	
γ_t	discount factor for 5-year periods	rate = 4% y^{-1}	BFEC, 2013
$d_{s.m}$	distance between a landscape unit centroid to which a stratum belongs to and the closest mill (m) $\forall$ s	31 -255 km	
Simulated attributes (Equations 4.13 – 4.17)			
$\tilde{x}_{sat}$	forest area of stratum s, age class a, of at period t (ha) obtained from landscape simulation model, $\forall$ s, a and t		
$\tilde{h}_{sat}$	harvest area (ha) after accounting for the stochastic fire in stratum s, age class a, in period t $\forall$ s, a and t		

[1] in the model construction, x_{sat} act as decision variables but are generated by periodic movement of age-class using initial age class x_{sa0} subjecting to area accounting constraints as Eqs. 4.4 -4.6.

[2] Quebec Forest Industry Council

The annual burn rate for each FMU was estimated empirically (annual area burned as a fraction of total terrestrial area at the spatial scale of homogeneous fire region (HFR)) using data that described past fire events (1971 - 2014). Because forest management units were deemed too small to estimate an FMU specific fire burn rate (Boulanger et al. 2012; 2013), we used the spatial scale of HFR delimited by Chabot et al. (2009- Fig. 7), which encompasses the management units in our study area (Fig. 4.1). An HFR is a contiguous area of similar fire fuel environment (weather, topography, soil and fuel combustibility) (Chabot et al., 2009). The Société de Protection des forêts contre le feu (SOPFEU) provided us with the fire data.

4.2.3. Simulation framework

Our simulation framework consisted of two components, namely: a) a deterministic timber harvest scheduling optimization model, and b) a stochastic landscape simulation model (Fig. 4.2). The deterministic model component uses a constant burn rate over the entire planning horizon. The linear programming model solution prescribes a harvesting plan and produces a set of planned harvest attributes (harvest volume, area and revenue) and standing volume. The landscape simulation component generates the stochastic burn rate with a random draw from a pool of empirically-calculated values for each period. The landscape model interacts with the planned harvest and the simulated fire and produces simulated (we described as realized) harvest attributes, which we use for further analyses and serve as initial condition for the next replanning cycle (Fig. 4.2).

We considered three management policies in our simulation experiment. The first policy consisted of sustained yield of timber volume and attempted to maximize the harvest volume. The second consisted of sustained yield of timber volume and aimed to maximize net present value (NPV) of the harvest timber. Transportation cost from harvest site to mill was considered. The third policy was sustained yield of value-added products as well as timber volume throughout the planning horizon with NPV maximization from the primary processed products for the first two periods. We valued the harvest in terms of revenue when it was processed at the sawmill. We used our simulation framework to generate an array of possible solutions (outcomes) with respect to stochastic burn rates. We used these simulated outcomes to construct frequency (and empirical probability) distributions in addition to central tendencies (median) and 90 percentiles (±5%) confidence intervals. The following three subsections (§4.2.3.1 - §4.2.3.3) describe the processes in more detail.

We considered any stand that reaches 100 years of age or more to be old-growth (Jetté et al., 2013). In order to maintain a strict requirement of at least 20% old-growth forest by period, we added a constraint on old-growth area in all planning models. We then compared the expected outcomes obtained when we employed or did not employ the old-growth forest area constraint. Hence, we had six scenarios overall. We chose a constraint for preserving at least 20% old-growth forest area in our study to correspond to the proportion recommended in the study area. The basic retention rule is to retain between 30 and 50% of historical proportion of old-growth forest area-wise (Bouchard et al., 2015; Jetté et al., 2013).

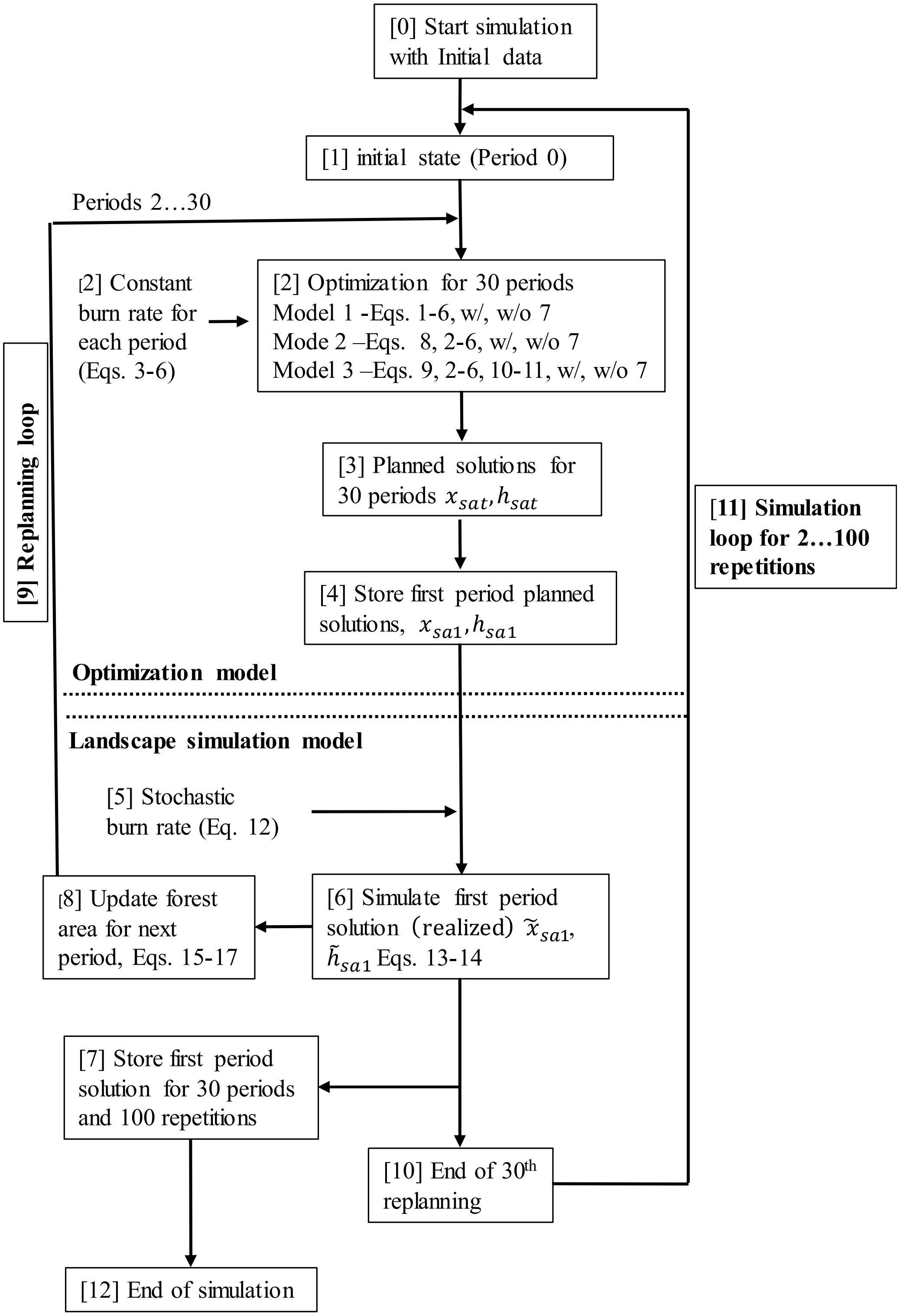

Figure 4.2. A process flow diagram of the simulation experiment. The optimization models (step 2) have with (w/) or without (w/o) constraints. The notation is defined in Table 2 and relevant texts.

4.2.3.1. Timber harvest scheduling optimization models

Corresponding to the forest management policies we evaluated, we constructed three harvest planning models, namely: a) harvest timber volume maximization over the planning horizon, b) net present value (NPV) maximization from the sale of harvested timber over the planning horizon, and c) the NPV maximization from the sale of primary-processed products for the first two periods of the planning horizon with different sets of constraints (Table 4.3). Because the first model is most common in practice, we termed this as a base model. All three models were constructed in linear programming framework using a Model III network structure in the age class movement by period while interacting among growth, fire disturbances and harvesting (Garcia 1984; Gunn and Rai 1987; Reed and Errico, 1986). The main justification for using this model is the ease of including fire disturbances (Savage et al., 2010). We used the AMPL modeling language (Fourer et al., 2003) to model the optimization problems and Gurobi 5.6.0 (Gurobi Optimization Inc., Houston, TX) to solve them.

Detailed description of the three model objective functions and constraints are presented below along with their respective notations, indices, decision variables and parameters as presented in Table 2. The model formulations below were executed separately for each FMU.

Model 1: Harvest planning model that maximizes the harvest volume over a planning horizon:

The objective function is:

$$Z = \max \sum_{s=1}^{S} \sum_{a=a_{min.s}}^{30} \sum_{t=1}^{30} v_{sa} \, h_{sat} \qquad [4.1]$$

Constrained to:

Even-flow of harvest volume:

$$\sum_{s=1}^{S} \sum_{a=a_{min.s}}^{30} v_{sa} \, h_{sa(t-1)} = \sum_{s=1}^{S} \sum_{a=a_{min.s}}^{30} v_{sa} \, h_{sat} \text{ ,} \forall \text{ t} \in \{2..30\} \qquad [4.2]$$

Table 4.3. A summary table of timber harvest policies and corresponding timber harvest planning models. Model 1 is referred to as the base model because of its wide use.

