

Design of Forest Supply Chain Under Uncertainty: The Impact of Spruce Budworm Infestation on the Wood Supply

by

Siamak MUSHAKHIAN

MANUSCRIPT-BASED THESIS PRESENTED TO ÉCOLE DE
TECHNOLOGIE SUPÉRIEURE IN PARTIAL FULFILLMENT FOR THE
DEGREE OF DOCTOR OF PHILOSOPHY
Ph.D.

MONTREAL, FEBRUARY 26, 2021

ÉCOLE DE TECHNOLOGIE SUPÉRIEURE
UNIVERSITÉ DU QUÉBEC



Siamak Mushakhian, 2021



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FOREWORD

This thesis is prepared as an insertion thesis comprising of five chapters starting with the introduction, following three published or submitted articles regrouped in chapter 1, 2, and 3, finally, ending with a conclusion. Here is the information on the mentioned articles:

- Mushakhian, S., Ouhimmou, M., Rönnqvist, M., Montecinos, J. (2020) “The integration of spraying and harvesting to minimize the wood losses during an outbreak of spruce budworm”, Submitted on Canadian Journal of Forest.
- Mushakhian, S., Ouhimmou, M., Rönnqvist, M., (2020) “Salvage Harvest planning for Spruce Budworm Outbreak using Multi-stage Stochastic Programming”, Canadian Journal of Forest Research (forthcoming).
- Mushakhian, S., Ouhimmou, M., Rönnqvist, M., Lussier, J-M., (2019) “How the minimum number of periods between regeneration harvests induce modeling errors in the well-known Model II forest management?”, Publication CIRRELT, October 2019.

In addition, the results of this work were presented during the following conferences:

- Wood losses and economic effects of Spruce Budworm defoliation on the forest value chain, Expo-conference, Université Laval, Québec, Canada, January 29, 2020.
- A multistage stochastic programming model for optimal forest harvesting in the context of wood infestation, 13th International Conference CIGI Qualita, Montreal, Canada, June 25-28, 2019.
- Design of supply chain under uncertainty: The impact of Spruce Budworm Infestation on the wood supply, 18th Symposium on System Analysis in Forest Resources (SSAFR), Puerto Varas, Chile, March 3-7, 2019.
- How the minimum number of periods between regeneration harvests induce modeling errors in the well-known forest management Model II?, 18th Symposium on System Analysis in Forest Resources (SSAFR), Puerto Varas, Chile, March 3-7, 2019.
- Design of supply chain under uncertainty (Spruce Budworm Infestation) Info-FORAC / FORAC News, Expo-conference, January, Québec, Canada, 2019.
- Design of supply chain under uncertainty, Expo-conference, Université Laval, Québec, Canada, January 30, 2018.

ACKNOWLEDGMENTS

First of all, I wish to acknowledge my parents for their love and support throughout my life. Thank you both for giving me the strength and support me to chase my dreams.

Then, I would like to thank my supervisors, Prof. Ouhimmou and Prof. Rönqvist, for their guidance, comments, questions, and all their supports financially and emotionally throughout this study. This journey would not have been possible to accomplish without their guidance, encouragement, and supports.

I would like to pay special regards to FORAC Research Consortium for their financial support, conferences, and summer schools during all these years. Without their support and funding, this project could not have reached its goal.

I wish to thank all the people whose assistance was a milestone in the completion of this project. I deeply appreciate Mr. Jean-Martin Lussier (Canadian Wood Fibre Centre), Mr. Mathieu Bouchard (Ministère des Forêts, de la Faune et des Parcs (MFFP)), Mr. Sylvain Dallaire and Mr. Frédéric Leblanc (Bureau de mise en Marché des bois (BMMB)), and Mr. Nicolas Girard (Société de protection des forêts contre les insectes et maladies (SOPFIM)) for their time, energy, and collaboration such as providing the required information and technical advice. I wish to express my deepest gratitude to Prof. Ouhimmou for arranging the meetings and all his supports.

I want to thank all my colleagues in the C2SP lab and would like to address a special thanks to Julio for his help, comments, and contribution.

Finally, to all my friends, thanks for your help, encouragement, and support during this journey. I cannot list them here, but you are always on my mind and I wish you the best of luck.

Conception de la chaîne d'approvisionnement forestière sous l'incertitude: l'impact de l'infestation de la de la tordeuse des bourgeons de l'épinette sur l'approvisionnement en bois

Siamak MUSHAKHIAN

RÉSUMÉ

L'industrie forestière joue un rôle important au Canada aux niveaux environnemental et économique. En 2017, la production du secteur forestier a contribué pour environ 25 milliards de dollars au produit intérieur brut (PIB) du Canada en plus de 210 000 emplois directs et 107 000 emplois indirects. Cependant, des millions de dollars représentent le coût des dommages causés par les espèces envahissantes aux propriétaires forestiers tels que le gouvernement, les industries et les particuliers. Les pertes de revenus, les investissements de prévention et de contrôle et les efforts d'atténuation environnementale ont coûté au Canada des centaines de millions de dollars au cours des dernières années. Les éclosions de tordeuse des bourgeons de l'épinette sont une perturbation naturelle majeure bien connue dans l'est du Canada. C'est l'insecte le plus destructeur des peuplements de conifères en Amérique du Nord. La réduction de l'approvisionnement en bois est l'un des principaux effets directs des épidémies d'insectes. À titre d'exemple, en 2017, plus de 7 millions d'hectares ont été défoliés par la tordeuse des bourgeons de l'épinette au Québec. Une défoliation répétée entraîne la mortalité des arbres, une réduction des taux de croissance et une diminution de la qualité du bois. Il existe différentes méthodes de contrôle pour protéger la forêt contre les insectes et les maladies. Les méthodes de lutte sylvicole telles que la récolte de récupération et la récolte préventive sont utilisées pour satisfaire la demande des entreprises forestières et des méthodes chimiques comme la pulvérisation d'insecticide biologique *Bacillus thuringiensis* ssp. *kurstaki* (Btk) est pris en compte pour maintenir les arbres en vie pendant une infestation à grande échelle pour une récolte ultérieure.

Dans mon article, intitulé «Planification de la récolte de récupération pour l'éclosion de la tordeuse des bourgeons de l'épinette à l'aide de la programmation stochastique multi-étapes», nous avons examiné l'effet des changements d'intensité de l'épidémie sur les valeurs du bois dans toute la forêt, car l'infestation du bois peut changer la qualité du bois. La récolte de récupération est considérée comme une action visant à atténuer les dommages économiques et environnementaux. Nous proposons un modèle de programmation stochastique en nombres entiers multi-étapes pour la planification des récoltes sous diverses intensités d'épidémie. L'objectif est de maximiser les revenus de la valeur du bois moins les coûts logistiques tout en satisfaisant la demande de bois dans l'industrie. Les résultats montrent qu'en cas d'épidémie dans toute la forêt, la plus haute priorité pour la récolte de récupération est de se concentrer sur les zones forestières présentant le niveau d'infestation le plus bas.

L'autre article, intitulé «L'intégration de la pulvérisation et de la récolte pour minimiser les pertes de bois lors d'une épidémie de tordeuse des bourgeons de l'épinette» utilise deux

techniques de lutte, la pulvérisation et la récolte, contre la défoliation par la tordeuse des bourgeons de l'épinette dans la forêt. À chaque période, l'estimation du volume de bois pour chaque peuplement est mise à jour en fonction de ses attributs caractéristiques, de l'historique de la défoliation et du fait qu'il a été pulvérisé ou non. Cette étude fournit un modèle déterministe abordant les questions de savoir où et quand doit être récolté ou pulvérisé pour maximiser les revenus du bois récolté moins les coûts logistiques et maximiser la valeur des arbres sur pied à la fin de l'horizon de planification tout en satisfaisant la demande de bois dans l'industrie et minimiser les coûts de protection des forêts. Le modèle a été appliqué à une étude de cas située dans la région du Bas-Saint-Laurent au Québec. Les résultats montrent que les avantages de la récolte l'emportent sur les avantages de la pulvérisation et les modèles préfèrent récolter plutôt que pulvériser; cependant, cela ne signifie pas que la pulvérisation n'est pas efficace. La pulvérisation est utile mais elle n'est pas économique par rapport à la récolte. De plus, les peuplements qui ont la plus forte perte de bois, en d'autres termes, ils ont une proportion élevée de sapin baumier et l'épinette blanche et le score de défoliation cumulatif est autour du point de retournement de la courbe de mortalité cumulée sont choisis pour la récolte. Enfin, les peuplements qui ont un rapport de densité élevé (volume / surface) sont des choix économiques pour la pulvérisation.

