MEASURES AND PROCEDURES TO MANAGE WILDFIRE RISK WITH APPLICATIONS TO THE SUSTAINABILITY OF TIMBER SUPPLY IN AN EASTERN CANADIAN BOREAL FOREST

Thèse

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Sous la direction de :

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Résumé

Bien que les stratégies de gestion du risque et de l'incertitude soient de plus en plus reconnues comme une dimension critique de l'aménagement des ressources naturelles, leur mise en œuvre reste encore à développer. Cependant la gravité du risque, les dommages potentiels qui y sont associés ainsi que sa probabilité d'occurrence demeurent souvent méconnus. Cette étude analyse différentes stratégies de gestion des risques utilisées dans la planification de l'aménagement forestier. Nous avons évalué des stratégies qui pouvaient protéger le niveau de récolte face aux risques de feu. Un modèle d'optimisation et de simulation a été conçu pour évaluer l'impact du risque de feu sur les calculs de possibilité forestière dans un contexte d'aménagement écosystémique de la zone boréale de la province de Québec au Canada. Nous avons comparé deux stratégies de mitigation des impacts. La stratégie dans laquelle les coûts d'une prime d'assurance sont pris en compte s'est révélée relativement meilleure que celle consistant à une mise en réserve de bois (chapitre I). Nous avons également évalué une stratégie menant à l'exclusion des peuplements les plus vulnérables au feu en raison de leur faible taux de croissance (chapitre II). Cette stratégie s'est également révélée meilleure que celle visant la mise en réserve de bois. Finalement, nous avons évalué le potentiel que présente la coupe partielle comme stratégie visant à réduire le temps d'exposition au risque. Combinée la mise en réserve de bois (fond de réserve), la coupe partielle s'avère un outil des plus utile (chapitre III). L'étude révèle qu'une stratégie ciblée telle que l'exclusion des peuplements vulnérables ou l'augmentation de la proportion des coupes partielles performe mieux qu'une stratégie non ciblée telle que le fond de réserve. Bien que nous ayons abordé différentes stratégies d'aménagement forestier dans cette thèse, des points importants restent

encore à éclaircir, en particulier la tolérance au risque et le contexte dans lequel il se développe.

Abstract

Although, management strategies dealing with risk and uncertainty have become a critical issue over the past several years, solutions are still to be developed. However, how can one judge the severity of risk when the potential damage and its probability are unknown? This study develops a framework for analyzing risk management strategies in forest management planning. We delineated how these management strategies could address the risk to protect timber harvest against disruptions. We tested optimization and simulation model to estimate the impact of risk associated with fire in timber supply calculations in an ecosystem context in boreal zone of the province of Quebec, Canada. Since paying, an insurance premium appeared to produce better results than partitioning buffer stock, (chapter I). The rating of wood volume available to harvest as a function of its vulnerability to fire can be used to reduce the impacts of fire on timber supply (chapter II). This idea was extended to test the adaptability of partial cutting coupled with buffer stock and accounting for the uncertainty induced by fire and projected climate scenarios (chapter III). As there are different levels of risk and different levels of tolerance to risk, the study results have shown that the process of risk evaluation itself needs to be accepted in its degree of uncertainties and its severity. As far as the insurance is concerned, it looks like a good strategy, but find an insurance company that is interested enough to believe there are enough potential customers to pay the premiums to make a profit could be required. The results also reveal that a targeted strategy such as excluding vulnerable stands from timber supply or adaptation of silvicultural treatment such as partial cutting may greatly interesting when facing risk scenario. Although, we covered different forest management strategies in this thesis, important issues still need to be

considered in order to improve the knowledge associated with risk of fire; especially the context in which it develops.

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Preface

This thesis is submitted in partial fulfillment of the requirements for the degree of philosophiæ doctor (PhD) in forest science at Université Laval. The work presented here was directed by Professor Frédéric Raulier, co-directed by Professor Alain Leduc. This document has been prepared as an article insertion thesis, and includes one journal articles for which I have acted as the principal researcher and principal author. My contributions to these papers include the problem definition, literature review, experimental design, mathematical modelling, experimentation, validation, and the writing of the manuscripts. The co-authors contributed to these papers on several fronts, including problem definition, experimental design, mathematical modelling, and writing of manuscripts. This thesis consists of five sections; General Introduction, Chapter 1, Chapter 2, Chapter 3, and General Conclusion.

Chapter 1 to 3 correspond to the following (published, submitted or under preparation) articles:

1. The first chapter entitled « *Rating a wildfire mitigation strategy with an insurance premium: a boreal forest case* » was co-authored by Frédéric Raulier and Alain Leduc. This paper has been published in Forests.
2. The second chapter entitled « *Forest vulnerability through fire risk and its potential impact on forest management planning*» was co-authored by Frédéric Raulier, Alain Leduc and Hakim Ouzennou (Manuscript under preparation).
3. The third chapter entitled « *Sourcing strategy to mitigate the impact of timber supply disruptions caused by fire* » was co-authored by Frédéric Raulier, Alain Leduc and Hakim Ouzennou (Manuscript under preparation).

General introduction

Forest management approach was defined by Haeussler and Kneeshaw (2003) as human intervention into the nature for obtaining desired goods and services. Canada's commitment to sustainable forest management involves social, economic and conservation issues for the benefit of present and future generations (Ferguson 1996). In Canada provincial governments, have the responsibility for managing protecting and developing public forests under sustainable practices which should not diminish the productive capacity of the forest (CCFM, 2008).

Weather and climate are the most important factors influencing fire activity in boreal forests (Flannigan et al. 2009). The Intergovernmental Panel on Climate Change (IPCC 2007) established different climate scenarios, which lead to predicted future climates (Randall et al. 2007). Forest fires are challenging for forest management. For example, in 2015, 7,068 forest fires burned about 3.9 million hectares in Canada. Meanwhile, in Quebec, the area burned was less than 2% of its 10-year average (CIFFC 2015). By the end of this century, the fire burn rate in the eastern Canadian boreal forest is projected to increase under future climate conditions (Bergeron et al. 2010; Flato et al. 2000), and it may have important implications in timber supply (Burton et al 2003; Flannigan et al. 2005). Wildfire is the main natural disturbance in boreal ecosystems (Rowe and Scotter 1973; Wein and MacLean 1983). The fire regime in a given region can be described by multiple attributes of the disturbance, among which are the fire interval, size, severity and spatial distribution (Belleau et al. 2007; Chabot et al. 2009). In black spruce-feather moss bioclimatic sub domains, most fires are started by lightning (Robitaille and Saucier 1998), and are characterized by the annual area burned. This variable depends on fuel moisture which is a function of vegetation type, weather conditions during the passage of the fire, and the topography of the site burned (Kane et al. 2007; Payette et al. 2000; Stocks et al. 2002). Fire is the major natural disturbance driving forest succession and the spatial variations introduce heterogeneity in the vegetation mosaic of the boreal forest landscapes (Van Wagner 1978; Lecomte et al. 2005).

Landscapes are marked by different fire regimes and have different proportions of old uneven-aged stands and young stands dominated by pioneer species (Van Wagner 1978; Chabot et al. 2009). As, in the long term, forest management influences landscape stands composition and structure (Bormann et al. 1979). Ecosystem-based management is recommended to reduce ecological differences between natural and managed ecosystems (Seymour and Hunter 1999; Burton et al. 1999; Gauthier et al. 2004). Silvicultural strategies are developed to meet management objectives, based on knowledge and understanding of natural forest dynamics and site attributes (Bergeron et al. 2007; Belleau 2009). Therefore, partial cuts might be used to recreate or maintain old open forest structures (Lecomte and Bergeron et al. 2005). A forest mosaic is a complex system and is in constantly changing, and these changes could have a negative impact on planned timber harvest and production disruptions especially in long strategic planning extending over 150 years.

Risk and uncertainty in timber supply analyses

The concept of risk exists in many areas and different approaches can be used to define them. In forestry decision analysis Kangas and Kangas (2004) dealt with different definitions, sources, theories and classifications of uncertainty. In the decision-making process, risk management is defined as a process, which combines risk assessment with knowledge and understanding on how to address the risk within the larger decision process (Annaert 2007; Käki et al. 2013.).

Risk assessments systemise the knowledge and uncertainties about the likelihood of threats to determine the magnitude of damage and establish whether measures are needed to mitigate or control risks to an acceptable or tolerable level or to support the decision-making process (Wynne 1992; Aven 2011). When a risk cannot be reduced, or eliminated, the focus must turn toward reducing vulnerabilities by describing the susceptibility of exposed elements to injury or damage due to hazardous events (Banks 2009). Under climate change scenarios, forests are considered more vulnerable over the long term (Lawrence 2011). In Canada climate, change will have an important impact on natural disturbances and may strongly affect the economic productivity and represent potential losses (Flannigan et al. 2009). A main issue is how to cope with such losses. Several options have been proposed to reduce the occurrence and the negative outcome of a natural disturbance, many of them focused on diversification and silvicultural strategies (Brunette and Couture, 2013). The theory of natural disturbances as sources of uncertainties in timber supply analyses was already included for several authors (Reed and Errico 1986; Armstrong 2004; Peter and Nelson 2005). A timber supply model is used to project long-term sustainable forest management providing schedule of harvesting in an uncertain environment (Regan et al. 2005; Raulier et al.2014).

Modelling developed by experts (Sheppard and Meitner 2005) can be used to predict and generate options that can help in the decision-making process of managers and other responsible persons. Forest managers are seeking to protect against wildfires by incorporating mechanisms arranged in advance of a loss, including insurance, hedging, diversification, withdrawal, and so on that neutralize or offset the original risk (Banks 2009). Given this context, I compare different fire mitigation strategies in forest management planning.

Thesis outline

The aim of this thesis is to incorporate risk into timber harvest planning by optimization and simulation model. The three main chapters in this thesis have common objectives that link both the research related to forest management planning under risk in an uncertain environment.

This thesis is composed of three chapters.

In the first chapter an actuarial approach based on cumulative probability distributions was developed to reduce the adverse effects of wildfire. To this effect, I developed spatially explicit landscape models to simulate the interactions between harvest, fire and forest succession over time in a boreal forest of eastern Canada. I estimated the amount of reduction of timber harvest necessary to build a buffer stock of sufficient size to cover fire losses and compared it to an insurance premium estimated in units of timber volume from the probability of occurrence and the amount of damage.

In the second chapter I examined the impact of uncertainty concerning current and future fire cycles on timber supply management (Mm^3/ $period^{-1}$), the goal being to analyze the levels of vulnerability via the estimation of the production of timber, while excluding low-productivity stands considered vulnerable to wildfire and evaluating the likelihood that those loss event will impact planned timber harvest. I combined fire occurrence processes alongside the harvest schedule to evaluate quantitative fire survival likelihood probabilities.

In the third chapter, using the same spatially explicit landscape model and forest management planning model, I evaluated flexible approaches by combining a reduction of timber harvest necessary to build a buffer stock with alternative silvicultural practices (partial cutting) for managing forested ecosystem under an assumption that the future fire regime will increase, the efficacy of which being challenged by the rate of success of planned timber harvest.

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Chapter 1: Rating a Wildfire Mitigation Strategy with an Insurance Premium: A Boreal Forest Case Study

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Résumé

Dans la forêt boréale d’Amérique du Nord, les feux de forêt sont un moteur clé de la dynamique forestière et peuvent entraîner des pertes économiques très importantes. Une approche actuarielle de l'analyse des risques fondée sur les distributions de probabilité cumulatives a été élaborée afin de réduire les effets négatifs des incendies de forêt. À cet effet, nous avons élaboré des scénarios spatialement explicites pour simuler les interactions entre la récolte, le feu et la succession forestière au fil du temps dans une forêt boréale de l'est du Canada. Nous avons estimé la réduction du volume de récolte de bois nécessaire à couvrir les pertes liées à un incendie forestier. Nous avons comparé cette réduction de récolte à une stratégie consistant en l’achat d’une prime d'assurance estimée en unités de volume de bois à partir de la probabilité d'occurrence et de l’importance des dommages. Dans l'ensemble, la réduction du volume de récolte de bois s’avérait plus coûteuse que la prime d'assurance, même avec un taux d'intérêt nul. Cela est dû au fait que la prime d'assurance est directement liée au risque alors que la réduction de récolte de bois ne l’est pas et est par conséquent moins efficace. Ces résultats, en particulier la comparaison avec un indicateur standard comme une prime d'assurance, ont des implications utiles au moment de choisir une stratégie d'atténuation pour protéger les approvisionnements en bois contre les risques de pertes sans diminuer de façon excessive les approvisionnements. Ils encouragent également le recours à des assurances contre les événements désastreux dans la planification de la gestion forestière.

Abstract

Risk analysis entails the systematic use of historical information to determine the frequency, magnitude and effects of unexpected events. Wildfire in boreal North America is a key driver of forest dynamics and may cause very significant economic losses. An actuarial approach to risk analysis based on cumulative probability distributions was developed to reduce the adverse effects of wildfire. To this effect, we developed spatially explicit landscape models to simulate the interactions between harvest, fire and forest succession over time in a boreal forest of eastern Canada. We estimated the amount of reduction of timber harvest necessary to build a buffer stock of sufficient size to cover fire losses and compared it to an insurance premium estimated in units of timber volume from the probability of occurrence and the amount of damage. Overall, the timber harvest reduction we applied was much more costly than the insurance premium even with a zero interest rate. This is due to the fact that the insurance premium is directly related to risk while the timber harvest reduction is not and, as a consequence, is much less efficient. These results, especially the comparison with a standard indicator such as an insurance premium, have useful implications at the time of choosing a mitigation strategy to protect timber supplies against risk without overly diminishing the provision of services from the forest. They are also promoting the use of insurance against disastrous events in forest management planning.

Introduction

Human activities depend on the sustainability of natural resources and proving sustainability requires making forecasts. In forest management, uncertainty is an important issue in the support of any planning decision and in evaluating the consequences of alternative strategies (Kangas et Kangas 2005). Uncertainty stems from known variability (risk), lack of knowledge (uncertainty), ignorance and indeterminacy (Wynne 1992). Ignorance and indeterminacy are difficult to account for, cannot be anticipated and require scenario planning (Peterson et al. 2003) or adaptive methods (Wynne 1992). Risk and uncertainty are somewhat easier to evaluate beforehand with risk analysis methods (Hoffman and Hammonds 1994). Such analyses are required when there is a possibility that the outcome of an event can deviate from expectations and have a negative effect on an objective (Bagajewicz and Uribe 2008). For instance, the negative effect of a disturbance on the profits from timber harvesting provides the cost of that disturbance (Armstrong and Cumming 2003).

Situations where risk and uncertainty are at the core of the problem as it is in risk management require different strategies and coherent risk measures (Bertsimas et al. 2004). The development of methods to account for risk and uncertainty has made considerable progress and they already play a role in environmental decision-making, particularly in cases of severe uncertainty due to extremely long planning horizons (Hildebrandt and Knoke 2011). Although the application of risk analysis in forest planning remains rare (Von Gadow and Hui 2001), attention to risk analysis in forestry should grow even more in the coming years (Yousefpour et al. 2012; Pasalodos-Tato et al. 2013).

Forest managers should account for many different sources of risk and uncertainty, one of them being wildfire. Fire is a critical component of terrestrial and atmospheric dynamics

(Flannigan et al. 2009) and is a primary driver of forest dynamics across the boreal forest region of North America. Fire is also a major source of risk and uncertainty that can cause important damages to timber resources (Taylor et al. 2006). Fire-dominated forests present challenges when designing forest management plans that maximize sustained and constant harvest volume flows because of the wide spatial and temporal variation in the frequency and severity of fire events (Martell et al. 1998). In Canada, each year, fire burns large portions of the forest area, which causes significant losses to management agencies (Boychuk and Martell 1996). Despite the uncertainty, that characterizes forest management planning; most planning models used for strategic planning remain deterministic in North America (Kaya et al. 2016; Bettinger and Chung 2004).