Forest management policy	Harvest planning model	Objective function of harvest planning model	Constraint implemented in the harvest planning model
Sustained yield of timber volume	Model 1 (base model)	Maximize harvest timber volume for 150 years	- Constant timber harvest volume over a 150-year planning horizon with 5-year periods
	Model 2	Maximize net present value from the sale of timber harvest for 150 years	
Sustained yield of timber volume and high-value products	Model 3	Maximize the net present value from the sale of primary-processed products for the first 10 years	- Constant timber harvest volume over a 150-year planning horizon with 5-year periods, - Timber harvest that produces a constant flow of lumber volume over a 150-year planning horizon with 5-year periods, - Timber harvest that produces distance weighted constant lumber volume over a 150-year planning horizon with 5-year periods so harvest would not be concentrated in the stands near the mill (cost constant)

The planned harvest area is limited to be less than or equal to the area that is available for harvest in each stratum, age class and period, after accounting for the fire loss in any given period:

$$h_{sat} \leq (1 - b_f)x_{sat}, \quad \forall\, s, a \text{ and } t \qquad [4.3]$$

where b_f is a constant periodic burn rate (fraction of the forest burned during each period) and used over the planning horizon and repeated simulations. We followed Reed and Errico (1986)'s assumption, where they assumed that stands burn independently with age classes. Therefore, b_f does not vary by age, stratum or period in our optimization models for the selected FMU.

Area accounting constraints:

For the youngest age class (*a=1*)

$$x_{s1t} = \sum_{a=1}^{30} h_{sa(t-1)} + b_f \sum_{a=1}^{30} x_{sa(t-1)}, \quad \forall \text{ s, a and t} \in \{2...30\} \qquad [4.4]$$

For the oldest age class (sink, *a=30*)

$$x_{s30t} = (1 - b_f) \sum_{a=29}^{30} x_{sa(t-1)} - \sum_{a=29}^{30} h_{sa(t-1)}, \quad \forall\, s \text{ and } t \in \{2...30\} \qquad [4.5]$$

For intermediate age classes (*a=2...29*)

$$x_{sat} = (1 - b_f)\, x_{s(a-1)(t-1)} - h_{s(a-1)(t-1)}, \quad \forall\, s, a \in \{2...29\} \text{ and } t \in \{2...30\} \qquad [4.6]$$

Old-growth forest area constraint at forest level:

$$\sum_{s=1}^{S} \sum_{a=20}^{30} (x_{sat} - h_{sat}) \geq 0.20 * A_f \ \forall\, t \in \{1...30\} \qquad [4.7]$$

Model 2: Harvest planning model designed to maximize the NPV of the harvest over a planning horizon from the sale of the harvest volume.

The preceding model assumes that all the harvested volumes have an equal economic value, whatever the distance between stand (harvest site) and mill, and the average tree size. This model will likely overestimate the harvested area by including volume that is not economically profitable. A first classical alternative solution to this problem is to change the model with maximization of the net present value of the harvest timber at the mill gate in the objective function. As formulated, this model aims to maximize the net present value (using present prices) by accounting for all types of forest management, harvest and transportation costs. The costs are to be deducted from the income from the sale of harvest timber at mill (entrance). It maximizes the forest economic value to the forest owner. The mathematical form of the model is given as:

$$NPV_{timber} = \sum_{t=1}^{30} [\gamma_t \sum_{s=1}^{S} [(r_{timber.sm} - c_{timber.sm}) \sum_{\mathrm{a=min.s}}^{30} v_{sa}\, h_{sat}\,]] \quad [4.8]$$

Subject to constraints: even-flow of harvest volume (Eq. 4.2), availability (Eq. 4.3) and area accounting or balancing (Eqs. 4.4-4.6), and with or without old-growth forest area constraint (Eq. 4.7).

Models 3: Harvest planning model designed to maximize the NPV from the sale of processed wood over the first two periods–an integrated model:

Maximizing NPV (model 2) is a greedy approach because it favours the most profitable action for the short-term and defers least profitable for later. Typically, all decisions taken over 50 years from now have little impact with a typical 4% compound interest rate. It tends to leave less economic opportunities for the future generations and therefore it may jeopardize the sustainability of forest for industrial wood production. To address this problem, further consideration is required to ensure the even-flow of the wood production over the planning horizon.

Model 3 was designed to maximize the net present value of primary-processed wood products produced during the first two periods because we wanted to maximize the short-term economic values (González-Cabán 2008; Szaraz 2014, *unpublished*). It may correspond to the planning horizon of primary-processing softwood sawmill (Gunn, 2007) as well. Because lumber has the highest value (price) among the three products (lumber, chips and sawdust), maximizing the net present value of primary-processed wood products will deplete the high-value timber over time by rapid exploitation during the early periods. Likewise, transportation costs may result in the harvest being prescribed from the stands located near the processing mill. This problem was addressed by considering: a) long-term even flow of lumber volume to ensure the maintenance of production quality, and b) distance-weighted lumber volume by period over the entire planning horizon to make sure the transportation cost would not increase later in the period, in addition to the even flow of timber harvest volume. The mathematical formulation of the model is:

To maximize:

$$NPV_{Products} = \sum_{t=1}^{2}\left[\gamma_t \sum_{p=1}^{3} \sum_{s=1}^{S}\left[\left(r_{p.m} - c_{fs} - c_{pr.m} - c_{tr.pm}\right) \sum_{a=a_{min.s}}^{30} v_{psa}\, h_{sat}\right]\right] \quad [4.9]$$

Constrained by even-flow of volume (Eq. 4.2), availability of harvestable area (Eq. 4.3) and area accounting constraints (Eqs. 4.4 to 4.6), and with or without old-growth forest area constraint (Eq. 4.7). In addition, this model has two more constraints:

Even-flow of lumber volume produced by the mills:

$$\sum_{s=1}^{S}\sum_{a=a_{min.s}}^{30} v_{psa}\ h_{sa(t-1)} = \sum_{s=1}^{S}\sum_{a=a_{min.s}}^{30} v_{psa}\ h_{sat},\ p = \text{lumber},\ \forall\ t \in \{2..30\} \quad [4.10]$$

Even flow of distance-weighted lumber volume:

$$\sum_{s=1}^{S}\frac{1}{d_{sm}}\sum_{a=a_{min.s}}^{30} v_{psa}\ h_{sa(t-1)} = \sum_{s=1}^{S}\frac{1}{d_{sm}}\sum_{a_{min.s}}^{30} v_{psa}\ h_{sat}\ ,\ p = \text{lumber t} \in \{2..30\} \quad [4.11]$$

4.2.3.2. Landscape simulation model

The landscape simulation model simulates the dynamics of forest age structure over the planning horizon by accounting for the cumulative impact of harvesting and stochastic fire. It uses the same equations as those used for the area accounting constraints to incorporate the effects of fire (Eq. 4.4-4.6). But the constant periodic burn rate, b_t, varies from period to period and is generated from random draws of annual burn rates that were empirically calculated based on fire data between 1971 and 2014 in the three HFR corresponding to each management unit.

Assuming the annual burn rates are independently distributed through time and the rates are equivalent to annual fire probabilities (van Wagner 1978), the burn rate that is observed during a specific time period (e.g., 5 years) is equal to the product of annual probabilities of observing no fire (complementary probability). Hence, the 5-year periodic burn rate is:

$$b_t = 1 - \prod_{i=1}^{5}(1-\beta_i) \quad [4.12]$$

The realized harvest, $\tilde{h}_{sat}$, which corresponds to the minimum of the planned harvest h_{sat} obtained from optimization model and area that is available in the same age class (a) in the same stratum (s) during period (t) ($\tilde{x}_{sat}$):

$$\tilde{h}_{sat} = \min(\tilde{x}_{sat}, h_{sat}) \quad [4.13]$$

Harvesting occurs after accounting for the fire in each period. These changes lead to the following stochastic simulation model:

$$\tilde{x}_{sa1} = (1 - b_t)x_{sa} \quad , \forall \text{ s and a} \qquad [4.14]$$

$$\tilde{x}_{s1t} = \sum_{a=1}^{30} \tilde{h}_{sa(t-1)} + b_{(t-1)} \sum_{a=1}^{30} \tilde{x}_{sa(t-1)} , \forall\ s, a \text{ and } t \in \{2..30\} \qquad [4.15]$$

$$\tilde{x}_{s30t} = (1 - b_t) \sum_{a=29}^{30} \tilde{x}_{sa(t-1)} - \sum_{a=29}^{30} \tilde{h}_{sa(t-1)}, \forall\ s \text{ and } t \in \{2..30\} \qquad [4.16]$$

$$\tilde{x}_{sat} = (1 - b_t)\ \tilde{x}_{s(a-1)(t-1)} - \tilde{h}_{s(a-1)(t-1)}, \forall\ s, a \in \{2...29\} \text{ and } t \in \{2..30\} \qquad [4.17]$$

4.2.3.3. Repeated simulation

We solved the optimization model in the periodic replanning framework (Fig. 4.2). When the optimization model was solved, a set of planned harvest attributes (timber harvest area (ha), harvest volume (m^3), the age structure of forest area (ha), the standing timber volume (m^3) and the (net) revenue ($)) were obtained by 5-year age class and 5-year period for each stratum over a 30-period planning horizon. Because we implemented the optimization model in a periodic replanning framework, we used only the first period outputs. The planned harvest volume and standing volume in the first period served as inputs to the landscape simulation model, which in turn provided the simulated realized harvest by period with respect to the stochastic periodic burn rate (Fig. 4.2). Of the realized attributes obtained from the simulated implementation of landscape model, harvest area was taken as an output to be implemented for harvesting (prescribed harvest) and it was used to readjust the available forest area for replanning at the start of the next period, and hence it served as an input for the next period. The replanning simulation process was continued through the 30th period, and the realized harvest attributes and forest area in each age class obtained in the first period of each repeated optimization were retained for further analyses.