Lors de l'étude des modèles de gestion stratégique des forêts, nous avons observé deux erreurs dans la formulation originale de l'un des modèles bien connus appelé Modèle II si le nombre minimum de périodes entre les récoltes de régénération est négligé. Le premier est une erreur dans les contraintes de surface et le second dans le calcul d'un paramètre important du modèle représentant le revenu net actualisé par hectare entre les périodes. Nous fournissons un modèle révisé avec des commentaires sur les calculs d'un paramètre utilisé dans la formulation du modèle. Ensuite, afin de valider le problème identifié, nous résolvons le modèle II avec des données réalistes pour corriger les erreurs de modélisation et expliquer comment notre formulation révisée fonctionne avec les mêmes données. Nous décrivons également des situations où les erreurs peuvent avoir un impact plus important et expliquons pourquoi elles n'ont pas été identifiées plus tôt. Cette étude est le premier article intitulé «Comment le nombre minimum de périodes entre les récoltes de régénération induit des erreurs de modélisation dans la gestion forestière du Modèle II».

Mots-clés: Planification de la gestion forestière, récolte du bois, planification de la récolte, programmation linéaire, modèle II, tordeuse des bourgeons de l'épinette, infestation, défoliation, approvisionnement en bois, récolte de récupération, pulvérisation, programmation stochastique.

Design of forest supply chain under uncertainty: the impact of spruce budworm infestation on the wood supply

Siamak MUSHAKHIAN

ABSTRACT

The forest industry is very important from both environmental and economic perspectives for Canada. In 2017, production in the forest sector contributed around \$25 billion to Canada's real gross domestic product (GDP) through 210 thousand direct and 107 thousand indirect jobs. However, millions of dollars are the cost of damage of invasive species to forest owners such as government, industries, and private citizens. Revenue losses, prevention and control investments, and environmental mitigation efforts have cost Canada hundreds of millions of dollars during the last years. Spruce budworm (*Choristoneura fumiferana* (Clemens)) outbreaks is a well-known major natural disturbance in eastern Canada. It is one of the most destructive insects in North America's conifer stands. Reduction in the wood supply is one major direct impact of insect outbreaks. As an example, in 2017, more than 7 million hectares were defoliated by spruce budworm in Quebec. Repeated defoliation causes tree mortality, reduction of growth rates, and reduced lumber quality. There are different control methods to protect forest against insects and diseases. Silvicultural control methods such as salvage harvesting and pre-emptive harvesting, are used to satisfy the forestry companies' demand and chemical methods like spraying biological insecticide *Bacillus thuringiensis* ssp. *kurstaki* (Btk) is taken into account to maintain trees alive during large-scale infestation for later harvest.

In my article, titled "*Salvage Harvest planning for Spruce Budworm Outbreak using Multi-stage Stochastic Programming*", we considered the effect of changes of outbreak intensity on wood values throughout the forest as the wood infestation can change the lumber quality. Salvage harvesting considered as an action to mitigate the economic and environmental damages. We propose a multistage stochastic mixed-integer programming model for harvest scheduling under various outbreak intensities. The objective is to maximize revenues of wood value minus logistic costs while satisfying demand for wood in the industry. Results show that when there is an outbreak throughout the forest, the first priority for salvage harvesting is to focus on forest areas with the lowest level of infestation.

The other article, titled "*The integration of spraying and harvesting to minimize the wood losses during an outbreak of Spruce Budworm*" uses two control techniques, spraying and harvesting, against spruce budworm defoliation in the forest. In each period, the estimation of wood volume for each stand is updated based on its feature attributes, history of the defoliation, and whether it has been sprayed or not. This study provides a deterministic model addressing the questions of where and when should be harvested or sprayed to maximize revenues of harvested wood minus logistic costs and maximize the value of standing trees at the end of the planning horizon while satisfying demand for wood in the industry and minimizing the forest protection costs. The model has been applied to a case study located in the Bas-Saint-Laurent

region in Quebec. The results show that the benefits of harvesting outweigh the benefits of spraying and the models prefer to harvest rather than spraying; however, it does not mean that spraying is not effective. Spraying is helpful but it is not economical in comparison with harvesting. Furthermore, stands which have the highest wood loss, in other words, they have a high proportion of BF and WS and the cumulative defoliation score is around the turning point of the cumulative mortality curve are elected for harvesting. Finally, stands which have a high-density ratio (volume to the area) are economical choices for spraying.

While studying strategic forest management models, we observed two mistakes in the original formulation in one of the well-known models called Model II if the minimum number of periods between regeneration harvests is overlooked. The first is a mistake in the area constraints and the second in calculating one important parameter of the model representing discounted net revenue per hectare between periods. We provide a revised model together with comments on the computations of a parameter used in the model formulation. Then, in order to validate the problem identified, we solve the Model II with realistic data to address the modeling mistakes and explain how our revised formulation works with the same data. We also describe situations where the mistakes may have a larger impact and explain why they have not been identified earlier. This study is the first article called “*How the minimum number of periods between regeneration harvests induces modeling mistakes in the well-known Model II forest management*”.

Keywords: Forest management planning, timber harvest, harvest scheduling, linear programming, model II, spruce budworm, infestation, defoliation, wood supply, salvage harvesting, spraying, stochastic programming.

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LIST OF ABBREVIATIONS

AAC	Annual Allowable Cut
BMMB	Bureau de mise en Marché des bois
BF	Balsam Fir
Btk	Bacillus thuringiensis ssp. Kurstaki
CDS	Cumulative Defoliation Score
CMR	Cumulative Mortality Rate
CT	Commercial Thinning
DBH	Diameter at Breast Height
DS	Defoliation Score
GDP	Gross Domestic Product
LP	Linear Programming
MFFP	Ministère des Forêts, de la Faune et des Parcs
NPV	Net Present Value
PCT	Pre-Commercial Thinning
SBW	Spruce Budworm
SOPFIM	Société de protection des forêts contre les insectes et maladies

INTRODUCTION

After Russia and Brazil, Canada has the 3rd largest forest area in the world and abundant forest resources. In 2017, the forest industry employed about 210,000 people across the country and contributed around \$24.6 billion to Canada's economy. It was accounted for about 7.2% of Canada's total exports in that year (Natural Resources Canada, 2020a). The importance of forest industry is growing because of some significant contributions in our society such as, creating jobs, creating economic values, enhancing our environment, and generating renewable energies. Therefore, it plays an important role in both national and international landscapes.

In forest value chain, business activities including forest resource management, harvesting operations, logistics, manufacturing, product distribution, sales and marketing performed by a single or several companies which are inter-dependent so that a decision in one area of business can have ensuing effect on the others. Creating greater values by transforming process from raw materials to products that meet the consumers' needs in the market can be achieved by managing and coordinating the chain of business activities. However, uncoordinated business activities can lead to serious adverse effects such as excessive inventories, waste of resources, long lead times, uncertainties, and customer dissatisfaction.

The companies within the value chain network are usually independent and complete units with their own business goals and strategies, however they are inter-dependent through business deals and customer-supplier relationships throughout the value chain. Nowadays the forest value chain is recognized as an integrated system through which environmental, social, and economic values flow from Canada's forests (D'Amours et al., 2016).