Linear mathematical programming (LP) is the approach most often applied in practice to such planning problems (Siry et al. 2015; Gunn 2007), despite the fact that many other techniques exist (Kaya et al. 2016), the assumption that all data are assumed to be known exactly and the fact that decisions made today with optimal solutions will probably be suboptimal in the future (Acuña et al. 2010). Incorporating a fire regime into timber harvest-level determination procedures leads to reductions in harvest levels when desiring a sustainable timber harvest (Boychuk and Martell 1996; Van Wagner 1983; Reed and Errico 1986). Such reductions help implement a timber buffer stock, providing a contingency inventory in the case of unexpected timber losses. The implementation of such measures therefore implies losses of short-term revenues that must be thoroughly justified and understood.

Successful methods of dealing with uncertainty and risk need to be simple and comprehensible enough to be useful in planning and decision-making in forestry practice

(Armstrong 2004). The best strategy for dealing with uncertainty depends on the risk preference of the decision makers, how much risk they are willing to face, and the degree of uncertainty involved. One example of a successful method is the cost-plus-loss analysis, which estimates the cost of sub-optimal decisions. It has been used effectively to justify the costs implied by sampling intensity in forest inventory (Eid 2000; Borders et al. 2008), the cost of fire-fighting (examples provided in (Martell et al. 1998) or the cost of forest planning (Duveno et al. 2014). In practice, the minimization of risk exposures and potential losses involves risk processes with one or more techniques considered in the context of financial and nonfinancial exposures (Banks 2009).

Financial risk modelling refers to the use of formal econometric techniques to determine the aggregate risk of a financial portfolio that depends on the probability distributions of losses that can arise from damage. Actuaries combine the likelihood and size information to provide average, or expected losses (Baranoff et al. 2204). For instance, Value at Risk (VaR) is a widely used risk measure (Jorion 2002), is easy to explain and easy to estimate (Ardia 2008; Hoogerheide and Van Dijk 2010). In portfolio management, Bagajewicz and Barbaro (2003) defined VaR as the worst expected loss under normal market conditions over a specific time interval and at a given confidence level. VaR has become a popular risk measure used by both regulated banks as well as investment practitioners. Although specific indicators such as VaR cannot guarantee the identification of the best risk-reduced solution, in many instances the use of different risk measures help identify potentially robust solutions.

With financial risk management, the expected loss is expressed in monetary terms. One loss-adaptation option is insurance (Holecy and Hanewinkel 2006). Insurance transfers the cost of financing losses in exchange for a premium. For instance, a forest manager may seek to protect his planning decisions against wildfire and he can purchase an insurance policy from an insurer by paying a premium to receive a compensatory payment that should cover the loss generated by fire (Banks 2009). The determination of the premium to pay for the cover requires evaluating risk as an actuarial process of valuing the insurable risk, i.e., by summing the values at risk compounded at the start of the planning horizon. Such an insurance strategy covering losses caused by fires may be interesting if the interest rate is higher than the mean volume increment rate of the forest under study.

The idea of insurance in forestry is not new, it was proposed decades ago by Shepard (1935; 1937) who noticed that the proper valuation of forest properties is a necessary prerequisite to any successful fire-insurance undertaking. Holecy and Hanewinkel (2006) proposed an actuarial model calculating appropriate probabilities to estimate insurance premiums. Lankoande et al. (2005) evaluated efficient wildfire insurance in the presence of government intervention through a subsidy for risk. Chen et al. (2014) proposed an insurance instrument to protect timber owners against wildfire risks as a management instrument. Although insurance is an effective mechanism to lessen the burden of loss by wildfire and is simple to explain, studies in wildfire insurance still remain limited.

The main objective of this study was therefore to provide a comparative analysis of the alternative advantages produced by two different risk management strategies: insurance premium and timber harvest reduction to build a buffer stock of timber. In the context of planning and scheduling forest harvesting, the first aim of our study was thus to quantify potential harvest losses due to wildfire under an ecosystem-based management scenario in an eastern Canadian boreal forest. We used a linear programming (LP)-based timber harvest scheduling model to determine the maximum even-flow harvest volume a forest area can sustain over the planning horizon. Interaction between fire and harvest was simulated with a landscape dynamics model to evaluate harvest losses, insurance premium and amount of buffer stock required to cover such loss.

Materials and methods

Study Area

The study area corresponds to the Forest Management Unit 085-51 located between 48˚ 50′ N and 50˚_09′ N latitude, and between 78˚ 05′ W and 79˚ 31′ W longitude in western Quebec, Canada (Figure 1.1). It belongs to the bioclimatic domain of balsam fir-white birch to the south (14%) and black spruce-feather mosses to the north (86%) (Robitaille and Saucier 1998). Mean annual temperature varies from -2.5˚ C to 0˚ C, and total precipitation from 700 to 800 mm. The area covers 1.08 million ha, of which 542,000 hectares are timber productive. Black spruce (*Picea mariana (Mill.) B.S.P.*), and jack pine (*Pinus banksiana Lamb*.) are the most abundant tree species and also the most economically important ones. Hardwoods such as trembling aspen (*Populus tremuloides Michx*) and white birch (*Betula papyrifera Marsh*.), and to a lesser extent, balsam poplar (*Populus balsamifera*) can also occur in mixture with black spruce. The forest dynamics in the region may be simplified into three main successional pathways either dominated by black spruce, jack pine or trembling aspen (Nguyen-Xuan 2002; Bergeron et al. 2002). Fire dominates the natural disturbance regime in the study area (Bergeron et al. 2002; Gauthier et al. 2004). Current (1920–2000) and past fire cycles (1850–1920) were estimated to be around 398 and 135 years (Kangas and Kangas 2005). Forest management planning should account for climate change as it should affect fire regimes in the boreal forest of North America (Bergeron et al. 2006). For our study area, fire burn rate is projected to increase gradually over the period 2001–2100. Bergeron et al. (2010) estimated that under B1 (2 x CO_2) and A2 (3 xCO_2) climate scenarios, fire cycles should lower to around 254 and 79 years respectively, values lying either in between the current and historical fire cycles (Cyr et al. 2009) or below the historical fire cycle.

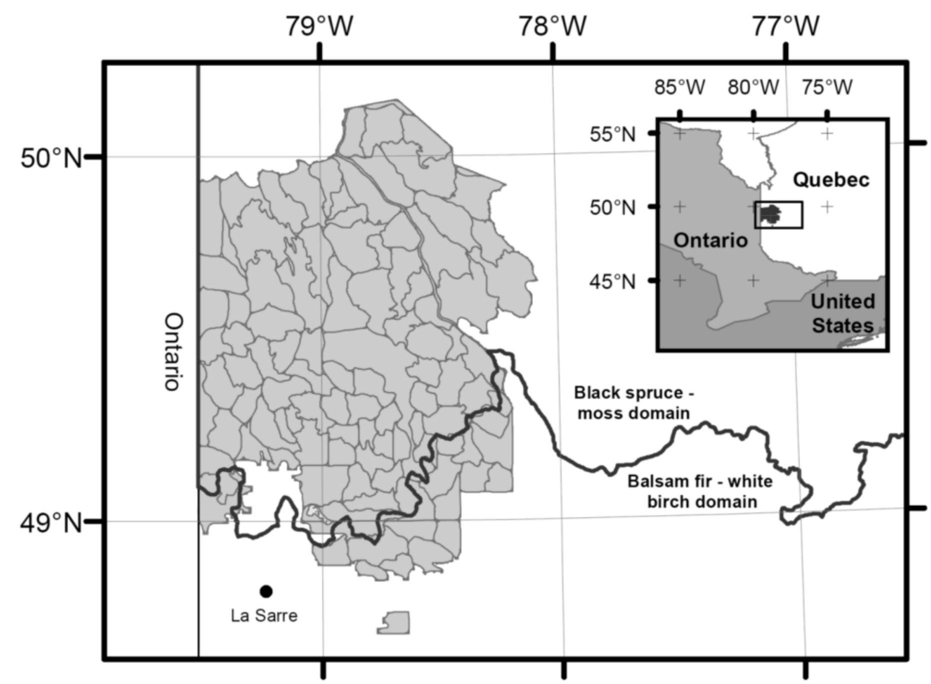

Figure 1.1. Location of study area Forest Management Unit 085-51. Grey polygons correspond to operating areas (Belleau et al.2009).

Timber supply model

We formulated the timber supply model as an optimization problem solved with linear programming, as it is the current practice in Quebec. No mitigation strategies were included at first against potential fire losses. The planning horizon was set to 150 years and divided into 30 periods of 5 years. The objective function of this model maximized harvest volume (i.e., Mm3/period^{-1}) (Equation 1.1). The first constraint provided an even flow of harvest volume over time (Equation 1.2). For harvest planning purposes, the study area was divided into different spatially organized compartments (operating areas between 30 km^2 and 150 km^2) as a function of canopy closure and species composition (Belleau 2009) to emulate fire size distribution (Bergeron et al 2004). These operating areas are open to harvest when more than 30% of their timber productive area is eligible to harvest (Equation 1.3) (Dhital et al. 2013). Planting of jack pine after a clear-cut was limited to less than the actual plantation level (7500 ha per period (Equation 1.4). A forest age structure was also targeted with a minimal abundance of three age classes (0–150 years: 63%, 150–275 years: 21% and more than 275 years: 16%) (Equation (1.5) (Gauthier et al. 2004). Two harvesting systems were implemented, careful logging around advanced regeneration (Groot et al. 2005) and irregular shelter-wood cuts (50% removal of merchantable volume; (Raymond et al. 2009). The areas planned to be harvested must be positive (Equation 1.6).

Let

o: operational area (1 … 107)

s: successional pathway (1 … 3)

p: period (1 … 30)

a: stand age

h: harvest type (1 … 2)

c: cohort number (1 … 3)

T_C: Timber production area belonging to cohort c, ∀ c, following the targeted forest structure

Variables

$$X_{op} = \begin{cases} 1, \text{if operating area is open to harvest} \\ 0, \text{otherwise} \end{cases} \forall\, o, p$$

A_{ashop} : Area harvested (ha), $\forall\, a, s, h, o, p$

e_{ashop}: Area eligible for harvest (ha), $\forall\, a, s, h, o, p$

C_{cp}: Area belonging to cohort c (ha), $\forall\, c, p$

Parameters

V_{ashop}: Volume yield ($m^3\ ha^{-1}$), $\forall\, a, s, h, o, p$

Objective function

$$Z = \sum_{a=1}^{30} \sum_{s=1}^{3} \sum_{o=1}^{107} \sum_{h=1}^{2} \sum_{p=1}^{30} V_{asohp} A_{asohp}, \tag{1.1}$$

Subject to

$$\sum_{a=1}^{30} \sum_{s=1}^{3} \sum_{o=1}^{107} \sum_{h=1}^{2} V_{asoh(p-1)} A_{asoh(p-1)} - \sum_{a=1}^{30} \sum_{s=1}^{3} \sum_{o=1}^{107} \sum_{h=1}^{2} V_{asohp} A_{asohp} = 0\ , \tag{1.2}$$

$$A_{asohp} \leq \quad e_{asohp} X_{op}\ \forall\ a, s, o, h, p, \tag{1.3}$$

$$A_{hp} <= 7500, h \text{ being a clear cut followed by a jack pine plantation}, \forall\ p, \tag{1.4}$$

$$C_{cp} \geq T_c, \forall \text{ c; p } \in [11;\ 30]\ , \tag{1.5}$$

$$A_{asop} \geq 0\ . \tag{1.6}$$

To develop the timber supply model (Model II formulation— (Davis et al. 2001, pp. 608–611)), we used the Remsoft Spatial Planning System (version 2013.12, Remsoft, Fredericton, NB, Canada) and solved it with Mosek 5.0. (Mosek ApS, Copenhagen, Denmark).

Interaction between Harvest Scheduling and Stochastic Processes

We simulated the interaction existing between harvest, fire and forest succession by adapting pre-existing modules of harvest, fire and succession already developed in the Spatially Explicit Landscape Event Simulator (SELES) (Fall and Fall 2001). Inputs are spatial rasters (forest type, stand age, operating areas), data tables (e.g., yield curves, harvested area planned by harvesting systems per operating area and per period, matrix of succession probabilities, other parameters such as a mean burn rate and a mean fire size).

Fire was modeled as a percolation process (Cumming 2001) parameterized from historical fire occurrence data (Gauthier et al. 2004) to reproduce basic characteristics of a fire regime (Fall et al. 2004). The model uses a negative exponential distribution to determine the number of fires and a Weibull distribution to determine fire sizes (Bouchard and Pothier

2011). Simulated fires burn independently of terrain, and there is equal forest flammability regardless of stand age (Van Wagner 1983; Gauthier et al. 2015). The harvest module prioritized the harvest of salvageable volume (30% of pre-fire standing volume) and subsequently the harvest scheduled by the timber supply model. If the harvest module was not able to find the harvest volume planned in designed operating areas, then it selected productive stands (with a volume greater than 50 m^3 ha^{-1}) not prescribed in the harvest plan until it reached the targeted timber supply level.

Disturbance-specific changes in forest composition and age structure drive the interactions between fire, succession and harvest. Natural succession was modelled as a semi-Markov process (Fall et al. 2004) with probabilities of transition estimated from the proportions of each stratum by stand age class (20-year interval) observed in the forest map. The spatial resolution of the model was 10 ha per pixel and the temporal resolution five years. We performed 100 replications of each scenario, which provided stable estimates of indicators, especially VaR (Raulier et al. 2014). We used the technique of common random numbers (Schruben 1979) to reduce the variability generated by random effects between the scenarios (Law and Kelton 1982). Simulation outputs allowed us to quantify loss likelihood distributions and estimate insurance premiums as detailed below.

Risk Management

Simulation results with the landscape dynamics model served to estimate loss distributions (frequency distributions of differences between planned and harvested volumes per period). Value at Risk served to assess risk was estimated with the 5th percentile (α) of the loss (L) distribution for a given period p:

$$\text{Prob}\left(\mathrm{L}_p \leq \mathrm{VaR}_p\right) = \alpha. \quad (1.7)$$

VaR computation was performed using the R statistical software environment (R Foundation 2014).

Risk Characterization

If fire risk is indeed part of the risk of timber supply disruptions, another part results from the inadequate consideration of fire risk in the timber supply planning process (Boychuk and Martell 1996). We have assumed with the timber supply model used in the present study that fire suppression is totally effective (i.e., no fire risk), which is not true (Flannigan et al. 2009) and, consequently, overly optimistic. Risk can therefore be subdivided into two different risk types, effective risk, when effectively implementing planned forest management strategies despite fire risk, and planning risk caused by the optimism of the planning procedure.

To distinguish both sources of risk, we fixed a planned timber harvest (PTH) threshold below which PTH is equal to the median realized harvest level that has been simulated with the landscape dynamics model (Leduc et al. 2015) and above which PTH cannot fully be implemented anymore because of fire disturbances. Below this threshold, risk of losses (difference between median and 5th percentile) is caused by fire risk only. Above this threshold, risk of losses is a compound of risks caused by fire and planning optimism.

To characterize risk, we therefore looked for three PTH values, one for which no risk exists (*i.e.*, disruptions not occurring anymore, such that $VaR_p = 0, \forall\ p$), one for which risk is the highest while respecting all the constraints of the timber supply model and one for which PTH is equal to the median realized harvest level. We used the landscape simulation model for this purpose by decreasing the PTH originally estimated with the timber supply model by steps of 10% until no risk occurred anymore for three fire cycles. We then estimated the parameters of a piecewise linear model with one knot between realized harvest and planned timber supply values:

$$\tilde{h} = PTH \text{ if } PTH \ \leq PTH_{th}, \tilde{h} = PTH_{th} + \beta(PTH - PTH_{th}) \text{ if } PTH > PTH_{th}, \qquad (1.8)$$

where $\tilde{h}$ is the periodic median realized harvest implemented with the landscape simulation model, PTH is the timber harvest planned with the timber supply model and β and PTH_{th} are parameters estimated with the MODEL procedure (SAS Institute Inc., Cary, NC, USA).