The stochastic burn rate was integrated in the simulation process through the landscape simulation model (Eqs. 4.12 - 4.17). In response to such stochastic fire input, we constructed frequency and empirical probability distributions of expected outcomes using 100 times repetition of the 30 periods replanning process by considering the randomly drawn burn rate (Eq. 4.12) while implementing the landscape simulation model for each period (Fig. 4.2). It produced an array of 3,000 (100 times 30 periods) random outputs. In order to determine how many simulations was sufficient, we first repeated the simulation 1,500 times for the most flammable forest using model 1, where we expected the most variability in the outcomes. Based on preliminary analysis we assumed that 1,500 repetitions would be sufficiently large to be considered as a “population” of the revenue generated from the simulated harvest volume. We then performed random draws with replacement from the 1,500 simulated revenues, with a number of draws corresponding to a chosen number of repeated simulations (25, 50, 100, 200, ..., 1,500). This process was repeated for 1,000 times and used to estimate coefficients of variation of the 5th, 50th and 95th percentiles of the harvest revenues with respect to the corresponding number of simulations (Supplementary Fig. 4.1a). We found that 100 repetitions were sufficient to obtain coefficients of variation of the 5th, 50th and 95th percentiles of the revenue below ± 5% of their median values for the most flammable forest (Supplementary Fig. 4.1b). The assumption of population can be validated by further analysis as it can be seen from the relatively stabilized coefficient of variations after 300 repetitions (Supplementary Fig. 4.1b).

4.3. RESULTS

Old-growth forest covered 24%, 21% and 73% of the total area of the western, central and eastern forests, respectively before the beginning of the simulation. All the results presented here are the “realized” harvest attributes obtained from simulated implementations of the landscape models. The simulation consists of 100 repetitions of a periodic replanning loop of a 30-period planning horizon (Fig. 4.2) for each policy model and forest management unit.

4.3.1. Old-growth forest area in base model

When the volume-maximizing planning policy (model 1) was simulated without an old-growth area constraint, proportion of the old-growth forest area declined rapidly reaching zero by the 15th period of the planning horizon, even in the case where the forest was dominated by old-growth, such as in the eastern forest (Fig. 4.3). Consequently, the median proportion of the old growth forest area retained using this model was almost zero in all three FMUs (Table4.4).

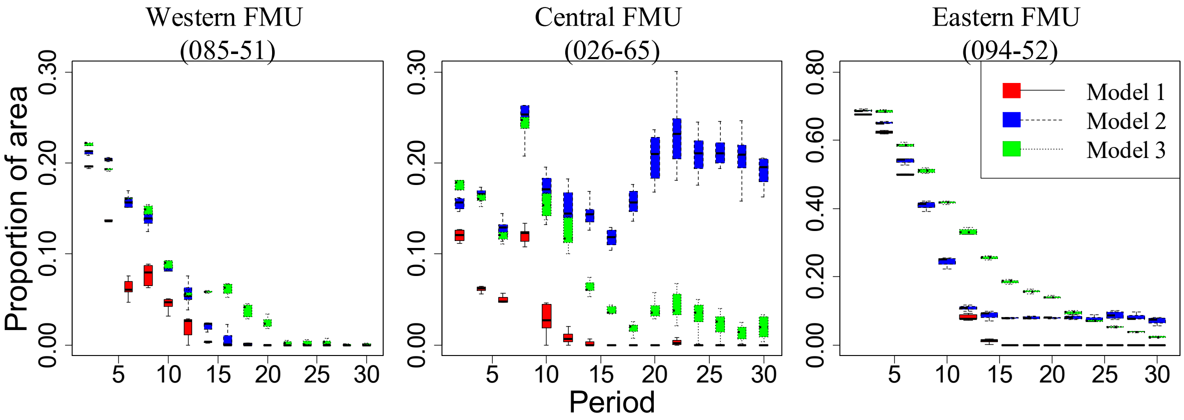

Figure 4.3. Boxplots showing distribution of the proportion of old-growth forest area preserved by period over a planning horizon without a 20% old-growth forest area constraint using the simulated implementation of three timber harvest scheduling models in three forest management units (FMU). The y-axes are presented in different scales for the three FMUs.

4.3.2. The impacts of harvest policy on the proportion of old-growth forest

When the harvest policies were changed to maximize NPV of harvested timber (model 2) and NPV of primary processed products (model 3) and simulated, the proportions of retained old-growth forest area vary depending on model and forest (initial forest age structure and fire regimes). With model 2, the proportions of old-growth forest drastically varied for all three forests (Fig. 4.3). The proportion gradually declined in the western forest, and reached zero starting from the 14th period. The proportion in central forest did not systematically decline to zero, but fluctuated by period ranging the values from 0.10 to 0.30. In the eastern forest, it declined from 0.73 to 0.05. This model did not schedule harvests in 4-25% of total area, which belonged to 26-30 strata located farther than ~200 km from the two forests to the respective mills. In contrast, model 1 prescribed harvesting in all strata in three FMUs because costs were not associated with the model. In the western forest, all the strata are located within profitable distances (Table 4.1), which resulted in the reduction of the proportions of old-growth to almost zero over the periods when either model 1 or 2 was used (Fig. 4.3).

Model 3 maximized the NPV from the sale of primary-processed products. With this model, the proportion of old-growth forest gradually decreased but the gradient of reduction was smaller than that of model 1. Over the 30 periods simulation using model 3, the proportions went zero in the western forest, approached zero in the eastern forest, whereas it fluctuated after the 15th period in the central forest (Fig. 4.3). As a consequence, the median proportions of the old-growth forest in three forests using this model were 6 - 25%, which were substantially higher than that using model 1 (Table 4.4). Unlike with model 2, model 3 led to harvesting activities in all the strata by deferring the harvest age, which offered a better lumber recovery value.

4.3.3. The impacts of retaining at least 20% old-growth forests

When an old-growth constraint was used, it was expected to affect on harvesting activities and their consequences to the economics and the ecosystem over the planning horizon. We evaluated three harvest attributes: a) harvest volume flow, b) revenue generated by the harvest prescriptions, and c) harvest rate obtained by simulated implementations of three policy models, and compared them with respect to median values, fluctuations and probability of receiving equal or more than specified volume and revenue over a planning horizon. The following three subsections §4.3.3.1.3 present the results relating to the impacts of added constraint on the three harvest attributes interacting with different initial forest structures and fire regimes.

4.3.3.1. Harvest volume

The impacts on harvest volume in terms of quantity and variability that resulted from the old-growth forest area constraint were different depending on the forest condition, fire regime and planning model. When we used model 1 with the old-growth forest area constraints, the medians of prescribed harvest volumes were 0.82 m^3y^{-1}, 0.81 m^3y^{-1} and 0.68 m^3y^{-1} in the western, central and eastern forests, respectively resulting in a reduction of 12%, 20% and 10% in the respective forests as compared with the unconstrained results (Table 4.4). More importantly, when we implemented the old-growth constraint and accounted for the possible impact of fire, there were many cases where we did not find a feasible solution due to unavailability of 20% old-growth forest area. We considered no harvest if the model optimization process encountered infeasibility. This infeasibility hence resulted in no (zero) harvesting in many periods and repeated iterations giving rise to wide variability within- and between- periods over a planning horizon (Fig.4.4). The numbers of in/feasible iterations can be presented in term of empirical probability. The probability of finding a feasible solution to the optimization model using model 1 were 0.83, 0.71 and 0.80 in the western central and eastern forests, respectively. (Fig. 4.5; probability of harvest volume >0 is < 1). Similarly, the probability of achieving greater than or equal to a specified volume (for example, 0.75 $m^3ha^{-1}y^{-1}$) with constrained model 1 varied in all three forests (Fig. 4.5). A noteworthy point is that we were able to find feasible solutions for every period and forests when we did not include the old-growth constraint (Fig. 4.4), though the probabilities of achieving specified harvest volumes differed. For example, the central FMU, the probability of harvesting at least 0.75 $m^3ha^{-1}y^{-1}$ shifted from 1.0 to 0.65 when the old-growth constraint was applied (Fig. 4.5).