Natural disturbance processes are the main sources of uncertainty complicating forest management in Canada. Insect outbreak is one of the major natural disturbances on the landscape. Between 1990 to 2017 forest insects like spruce budworm (*Choristoneura fumiferana* (Clemens)), forest tent caterpillar (*Malacosoma disstria* Hubner), and mountain pine beetle (*Dendroctonus ponderosae* Hopkinss, 1902) have, on average, annually defoliated

around 11 million hectares in Canada (National Forestry Database, 2019). Revenue losses, prevention and control investments, and environmental mitigation efforts have cost Canada hundreds of millions of dollars during the last years (Natural Resources Canada 2017).

Spruce budworm outbreak is a well-known natural disturbance in the Eastern Canada. In 2017 only, spruce budworm (SBW) infested over 7 million hectares in Quebec (National Forestry Database 2019). At a rough estimate, annual timber harvest volume losses from forest insect outbreaks are around half of the annual harvest level in Canada (MacLean 2004). The major direct impact of insect outbreak is wood supply reduction. Therefore, one of the main challenges for forestry companies is to ensure that they have access to reliable sources of wood and fiber (quantity and quality).

Strategic Forest Management

Strategic planning is designed to invest in some beneficial way. Strategy is a combination of past experience and present creativity for future. Strategic forest-management concentrates on the cooperation between forest-management decisions. Implementation of a strategy provides more information on the strengths and weaknesses, costs and benefits of a strategy and suggests to management the need for modifications to the strategy (Gunn, 2007).

D'Amours et al. (2016) state that the Canadian forests are unique because of diversified species and forest types. Owning and managing the forests mainly by provincial and territorial government agencies, Canada is distinguishable from many other countries. Furthermore, it is characterized by different forest management regimes with ownership/tenure structures and by environmental and ecological regulations that can change dramatically not only from region to regions but also within some regions. This uniqueness has a fundamental impact on strategy and decision support needs.

Industrial strategy is usually considered within the domain of forest companies that contribute an integrated viewpoint internally within their company. In the new forest industry, with

multiple interacting sectors such as solid wood, fiber, chemicals, and energy, interindustry strategic collaboration would appear to be a necessity. This suggests that collaborative strategic approaches between forest management and industry are necessary to ensure that the management of the forest resources is consistent with industrial requirements in species and quality, both spatially and temporally.

Government and industry are not the only players. Society, often represented through various nongovernmental organizations (NGOs), has a strong interest in the ecological and social values as well as the economic benefits provided by the forest (Burton et al., 2003). The need for decision making in these complex, multistakeholders, and collaborative environments creates new decision support challenges (D'Amours et al., 2016).

The goal of forest management strategy is to answer to the following questions: what to supply, from where to supply to, to which market, and for what use to create value and jobs for local communities. Long-term supply is often depicted in terms of level flow or nondeclining yield. Renewability is the key feature of the forest as a supplier of raw materials (D'Amours et al., 2016).

Simple decision support systems cannot be created and applied universally because strategic planning of the forest value chain includes many different players in many different business contexts. Decision support for strategic planning helps decision makers assess the potential consequences of strategic business choices (Anthony (1965), Drucker (1995)). For strategic planning, we should take decision makers' values, objectives, and their future business anticipations into account because these decisions will change the future by reformulating the resources and opportunities available to the company (Gunn, 2003).

Strategic Forest Management Planning Models

There are different strategic forest management models such as ecosystem, forest economic system, and forest land and ecosystem management models. Ecosystem models, including gap

and landscape models, usually have been introduced by ecologists. Forest economic systems, like stand level economics and forest products markets, are introduced by economists. In this thesis, we are going to consider forest land and ecosystem management models made mostly by foresters.

Models are considered as the basic tools of strategic forest planning by most foresters because they examine long-term consequences of forest-management inputs. Linear programming and simulation models are two classes of such models. The crucial assumption is that forest management model does not change the capability of the soil to produce fiber and the capability of the economic system to absorb the forest products produced (Gunn, 2007).

In literature, four modelling approaches can be found for forest management planning including the well-known Model I and Model II (Johnson & Scheurman, 1977), Model III which is less common (Garcia et al., 1990), and the new proposed model for spatial forest harvest scheduling called Model IV (John & Tóth, 2015).

A forest manager aims to schedule timber harvest and investment on an area of timberland under even-aged management. His goal is to maximize the volume or value produced from its timberland, while encountering constant or decreasing prices in the volume of timber output (Johnson & Scheurman, 1977). The manager may come across land availability limits for harvesting in each time period when the whole area is managed under one silvicultural treatment regime. A silvicultural treatment regime is any sequence of silvicultural practices such as planting, pre-commercial thinning, commercial thinning, and fertilization (See Figure 1).

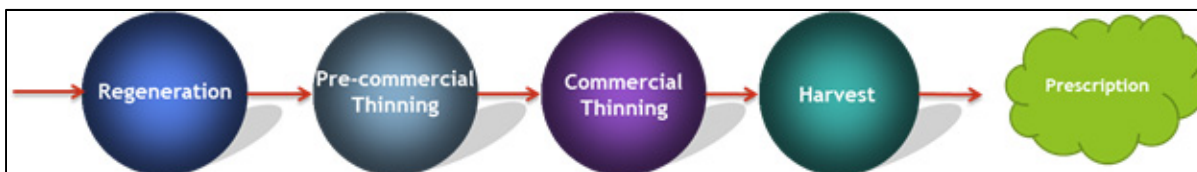


Figure 1 An example of silvicultural treatment regime

In addition to area constraints, the manager may also consider flow constraints (harvest fluctuation and sustainability). There are seven simplifying assumptions:

1. The forest has one type-site consisting of different age classes.
2. The area of forestland is fixed during the planning horizon.
3. The number of years representing each time period in the planning horizon is consistent with the years of each age class.
4. For regeneration harvest, we use clear-cutting.
5. Regeneration occurs in the same period as a regeneration harvest.
6. Yield estimates take into account all uncertainties such as fire, insect, and diseases implicitly.
7. The only out-of-pocket costs that should be paid are silvicultural treatment costs.

Davis et al. (2001) expressed that in forest management problems, there are usually three kinds of economic goals for timber management stated in physical or economic terms, such as:

- to maximize the physical volume of sustainable timber harvest, it might consider when the forest is the main log supply for a processing plant.
- to maximize the net present value of the forest, it occurs when the forest is considered as a separate profit center and also can clearly recognize income or benefits from non-timber outputs and services.
- to maximize the non-discounted net cash flow of the forest, this objective highlights the importance of current forest income to the owner.

Model I

In Model I (Johnson & Scheurman, 1977), the integrity of each age class in the first period is kept throughout the planning horizon. Each age class is recognized as a management unit whose integrity should be retained throughout the planning horizon (see Figure 2). Note that for each management unit we need a constraint to control the total number of hectares that can be assigned to all regeneration harvest sequences.

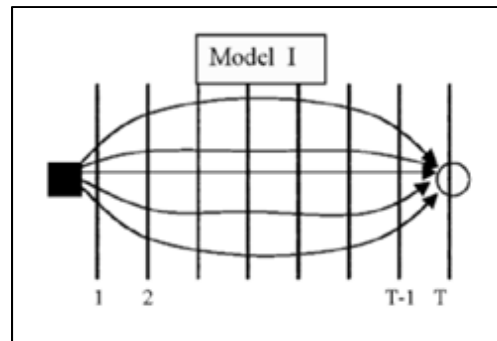


Figure 2 Model I network

Taken from Gunn (2007, p.329)

Model II and Model III can be substituted by this formulation with a big reduction in the number of variables but at the cost of numerous constraints and more complex constraints (Gunn, 2007).