Insurance Premium

A loss function proportional to the forest value may serve to characterize wildfire risk in a forest. Forest managers may seek to be protected against wildfire damages to timber supply by taking out an insurance contract. We therefore calculated the insurance premium with probabilities of the potential losses provided with periodic VaRs. Putting this into a formula, one needs to find the value of a periodic premium (P) such that (Equation (9)):

$$\sum_{p=1}^{30} \left(P - VaR_p \right) \ \frac{1}{(1+i)^{5*p-2.5}} = 0, \qquad (1.9)$$

where p corresponds to a number of five-year periods, and i is an interest rate. Harvest is assumed to take place in the middle of the period (hence the term _2.5). We selected different interest rates (0%, 1%, 2%, and 4%) used for discount rates for public investment (Moore et al. 2004). Statistical computations were performed using the R statistical software environment (R Foundation 2014).

Timber Supply Reduction

To prevent operational disruptions, a reduction in periodic wood harvest can be used to build a buffer stock of timber (Boychuk and Martell 1996) serving as a back-up plan in the event that a supply disruption occurs. A supply disruption occurred whenever realized timber harvest was below 90% of the planned timber harvest volume (Peter and Nelson 2005). We were interested in estimating the harvest target reduction that helped deal with timber losses caused by only fire and therefore used the difference between the maximum PTH value equal to the median realized harvest level (PTH_{th} in Equation 1.8) and the one for which disruptions do not occur anymore (*i.e.*, $VaR_p = 0, \forall p$).

Comparison of risk management strategies

At first, we estimated harvest loss distributions by simulating the implementation of the timber supply solution with the landscape simulation model for three fire cycles (100, 200 and 400 years). Simulations were then redone with the landscape simulation model for the three fire cycles by reducing the PTH value by steps of 10% until we found a PTH value that could be implemented with no risks. Periodic VaR_p and median VaR values were computed from these loss distributions. We also used these simulation results to estimate the parameters of piecewise linear models (Equation (1.8)) in order to find the PTH value equal to the median realized harvest level for each considered fire cycle. Premium insurance was then computed (Equation (9)) for a range of interest rates used for public investments (0%, 1%, 2% and 4%) (Moore et al. 2004) at the threshold PTH value equal to the median realized harvest level. Finally, we compared the timber supply reductions required to cancel risk to insurance premiums for each fire cycle.

Results

Risk Assessment

Periodic timber harvest with an ecosystem management strategy may reach values up to approximately 3.8 Mm^3 $period^{-1}$ in an environment where no fire occurs (Equation 1.1). However, a blind implementation of such a strategy will not enable the procurement of expected timber levels (Figure 1.2) and timber supply disruptions caused by fire are expected (Figure 1.3). Despite the likely occurrence of such disruptions, the median rate of planning success reaches 97% (3.7 Mm^3 $period^{-1}$) of the optimal solution provided by the timber supply model with a fire cycle of 400 years and decreases only up to 73% (2.8 Mm^3 $period^{-1}$) with a fire cycle of 100 years (Figure 1.2). The chances of obtaining such a rate of success are, however, threatened by infrequent but possibly very significant disruptions. Timber supply disruptions may start to occur as soon as the 6th planning period (30 years) and, depending on the considered fire cycle, either tend to disappear after 50 years (and occur again approximately after one mean stand rotation) or maintain themselves for the rest of the planning horizon (Figure 1.3).

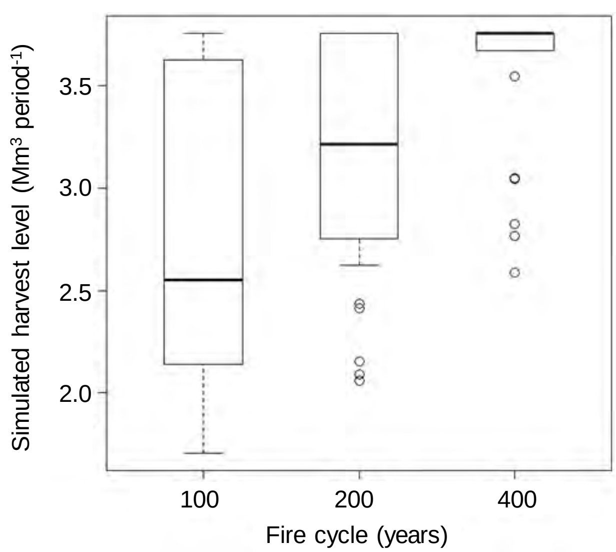

Figure 1.2. Box and whiskers plots representing the probability distributions of the simulated implementation of the optimal solution (3.8 Mm^3 $period^{-1}$) provided by the timber supply model (Equations (1.1)–(1.6)) under current (400 years) and probable interval for future fire regimes (100 and 200 years).

Maximum periodic VaRs, which provide an indication of the expected vulnerability of timber supplies to wildfire, are substantial in our study area (2.1 to 2.8 Mm^3 $period^{-1}$) and represent 55 to 74% of the periodic timber harvest, depending on the fire regime that is considered. Median VaR across the planning horizon with the longest fire cycle (400) years is substantially lower than the maximum VaR (0.9 *vs*. 2.2 Mm^3 $period^{-1}$) when compared to that resulting from a fire cycle of 100 years (2.4 *vs*. 2.9 Mm^3 $period^{-1}$), indicating more frequent occurrences of important timber supply disruption throughout the planning horizon with a higher burn rate (Figure 1.3c).

Successive implementation of a portion (30% to 90%) of the optimized timber supply solution helped find a median realized harvest level equal to PTH values for timber harvest levels up of 2.8 to 3.3 Mm^3 $period^{-1}$, depending on the considered fire cycle (Figure 1.4, Table 1.1). At the threshold PTH value beyond which the implementation success decreases, median VaR values (0.02 to 1.12 Mm^3 $period^{-1}$ depending on the fire cycle) are much lower than those induced by the implementation of the entire optimized timber supply solution. They are in fact reduced by a factor varying between two and 20. Maximum VaR values are less reduced, by a factor between 1.6 (for a fire cycle of 100 years) and 1.9 (for a fire cycle of 400 years). This means that ignoring fire in the timber supply model and assuming that fire risk is totally controlled (planning optimism) increased the risk of supply disruptions by almost one order of magnitude, even with a fire cycle of 400 years. Such increased risk is, however, accompanied by an increase in realized harvest level, the rate of which varies between 0% and 60% (= slope of the second segment of the piecewise regression) (Figure 1.4, Table 1.1). This increase is only significant with a fire cycle of 400 years (Table 1.1).

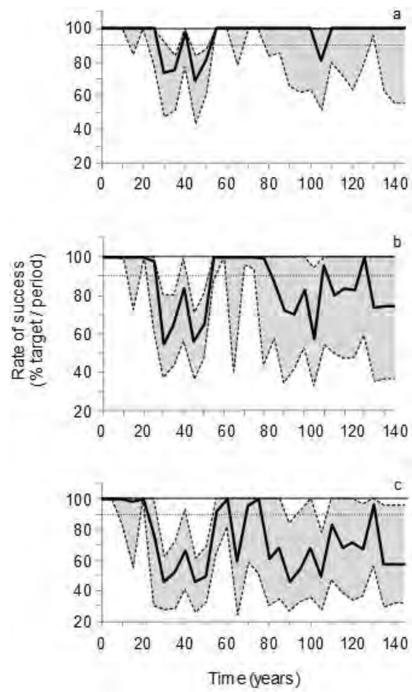

Figure 1.3. Probability distributions of the success rate of the simulated harvest schedule implementation under current ((**a**) 400 years) and probable future fire regimes ((**b**) 200 years; (**c**) 100 years). From bottom up, broken and bold lines represent the 5th, median and 95th percentiles. One hundred percent represents the target (continuous line) and ninety percent correspond to a cutoff value below which a timber supply disruption was considered to occur (Schruben 1979).

Table 1.1. Parameter values of piecewise linear models with one knot (threshold planned timber harvest (PTH)) (Equation (8)) relating PTH and periodic median realized harvest levels implemented with the landscape simulation model under current (400 years) and probable interval for future fire regimes (100 and 200 years).

Fire Cycle	Threshold PTH (Mm^3 Period^{-1})	β
100	2.77 (0.18)	0.04 (0.26) [a]
200	3.23 (0.15)	−0.01 (0.39) [a]

400	3.34 (0.18)	0.60 (0.25)

[a] Not significantly different from 0 at $\alpha = 0.05$ ($p = 0.78$ and $p = 0.96$, respectively). Numbers in parentheses represent a half-confidence interval.

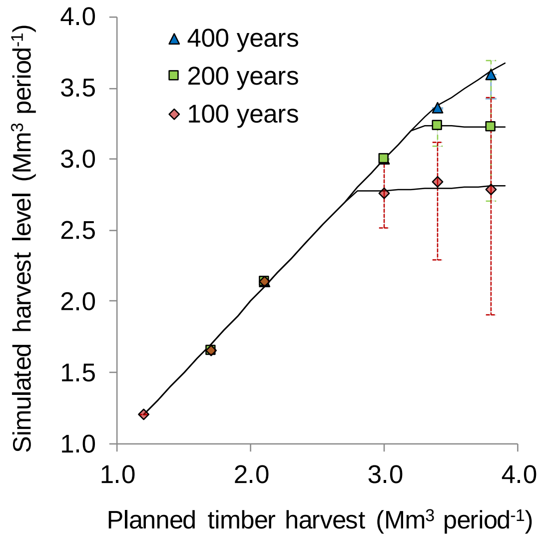

Figure 1.4. Relationship between planned timber harvest and its simulated implementation (median value) when considering the risk of fire for three fire cycles (100, 200 and 400 years). Parameters of the segmented linear models are provided in Table 1. Error bars represent the 5th and 95th percentiles of the probability distribution of simulated harvest levels.

Risk Management Strategies

Timber harvest reductions are required to deal with wildfire risk throughout the planning horizon: according to a timber harvest reduction strategy, a 23% of harvest reduction is necessary to avoid significant disruptions (*i.e.*, $VaR_p = 0, \forall\ p$) with the current fire regime (400 years, Figure 1.3), and such reductions increase to 40% and 52% for fire cycles of 200 and 100 years, respectively. Harvest reductions therefore seem to increase non-linearly with an increase of the fire cycle (*i.e.*, +9%/100 years between 200 and 400 years and +12%/100 years between 100 and 200 years). In fact, the sensitivity of maximum VaR to a timber harvest reduction decreases as maximum VaR tends to zero (Figure 1.5). Depending on the interest rate and the fire cycle, we looked at the changes in the amount of insurance premium an insurer should hold against unexpected losses as a function of fire risk (Figure 1.6). Insurance premiums represent between 0.6% and 1.0% of the level of supply for a fire cycle of 400 years (Figure 1.6), which are noticeably lower than for a timber harvest reduction strategy. With a change of fire cycle between 200 and 400 years, premium increases are also lower than those of a timber supply reduction strategy (between 3% and 10%/100 years depending on the interest rate), but increase more between 100 and 200 (between 4% and 16%/100 years). Such premium increases are more directly related to an increase in median VaR rather than to an increase in fire cycle (Figure 1.7).

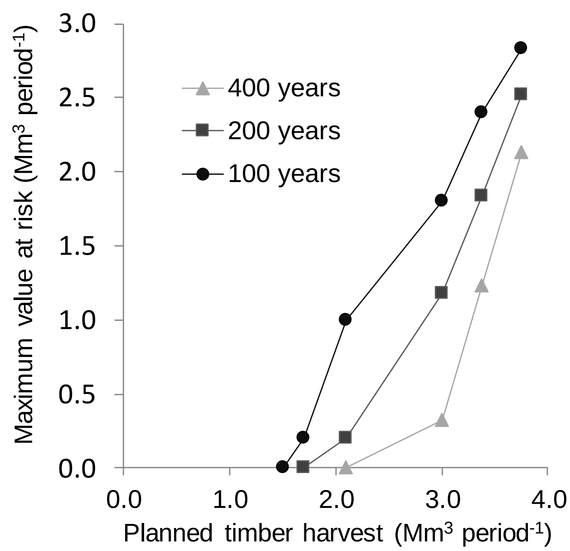

Figure 1.5. Relationship between planned timber harvest and maximum value at risk for three fire cycles.

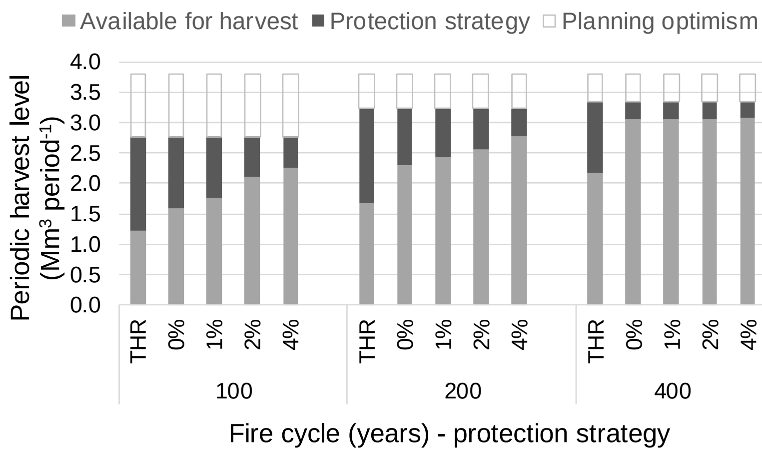

Figure 1.6. Distribution of the planned timber harvest into: a part that is not entirely feasible (planning optimism, in white, see Figure 1.4), a part that should be used to build a buffer stock of timber (dark gray) (with a timber harvest reduction—THR, which should not be harvested, or with an insurance premium, which should be harvested and set apart, with an interest rate between 0% and 4%) (protection strategy), and a part available for harvest (light grey), considering three possible fire cycles.

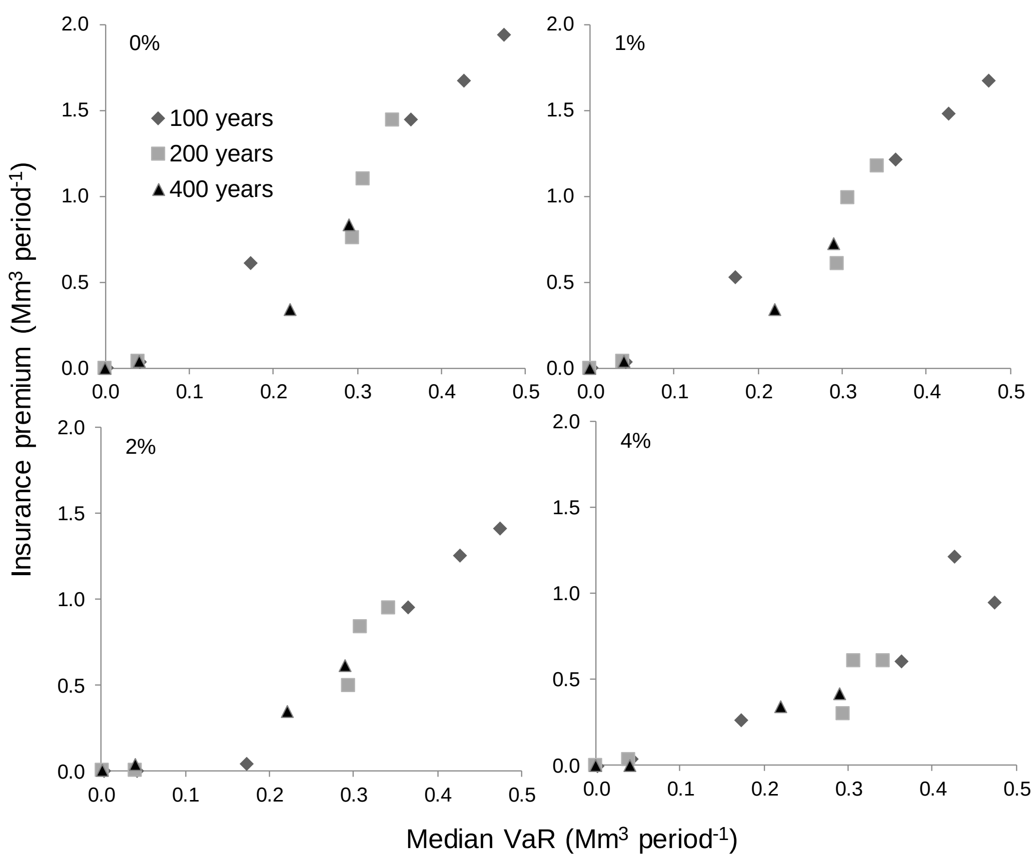

Figure 1.7. Relationship between median value-at-risk (VaR) and insurance premium as a function of interest rates (0% to 4%) and present (400 years) or probable fire cycles (100 and 200 years).