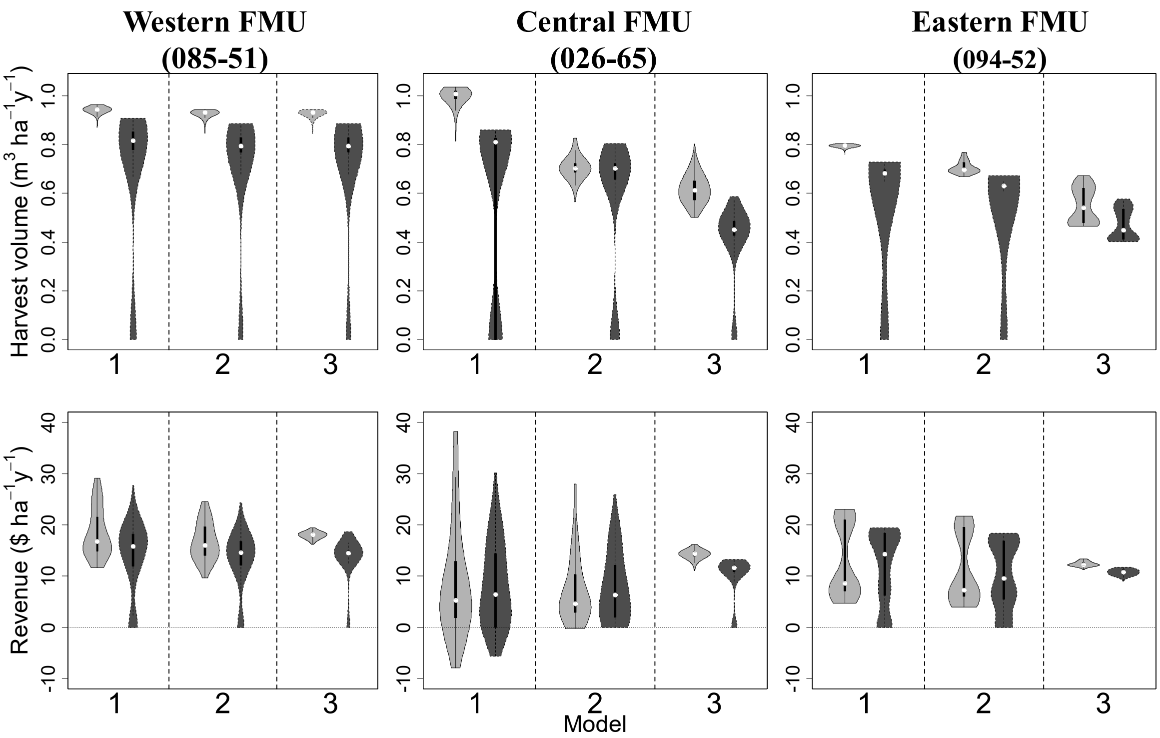

Figure 4.4. Violin plots showing the impact of at least 20% old-growth area constraint on harvest volume and revenue for the entire planning horizon and repeated simulation (30 periods X100 repetition) using three models in three forest management units (FMUs). Light gray corresponds to “no constraint” and dark gray to “with the constraint”.

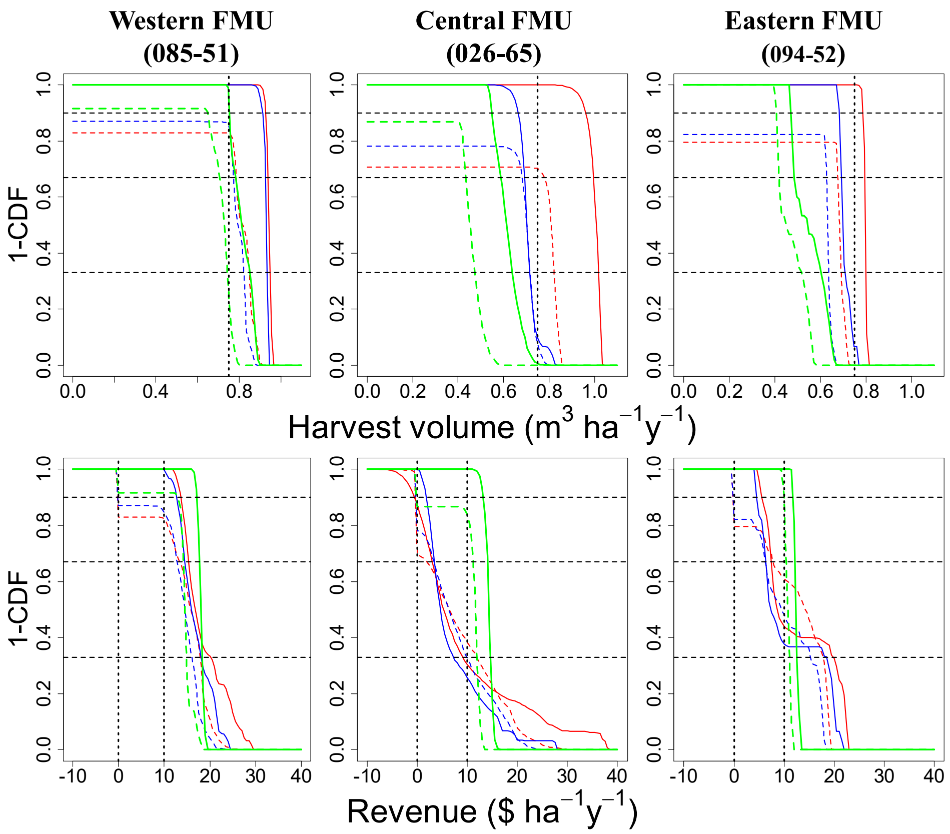

Figure 4.5. Complementary cumulative density function (1 - CDF) plot of the prescribed harvest volume and corresponding revenue using three harvest planning models (model 1: red; model 2: blue, and model 3: green) without (continuous line) and with (dotted line) imposing old-growth forest area constraint over a 30-periods planning horizon and 100 time repetitions in three forest management units (FMUs).

The inclusion of an old-growth constraint in model 2 substantially reduced the harvest volume along with increased variability as in the realized harvest volume using constrained model 1. However, the median proportions of the reduction were 15% and 10% in the western and eastern forests, but almost the same in the central forest (0%) compared with unconstrained model 2 (Table 4.4). The lower medians and smaller variations in constrained model 2 were observed compared to the values obtained suing constraint model 1 (Fig. 4.4). It was because model 2 did not prescribed harvest resulting in negative revenues (without constraint) and protected against further losses due to unharvest in order to meet the 20% old-growth requirement (with constraint, but has confounding effect, which was beyond the scope of this analysis). It is noticeable that the reduced harvest volume due to the old-growth constraint helped improve the availability of harvest for the successive periods. As a result, model 2 had a higher probability of getting feasible solutions compared with model 1 in the successive periods as we see the respective probabilities of 0.78 (vs. 0.71), 0.87 (vs. 0.83) and 0.82 (vs. 0.80) in three forests. The variability of harvest volume, however, varied widely from no harvest (when model encountered infeasibility) and different level of harvests by gradual accumulation of timber supply through the periods over the planning horizon.

Model 3 led to different results because only the high value timber to sawmill was prescribed to be harvested. It caused substantial reductions in the harvest level over the planning horizon in both cases whether or not the old-growth constraint was included. Constrained model 3 reduced the harvest volume by 10 - 26% as compared with unconstrained model (Table 4.4). The probability of obtaining a feasible solution was higher with constrained model 3 compared with constrained models 1 and 2 as the probabilities of getting solutions were 0.92, 0.87 and 1.0 in western, central and eastern forests with lower variability, respectively (Figs. 4.4, 4.5).

4.3.3.2. Revenue

The impact on revenue of including the old-growth forest area constraint varied depending on the harvest planning policy (Table 4.4). Unlike the case of decreased harvest volumes in all cases (models and forests), revenues were often increased by the constrained models 1 and 2 compared with unconstrained models. When we implemented model 1, the constrained model reduced the median revenue by 5.3% in the western forest.

Table 4.4. Medians of the performance measures of the three policies with and without employing a hard constraint of preserving at least 20% old-growth forest area by period over a planning horizon in three forest management units (FMUs). Numbers in the parentheses are the 90% (±5%) percentile confidence intervals. The bold letters marks the fulfillment of the old-growth area requirement.

Forest (FMU)	Measurement attributes	Without old-growth constraint			With old-growth constraint		
		Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
Western (085-51)	Harvest volume	0.94	0.93	0.81	0.82	0.79	0.73
	(m^3 $ha^{-1}y^{-1}$)	(0.92-0.96)	(0.90-0.94)	(0.75-0.89)	(0.00-0.89)	(0.00-0.86)	(0.00-0.78)
	Revenue	16.73	15.99	18.06	15.85	14.57	14.53
	(\$ $ha^{-1}y^{-1}$)	(13.04-27.26)	(12.02-23.39)	(16.89-19.00)	(0.00-21.47)	(0.00-19.49)	(0.00-17.5)
	Harvest rate	0.81	0.83	0.75	0.64	0.66	0.60
	(% y^{-1})	(0.67-1.26)	(0.72-1.27)	(0.60-0.90)	(0.00-0.76)	(0.00-0.79)	(0.00-0.72)
	Proportion of	0.00	0.02	0.06	**0.21**	**0.22**	**0.21**
	old-growth area	(0.00-0.28)	(0.00-0.27)	(0.00-0.32)	(0.20-0.43)	(0.20-0.42)	(0.20-0.44)
Central (026-65)	Harvest volume	1.01	0.70	0.61	0.81	0.70	0.45
	(m^3 $ha^{-1}y^{-1}$)	(0.94-1.03)	(0.65-0.81)	(0.54-0.71)	(0.00-0.85)	(0.00-0.76)	(0-0.53)
	Revenue	5.31	4.63	14.35	6.4	6.35	11.67
	(\$ $ha^{-1}y^{-1}$)	(-1.89-36.77)	(1.2-19.53)	(12.86-15.39)	(0.00-21.57)	(0.00-19.55)	(0.00-12.84)
	Harvest rate	1.03	0.73	0.57	0.68	0.68	0.41
	(% y^{-1})	(0.82-1.26)	(0.63-0.88)	(0.49-0.76)	(0.00-0.84)	(0.00-0.84)	(0.00-0.50)