Model II

In Model II, each age class forms a management unit, and they are harvested. Having regeneration harvested, new age class and management unit is formed till they are again regeneration harvested (see Figure 3).

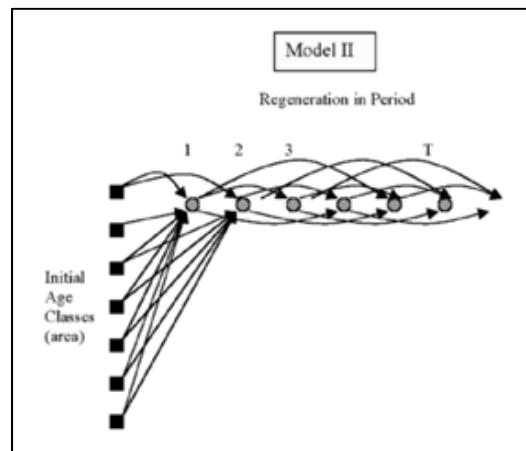


Figure 3 Model II network

Taken from Gunn (2007, p.329)

Note that the original formulation of Model II given by Johnson & Scheurman (1977) has a few mistakes which has been discussed in detail in chapter 1.

Model III

Garcia (1984) proposed a strata-based forest management planning model which is now known as Model III. Garcia (1984) categorized the forest according to crop types and age classes. Length of time periods are as equal as the number of years in each age class (see Figure 4).

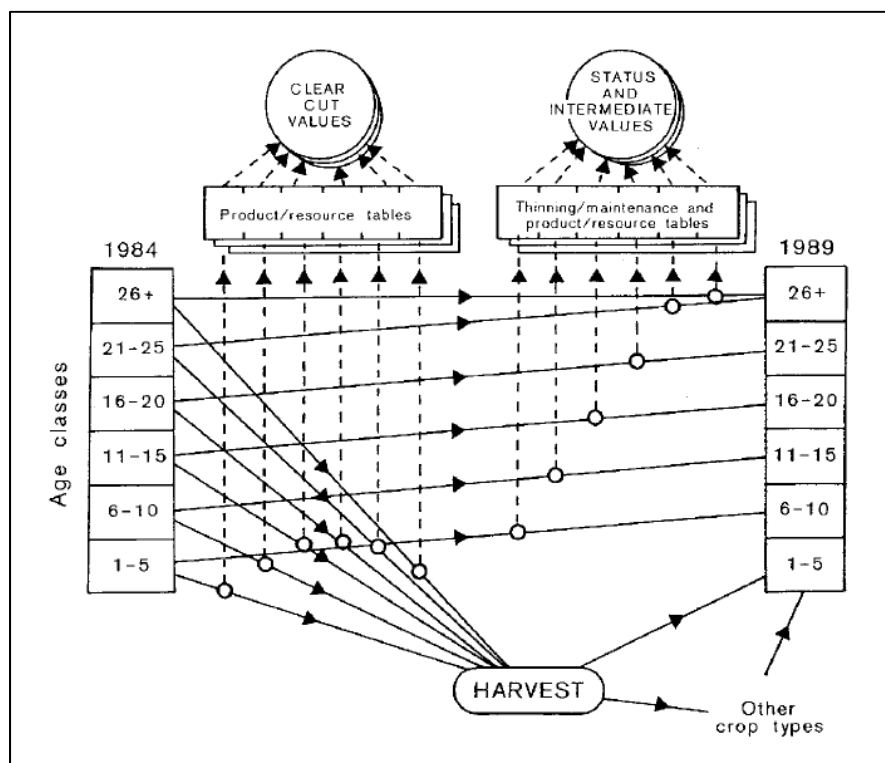


Figure 4 Conceptual Model III for one crop type and with 5-year age classes

Taken from García (1984, p.3)

In Figure 4, at the beginning of each time period, the state of the forest is described by the area in each crop type and age class. In each time period, the area in each age class may be harvested or remained intact. The harvested areas can be replanted into the same or different crop types, or put aside unplanted; however, the intact areas move into the next age class for the next time

period. Figure 5 represents the network for Model III. Note that according to this figure, all stands reaching the maximum age are assumed that they are clear-cut immediately.

In Model III, all the stands with the same age class are aggregated. In each period, each management unit is either harvested and reverted to the regeneration age class or moved to one age class older. Harvesting and growth can be represented as the flow through a network like in Figure 5 (Gunn, 2007). It has been pointed out that Model III works very well as a way of representing the mean fire/insect consumption (Reed and Errico, 1986). The formulation of the third strata-based forest management planning model was developed by Gunn and Rai (1987).

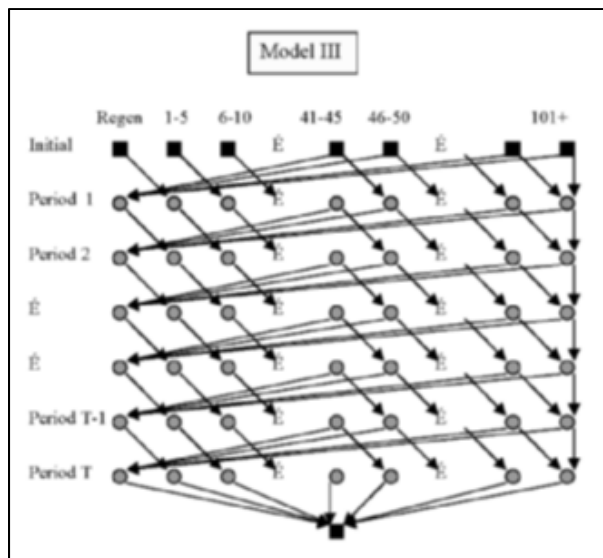


Figure 5 Model III network
Taken from Gunn (2007, p.329)

Model IV

When there are many harvest units or time periods, the aforementioned models are often hard to solve. Furthermore, previous models are aspatial and also depend on static volume and revenue coefficients that must be calculated before starting optimization. John & Tóth (2015) introduced an integer programming model for spatial forest harvest scheduling which defines stand volumes and revenues as variables and calculates them during optimization, so it

provides a higher level of flexibility in the model, in comparison with the previous ones. Moreover, in order to transition forest units from one planning period to the next, they used different equations and Boolean algebra.

They pointed out that it can perform computationally better than Model I and Model II. In addition, this model uses fewer variables and constraints to handle intermediate treatment decisions. To best fulfill the management objectives like revenue maximization or carbon sequestration subject to environmental, logistical, or budgetary constraints, we use these forest harvest scheduling models to optimize the spatiotemporal layout of harvests.

LP-based harvest scheduling models have a common shortcoming, they cannot explain spatial concerns like habitat fragmentation or clear-cut size constraints (harvest opening size restrictions) which are usually present in forest regulations. Model I is well suited for spatial optimization, because the harvesting areas can simply be disaggregated into stands. In addition, for each period, just one harvest variable is required in Model IV; however, all possible prescriptions should be enumerated upfront in the other models.

Spruce budworm

There are 347 million hectares of forest in Canada. In 2015, 0.77 and 3.9 million hectares of them has been harvested and burned in forest fires, respectively. In this year, 17.6 million hectares has been damaged by insects and around 36% of them occurred in Quebec.

Spruce budworm is one of the most destructive insects in Canada. In 2015, more than 6 million hectares has been damaged by spruce budworms (see Figure 6) mostly in the province of Québec.