Discussion

We have evaluated two strategies to protect timber supply against disruptions with the objective of achieving over the planning horizon at least 90% of the planned harvest level: an insurance policy based on probabilities of potential losses and a reduction of timber harvest. Both mitigation strategies help build a buffer stock of available timber as a back-up plan. Our results show, however, that a constant reduction of timber harvest is costlier than an insurance policy (Figure 1.6) and is therefore less efficient. This result is linked to the fact that the premium insurance is directly related to risk (Equation 1.9), contrary to a timber harvest reduction strategy, which provides only an indirect way of managing a buffer stock (Raulier et al. 2014). The insurance premium also acts as an asset protected from fire. The consideration of fire impact and level of planned timber supply are the factors that most influence the planning success rate when implementing the optimized plan with a landscape dynamics model (Raulier et al. 2014). These two factors were varied in a systematic fashion in the present study. Both mitigation strategies were evaluated at the maximum PTH value that could be implemented in interaction with fire with the landscape simulation model, as proposed by (Leduc et al. 2015). We therefore succeeded in differentiating two types of risk, one due to fire only and another one due to the planning method used for the dimensioning of a sustainable timber supply.

Analysis of the risk related to the use of a specific planning method was discarded in the present study but deserves more consideration, especially in a real decision-making process: for the highest fire cycle that we have considered (400 years), the implementation of the timber supply optimal solution (3.8 Mm^3 $period^{-1}$) in interaction with fire had a success rate of 97%. The maximum PTH value that could be totally implemented with the landscape simulation model was 2.8 Mm^3 $period^{-1}$. This means that a timber harvest reduction of 36% would be required to increase the success rate up to 100%, which is clearly very expensive (Boychuk and Martell 1996; Gassmann 1989). In fact, since absolute protection against losses cannot be guaranteed, some level of acceptable loss expressed as a risk tolerance must be established, which can widely vary based on knowledge of exposures and proposed risk management solutions (Banks 2009). This points to the importance of choosing a level of tolerance to risk when facing a relatively low fire cycle, as already noted by Leduc et al. (2015). Increasing tolerance to risk requires the availability of other mitigation strategies, such as the diversification of procurement sources (Tomlin 2006), when supply disruptions occur.

Manley and Watt (2009) mentioned that the possible reasons why uncertainty might have been ignored in the design of optimal forest management strategies is that it has often been assumed that forest management is based upon purely risk-neutral preferences. Brumelle *et al.* (1990) made a survey of the literature on optimal forest management that took into account the presence of risk and found that 70% assumed risk neutral preferences and only 10% openly used risk averse preferences. A risk neutral forest manager would prefer adopting a strategy of passive acceptance whereas a risk adverse manager might prefer to adopt a risk mitigation strategy and continually revise his strategy in a dynamic replanning process (Savage et al. 2010). Clearly, adopting a risk neutral strategy in the present case is an unsustainable strategy since important timber supply disruptions are to be expected (Figure 1.3), even with the present fire cycle of 400 years (Figure 1.3a) and despite an expected success rate of 97% of the harvest plan implementation. Furthermore, Gauthier *et al.* (2015) showed that the increase in burn rates expected in the future, especially for the 2071 to 2100 period will impact the vulnerability of the harvest in most of western Quebec where our study area is located.

Inclusion of fire risk into the timber supply planning process has already been the subject of numerous research studies and different techniques are available for this purpose (Yousefpour et al. 2012; Pasalodos-Tato et al. 2013). However, the implementation of these techniques in a real decision-making situation remains limited in North America. For instance, inclusion of fire impact on timber supply models with linear programming requires a model structure seldom available in software designed for timber supply modeling (Gunn 2007; Bettinger et al. 2009). Other approaches (Boychuk and Martell 1996; Reed and Errico 1986; Gassmann 1989) remain too complex to implement with the typical problem size required to solve optimization problems of real timber supply models (Gunn 2010; Bettinger et al. 2009). Heuristic optimization methods may overcome these limitations but do not guarantee optimality, which restrains their use in practice (Kaya et al. 2016; Bettinger and Chung 2004). To the opposite, landscape simulation models are designed and therefore suited to analyze the interaction between harvest, natural succession and disturbances (Fall et al. 2004; Sturtevant et al. 2009; James et al. 2007). Clearly, such an approach offered two main advantages. First, simulation of the implementation of the optimized solution of a timber supply problem with such a landscape dynamics model helped assess the feasibility of the optimal solution, which conducted us to reduce the planned harvest down to a level where it was feasible at least 50% of the time. Second, at that level, we were able to estimate the amount of risk caused by fire only (and not by fire and planning method combined) and to express the simulated risk into an insurance premium, which is a common standard used for risk assessment and protection. The central view of any insurance scheme is an understanding of risk probabilities to inform the decision-making process.

Conclusions

Wildfire events impact optimal forest management decisions because such stochastic events may disturb the planned solution. In this paper, we used VaR as a tool to measure risk to characterize expected losses caused by fire during the implementation of a timber supply model solution in a boreal forest. We did not aim to investigate all possible mitigation strategies but rather to focus on two simple strategies: the use of an insurance premium and of a reduction of timber harvest. These strategies assume that decision-makers do not have prior information on which to base their weighting of the opinions and decisions. At the moment, the prospects around climate change are hardly encouraging and it is probable that the forest economy will diminish but decision-makers should consider shifting their attention to other promising potential schemes of strategies that could be used to deal with risk, and, maybe, only then will the risk of fire lower significantly.

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Author Contributions: G.R. and F.R. conceived the experiments and analyzed the data. All authors discussed the results, and co-wrote the paper. All authors contributed to writing the paper.

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Chapter 2: Forest vulnerability through fire risk and its potential impact on forest management planning

Résumé

L'aménagement durable des forêts devrait permettre de récolter des volumes suffisants de bois de manière soutenue. Pour cela, le risque de perte de bois due aux feux doit être intégré dans la planification à long terme. Le risque implique la probabilité de conséquences négatives qui peuvent être réduites à l'aide de mesures d'atténuation. L'objectif de cette étude est d'analyser les niveaux de vulnérabilité des peuplements par l'estimation de la production de bois tout en excluant les peuplements à faible productivité car il faut plus de temps avant d'être récoltable qu'un autre plus productif. Dans cette étude, nous examinons l'effet de l'occurrence de feu sur le calendrier de récolte et évaluons les taux de survie dans une plage de 20 % à 80 % selon différents niveaux de productivités. Nous avons utilisé des cycles de feux qui sont représentatifs pour la zone d'étude. Nous avons retenu un seuil optimal de récolte des peuplements ayant plus de 50 m^3 / ha. Les estimations ont été utilisées pour modifier la probabilité de rupture de stock pour différents niveaux d'exclusion de peuplements forestiers particulièrement vulnérables au feu en raison de leur faible taux de croissance. Nous avons évalué l'efficacité de deux stratégies d'atténuation des risques (la constitution d'une réserve forestière versus l'exclusion des peuplements à faible productivité) en tenant compte des cycles de feux actuels et futurs. Le taux de réussite de la médiane de la récolte simulée est supérieur à 90 % pour les deux stratégies dans le cas du cycle de feu actuel, mais il est inférieur à 90 % dans le cas d'un cycle de feu futur. Les résultats des analyses ont été utilisés comme cadre de prise de décision pour la gestion des risques basée sur la compréhension de la vulnérabilité des peuplements face aux cycles de feux actuels et futurs.

Abstract

Sustainable forest management enables adequate quantities of timber harvest, but it requires the incorporation of risk and uncertainty into long-term planning. Risk involves the likelihood of negative consequences that can be reduced by mitigating the impacts.

The goal of this study is to analyze the levels of vulnerability via the estimation of the production of timber, while excluding low-productivity stands considered vulnerable to wildfire and evaluating the likelihood that those loss events will affect the planned timber harvest. In this study, we combine fire occurrence processes alongside the harvest schedule to evaluate quantitative probabilities of fire survival ranging from 20% to 80%. We used fire cycle lengths, which are representative of historical as well as future fire cycles as reported for the study area. The assumption being that the harvest takes place at the optimal stand harvesting threshold of 50 m^3/ha. The estimates have been used to change the probability of loss in timber supply when different percentages of forest stand species that are particularly vulnerable to fire are excluded. We assessed the efficacy of two risk mitigation strategies by considering current and future fire regimes. The median of simulated harvest shows that the success rate for both strategies is useful to protect timber harvest under the current fire regime, but was negatively affected by the planned harvest under the future fire regime. The results from the analyses were used as a decision-making framework for risk management based on an understanding of the stand vulnerability in present and future fire regimes.

Introduction

In forest planning, risk is defined as a function of the magnitude and frequency of a hazard for a given area and reference planning horizon (Gadow 2000), whereas the planning horizon is quantified by the value of elements exposed to risk and their vulnerability. Furthermore, some losses can be prevented and others cannot. In cases when a risk cannot be reduced or eliminated, the focus must turn toward reducing vulnerabilities based on rules, regulations, and safety measures as resistance technique, which, in turn, reduces the effects of risk through safety precautions in vulnerable areas (Banks 2009). Vulnerability is defined by the degree of loss to a given element at risk resulting from the impact of a natural hazard (Haque 2005). Fuchs et al. (2011) suggested a dependency of the degree of loss on the hazard impact, and respective vulnerability.

Risk analyses aim at estimating potential expositions and consequences of natural hazard events on timber supply. Forest managers use a number of strategies to mitigate the risk, and take actions in advance, regardless of whether a disruption occurs. An analysis of timber supply vulnerability could provide an appropriate decision basis for risk management strategies. Although there is certainty that fire will occur, uncertainty remains regarding magnitude, location, and timing of these events (Raulier et al.2013). One source of this uncertainty is the vast unpredictability of future climatic reality. Notably, the boreal forest is vulnerable to future climate change (Weber and Flannigan 1997), probably more vulnerable to climate change than other forest (Houghton et al. 1996). Thus, climate change has implications for both current and future timber supply, and may also have an impact on the ability to achieve objectives for sustainable forest management. Fire is the dominant natural disturbance in boreal forests (Johnson 1998, Weir et al. 2000); and forest fire activity has increased significantly over the last 40 years (Flannigan and Van Wagner 1991; Bergeron et al. 2001) despite knowledge of inclusion of fire risk into a forest planning process, which, arguably, represents an emerging task. Indeed, applications of risk analysis in forest planning remain very rare (Gadow 2000). Incorporating natural disturbances into planning varies among jurisdictions (Armstrong 2004, Gadow 2000). Given the difficulty of predicting the location or severity of the natural disturbance of events, some prefer to ignore the potential effect of natural disturbance altogether (Tomlin 2006), readjusting their plans after considering the grave importance of fire damage (Savage et al 2010; Bessie and Johnson 1995).

Many models have been developed to examine the uncertainty of timber supply caused by fire risk, and results indicate that a reduction in harvest volume is required to ensure long term sustainability (Armstrong 2004; Peter and Nelson 2005; Savage et al. 2010a). Van Wagner (1983) demonstrated that when harvest rates are sufficiently reduced, the harvest becomes relatively insensitive to the amount of fire. Avoiding the risk of fire can be achieved by excluding vulnerable stands from the timber supply productivity areas (Raulier et al. 2013). In this study, we explored how can productivity be included in the assessment of vulnerability in forest management planning. Our focus is to reduce the risk of timber harvest disruptions through the identification of low-productivity stands (LPS) most vulnerable to fire and excluding from planned timber harvest (PTH). Site index and density index were used to estimate the time required to reach different harvesting thresholds based on tree density (m^3/ha). We estimated the time required to reach these thresholds considering three fire cycle length (100, 200, 400 years for the study area).

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I compared with another mitigation strategy by reducing the level of timber supply throughout the planning horizon to manage buffer stock (BFS) (Raulier et al 2014; Rodriguez et al. 2016). Therefore, in this study we investigate the extent to which the two mitigation strategies mentioned may protect against timber harvest disruptions across the whole planning horizon.

Materials and method

Study area

The study area is the Forest Management Unit (FMU) 085-51 which is located in Western Quebec, Canada (Figure 2.1). The total area covers 1.08 million ha, and approximately half of the territory is considered productive (487235 Ha). The FMU includes 1509 inventory strata covering a gross productive area of 542 000 ha. Dhital et al. (2013) grouped forest polygons into inventory strata based on cover type, stand density as well as height, age class, and ecological type (Pothier, and Savard 1998; Didion et al. 2007). The understory of the study area is dominated by bryophytes and ericaceous shrubs with rare herbaceous species and organic layer allowing paludification across the landscape (Fenton and Bergeron 2006). This study was conducted in the boreal forest dominated by black spruce (*Picea mariana (Mill.)* B.S.P.), jack pine (*Pinus banksiana Lamb.)* and trembling aspen (*Populus tremuloides* Michx.), which configure the three main successional pathways (Nguyen-Xuan 2002; Bergeron *et al.,* 2002; Gauthier *et al.,* 2004) exposed to historical and current fire cycles reported for the study area. The fire cycles defined by Johnson and Van Wagner (1985) as the time required to burn an area equal in area to the study area, was used to calculate the proportion of vulnerable stand. Bergeron et al. (2006) estimated the future fire regimes by considering climatic simulations from the CGCM1 for 2040–2060 (2×CO_2) – around 200 years, and for 2080–2100 (3×CO_2) – around 100 years while the current fire cycle (1920–2000) was estimated to be around 400 years for the study area.