	Proportion of old-growth area	0.00 (0.00-0.14)	0.19 (0.13-0.25)	0.06 (0.01-0.24)	**0.21** (0.19-0.28)	**0.22** (0.19-0.32)	**0.23** (0.20-0.36)
Eastern (094-52)	Harvest volume ($m^3ha^{-1}y^{-1}$)	0.80 (0.79-0.8)	0.70 (0.68-0.77)	0.54 (0.47-0.65)	0.68 (0.00-0.72)	0.63 (0.00-0.66)	0.45 (0.41-0.56)
	Revenue ($\$ ha^{-1}y^{-1}$)	8.57 (5.11-22.78)	7.24 (4.30-21.26)	12.24 (11.83-13.29)	14.3 (0.00-19.06)	9.53 (0.00-17.87)	10.75 (9.85-11.70)
	Harvest rate (% y^{-1})	1.23 (0.98-1.46)	1.17 (0.77-1.47)	0.92 (0.77-1.09)	0.83 (0.00-1.17)	0.88 (0.00-1.17)	0.72 (0.63-0.87)
	Proportion of old-growth area	0.01 (0.00-0.70)	0.09 (0.07-0.71)	0.25 (0.03-0.73)	**0.2**6 (0.20-0.73)	**0.24** (0.20-0.73)	**0.35** (0.21-0.73)

In contrast, the median revenue increased by 20% and 66% in central and eastern forests when the old-growth constraint was implemented. This increase in revenue was due to the fact that the constraint protected against losses of revenue associated with non-profitable stands composed of young and small trees (Fig. 4.4); harvesting was not allowed in non-profitable stands. In turn, it created an opportunity to accumulate forest value for the successive periods. Such protections could be realized prominently in the later periods (Fig. not shown). As a result, probability of generating negative revenue by model 1 with the old-growth constraint (p = 0.20) was lower than that without the constraint (p = 0.30) in the central forest (Fig. 4.5).

While implementing the old-growth constraint, model 2 generated revenue similar to model 1 except it protected the potential losses (negative revenue for timber) incurred due to high transportation costs. The median revenue was decreased by 9% in western forest, but increased by 37% and 32% in central and eastern forests, respectively, despite the reduction of harvest volume (Table 4.4). Beside a shorter "tail" towards the lower values, the probability distributions between models 1 and 2 are similar in their shape and spread for the three FMUs.

Model 3 out performed the two other models with higher and more consistent revenues (Fig. 4.4) with or without the old-growth constraint. Unlike models 1 and 2, which increased or decreased the revenues depending on the FMU, the old-growth constraint in model 3 reduced the median revenue in all FMUs (20% in western, 19% in central and 12% in central forests). The decreased revenue that resulted when we implemented the old-growth forest area in model 3 in central and eastern forests were due to increased revenue by accounting for the age-related value of the forest even without using the constraint. This is unlike models 1 and 2, where constraints substantially helped increase value-added harvest in the succeeding periods. The probability of getting more than or equal to specified revenue varied with forests and models over a planning horizon (Fig. 4.5). When we implemented the old-growth forest area constraint, the probability of getting positive (>$0) revenue increased (0.78 - 0.87) in model 3 compared with model 1 (0.70 - 0.83) in all three forests (Fig. 4.5).

4.3.3.3. Harvest rate

Like harvest volume, the constrained models reduced the harvest rate but increased the variability depending on the forests and models we used. The constrained model 1 reduced the harvest rate by 20%, 35% and 26% in the western, central and eastern forests, respectively (Table 4.4). As presented in the subsection §4.3.3.1 with harvest volume, the wide variability in harvest rates were observed due to infeasibility of the constrained model solutions in three forests (Fig. 4.6). Model 2 had no substantial differences in median and variability within- and among- periods compared with model 1 except a few more cases of feasible solutions (Figure 4.6). The distributions of harvest rates when applying the old-growth constraint were often higher than the rates obtained without the constraint. This was due to lower or no harvest at the preceding periods. When model 3 was used, the reductions in the harvest rates were 18%, 29% and 19% in western, central and eastern forests, respectively (Table 4.4). More importantly, we see that the reduced harvest rate in model 3, regardless of whether or not the old growth constraint was used, produced more revenues (Table 4.4), hence more efficient in terms of more revenue per unit of harvest area (details do not belong to the scope of this paper). In addition, model 3 prescribed the harvest rate with the least fluctuation within and among periods (Fig. 4.6) implying the least impacts on forest ecosystem by harvesting activities.

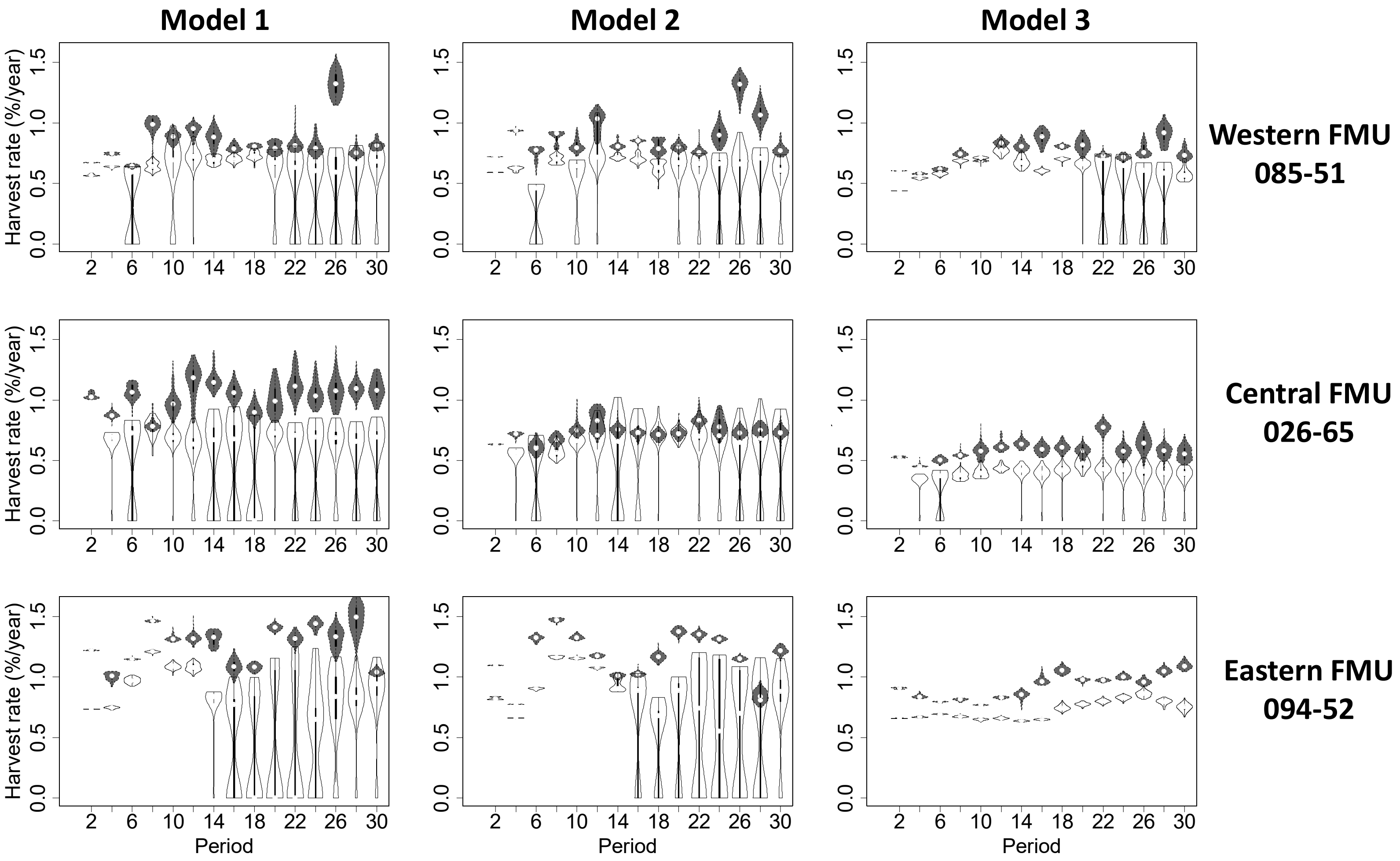

Figure 4.6. Violin plot showing the harvest rate (% / year) simulated by three models without (dark gray) and with (light gray) imposing old-growth forest area constraints in three forest management units (FMU).

4.4. DISCUSSION

The most commonly-used volume maximizing sustained-yield harvest planning model, when implemented, depletes the old-growth stage of forest because harvesting is scheduled at a specified rotation age (van Wagner, 1983) or begins harvesting when the stand attains minimum age at harvest (Rijal et al. Chapter 1; Savage et al., 2010; 2011). If we consider the existence of specified proportion of old-growth forest to be an indicator of natural ecosystem function (Koskela et al., 2007; Seymour and Hunter, 1999), a policy without an old-growth constraint is likely to produce adverse impact on the ecosystem. Our linear programming solution indicates that the age structure of the forest depends on the harvest planning models as in the previous studies (e.g., Didion et al. 2007; Fall et al., 2004). Fall et al. (2004) simulated the age structure of forest using a constant harvest rate and a scenario-based constant burn rates deterministically and presented that cumulative effect of fire and harvest accelerates the losses of old-growth forest area. Savage et al. (2011) and Conrod (2010) presented their simulated results in the linear programming (LP) framework with embedding the potential impact of fires in their models. Their results showed that infeasibility problems in some periods were encountered when employing old-growth forest constraints. Our study with LP framework matched past studies in the magnitudes of the harvest attributes (especially, harvest volume, to which most studies were confined), and we extended our analyses to present the result as likelihood event for the outcomes, but mostly focusing on revenue generated by the sale of primary-processed products. In the classical NPV maximization model (model 2), harvesting is scheduled when a stand reaches its financial rotation age. Depending on the discount rate and cost used, the rotation age in model 2 varies (Clark, 2005) and is always shorter or equal than that of model 1.