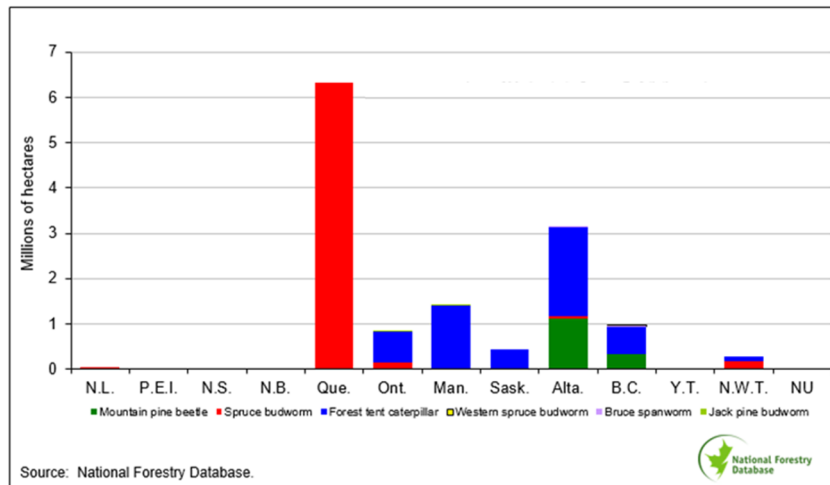


Figure 6 Major forest insect damage in Canada, 2015

Taken from Zhu et al. (2017. P.58)

The total wood volume in Canada's forests is about 47 billion m^3 . The main hosts of spruce budworm are balsam fir (*Abies balsamea*) and white spruce (*Picea glauca*) and to a lesser extent red spruce (*Picea rubens*) and black spruce (*Picea mariana*). Figure 7 illustrates that almost half of the total wood volume is constituted by balsam fir and spruce trees. They can be found through all Canada's provinces, from British Columbia to Newfoundland.

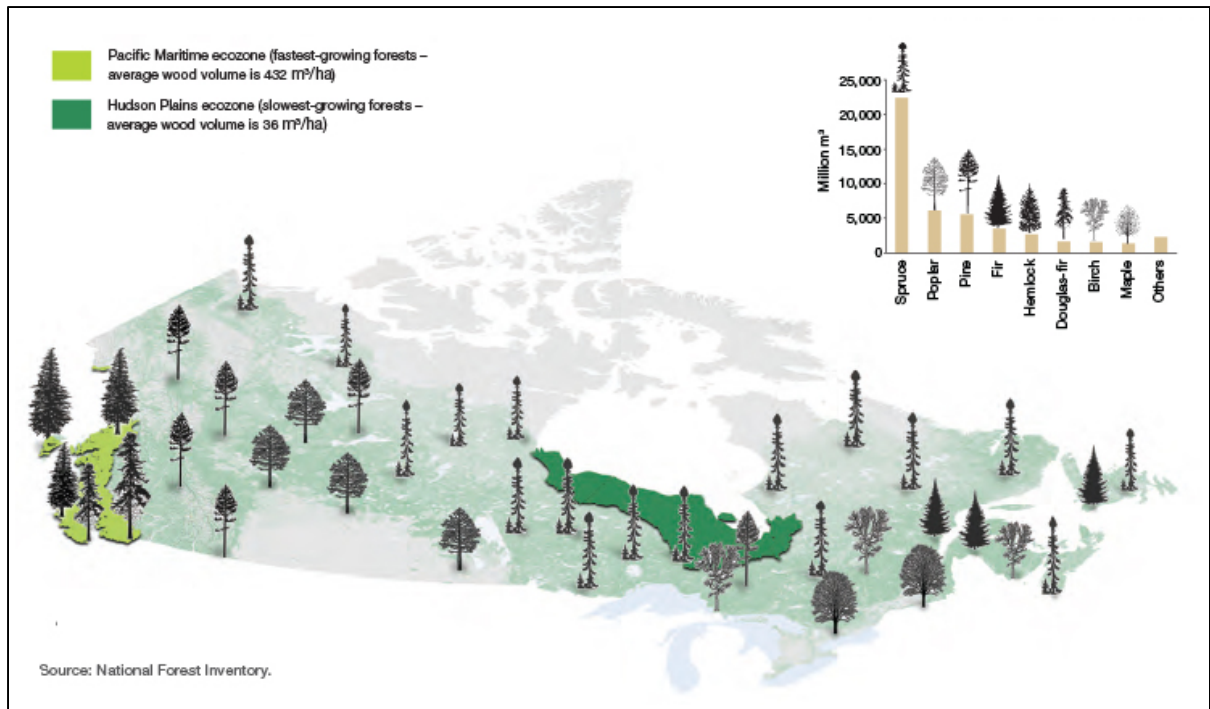


Figure 7 Different kinds of trees in Canadian forests
Taken from Natural Resources Canada (2016a, P.21)

In the 1970s, the last extensive outbreak of spruce budworm reached its peak in Canada and damage more than 50 million hectares. By the late 1990s, the outbreak had dropped to fewer than 1 million hectares.

During an outbreak trees can be severely damaged. It may last several years and cause serious levels of mortality and growth loss. As natural disturbances, outbreaks of eastern spruce budworm are an integral part of ecosystem and occur regularly in different regions of Canada such as boreal, Great Lakes, and Acadian forest.

Approximately every 35 to 40 years, there is an outbreak of SBW in Eastern Canada (Natural Resources Canada 2018b, Royama et al. 2005). Cyclical SBW outbreaks have affected eastern Canadian forests for a long time (Royama et al. 2005). The primary contributor to the development of widespread outbreaks is the availability of broad forests with susceptible host trees helping the survival of larvae and maturation of moths which migrate to new areas and

reproduce there. New evidence has showed that spruce budworm populations increase first wherein natural enemies cannot curtail increases in the local density of budworms. Reduction in resources, resulting from damaged tree, on the one hand and increases in spruce budworm mortality, caused by many natural enemies like birds, parasites, and disease, on the other hand lower local budworm survival and in turn end the outbreaks (Natural Resources Canada 2018b).

An outbreak that has just started and populations of spruce budworm in Quebec have grown steadily and exacerbated since 2006, reaching about 2.6 million hectares in 2013. This outbreak started unusually far north, on the north shore of the St. Lawrence River and north of 33 Lac St-Jean. It reached the Lower St. Lawrence River near Rimouski in 2010. The Atlantic provinces have remained free of budworm-caused damage since 1995. However, the development of the outbreak in the Lower St. Lawrence in Quebec suggests that outbreaks may soon occur in nearby northern New Brunswick (Natural Resources Canada, 2016b). Annual total affected areas in Quebec by spruce budworm can be found in Figure 8.

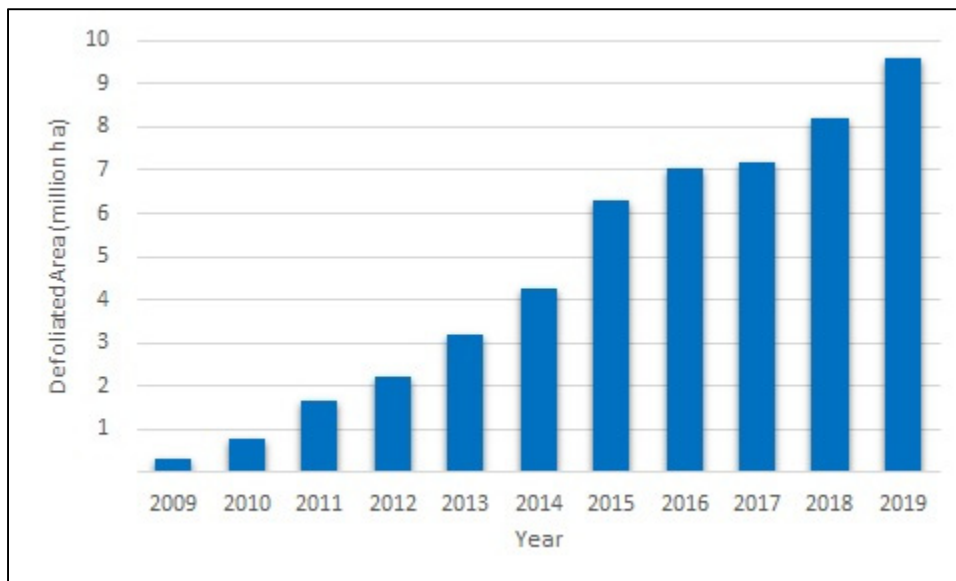


Figure 8 Defoliated area caused by spruce budworm outbreak in Quebec
Taken from Ministère des Forêts, de la Faune et des Parcs (2019a, p.5)