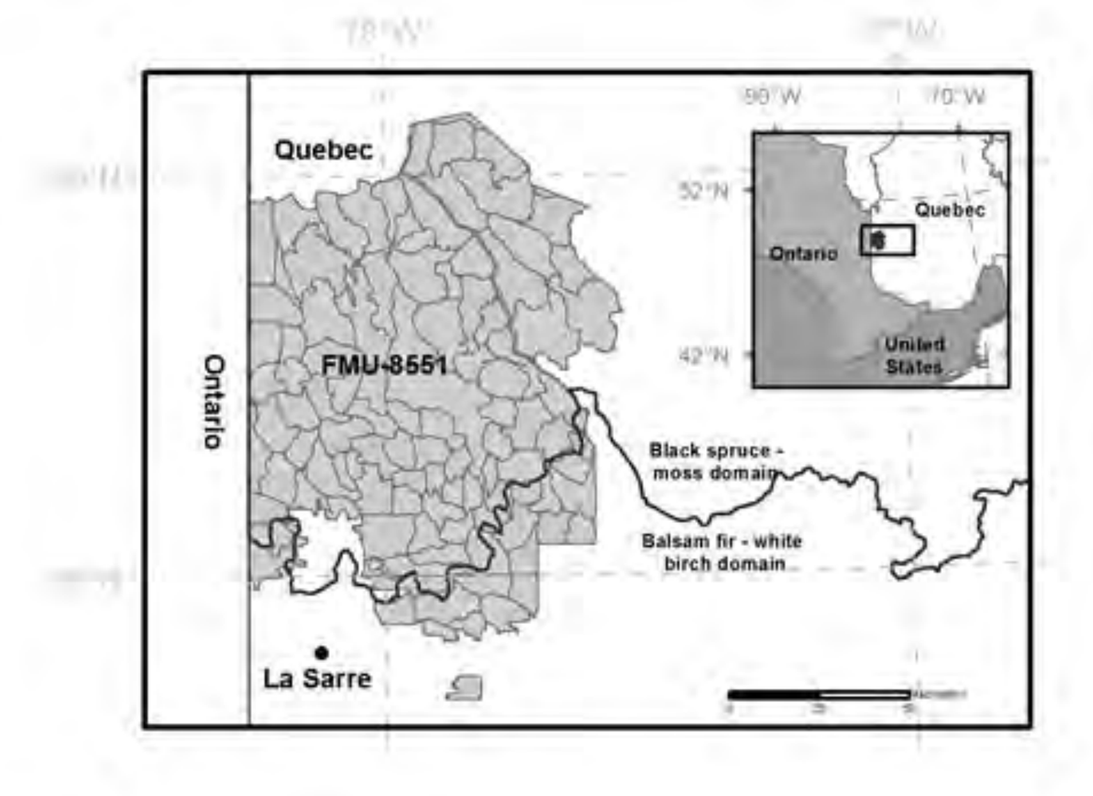

Figure 2.1. Study area, Forest Management Unit 85-51

Timber supply model

The timber supply model formulated as an optimization problem allowed for a planned periodic harvest level of 3.8 Mm^3 $period^{-1}$. The timber supply model was formulated as an optimization problem solved with linear programming (Rodriguez et al. 2016). The planning horizon was set to 150 years and divided into 30 periods of 5 years. The objective function maximized harvest volume (i.e., $Mm^3/period^{-1}$) (Eq. 2.1). The first constraint provided an even flow of harvest volume over time (Eq. 2.2). Within harvest planning, the study area was divided into different spatially organized compartments (operating areas between 30 km^2 and 150 km^2) as a function of canopy closure and species composition to emulate fire size distribution. These operating areas are open to harvest when more than 30% of their timber productive area is eligible to harvest (Eq. 2.3). Two silvicultural regimes was implemented by careful logging around advanced regeneration (CLAAG) and irregular shelter-wood cuts (50% removal of merchantable volume) (Raymond *et al.* 2009).

Let

o: operational area (1 ... 107)

s: successional pathway (1 ... 3)

p: period (1 ... 30)

a: stand age

h: harvest type (1 ... 2)

T_C: Timber production area belonging to cohort c, ∀ c, following the targeted forest structure

Variables

$$X_{op} = \begin{cases} 1, & \text{if operating area is open to harvest} \\ 0, & \text{otherwise} \end{cases} \quad \forall\, o, p$$

$$P_{ashop} = \begin{cases} 1, & \text{if survivalle likhood} \geq \text{Survival likelihood threshold} \\ 0, & \text{otherwise} \end{cases}$$

A_{ashop} : Area harvested (ha), $\forall\, a, s, h, o, p$

e_{ashop}: Area eligible for harvest (ha), $\forall\, a, s, h, o, p$

Parameters

V_{ashop}: Volume yield ($\mathrm{m}^3\ \mathrm{ha}^{-1}$), $\forall\, a, s, h, o, p$

B_o: Productive area (ha) of the operating area, $\forall\, o$

Objective function

$$Z = \sum_{a=1}^{30}\sum_{s=1}^{3}\sum_{o=1}^{107}\sum_{h=1}^{2}\sum_{p=1}^{30} V_{asohp}A_{asohp} \tag{2.1}$$

Subject to

$$\sum_{a=1}^{30}\sum_{s=1}^{3}\sum_{o=1}^{107}\sum_{h=1}^{2} V_{asoh(p-1)}A_{asoh(p-1)} - \sum_{a=1}^{30}\sum_{s=1}^{3}\sum_{o=1}^{107}\sum_{h=1}^{2} V_{asohp}A_{asohp} = 0 \tag{2.2}$$

$$A_{asohp} \leq e_{asohp} \quad X_{op}P_{asohp} \;\; \forall\, a, s, o, h, p \tag{2.3}$$

To develop the timber supply model (Model II formulation), we used the Remsoft Spatial Planning System (Remsoft, Fredericton, NB, Canada) and solved it with Mosek 5.0. (Mosek ApS, Copenhagen, Denmark).

Integrating stochastic process in timber harvest model

The harvest schedule has been simulated using a spatially explicit model written with the Spatially Explicit Landscape Event Simulator (SELES) under current and future fire regimes. The model relates cause and effect in an attempt to create a landscape management tool through the interaction between harvest planning and stochastic processes such as fire and succession. The model describes flows within compartments (operating areas) as well as spatial processes according to specific algorithms. SELES have been applied to evaluate the consequences of shifting management regimes on forest age structure (James et al. 2007; Côté et al. 2010) and support forest landscape decision processes for land-use planning (Fall and Fall 2001). Inputs for a given model can include spatial raster (grid) data (e.g. stand age), tables (e.g. yield curves) and parameters (e.g. fire cycles). The model includes sub-models to simulate fire, harvest and succession. Fire stochastic processes create risk and uncertainty in timber supply planning, which require long periods of stability (Savage et al 2010b). The harvesting model has been implemented based on the timber supply optimization model specified as targeted volumes per stratum. Harvest blocks have been built up from individual cells and are placed preferentially near cells that have high wood volume within active operating areas. The wood volumes themselves, in each cell, are based on the yield curves used by a timber supply model. The fire history map realized by Bergeron et al. (2004) has been used to calibrate the fire model and was simulated as a percolation algorithm parameterized from historical fire occurrence data to reproduce relevant characteristics of a fire regime (Fall et al. 2004). Furthermore, figure 2.2. simulate the effects of wildfire on timber supply at the landscape scale based on historical information for the study area. Whereas, succession model was designed to alter species composition over time and in response to disturbance in site types with similar succession trajectories. Species transitions are modeled as a semi-Markov process, whereby following disturbance, a trajectory of transitions is computed using (one-year) intervals. This trajectory represents the subsequent species based on the important assumption that actual observed patterns in species and age reflect succession processes over time (James 2007). The spatial resolution is based on a coarse resolution of 10 ha per pixel, the simulations were done with a timestep of 5 years and a simulation horizon of 150 years corresponding to one and a half times the mean rotation age.

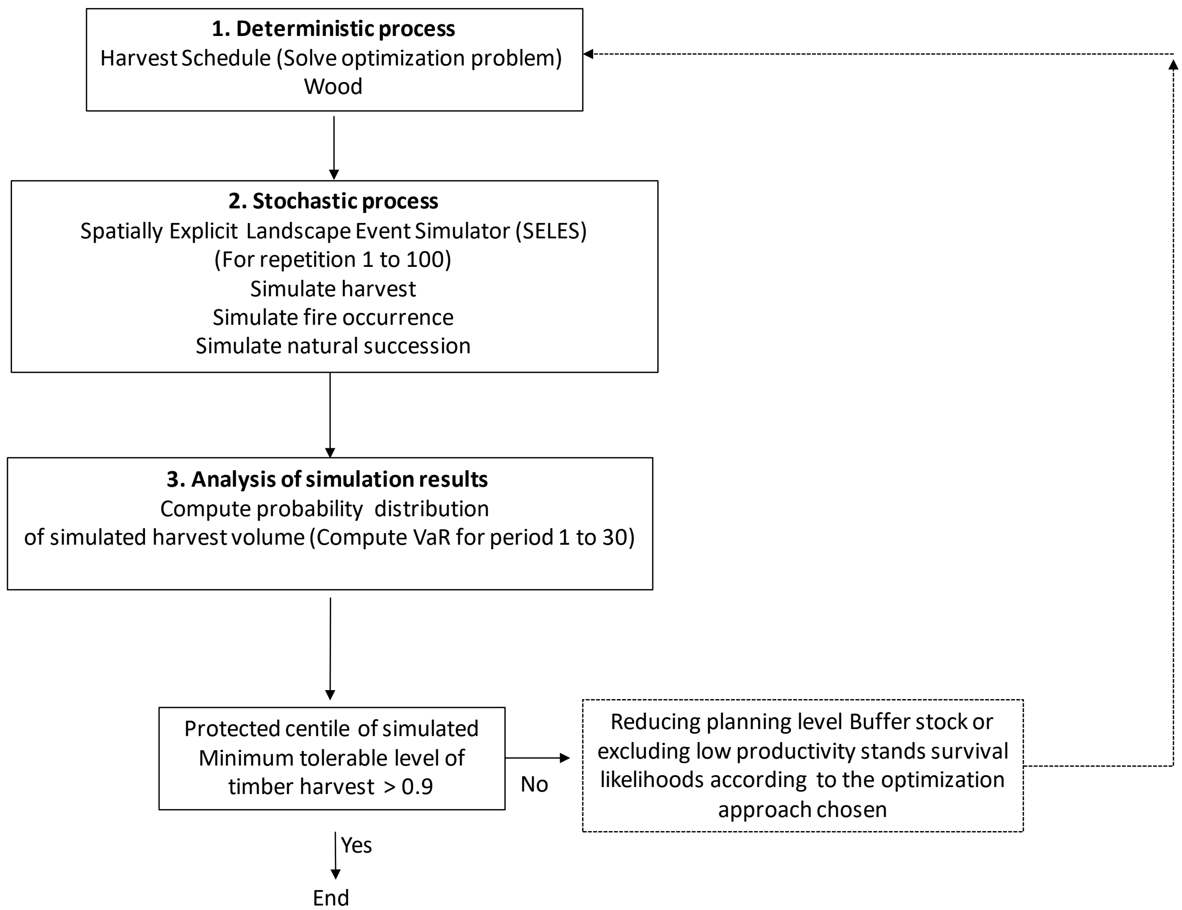

Figure 2.2. Conceptual framework of optimize and simulation model scheme

Estimating the proportion of vulnerable stands considering fire

The estimation of the expected proportion of forest stands that will likely reach their minimum harvesting age is given by:

$$p(A_{ht}) = \exp(-\frac{A_{ht}}{Tf}) \quad \text{(Eq. 2.4)}$$

where A_{ht} is the age required for a stand to reach a minimum harvesting threshold and T_f is a fire cycle (years). The equation describes the survival likelihood (20, 40, 60 and 80%) of a specific stand for A_{ht} years in an area submitted to a particular fire cycle (100, 200 and 400 years) (Raulier et al. 2013). The area eligible to harvest was where stand reached the age of exploitability and probability of survival. Furthermore, in describing quantitative probability ranges, specific qualitative language presented by Patt and Schrag (2003) is utilized to describe quantitative probability ranges. To estimate the probability that a stand escapes from fire, we assessed exposure to fire regimes variability within a spatially explicit model under scenarios of climate change. This analysis makes it possible to compare how fire regime affects the vulnerability forest structure and timber production over time.

Timber supply reduction

In timber supply models, various levels of reduction were considered as a buffer, reducing the planned harvest level (Raulier et al 2014) by a constant proportion and serving as a back-up plan in the event that a supply disruption occurs (Boychuk and Martell 1996). In the simulation model the minimum tolerable level of timber harvest is defined as the sustainable harvest target setting below 90%, because of protect against all eventualities, may be too expensive (Peter and Nelson 2005; Raulier et al. 2014). Harvest targets are constrained to the availability levels encountered throughout the simulations, by any reduction of timber volume when the primary allocation was not available at the time of harvest (Raulier et al. 2014; Rodriguez et al. 2016).

Risk analysis

Most measures of the risk are statistical quantities describing the loss distributions over some predetermined horizon as the Value at Risk (VaR) (McNeil et al. 2005). Risk measurement involves examining the probability distributions associated with random variables and estimating future outcomes drawn from these probability distributions to assess the trade-off between gains from risk reduction and the loss of opportunity (Jüttner et al. 2003; Tomlin 2006). VaR is a statistical technique used to measure the downside risk and quantify the level of risk within an economic activity exposed to over a specific period. In the context of risk management, VaR is given by the loss (L) distribution for a given period (p), equal to the difference between an expected profit and the profit corresponding to 5th percentile (α) of the cumulative probability distribution (Equation 2.5):

$$\text{Prob}\left(\text{L}_p \leq \text{VaR}_p\right) = \alpha \qquad \text{(Eq. 2.5)}$$

Based on previous studies (Belleau et al. 2007; Raulier et al. 2014) 100 replications were performed to stabilize the probability distribution of success rate of realized timber harvest (RTH). Statistical computation was performed using the R statistical software environment (R Core Team, 2014).

Results

The assessment of timber vulnerability to wildfire

The timber harvest solution served to estimate harvest loss distributions by simulation model for three fire cycles. Figure 2.3 shows PTH under three different scenarios across 30 period horizons. The average timber harvest per period for each scenario was approximately 3.6 $Mm^3/period^{-1}$. Both strategies behave in the same manner facing current fire risk, with success rate higher than the minimum tolerable level of risk exposure (90%) (Fig. 2.3). However, in the event of worst case scenario (100 years fire cycle) (Fig. 2.3b and d) change of fire regime for both strategies had a direct impact on probability distribution of the planning success rate. Median and maximum VaR for both scenarios for current and worst case scenario (100 years fire cycle) are around 3.6 – 1.6 $Mm^3/period^{-1}$ and 2.6 – 0.8 $Mm^3/period^{-1}$ (Fig. 2.3).

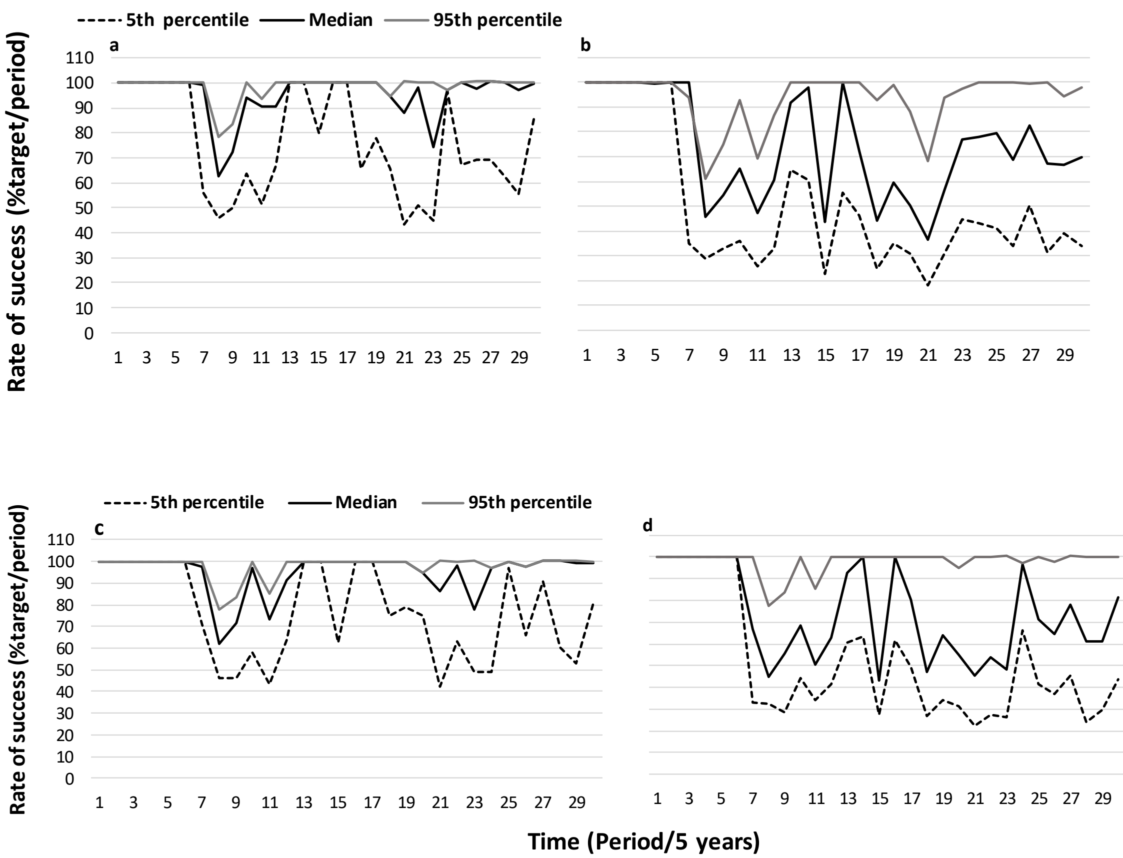

Figure 2.3. Rate of success for two protection strategies under current fire regime (Panels a or c) and possible worst-case scenario (Panels b or d) of increasing burn rate in the future (100years). Probability distributions of the planning success rate for excluding low-productivity stands vulnerable to fire (Panels a, b) and buffer stock (Panels c,d).