Some studies (e.g., Attiwill, 1994; Didion et al., 2007) further reinforce that the sustained yield-based forest management practice should be modified in order to maintain a specified amount of old-growth forest. We explored the harvest policy models interacting with potential impact of stochastic fires that would yield higher probabilities of success in terms of meeting the objective of retaining specified amount of old-growth forest area with lowering adverse impact on revenue over a planning horizon. When considered stochastic fire, a manager selects a decision rule that is less risky, i.e. high probability of success (Savage et al., 2010; 2011) with minimizing the losses (potent value or effect - Kaplan and Garrick, 1981; Schmoldt, 2001).

The probabilities of finding feasible solutions to the optimization model when we employed an old-growth constraint depended on the forest conditions (age structure), fire regimes and models we used. The age structure has only a short-term impact on maintaining old-growth over time because it may quickly decline as in the initially old-growth dominated eastern forest. On another hand, the models and fire regimes can have long-term impacts on the age structure (shown only old-growth - Fig. 4.3). Likewise, policy choices have impacts on the sustained flow of harvest attributes (e.g., harvest volume, revenue) but depend on forest structure as we observed in the six scenarios overall in three forests (Fig. 4.4).

Model 2 produced revenue similar to model 1, but reduced economic losses by not harvesting the timber volume that would generate negative revenue from the sale of the timber volume. Remote stands associated with higher transportation costs were left untouched (Fig. 4.4, Table 4.4). Hence, model 2 produced the highest revenue from the sale of timber harvested to the forest owner as specified (not presented here) by the model. However, revenue generated from the sale of primary-processed wood by the harvest prescriptions using models 1 and 2 did not have any substantial differences despite varying level of harvest volumes. We see a “paradox” in that the constraint reduced the median revenue in the western forest, but increased it in the central and eastern forests when we used constrained models 1 and 2. A closed examination of the results showed that when we employed the constraint, the uncut stands, which otherwise would have been harvested, had opportunities to add age-related product recovery value for successive periods. Imposing a constraint to preserve old-growth area helps accumulate value by postponing harvest to later periods, which increases the opportunity of increasing tree size, and hence lumber recovery fraction increases. Therefore, employing the old-growth forest area constraint can often (in the case of models 1 and 2) be economically beneficial over a planning horizon despite reduced harvest levels.

The economic potential to the mill is an important attribute of successful forest management in the changing paradigm of commodity to value production in Canada (Lefaix-Durand et al., 2009; Lehoux et al., 2012; MacKenzie and George, 2009). The objective of our study was therefore to explore alternative models that lower the adverse economic impacts to industry, i.e., magnitude and within- and among-periods variability of revenue over a planning horizon. Model 3 can be an alternative to the commonly-used policy model (model 1, including model 2) to reduce the adverse impact on revenue when employing an old-growth forest constraint. Median revenue generated by model 3 with old-growth forest constraint was higher with lower variation than the revenue generated by model 1 without (and with) the constraint in central and eastern forests and almost the same in the western forest (Fig. 4.4, Table 4.4). Compared with model 1, model 3 can be seen as “no-regret” risk mitigation because even if the constraint is relaxed, the probability of obtaining positive revenue is higher (Fig. 4.5). The same is true for the proportion of old-growth forest area through a planning horizon (Fig. 4.3). In addition, model 3 has higher probability of finding feasible solutions to the optimization model implying the model is more protective against the infeasibility by periods.

In our study, the variations in the revenue were functions of value potential (e.g., log-size) associated with stand age at harvest and distance from the harvest site to the sawmill. The mean distance between sawmill and western forest is 65 km. (31 - 120 km), whereas the distance between the closest sawmill to eastern forest is 196 km (140-255 km) (Table 4.1). Compared with model 1, model 2 increased revenue by reducing distance-related expenditure as we observed that 25% and 4% of the area was not harvested during any period throughout the planning horizon in the central and eastern forests, respectively. It resulted in a higher proportion of old-growth forest area at the forest level (Fig. 4.3). All the strata were within the profitable distances in the western forest, and thus there were no substantial differences in preserving the old-growth area preserved when either model 1 or 2 were implemented.

Model 3, as a vertically integrated model framework, takes into consideration the entire forest management processes, harvest and transportation costs, and revenues from the processed products. The model postpones harvest if this leads to lower revenue at the current period but will have opportunity to get higher revenue in the later periods letting the tree size get bigger and get higher processing values. Such a mechanism of value-selective harvest prescription ensures that forest resources that do not generated a positive financial return will not be sacrificed, which has two-fold benefits: increase opportunity of economic and ecological values. Model 3 prescribed harvest in the stands that have an older mean age at harvest (≈100 years; 75 -150 years) compared with models 1 and 2 (≈70 years; 45-100 years). Rijal et al. (Chapter 1) already demonstrated that the increased economic values due to age deferral from 70 to

100 years surpass the time-cost values due to discount rate (4% y^{-1}) and lower survival probability due to fire (Johnson and Gutsell, 1994).

The increased rotation age may also imply an opportunity for ecosystem conservation (Koskela et al., 2007). The reduced harvest rate in model 3 can allow for more flexibility to absorb natural disturbances (Boychuk and Perera, 1997; Rijal et al. Chapter 1). The lower harvest rate implies less there is less realized impact of fire on the harvest volume (van Wagner, 1983). These imply that the policy model 3 is more robust compared to models 1 and 2 when the timber supply encounters potentially increased disturbances. Hence, we confirmed our hypothesis of alternative modeling framework that embeds primary-processed product value can help reduce the adverse impacts on revenue when the strict requirement of old-growth forest is implemented by: a) increasing opportunity of revenue, b) deferring average harvesting ages, and c) reducing harvest area.

For the regions studied, the northern sections of the FMUs correspond to area where forest operation costs are high (Gauthier et al., 2014; Powers et al., 2013). It demands harvesting high-value products instead of high-volume. As we present, lowering the harvest rate not only reduces the management costs, but also increases the opportunity of ecosystem conservation and sustainability of economic productions. The reduced harvest rate may have still more importance while designing harvest planning in response to potential increase in forest fire as a result of climate change (Gauthier et al, 2015b; Wotton et al., 2010). As illustrated by the results of model 3, low harvests lead to forest stands that grow to full maturity and/or old-growth stage. It may also increase carbon sink. However, the positive or negative impacts of such policy on carbon balance would need to be investigated, but are beyond the scope of this study.

4.5. CONCLUSION

Implementation of different strategic harvest planning policies may have different impacts on the revenue generated, and the proportion of old-growth forest area preserved. We constructed and simulated implementation of three harvest scheduling optimization models with and without imposing a constraint of old-growth forest area. Among them, the first and second models maximized the harvest volume (model 1) and net present value of timber volume (model 2). The third model maximized revenue resulting from the sale of primary-processed products. None of the models, when implemented without the old-growth forest area constraint, could secure at least a targeted 20% old-growth forest area over the entire planning horizon. When the old-growth forest area constraint was employed in the models, the economic impacts in terms of magnitude and variability were different; particularly between the base model (model 1) and revenue-maximized model (model 3). The adverse impact on revenue using constrained model 3 was small as it produced more revenue over the planning horizon with the least within- and among-periods fluctuations as compared with constrained models 1 and 2. In addition, the lowest harvest rate and age-deferral harvest prescriptions by model 3 help ecosystems to be more protective from increased natural and anthropogenic disturbances as well as sustained economic wood production. Apparently, due to value selective harvesting over the planning horizon, model 3 reduces harvest flows that may have negative impacts on some product-specific wood industries, especially in the first few periods. But, now there is often mandatory policy requirement of maintaining natural ecosystem of fire-prone public forests. Our case study taken from fire-prone boreal forest presents that value-embedded policy (model 3) can be an alternative harvest policy to mitigate the adverse impacts on the revenue when minimal proportion of old-growth forest area requirements are implemented. This model marks significant differences than other two when transportation costs of harvest timber are substantially higher and age-related value recovery are substantially different. Age-deferral in harvesting using model 3 can provide more opportunity of value-added timber volume as well as enhance the preservation of old-growth forest and lowers harvest rate. Such policy model can consider several important elements (such as harvest volume, value, pressure, old-growth forest, high-value buffer stock, etc.) of sustainability of ecosystem and forest-based economics in an integral framework. We conclude that the cumulative adverse impact of forest fire and harvesting on the ecosystem and revenue can be lowered by selecting alternative harvesting policies.