The spruce budworm life cycle

The spruce budworms have a one-year life cycle. It starts with an egg stage, continues with six instars, a pupal stage, and finally an adult (moth) stage. In the first stage, budworm moths mate and the female lays up to 200 eggs and bunches of eggs (10 to 50) are imbricated on the underside of balsam fir needle, like fish scales. It usually occurs in mid-July or mid-August. Each egg mass on average contains 20 eggs and almost 15% of the eggs will survive to third to fourth-instar larvae. Having incubated, which lasts between 10 and 14 days, young caterpillars emerge. Instead of feeding, they immediately start weaving a silk cocoon known as a hibernaculum into the bark crevices, bud scales, tree lichen, or the cupules of its host's flowers and overwinter in silken webs as the second instar. It happens in mid-August until the end of April, or early May. In late April or early May, the young caterpillars come out of hibernation and start crawling to the ends of the branches to feed on flower pollen while waiting for the buds to open. If there are no flowers, they start looking for old needles and closed buds. As soon as the new shoots appear, the caterpillars weave a cocoonlike shelter composed of their own excrement and needle debris mixed with silk threads which usually occurs in May. At this time the most apparent damage can be found on the forest. They feed off the shoots until their sixth and last instar, i.e., until the end of June (Davidson, 2011). In fact, fifth and sixth instar caterpillars are responsible for more than 85% of all defoliation (Davidson, 2011).



Figure 9 Spruce budworm damage in the forest in May
Taken from The University of Georgia (2018)

Feeding continues through late June to early July when the caterpillars are fully grown. Then, they hang upside down on silk threads and begin to pupate (Ministry of Forests and Range, Government of British Columbia, 2018). Having the moth emerged, they only live for 10 and 14 days (mid-July). They do not feed during this period; it is long enough to mate. Air flows can sometimes help moth’s dispersal over large distances (Natural Resources Canada, 2016b). Figure 10 illustrates the spruce budworm life cycle through months of a year.

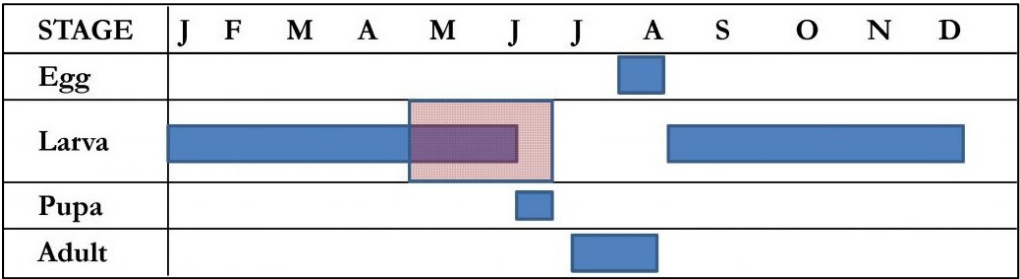


Figure 10 Life cycle stages of the spruce budworms and the duration of each stage in a year
Taken from New Hampshire, Department of Agriculture, Markets & Food, (2018)

The spruce budworm outbreak cycles

Outbreak of spruce budworm have occurred on almost a regular basis over extensive forested areas for at least the last three centuries (Blais (1954, 1961, 1965, and 1981), Morin et al. (1993)). Population densities have showed a regular cycle of roughly 30 to 40 years over a vast landscape for at least the last three centuries (Royama (1984, 1992)). Outbreak duration varies from 1 to 20 years in each region (Candau et al. (1998), Gray et al. (2000)). The population of the spruce budworm in the Province of the New Brunswick have been fluctuating almost periodically within the last two centuries and the average of the period is 35 years (Royama, 1984). Approximately every 35 to 40 years, there would be an outbreak of spruce budworms in eastern Canada (Natural Resources Canada, 2016c). Like previous outbreaks, the last spruce budworm outbreak was mainly restricted to eastern Canada (Blais, 1983). From one hand, reduction in resources resulting from damaged trees and on the other hand, increases in spruce budworm mortality, caused by many natural enemies like birds, parasites, and disease, can end an outbreak (Natural Resources Canada, 2016c).

Figure 11 shows that by examining radial growth patterns of some host surviving trees, older outbreaks can be discovered.

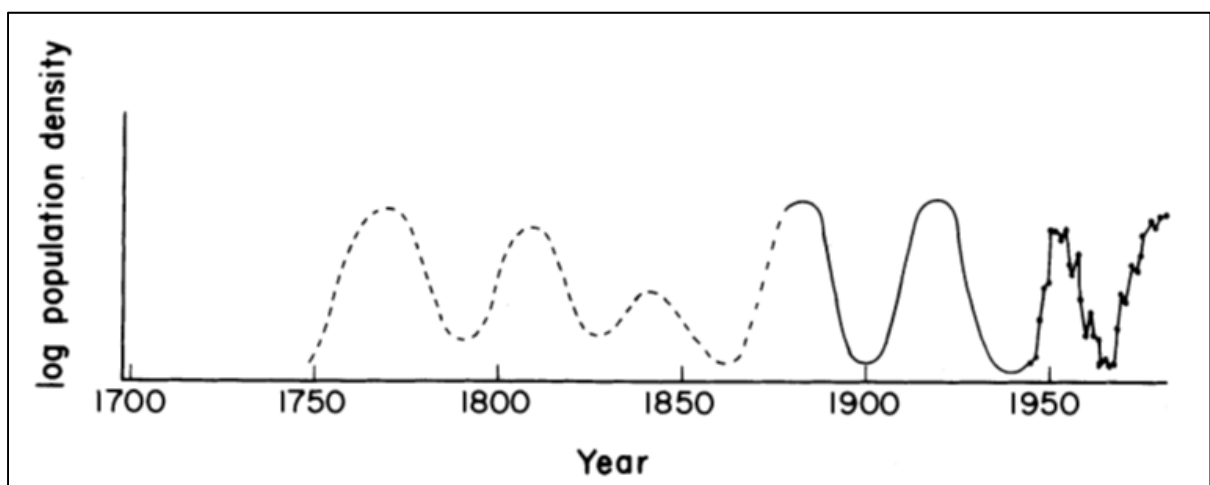


Figure 11 Population cycles of spruce budworms in the past two centuries

Taken from Royama (1984, p. 433)

Endogenous and exogenous factors like insect population dynamics, host tree vigor and distribution, and climatic variability are associated with cyclic outbreaks of western spruce budworm (Swetnam & Lynch (1989), Raffa et al. (2008), Bentz et al. (2010)). Climates have effects on outbreak characteristics of spruce budworm (Gray, 2008) and plays a significant role in determining the duration and severity of outbreaks (Gray & Mackinnon, 2006).

Insect outbreaks can significantly alter the Canada's forests by tree mortality, which changes the age-class distribution and species composition of the residual forest land, and growth reduction (MacLean (1985), MacLean et al. (2001)). Outbreak duration, severity, stand composition, and stand age can change growth loss and mortality from spruce budworm outbreaks (MacLean (1980), Erdle & MacLean (1999)). Evidence have showed that the timing, severity, variability and duration of spruce budworm outbreaks change with geographic location (Gray et al. (2000)). There are differences in the time of onset or severity of outbreaks in distinct outbreak areas in eastern North America (Blais (1983,1968)). Royama (1984) gave a special attention on the similarity in outbreak patterns among 30 regions in New Brunswick, however he indicated extremely large geographical differences in population fluctuations. Gray et al. (2000) pointed out that there is a relationship between the first year of the outbreak period and geographic location. The principal characteristics of defoliation patterns, like their relative regional timing, severity, duration, and stability are probably to be influenced in large part by regional environmental (excluding forest) characteristics and, thus, to be repeatable (Gray et al., 2000).