As expected, results across simulated scenarios (Fig. 2.3a) reveal that most of the stands are considered productive and even though the likelihood of vulnerability is increased to 80%, stands remain productive and reach planned timber harvest levels, whereas under short fire cycle (Fig. 2.3b) reach the PTH is unfeasible.

Figure 2.4. describes different spatial outputs of the proportion of operating area considered productive under three different fire cycles (400, 200 and 100 years) and four survival likelihood (20, 40, 60 and 80%). We calculated the probability of reaching specific harvest targets while excluding various proportions of vulnerable stands from PTH. Approximately half of the total area of the territory can be considered productive (Figure 2.4).

Excluding vulnerable stands from PTH cannot totally mitigate timber losses, because the time to reach the productivity thresholds makes the stands vulnerable to fire and its mitigation efficiency is highly dependent on productivity area (Figure 2.4). Under 100 fire cycle years, vulnerable stands become frequent or common for most of their timber production area. Figure 2.5 displays planned and realized timber harvest results in a decrease in the productive area assuming a 100-year fire cycle as compared to 200 and 400-year fire cycle.

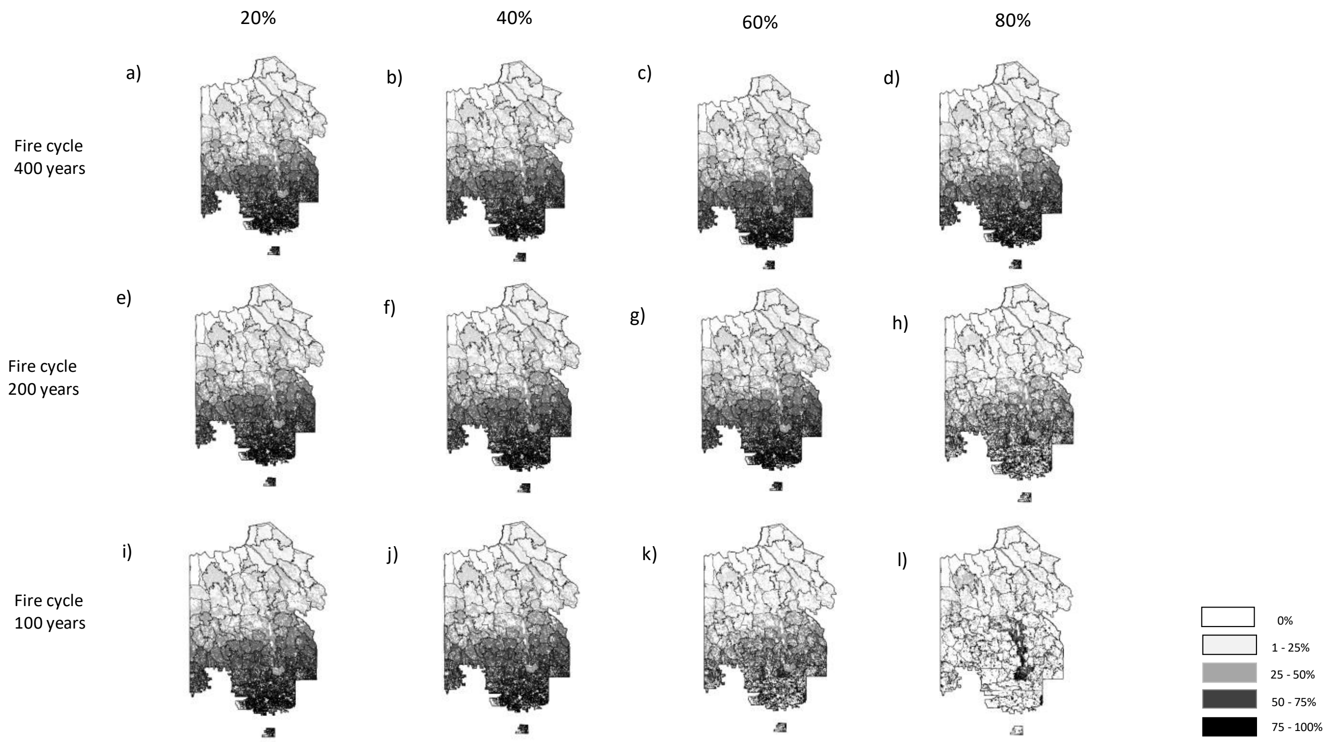

Figure 2.4. Proportion of operating areas considered productive which that reach the production threshold (Density of stand 50 m³/ha) under three different fire cycles 400,200,100) and four probability likelihood (20, 40, 60 and 80%).

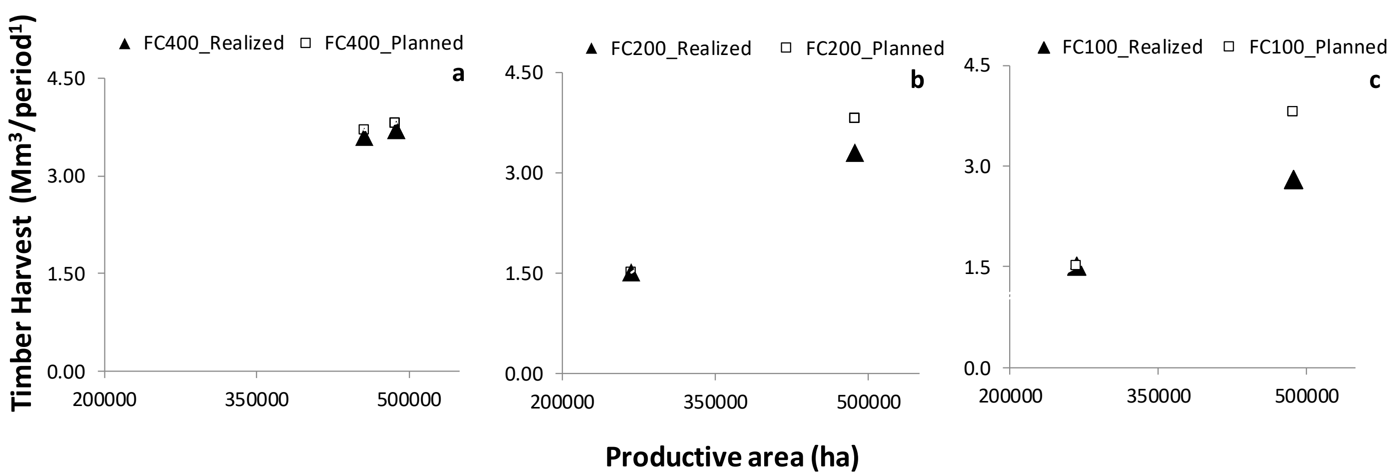

Figure 2.5. Amount of productive area as a function of planned and realized timber supply under current (400 years Figure a) and future fire regimes (200 years Figure b; 100 years Figure c)

Excluding vulnerable stands from the timber supply to avoid fire risk

Table 2.1 shows the timber harvest levels in PTH required to stabilize timber supply under a current and future fire regime throughout the planning horizon (slope figure 2.6). We observed a gradual increase in risk frequency while increasing the planned timber harvests and lower values of maximum risk frequencies as compared to those obtained in PTH (Figure 2.6).

Table 2.1. Threshold relating PTH and periodic median realized harvest levels (BFS and LPS). Numbers in parentheses represent a half-confidence interval

Fire cycle	**Threshold PTH (Mm^3 $period^{-1}$)**	
	BFS	**LPS**
100	2.60 (0.17)	2.50 (0.20)
200	3.06 (0.36)	3.08 (0.26)
400	3.37 (0.57)	3.35 (0.70)

Results (Table 2.1, Figure 2.6) show that regardless of mitigation strategy, the median realized harvest for each fire regime is similar. In this regard forest managers may evaluate the asset and loss facing wildfire risk. Hence, as even an indirect management strategy (BFS) is easy to understand and simple in application, other forest values need to be assessed. The probability of fire occurrence and consequence of adverse will increase under climatic conditions.

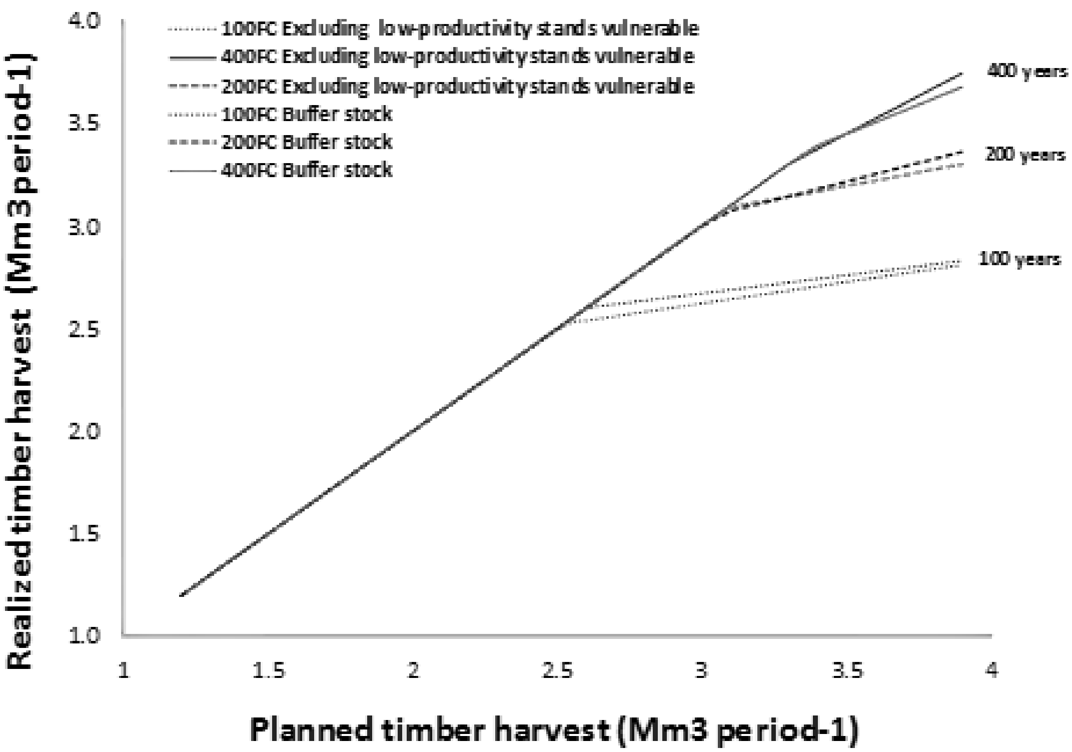

Figure 2.6. Relationship between planned timber harvest and realized harvest level (median value) for both strategies under three different fire cycles. The decrease in realized harvest is progressively increasing in shorter fire cycles.

Figure 2.6 shows PTH the median realized harvest level equal to RTH values for timber harvest around 2.6, 3.0 and 3.4 Mm^3 $period^{-1}$ under current and future fire cycle (Table 2.1), indicating more frequent occurrences of important timber harvest disruption across planning horizon with future fire regime.

Discussion

The effect of current vulnerability of timber supply to projected fire regimes is low but increases greatly under projected increases in burn rate. Vulnerability rises to the moderate level by considering climatic simulations from the CGCM1 for 2040–2060 (2 × CO_2) but high vulnerabilities are calculated for 2080–2100 (3 × CO_2) around 100-year fire cycles. In fact, dealing with fire risk scenario many studies suggest reductions in timber supply planning (Raulier et al. 2014, Boychuk and Martell 1996; Leduc et al. 2015).

Simulation results with the landscape dynamics model served to evaluate trade-offs between current harvest levels and the probability of sustainability under different future fire regimes. We aimed to evaluate the exclusion of vulnerable stands from timber harvest as a mitigation strategy to reduce the impact on timber supply in case such risk events occurred (Martell 1994). The present approach of excluding low-productivity stands vulnerable to fire was evaluated as a mitigation strategy to the inclusion of fire risk during the strategic planning phase as previously suggested by Raulier et al. (2013).

Several authors have developed models to examine timber supply uncertainty and their results indicate that a reduction in harvest volume is required to ensure long term sustainability (Boychuk and Martell 1996, Armstrong 2004; Peter and Nelson 2005). The Canadian boreal forest is vulnerable to climate change notwithstanding their relatively high adaptive capacity (Gauthier et al. 2014). Savage et al (2011) examined the long-term sustainability of timber supply under uncertainty and showed that the harvest levels predicted in the initial plan may never be realized in the future because of stochastic disturbance as well as mentioned by Leduc et al. 2014.

Gauthier et al. 2015 evaluated the vulnerability of timber supply facing the increase of forest fire at the level of forest management areas (FMAs) across the boreal forest of Canada. The vulnerability assessment approach has already been used in forestry context, and it was applied at a range of scales (Gauthier et al. 2014; Raulier et al. 2013). The probability that the stand will not reach its commercial maturity before being affected by fire is related to the time required to grow to that level (Gauthier et al. 2015; Van Wagner 1978).

We identify the vulnerability of forest productivity to fire risk to evaluated the planned timber supply effects when those are excluded from timber supply. Through optimisation and simulation models we determined the probability of survival of stands to each fire cycle (100, 200 and 400 years) according to rotation age. The optimum volume of wood to be harvested depend on the current state of the forest in terms of its growth rate and age class distribution (Van Wagner 1983). Planned timber harvest for a sustained yield unit is set with the intent of providing a sustainable timber harvest. This is usually understood to be the maximum even flow annual timber harvest that can be maintained over two forest rotations defined as typically 150-200 years (Armstrong 2004). Van Wagner (1983) demonstrated that when harvest rates are sufficiently reduced, the harvest becomes relatively insensitive to the amount of fire. We illustrate how these indicators allow forest managers to decide the appropriate minimum harvesting threshold when implementing a harvest strategy on a area as a function of productivity characteristic and fire regime.

Conclusions

In the context of climate change, forest managers are continuously facing different risks which require tolerance to avoid timber harvest disruptions. Decisions-makers improve their chances of success by choosing which strategic tools work best. This approach of rating wood volume available to harvest as a function of their vulnerability to fire can be used to reduce the impacts of fire on timber supply. To anticipate the impact of fire risk in timber supply calculations this paper suggests strategies for the forest management considering current and projected fire regimes, either by reducing the timber supply level by a fixed percentage throughout the planning horizon or by the assessment of timber vulnerability to fire by excluding low-productivity stands vulnerable to fire. However, managers constantly need to evaluate alternatives and make decisions regarding a wide range of matters under different degrees of uncertainty and to decide when to use one tool or combination of tools over another.