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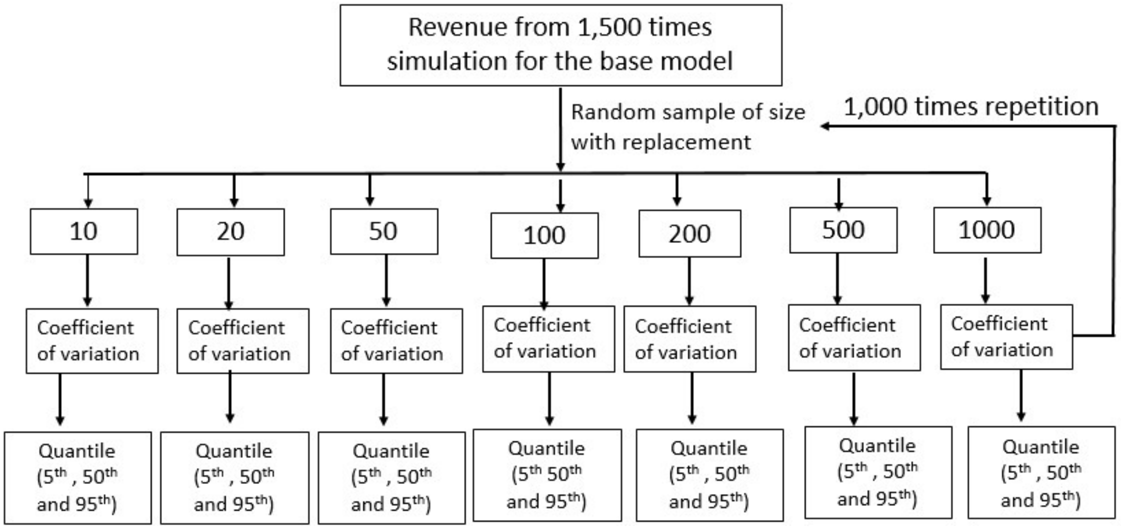
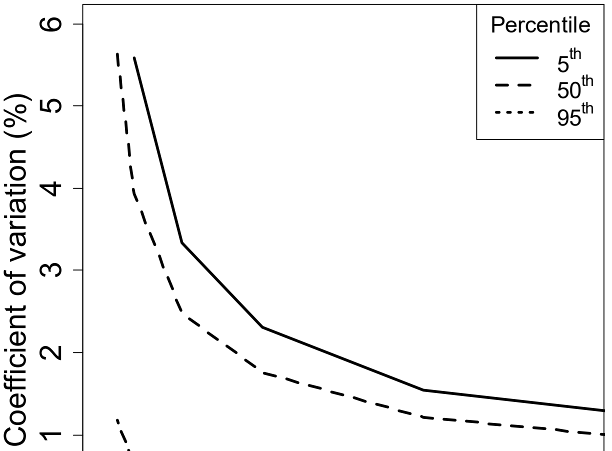


Supplementary Figure 4.1a. Schematic diagram of the process to find the number of simulations required for landscape simulation model.



Supplementary Figure 4.1b. Line plots showing the number of simulations required: coefficient of variation (CV) of the 5th, 50th and 95th percentiles of revenue using the process as in supplementary Fig 4.1a. The decision rule is the number that gives the CV less than 5%.

CHAPTER 5. GENERAL CONCLUSION

5.1. CONTRIBUTION AND ORIGINALITY

Canadian forest management is focused on achieving sustained supplies of value-added product thus ensuring the conservation of natural ecosystem in public forests. Possible supply disruptions due to wildfire and their impact on forest values is a significant challenge in long-term forest management planning. Using the data from the fire-prone boreal forest of Quebec Province, this thesis explored some alternative strategies to reduce the adverse impacts of fire on economic values of supply disruptions when we account for fire and the need to preserve a minimum old-growth forest in strategic planning process.

As original research, Chapters 2 - 4 contribute to fire and forest management concerns. Chapter Two indicates that selecting alternative harvest policies that include economic values in the planning model helps lower the adverse impacts of fire over a planning horizon as compared with status quo sustained yield-based harvest policies. As an original empirical research, Chapter Three deals with optimality of fire management efforts with added value. It also constitutes an alternative risk mitigation measure for dealing with supply disruptions due to fire. Finally, Chapter Four indicates that alternative policies can reduce the adverse impacts of fire on revenue while preserving old-growth forests. This chapter explored an alternative policy that increases the opportunity of preserving ecological and economic values in an integrated framework as compared with the status quo harvest policy. Overall, the study considers the economic value of forest management when timber is transported and transformed into industrial products in processing mills. This approach of valuing the transformed forest products helps ensure that harvest prescription are implemented only if it has a profitable value to wood industry.

5.2. RESULT SUMMARY

Natural fire has a positive impact on maintaining boreal forest ecosystems but large escaped fires often have adverse impacts on forest resources. Fire in commercial forests can disrupt harvest levels, which results in the loss of revenue and qualitative and quantitative shortfalls of industrial wood supply, and the sustainability of forest-based economy. The impacts of the fires on the forest economy depend on the harvest policy because different policies may prescribe variations in harvest areas, quality and quantity of harvest timber, and on revenues. The impacts of implementing different harvest policies on sustainability of forest economy therefore, merit scientific study. One policy may be an alternative to another in strategic forest management when forest conditions and/or management objectives change. I hypothesized that by changing the harvest policy that focuses on forest value to wood industry coupled with optimal fire management, when implemented, can reduce the adverse impacts of forest fire over a planning horizon. Value-selective harvest policy would produce higher revenues, but it reduces volume and area harvest. The reduced harvest area helps mitigate fire impact by creating a buffer for succeeding periods.

I evaluated four harvest policies by constructing four corresponding policy models. The first was a sustained-yield policy that maximized harvest volume over a planning horizon. I describe this as the status quo policy because of its wide use in forest management across Canada. The second policy was a timber revenue (NPV) maximized sustained-yield policy. I considered two variants of vertically integrated harvest planning policy. This policy maximizes the NPV from the sale of primary processed products subject to the sustained yield of harvest volume by period over a planning horizon. The third policy is the first variant of the integrated policy that maximized the NPV for the full planning horizon (30 periods) with an even-flow of harvest volume constraint. The second variant (fourth policy) maximized the NPV only for first two periods. This variant synchronizes the relatively short-term planning horizon of wood industry subject to even flow of harvest volumes and high-value product (lumber) for an entire planning horizon. Based on the objectives of each of three chapters, I evaluated either all or selected policies.

My approach was to develop a model-based simulation framework that consisted of linking two components: deterministic linear programming (LP) models and a stochastic landscape simulation model. The LP model component of the framework used a constant periodic mean burn rate, which was estimated using the empirical fire data between 1971 and 2014, by period throughout the planning horizon. The second-landscape simulation component was implemented by simulating the planned harvest by accounting for the impacts of stochastic periodic burn rates derived using a non-parametric procedure, which consisted of random draws of five observed annual burn rates and calculation of a 5-year periodic burn rate. The periodic burn rate was then employed in landscape simulation model to evaluate the implementation for the current period planned harvest. The two components exchanged their outputs by period and provided the harvest prescription and inputs for the next replanning period. The replanning loop continued for 30 periods and the simulation process was repeated 100 times. The outcomes obtained from simulated replanning were taken as random variables and statistical analyses were made using empirical probability distributions. Model parameters were derived from the data received for three commercially managed forests.

Chapter Two demonstrated that a vertically integrated policy that maximizes the NPV of processed products for two periods subject to an even-flow of lumber and harvest volume decreased the harvest area and volume by 27% (11-38%) and 28% (14-36%) respectively. The policy increased revenue by 130% (36-770%) with 0.90 probability depending on the fire regimes and generated the revenue with the least fluctuation by period compared to the status quo model. The integrated model was more robust in realizing the impacts of fire on revenue due to lower harvest area but, at the same time, generated more value using value-selective harvest prescription. The unharvested timber subsequently helped create buffer for the succeeding periods and hence reduce the risk of supply disruption. Because of value selection, the harvest age was deferred to 100 years from 70 years and the deferral built the high-value buffer stock, which help reduce the fluctuation of revenues by period over the planning horizon. The model may serve as a "no-regret" risk mitigation for the possible risk of revenue disruption due to accounting for fire when we use the status quo model.

Fire management was examined as another approach to risk mitigation in Chapter Three. The results show that increasing presuppression expenditure asymptotically reduces the burn rate. For example, presuppression expenditures of \$0.40 and \$1.00 $ha^{-1}y^{-1}$ produced burn rates of 1.48% y^{-1} (0.0-7.3% y^{-1}) and 0.29% (0.0-1.4% y^{-1}) respectively in the most flammable central forest. The decreases in burn rates reduced the losses in the NPV from a range of 3-34% to a range of 1-7% for the respective scenarios as compared with the respective values with "no-fire" situation, depending on the flammability of the three forests. I demonstrated that increased presuppression expenditure up to the specified ranges can be compensated for by reduced suppression costs and increased value-added harvests with lower risk.

In order to sustain the economic value of forest harvests, ecosystem health must be sustained. Preservation of old-growth forests is often considered to be an indicator of ecosystem functions. The main objective of the fourth chapter was to evaluate the impact of preserving old-growth forest on revenue generated applying three harvest policy models. The result without using a strict old-growth preservation constraint did not allow retaining specified old-growth area over a planning horizon. However, the proportions were slightly higher in the vertically integrated model. When we implemented the old-growth constraint, the integrated model yielded the revenue with the least variation. In addition, the model increased the probability of realizing feasible solutions for optimal harvest level to 0.87-1.0 compared with the probability of 0.7 -0.83 using the status quo model when implementing the constraint. The results lead us to conclude that, for our case studies, the old-growth forest constraint helped preserve ecological values and lower the adverse economic impacts on the forest with less risk over the planning horizon.