Spruce budworm dispersal

Contrary to common belief, there is no evidence to show that influx of the egg-carrying moths from other areas is the trigger point for outbreaks. In an upswing phase of an oscillation brought about by high survival of the feeding larvae, moth invasions act only as fertilizers and accelerate an increase in the local population to an outbreak level (Royama, 1984).

There are two dominating explanations of spruce budworm populations dynamics. The first concept is based on epicenters and zones of abundance (Hardy et al., 1983). In accordance with this concept, epicenters (hot spots) are the start of budworm outbreaks and then spread to adjacent areas through moth migration. The second one suggests that rise and fall in the spruce budworm populations approximately occurs at the same time as an action of local regulation (a large number of natural enemies) happens and that synchronization is obtained through spatially correlated perturbations related to weather (Royama, 1984, 1992).

Immigration and emigration of moths are highly correlated with the meteorological conditions (Royama, 1984). Vane et al. (2017) stated that the weight of evidence is against the idea that an outbreak occurs in an epicenter and moves so that it affects the surrounding areas through moth dispersal.

Spruce budworms are strong fliers. Having laid part of the eggs at the place of emergence, female moths immigrate which usually takes place in the evening. They climb decisively more than 100 meters in altitude and then move to new sites, which are usually 50 to 100 kilometers in the direction of the wind, but which can be as far as 450 kilometers (Royama, 1984). Figure 12 shows maximum yearly distance of expansion for defoliations and the frequency based on 72 observations from nine epicenters (Bouchard and Auger, 2014).

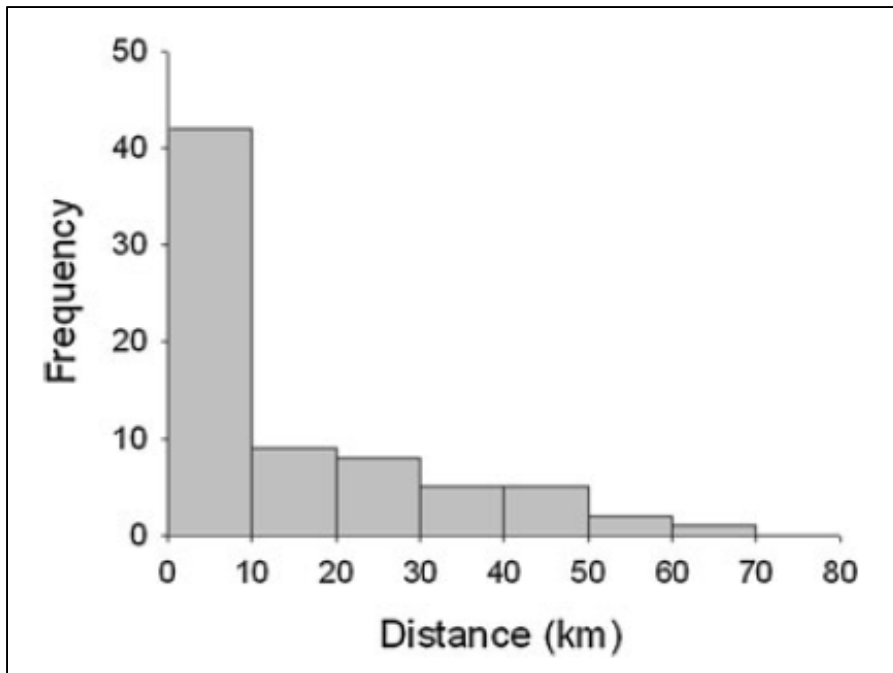


Figure 12 The frequency of maximum yearly distance of expansion for defoliations

Taken from Bouchard and Auger (2014, p. 115)

Royama (1984) stated that meteorological conditions, especially temperature, govern dispersal. There is no exodus when the temperature is less than 14 °C and if it occurs, they will come down with wings folded. In addition, no flight was observed at temperatures higher than 30 °C.

It is worth noting that, in this century, even during the low-density periods between major outbreaks a few scattered small areas with relatively high density can be found on the budworm infestation maps (Royama, 1984).

Spruce budworm and wood loss

There are two sets of factors affecting the incremental changes due to damage from pests. The first one is the severity of the damage which can be measured as a percentage of defoliation. Second, factors associated with vulnerability of trees being affected. For example, species,

maturity, and site quality are some of vulnerability-related variables. Note that these variables might differ for different pests and tree species (Erdle & MacLean, 1999).

Spruce budworm's preferred host is balsam fir (Miller, 1963). Defoliation of the current year's needles of balsam fir can be completed before the fourth year of outbreak (Morris, 1963) and death of tree will begin by the fifth year (Belyea, 1952). However, to a lesser degree spruce species (*P. glauca* (Moench.), *P. rubens* Sarg., and *P. mariana* (Mill.) BSP) are also affected (Greenbank (1963), Nealis & Regniere (2004)). The host volume cannot simply account for the spatial arrangement of outbreak, however, plentifulness of balsam fir, as a percentage of total host volume, seems to have a mild influence on outbreak (Gray & Mackinnon, 2006).

Tree mortality over large areas, reduction of growth rates, and reduced lumber quality are the outcomes of repeated budworm defoliation. After 4 to 5 years of sustained attack the result is complete defoliation (Ministry of forests, lands and natural resource operations, British Columbia, 2015). Non-lethal defoliation also lower tree growth (Gray & Mackinnon, 2006). If infestation subsides, it takes several years for defoliated trees to recover a full foliage complement, and therefore radial growth rates also need several years to reach normal growth level following defoliation by the budworm (Ministry of forests, lands and natural resource operations, British Columbia, 2015). After one year of defoliation, increase in the volume of balsam fir can be reduced by as much as 20% (Piene, 1980) and after a number of years of severe defoliation the radial growth which is measured at breast height can be reduced by as much as 75% (Miller, 1977).

According to a defoliation-sensitive stand growth model for 13 classes of spruce-fir stands, volume reduced 1-6% with 20% defoliation, 27-40% with 60% defoliation, and 82-99% with 90% defoliation (MacLean, 1996). Erdle & MacLean (1999) found that at a given level of defoliation younger trees have a better chance of survival. In addition, the trees would have a good chance of survival at a given defoliation level, if they are the dominant trees in the stand. Hennigar et al. (2008) showed consistent differences in defoliation level among host species of spruce budworm in all sampled stands. Zhang et al. (2018) found that fir defoliation is

remarkably lower as hardwoods increases. Figure 13 shows that spruce budworm has stronger impact on firs and mature trees in comparison with spruce and immature ones (Erdle & MacLean, 1999). In terms of wood loss, fir dominated stands have the highest wood loss, then fir-spruce mix stands, and finally, spruce dominated stands. Mature stands are suffering from more wood loss caused by SBW. It also illustrates the benefits of protection to wood saving.