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Chapter 3: Sourcing Strategy to mitigate the impact of timber supply disruptions caused by fire

Résumé

Les perturbations naturelles comme les feux de forêt complexifient la planification de la récolte du bois qui doit toujours faire face au risque. Nous avons modélisé l'effet de la variation du volume de récolte à long terme dans l'unité d'aménagement forestier 085-51. La récolte planifiée a été établie en utilisant un modèle de programmation linéaire maximisant le volume total récolté. La récolte, le régime de feu et la succession ont été mise en interaction à l'aide d'un modèle spatialement explicite. Nous avons évalué des approches flexibles en combinant une réduction des prélèvements de bois nécessaires à la création d'une réserve forestière avec différents niveaux de coupe partielle, en supposant que le cycle de feu futur diminuera. L'efficacité des scénarios a été évaluée par le taux de réussite à réaliser les niveaux de récolte planifiés. Nous concluons qu'une réserve de bois associée à un certain niveau de coupe partielle pourrait aider les gestionnaires à éviter les variations de volumes disponibles à la récolte de bois causées par le risque de feux de forêt dans le contexte de la gestion des écosystèmes forestiers.

Abstract

Planned timber harvest is hampered by uncertainty and to be difficult to reach because of natural disturbance such as wildfire. We modelled the effect of the variation of harvest volume on the likelihood of probability of maintaining the planned timber harvest in the eastern boreal management unit for a long term forest planning. The planned harvest was set using a linear programming model maximizing the total harvested volume. The harvest, fire regime and succession were simulated using a spatially explicit model. We evaluated flexible approaches by reduction of timber harvest necessary to build a buffer stock including silvicultural strategies for managing forested ecosystems under an assumption that future fire cycle will decrease. We conclude that a buffer stock coupled with partial cutting could help managers avoid potential timber harvest disruptions caused by wildfire risk in the context of forest ecosystem management.

Introduction

In boreal forests, the area disturbed by fires is highly variable both over time and space, and can have a wide range of impacts (Martell 1994). Such impacts represent multiple potential losses than can be extremely damaging (Brunette et al. 2015). Tools for mitigation or risk management vary in scope and objective; some serve to minimize the exposure to disturbances while others compensate for losses (Galik and Jackson 2009). The wood available to mills is certainly one of the crucial elements of forest economic analysis. Strategic sourcing and supply management offers managers the opportunities to set the stage for uninterrupted supply (Narasimhan and Talluri 2006).

The development of a sourcing strategy is an interesting way to mitigate supply disruptions (Tomlin 2006; Savage et al. 2010). Salvage logging is increasingly being used to mitigate economic losses due to fire (McIver and Starr 2001; Peter and Nelson 2005; Leduc et al.2015). However, the effects of salvage logging on the environmental, economic and social impacts are still limited (Nappi et al. 2004; Foster and Orwig 2006).

Much of the literature (Raulier et al. 2014; Martell 1994), states that a stable timber supply requires the establishment of a buffer stock which could be significant in compensating potential losses loss in long-term planning (Boychuk and Martell 1996; Reed and Errico 1986; Van Wagner 1983). We can also opt for a strategy consisting of a reduction of the exposure to fire risk through the exclusion of vulnerable stand from the timber production area (Raulier et al 2013) or via fire suppression or the introduction of impediments to reduce fire spread (Hirsch et al. 2001).

By producing more dispersed cut-blocks and reducing rotation length compared to clearcutting (Prévost and Pothier 2003.; Harvey et al. 2002), partial cutting be an alternative strategy to reduce exposure to risk. Bergeron et al (2002) suggests that silvicultural techniques designed to maintain forest compositions and structures at different scales should be taken for strategic-level forest management planning. Spatial and temporal variations of partial cutting have an important influence on forest composition and structure at the landscape and regional levels (Harvey et al. 2002). Partial cuttings are increasingly used in boreal forests to maintain natural structure and to increase residual tree growth (Pamerleau-Couture et al 2015) and could be a way of meeting both ecological and economic objectives based on the principles of sustained yield management (Eyre and Zillgitt 1953).

A decision quality framework for risk management would consider not only judgments and decisions about landscapes and ecosystems, but also strategic decisions that address the risks and trade-offs such as adaptive management, simulation models, and risk assessment (Borchers G. 2005). Several authors highlight, the silviculture as an important part of an integrated management program which and could play a determining role in the face of climate change issues (Stand 1989; Fujimori 2001; Mason et al.2012). In this paper, we evaluated the applicability of silvicultural strategy coupled with timber harvest reductions to provide a better chance of success of harvest planned.

Materials and methods

Study area

This study was carried out in FMU 85-51 in North-Western Quebec (Figure 3.1). The area of the FMU is around 1083513 ha localized in the sub-areas of balsam fir-white birch west and Black spruce-moss and crosses two ecoregions in the continuous boreal forest area of Quebec. The two ecological regions are identified as the Abitibi Lowland (5a) and the Lake

Matagami Lowland (6a). The southern ecoregion (Abitibi Lowland) belongs to the *Abies balsamea - Betula papyrifera* bioclimatic domain and the northern region (6a) belongs to the *Picea mariana-moss* bioclimatic domain. In the coniferous ecoregion (6a), the topography is generally flat, and the most important surficial deposit is organic soils (36% of the area) followed by clay deposits (29%). On the other hand, clay deposits (45%) are dominant in the southern ecoregion (5a) followed by organic deposits (18%). The southern region (5a) is characterized by a rolling topography whereas the northern part is flat, the average annual temperature of 1 °C and an average rainfall of 800-900 mm. The northern region (6a) is characterized by a mean annual temperature of 0 ºC and lower annual rainfall less than 800 mm respectively. In black spruce-moss the natural disturbances affecting the territory are fire (Bergeron et al. 20010. severe fires produce conditions conducive to the establishment of a productive population (Pollock and Payette 2010). Exposed mineral soil in a complete destruction of the organic matter and dead wood are indeed good seedbed for conifers such as black spruce (*Picea mariana-moss)* and jack pine *(Pinus banksiana* Lamb.*).* The majority of seedlings of black spruce and jack pine settle in the first three years following the passage of fire (St-Pierre et al., 1992, Charron and Greene 2002). Studies on the fire regime of the two ecoregions indicate that in both regions, the fire cycle changed around 1850, which corresponds to the end of the Little Ice Age. Before 1850, the fire cycle was less than 100 years, whereas after 1850 the cycles were extended to 200 and 400 years (Bergeron et al. 2010; Bergeron et al. 2001).

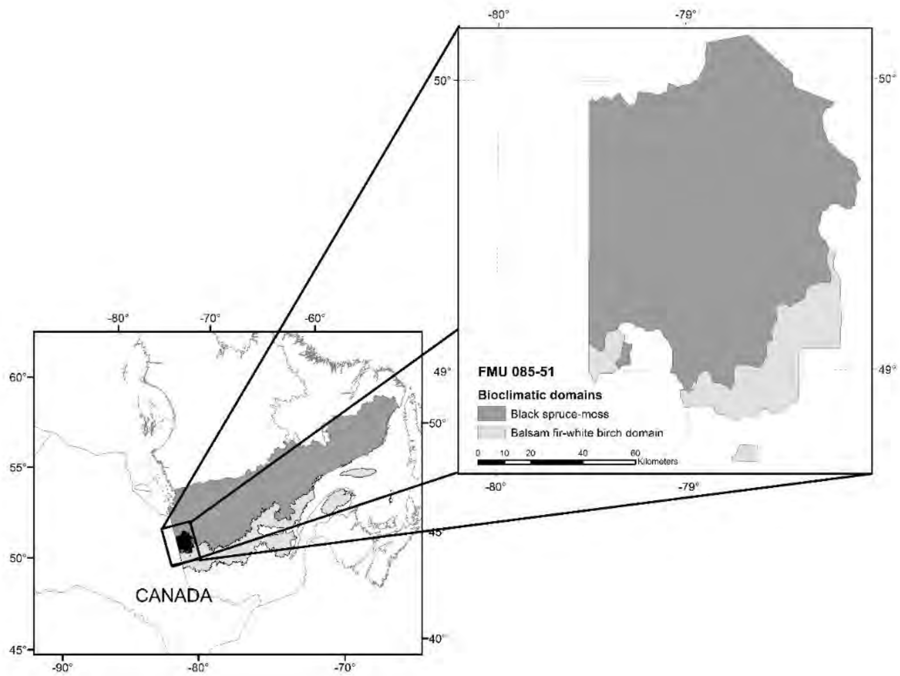

Figure 3.1. Forest management unit (FMU)- 8551

Optimization model

We calculated the planned timber harvest (PTH) based on the optimize model constructed in Woodstock (Remsoft Inc., Fredericton, NB) and solved with Mosek 5.0 (Mosek ApS, Copenhagen, Denmark).

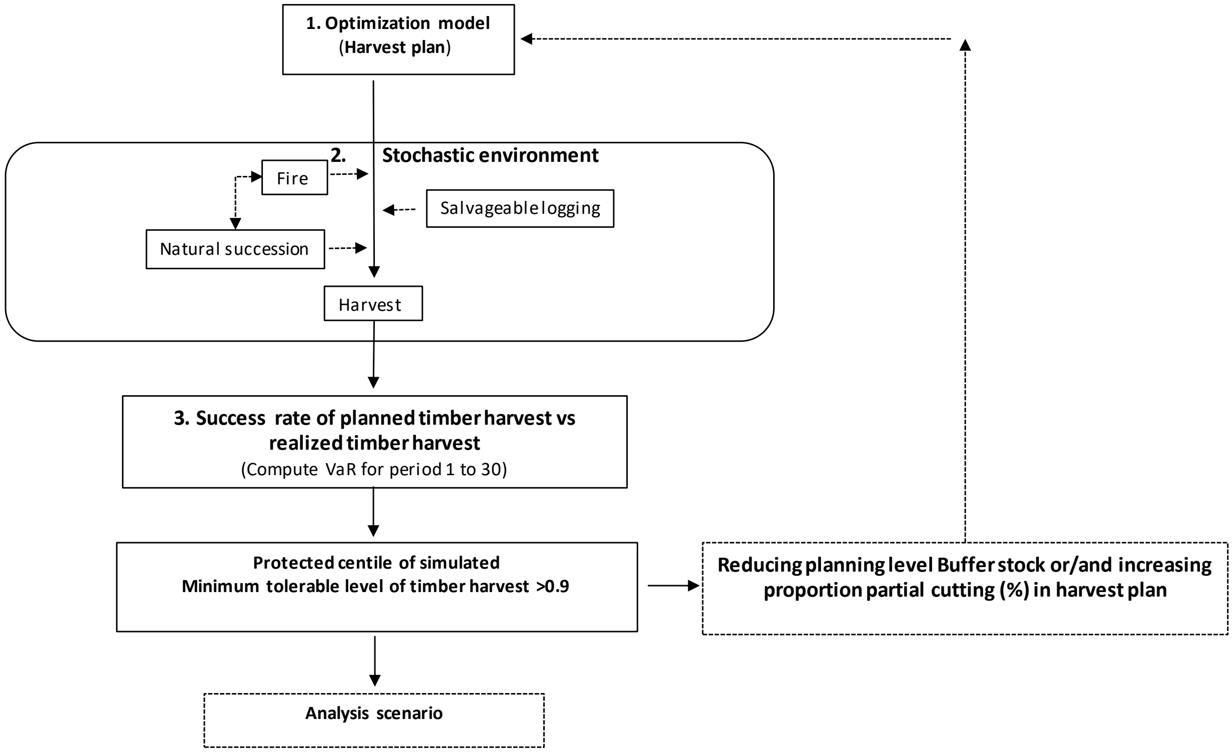

Figure 3.2. Optimization and simulation approach

The optimization model maximized the total harvest volume over 150 years (Eq. 1) solved using linear programming (LP) approach which was constrained to sustained yield (Eq. 2).

Maximize:

$$Z = \sum_{a=1}^{30}\sum_{s=1}^{3}\sum_{o=1}^{107}\sum_{h=1}^{2}\sum_{p=1}^{30} V_{asohp}A_{asohp} \tag{1}$$

Subject to

$$\sum_{a=1}^{30}\sum_{s=1}^{3}\sum_{o=1}^{107}\sum_{h=1}^{2} V_{asoh(p-1)}A_{asoh(p-1)} - \sum_{a=1}^{30}\sum_{s=1}^{3}\sum_{o=1}^{107}\sum_{h=1}^{2} V_{asohp}A_{asohp} = 0 \tag{2}$$

$$A_{asohp} \leq e_{asohp} \quad X_{op}P_{asohp} \;\; \forall\, a, s, o, h, p \tag{3}$$

$$A_{ashop} - e_{ashop} \leq 0 \quad \forall\, a, s, h, o, p \tag{4}$$
$$A_{ashop} \geq 0 \quad \forall\, a, s, h, o, p \tag{5}$$

$$X_{op} = \begin{cases} 1, & \text{if operating area is open to harvest} \\ 0, & \text{otherwise} \end{cases}$$

B_o: Productive area (ha) of the operating area, $\forall\, o$

The objective value z corresponds to the total volume that was planned to be harvested over the entire planning horizon (Eq. 3.1). Sustainable harvest flows within this model by constraining the model to harvest the same volume for each period (Eq. 3.2). a is stand age (5-year period), ∀a ϵ 2 (1..30), s is the successional pathway (1..3), o is the operating area, ∀o ϵ (1..107), h is the harvest type, ∀h ϵ (1..2), implemented by careful logging around advanced regeneration (CLAAG) followed by irregular shelterwood cuts (50% removal of merchantable volume) (Raymond *et al.* 2009), p is the 5-year period, ∀p ϵ (1..30); V_{asohp} is the volume yield (m^3 ha^{-1}), ∀a, *s,o,h,p,* A_{asohp} is the harvested area (ha), Va,*s,o,h, p*, e_{asohp} is the area eligible for harvesting (ha), ∀a, s, o, h, p, Xop takes the value of 1 if the operating area is to be harvested and of 0 otherwise, Bo is the timber production area within operating area.

Stochastic environment

In a stochastic environment, we integrated the harvest sub-model with fire and succession sub-models (Figure 3.2). The optimal harvest schedule was used in a harvest sub-model where salvage logging volume is expressed as 30% of the total volume of any productive pixel (volume greater than 50 m^3 ha-$^{1)}$ and to be harvested first. Spatially Explicit Landscape Event Simulator (SELES) (Fall et fall 2001), has been used to assess mu ltiple interrogations toward the spatial interaction between stochastics events such as fire and deterministic long term forest management alernatives (Titler et al. 2012; Raulier et al. 2014; Cyr et al. 2016). The spatial resolution is based on a coarse resolution of 10 ha per pixel.

The simulations were done with a timestep of 5 years and a simulation horizon of 150 years corresponding to one and a half times the mean rotation age. Harvest sub-model was built with a planning horizon of 150 years (30 periods of 5 years). In succession sub-model, forest inventory, site-specific soil and drainage conditions was characterized and was modeled as a semi-Markov process where the succession pathway selected has a function of the proportion of area underlying in the operating area of the initial stands younger then 20 years (Fall et al. 2004) and replaces stands killed by logging or fire. The fire sub-model uses a percolation algorithm to emulate fire events (Fall et al. 2004), the fire size distribution of the territory is described with a weibull distribution (Bouchard et al. 2008) and the fire frequency with a exponential negative distribution.

Scenarios design

We estimated the harvest target reduction (BFS) that helped deal with timber losses and different proportions of partial cutting (PC). Harvest loss distributions was estimated by simulating the implementation of the timber supply solution for three fire cycles (100, 200 and 400 years). Periodic median VaR were computed from these loss distributions by reducing the PTH and increasing the amount of partial cutting assigned by simply toggling each 5%. Simulations were redone until we found a PTH that could be implemented with no risks. Hundreds of replicates of each scenario were simulated for 150 years using a five-year time step.