Finally, a vertically integrated policy that embeds forest values in the model coupled with optimal investment in fire management enhance long-term timber harvest planning. It maximizes the ecological and economic benefits while accounting for the potential impact of fire. The description of the probability for any likelihood event helps managers select the alternative policy/action that has the highest probability of success.

5.3. STRENGTHS AND LIMITATIONS

5.3.1. Strengths

I used recent data such as forest products prices (2004 - 2013), fire event data (1971 - 2014), spatial maps (2012 - 2015), and provincial inventory data (2002 -2004). The regional variations in growth potential were addressed by using stratum-based growth and yield models with the NATURA - 2009. This study constructed yield tables for altogether 160 strata in three forests. A non-parametric procedure was used while embedding the periodic burn rates in the landscape simulation model. Therefore, the fire model used was completely free of any parametric assumptions and no evaluation was required to examine the goodness of fit. Likewise, all the results have been produced with non-parametric confidence interval (percentile) so any results presented here are distribution assumption free and unconditional with respect to forest fire at the strata level, although results are presented at forest level. The annual burn rate is spatially and temporally scale sensitive. I considered the use of the most recent 44-year data, which have been validated by both ground survey and remote sensing methods, as a significant strength for data quality as compared with many past studies of similar scope. Although different studies use different spatial scales while estimating the burn rate, I used homogenous fire regions that were delineated for regional homogeneity of the fire characteristics. Therefore, the process accounted for the fire weather and fuel, implying the scale reflects consistent fire behaviors over time. Unlike past studies, I have not only covered the revenue, but also other harvest-related attributes and presented the interconnection so it can be applicable to forest economic and ecological values in an integrated framework. Simulations and analyses were performed using readily available software so that the results can be reproducible or the methods can be replicable.

5.3.2. Limitations

The research was conducted with great care using the data, models and analytical procedures. Still many issues could not have been addressed due to data availability and model structure, and limited time and resources. Foremost, the product recovery models did not use regionalized parameters, nor were they validated for the three forests under study. Nevertheless, the best among the available models was used. Along with increasing concerns of ecosystem-based forest management, there may be increasing demand for forest succession models that were not considered in this study. Scope of this work focused only on commercial forests where the primary objective of the forest management is for timber supply of same species and sustained flow of same product (e.g., harvest volume) over the planning horizon.

I acknowledge that all the volumes prescribed by sustained-yield policies (first and second models) are “push” models. Simulation based on such models is not realistic because no mill would accept the low-value timber that would produce negative revenues. However, I considered the value of the harvest timber in terms of net revenue of transformed products at the mill in order to explicitly quantify the commercial value of harvest. Still, these models are being used in determining AAC and timber harvest scheduling. Even though the mills are considered to be a vertically-integrated structure in forest management (e.g., silvicultural activities including harvesting are implemented by the contracted mill), decisions concerning the AAC are determined by the forest owner (the government authority) unilaterally in Quebec (Canada).

Although transportation costs and product prices were regionalized up to the scale of the landscape unit within each forest, management and harvest costs, which were obtained from the western forest, were kept constant for all three forests. The three forests are characterized by varying geo-climatic complexities. I assumed similar management, harvest costs, and similar road condition between harvest sites to primary processing mills and to the final product delivery sites. I considered only three products: lumber (a high-value), chips and sawdust as primary processed products. A single mill would process the harvest timber and convert it into the three products. This is a simplification. There are several product-specific mills that directly process specific products. Likewise, a one-to-one trade relationship between forest and mill may be subjected to criticism because neither does a forest sell all of its timber to a specific mill only nor do the mills buy all their input from only one forest. Nevertheless, the lumber mill often serves as a principal stakeholder of the supply chain and delivers processed products to specific markets. Moreover, at the strategic planning stage, it is reasonable to assume a forest and a mill function as a group of forests and mills that have a similar product-based trade relationship. Because the demand and processing capacity of a wood mill is considered to be a tactical level parameter (Bouchard et al., 2016; D'Amours and Rönnqvist, 2008), is reasonable to assume that at the strategic stage, that a mill can process any input available from any harvest without limiting its processing capacity as long as it has profit-making opportunity.

The yield tables were constructed only for the softwood species group. The ignorance of hardwood species might have produced underestimates, and one can expect slightly more revenue per hectare per year than that produced in my Results Section of Chapters 2 - 4. Ignorance of post-fire salvage logging could have reduced some revenue (Leduc, et al., 2015; Lindenmayer, 2004). However, there is some criticism of salvage harvest relating to forest ecosystem (Nappi, 2004; Schmiegelow et al., 2006). Forest vegetation contributes to fire ignition and behavior (e.g., establishment, spread and escape). Species and age structure therefore, influence on forest fire (Bernier et al., 2016). However, I followed the commonly-used simplifying assumption that the forest burns independently of age-class (e.g., Armstrong, 2004; Martell, 1994; Reed and Errico, 1986; Savage et al., 2010). Nevertheless, this study used homogenous fire regions, where fire weather and fuel are spatially grouped. A more complex model might produce different results. Lastly, I assumed fire regimes would be the same throughout the planning horizon. It has been forecasted to keep on increasing due to climate change (Gauthier et al., 2015b) or it will require more investments in order to maintain the current fire regime (de Groot, 2003).

5.4. IMPLICATIONS AND FUTURE RESEARCH

This thesis provides an alternative solution for an important aspect of sustaining a value-added product supply and forest-based economy from commercial forest for the possible adverse impacts of wildfire on timber supply disruption. Most previous linear programming-based decision tools use deterministic model parameters, which yield deterministic single-value outcomes (Martell, 1994). There are some studies of scenario-based deterministic approach (e.g., Peter and Nelson, 2005) that uses a sample of very few possible events. Deterministic outcomes cannot represent all the possible outcomes generated while accounting for potential impact of stochastic fire in the policy models. There are a few studies (e.g., Gauthier et al., 2014; Savage et al., 2010) in the recent pasts that deal with the outputs as a likelihood event, and results are presented in terms of probability distributions. However, the process is limited only to the harvest volumes. Unlike those, this study has focused on revenue in a supply chain as well as other related harvest attributes (e.g., revenues for forest owner when harvested and transported to mill, and mill entrepreneur when the timber is processed, harvest volume, harvest rate, and age-structure) and presented them in terms of probability distributions. The approach presented here may therefore be worth incorporating in strategic harvest planning procedures because it accounts for the ecological and economic aspects of forest management in a single strategic-policy framework. In order to cover all the possible outcomes with variabilities, the DSS based on this approach requires more data and reasonable level of computational facility. Integration of expert knowledge concerning forest and fire ecology in empirical data increases the precision of the results by validating or rectifying the assumptions of forest growth process and market behavior.

Forest fires vary across small areas, and fire characteristics estimation processes (e.g., burn rate) are scale dependent. A non-parametric solution specific to a region of interest is often helpful to make a site-specific forest management plan in response to stochastic fire as this study has demonstrated. Because the non-parametric procedure is based only on available data, it can implicitly respond the fire dynamics over space and time.

I evaluated the impact of stochastic forest fire events on wood supply. However, when planning harvests, there are other stochastic events such as financial variability (cost, price, inflation, market demand, etc.), forest-products growth processes (stochastic climate, anthropogenic disturbances) and modeling errors, which may confound the impacts. Demand for a precise DSS may require the incorporation of as many stochastic attributes, but at the same time, the impacts can be disaggregated to implement the management and risk mitigation plans. Modern computing facility and advancing knowledge can design such a big data-driven DSS for the sustainability of forest ecosystem and forest-based economics.

Reduced harvest rates can also have other implications. Lower harvest rates and/or the need to preserve old-growth forest (until full maturity) can increase carbon sink, biodiversity and retaining old trees, which have biological legacy. There may be still more value that is important in the areas, where there is high risk of increasing fire. Finally, governments (provincial/federal) are not only the forest owners and managers, but being a regulatory body, they should take a leading role in building value-creation-networks among the participating stakeholders of the supply chain in an integrated framework. This can be achieved through policy changes with respect to valuing forests, the supply chains, monitoring product prices and progressive taxation with respect to forest management policy and possible disturbance regimes.

5.5. FINAL REMARKS

Wildfire occurrence in the boreal forest of Canada is forecasted to increase along with potential increases of fire weather and anthropogenic disturbances. This threatens both qualitative and quantitative timber supply available to the wood industry. In addition, the focus of forest management is shifting from commodity-based sustained-yield to high-value product-based policies. This research has come at a stage when managers are looking for alternative policy approaches in order to revise the sustained yield-based forest harvest policy and account for the impact of forest disturbances on harvest planning. The vertically integrated policy model can be used to help increase the economic and ecological values of the forest that can increase opportunity of sustained revenue over a supply chain. At the same time, implementation of such a policy can help create high-value buffers to protect against the adverse impact of disturbances to potential revenue and ecosystem over a planning horizon. The integration of forest values in the policy model in terms of revenue of a supply chain, and accounting other harvest attributes (e.g., harvest volume, stock volume, harvest area, etc.) which would have impacts on forest values over the planning horizon, plays an important role in the strategic DSS and policy implementation. Such a model can serve as a bridge that connects forest growth and development, and industrial requirement over a long-term planning horizon.

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