Managing risk

In the actual forest environment, tactics for managing disruptions risks, are those in which the managers take some action in advance of a disruption and incurs the cost of the action regardless of whether a disruption occurs (Tomlin 2006). The decision-makers need to consider how to maximize harvest volume in terms of probability and the assessment of potential loss (Eq. 3.1) to maintaining the PTH.

$$\mathrm{Prob}\left(\mathrm{L}_p \leq \mathrm{VaR}_p\right) = \alpha \qquad \text{(Eq. 3.1)}$$

Value at Risk served to assess risk was estimated with the 5th percentile (α) of the loss (L) distribution for a given period p. Supplier reliability and the nature of the disruptions are the most important determinants to achieving optimal strategies (Tomlin 2006).

Results

Proportions of partial cutting were estimated for a given BFS. Hence, according to the proportion of partial cutting successive implementation of the optimized timber supply solution helped find a median realized harvest level equal to PTH values for timber harvest levels (Fig. 3.2). We compared several scenarios required to protect the Median VaR. Under current fire cycle planned timber harvest is reduced by about 10% at 3.2 Mm^3 $period^{-1}$, moreover 15% of partial cutting is required to protect the Median VaR. However, a 15% of harvest reduction at 2.9 Mm^3 $period^{-1}$ with 20% of partial cutting and 15% of harvest reduction at 2.7 Mm^3 $period^{-1}$ with 30% of partial cutting are required to protect the Median VaR for fire cycles of 200 and 100 years respectively (Fig.3.3).

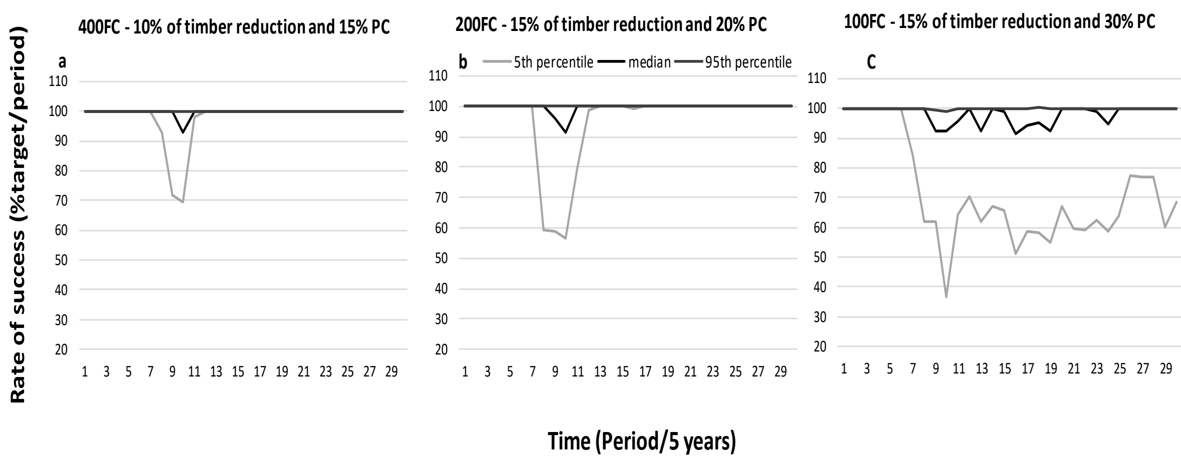

Figure 3.3. Successive implementation of a harvest target reduction (BFS) and increasing the amount of partial cutting required to protect the Median VaR implemented with no risks.

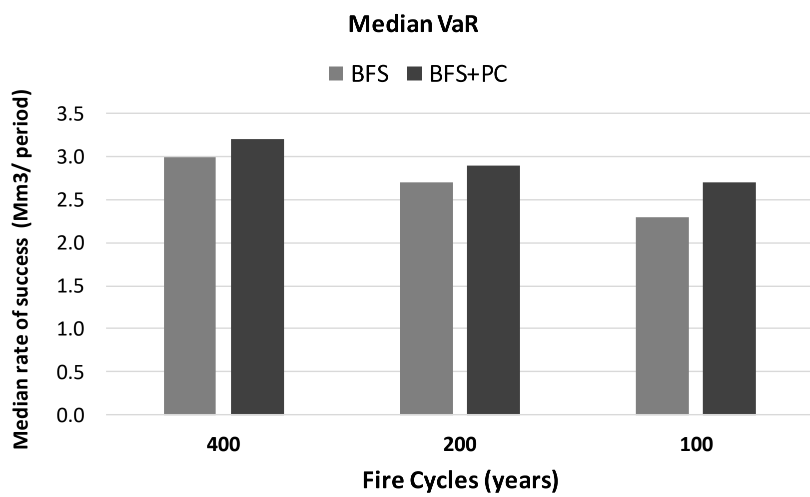

Figure 3.4. Median rate of success implemented with no risks for two protection strategies (indirect management of a buffer stock and combination with partial cutting).

Once the level on median protection was reached, the level of supply planned by optimization served to build up a buffer stock. Both indirect managements of a buffer stock and buffer coupled with partial cutting were efficient at protecting the rate of harvest success against the Median VaR, however, BFS coupled with PC provided greater median rate of success (Fig. 3.4).

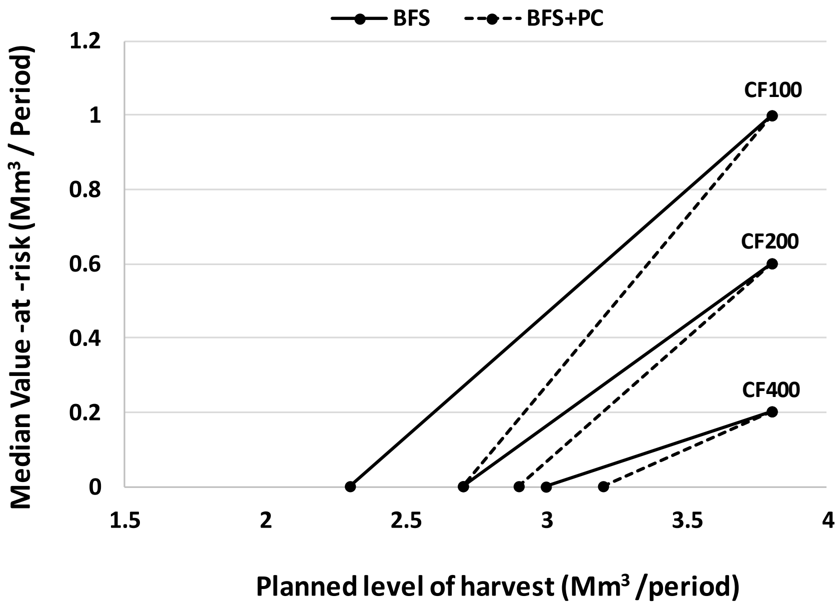

Figure 3.5. Median value–at-risk for two protection strategies: indirect management of a buffer stock of timber (BFS) and silvicultural strategy coupled with timber harvest reductions (BFS+PC).

Figure 3.5 presents the level of protection of median value-at-risk as a function of changes in the proportion of partial cutting and timber harvest reductions. Therefore, to protect de Median VaR under current fire cycle, 15% of timber reduction and 30% of partial cutting (2.8 Mm^3 $period^{-1}$) is required, while to protect de Median VaR under 200 fire cycle 25% of timber reduction and 50% of partial cutting (2.2 Mm^3 $period^{-1}$) is required, however to protect de Median VaR under 100 fire cycle, 40% of timber reduction and 50% of partial cutting (1.8 Mm^3 $period^{-1}$) is required.

Discussion

To handle risk assessment, different tools have been proposed (Borchers 2005). Risk management according to a timber harvest reduction strategy was already evaluated (Raulier et al. 2014; Savage et al. 2010); furthermore, in the previous chapter, timber harvest disruptions have been evaluated through the identification of forest areas most vulnerable to fire and excluding low-productivity stands from timber supply. Protection strategies can help reduce the risk of fire but does not necessarily alleviate the risk associate with exposure to timber harvest disruptions (Raulier et al. 2014).

To protect significant disruptions (Max VaR) under current fire regime, a 35% of harvest reduction is required and such reduction should be increased to 48% and 56% under 200 and 100 years fire cycles respectively (Rodriguez et al., 2016). Nevertheless, to protect Median VaR under current and future fire regime, 21%, 31%, and 12% of harvest reduction is required for indirect management of a buffer stock (Figure 3.3). It is possible to extract higher volumes of wood by combining a reduction of harvest level with alternative practices involving variable proportion of partial cutting (Fig. 3.4). Partial cutting is considered as one of the major forest management activities in many regions of the world (Zhou et al. 2013) and can serve to various purposes, including reduction of fire risk (Thorpe et al. 2007; Harvey et al., 2002). Within the context of landscape management unit, partial cutting can be used to have minimal impact on the targeted ecological objectives to the maintenance of biodiversity (Steeger et al.1999).

Long-term planning has challenges associated with time as well as spatial scale (Morgan et al. 2001). The implementation of an adapted silviculture regime, such as partial cutting was addressed for reducing differences between natural forest and forest management (Cimon-Morin et al. 2010), and to maintain old-growth attributes (Johnson et al. 1995; Côté et al. 2010). Partial cutting by reducing rotation period can reduce the time of exposure to the risk

(Steeger et al. 1999) and have significant impacts on forest structure and functions (Reich, 2011).

Salvage of burned timber have been evaluated by Leduc et al. (2015) to help mitigate the inclusion of fire in planned timber harvest. In the present study, salvage logging was given a higher priority to be harvested, fixed at 30% of pre-fire standing volume. Despite having faced the risk of wildfire for many decades, experts are currently reviewing wildfire prevention and mitigation. Notwithstanding such strategy will never eliminate the risk of wildfire completely (Borchers 2005). Risk should be tolerated rather than avoided (Peter and Nelson 2005).

This study addressed to protect the Median VaR using partial cutting and buffer stock. Hence, to protect median VaR; 10% of harvest reduction and harvesting of 15% using partial cutting (created 3.2 Mm^3 period-^{1}) under current fire regime is required. The protection strategies remained effective when 15% of harvest reduction at 2.7 Mm^3 $period^{-1}$ were practiced in combination with 30% of partial cutting, this combination allows for protecting the Median VaR of the success rate under future fire regime (100 years fire cycle). Our approach integrates indirect management as timber reduction and silvicultural treatments taking into account the impacts of potential changes in the fire regime. Creating a buffer stock and using silvicultural alternatives to clearcutting would be effective or even practical, and it might even help protect timber harvest disruptions. In contrast to clearcutting, old-growth stand structure and important wildlife values can be reconducted more rapidly after partial cutting (Steeger et al. 1999). As a whole, despite the fact that partial cutting is increasingly applied as an approach to balancing economic and ecological management objectives (Bose et al. 2013), many concerns should be addressed. such as increased costs in planning time and field layout (Picard and Sheppard 2002). Decision support in forest management is widely seen as necessary and the decision makers have to compare the alternatives by themselves, and choose an optimal one (Lawrence, A. 2011).

Conclusions

Over the last several decades, forest managers have increasingly looked for strategies to minimize the risks and maximize timber harvest under changing conditions. In this study, we assess whether partial cutting coupled with buffer stock may be useful to achieve timber supply target. The strategy involves the uses of variable proportion of buffer stock and partial cutting. Partial cutting coupled with buffer stock strategy appears to be a feasible management tool for meeting timber supply objectives. We suggest that no single strategy should overcome all challenges, especially in the context of wildfire risk and other multi mitigation approaches may be required to minimize fire risk. In fact, forest managers should be able to forecast the outcome of each management strategies to make a balanced decision.

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General Conclusion

Every decision we take involves a certain amount of risk (Tannert et al. 2007). In this context risk analysis and risk management becomes important in research field (Renn and Klinke 2004). Given the increasing importance of risk concerning natural disturbance in forest managing planning it is important to consider vulnerability and adaptation to climate variability and change (Dhital et al 2013; Brooks 2003). Currently the combination of mathematical and computational advances has made the estimation of risk-based performance measures possible for models (Keil et al. 1998; Maier and Ascough 2006), and may well lead to fundamental advances in ecology (Green et al. 2005) but specifications of parameters values is required (Mangel et al. 2001).

The importance of integrated models in sustainable development to proposed management options is required (Clark and Dickson 2003). To integrate dynamic interactions between nature and society, much work has also been done by combining social, environmental and economic assessment (Jakeman et al.2008). The literature about computer power and software are already well developed to achieve a better understanding including the feedbacks which occur in an ecosystem between the climate and human intervention *by* model integration (Chubaty and McIntire 2015).

Deelman and Szymanski (1998) reveals that the dynamic model can be useful but due to the complexities involved the predictive capacity of ecology needs to be applied discriminately. In this thesis, we used a tool for building and running models of landscape (SELES) but a model performance can be challenging by other Spatially Explicit Discrete Event

Simulation Models *(SpaDES)* at times to improve simulation performance (Chubaty and McIntire 2015).

Modeling and simulation in the last decades is becoming easier and faster through the implementation of advances technologies available for studying large and complex system (Carson and Maria 1997; Charette 1989). Simulation can help the implementation of the optimized solution of a timber supply problem to assess the feasibility of the optimal solution Zeigler et al. 2000). Understanding wildfire disturbance is a challenge because of complex interactions over of large temporal and spatial scales (He and Mladenoff 1999; Fall et al. 2004). Therefore, it is important to understand the impact of implementing forest management strategy in long range planning. Based on these insights, we developed a spatially explicit simulation model (Fall and Fall 2001) of timber supply optimization for assessing the effects of wildfire on timber harvest planned and describe the process of managing risk to reduce timber damage.

Many studies have focused on development and implementation processes about potential risks and the conditions under which certain outcomes (Jakeman et al.2008). Several techniques and tools are designed to account of risk induced by fire, succession and changing climatic scenarios. Techniques for the statistical measurement of risk is a part of the process of managing risk (McNeil and Embrechts 2015). We use VaR to characterize expected losses caused by fire and examining the rate of success of harvest planning. However, the identification of sources of uncertainty such as the development of risk-based performance measures is an important issue in the decision-making process (Maier and Ascough 2006). Scenario planning allows managers to assess strengths and weaknesses and understand more about the outcomes of different decisions made under conditions of risk and consider how to take advantage of opportunities (Miller and Waller 2003).

The focus of the first chapter was to estimate the amount of reduction of timber harvest necessary to build buffer stock and compared it to an insurance premium estimated in units of timber volume. As far as the insurance is concerned, it looks like a good strategy, but find an insurance company that is interested enough to 'crunch the numbers' to see if they believe there are enough potential customers to pay the premiums to make a profit could be required.

In the same context, in the second chapter we evaluated the exclusion of vulnerable stands from timber harvest (Raulier et al. 2013) compared to the situation where a buffer stock of timber is created by reducing the planned harvest level by a constant proportion during the strategic planning (Raulier et al. 2014).

The third chapter prescribe partial cutting coupled with buffer stock for developing harvest schedule in an uncertain environment. The combination of two strategies may allow managers to take advantage over other strategies (Quinn and Hilmer 1994). We did not incorporate an economic analysis of partial cutting which is important to demonstrate the feasibility of mitigation strategies in a boreal forest (Dhital et al. 2013).

Whilst most organizations have previously assessed risk as a key strategic issue, and often only partially addressed it, in this age of globalization risk management has become a critical issue (Clarke and Varma 1999). We suggest that no single strategy should overcome all challenges, and an integrated risk management approach is likely to result in higher performance while proactively managing risks.

Regarding the future, forest managers seek to maximize wood supply despite climate change conditions (decreasing fire cycles) which caused important failures in the level of realized harvested volume. Likewise, they are constantly required to evaluate many potential management alternatives to obtain optimal trade-offs between competing strategies. The effectiveness of different strategies for managing risk needs to be attentively assessed (Charette1989; Klinke and Renn, 2002) and it may will depend on several factors, such as the perceived importance and magnitude of the problem, as well as financial considerations in a way that suggests meaningful risk mitigation.

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