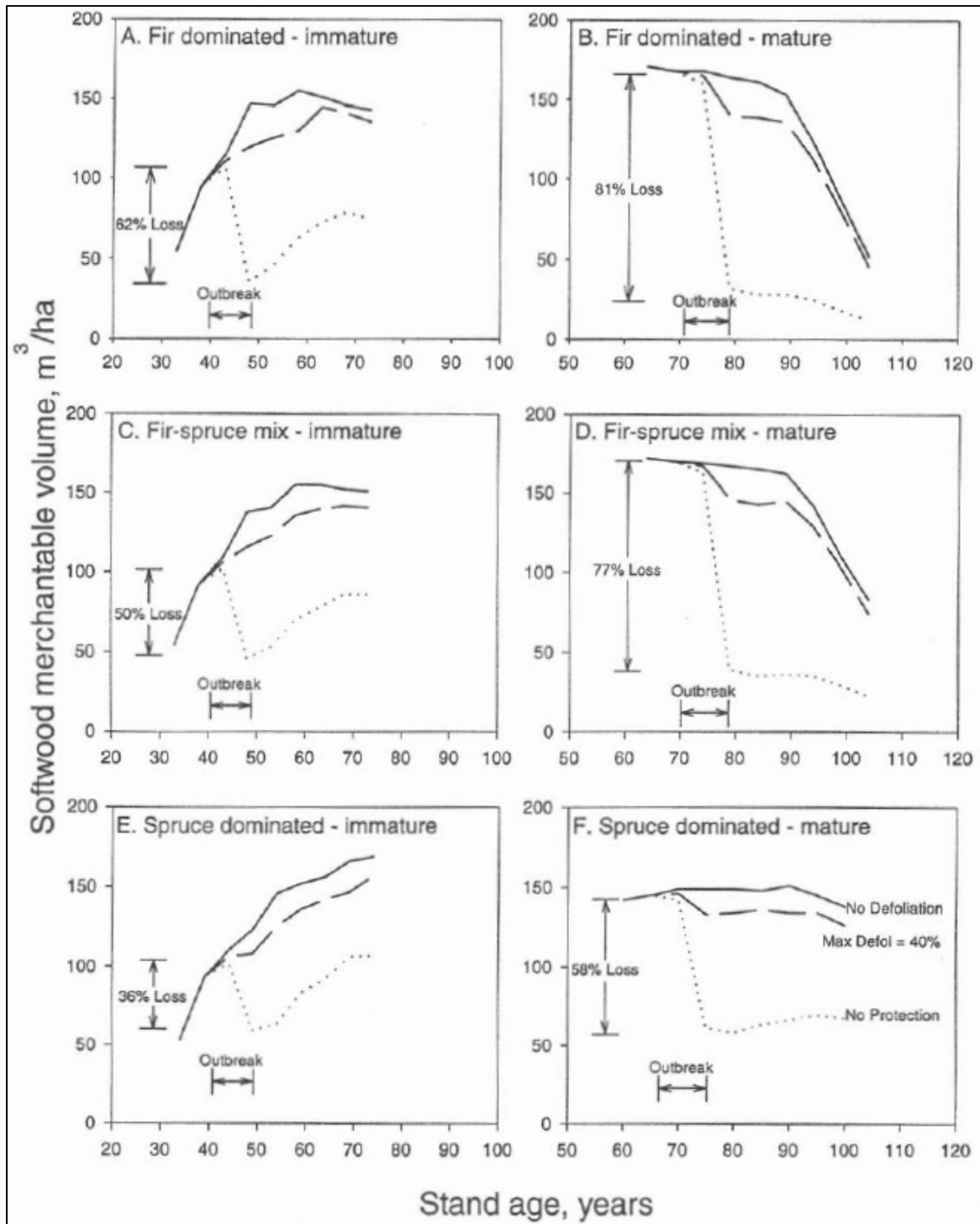


Figure 13 Predictions of stand development for six stand types under three scenarios: no defoliation, defoliation with a maximum of 40%, and defoliation with no protection

Taken from Erdle & MacLean (1999, p. 151)

Growth loss, top-kill, and tree mortality are the results of spruce budworm defoliation (Belyea (1952), Kulman (1971)). It also considerably affects the timber and wood fiber loss on the forest industry. Wood supply is negatively affected by insect outbreaks. It also disrupts harvest schedules (MacLean et al. (2001), Pedersen (2004)).

Wood loss estimation

Effects of damage translate across scales, from the tree to the stand to the forest, and result may include reduction in wood supply quality and quantity, modification in age structure, or change in stand type abundance and distribution (Erdle & MacLean, 1999).

Following steps are required for qualitative assessment of pest impacts: First, predict the pest incidence over time (Figure 14A). Second, find the type and severity of damage that those population levels inflict on tree or stand. The prediction of population level coupled with the relationship between populations and defoliation (Figure 14B) would results in prediction of defoliation (Figure 14C) (Erdle & MacLean, 1999).

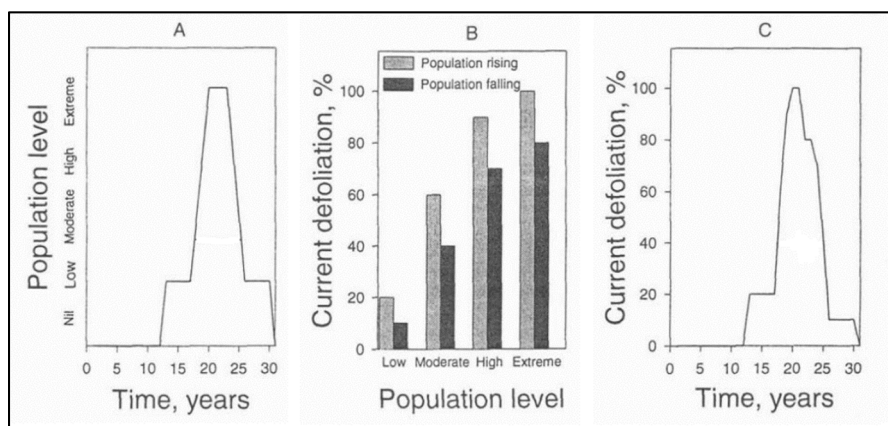


Figure 14 Spruce budworm defoliation
Taken from Erdle & MacLean (1999, p. 143)

Third, find how the defoliation can affect tree or stand development. In order to quantify the damage, consider the usual effects of tree defoliation such as diameter growth loss and reduced

survival into account. Figure 15 illustrates a linear relationship between tree diameter growth loss and cumulative defoliation, and a nonlinear relationship between reduced survival and cumulative defoliation. For the considered species, growth loss relationships were similar, but reduced survival relationships varied according to species and age classes (Erdle & MacLean, 1999).

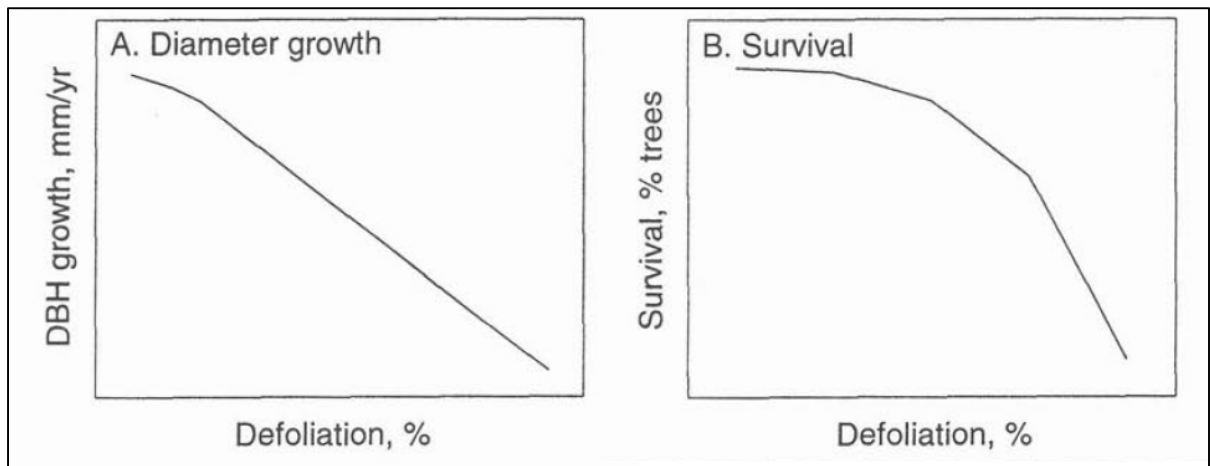


Figure 15 How defoliation can affect reductions of growth and survival

Taken from Erdle & MacLean (1999, p. 143)

Having discovered the effects of pests on trees, now forecasts of stand development can be constructed from the tree-level impacts relationships (Figure 16) (Erdle & MacLean, 1999).

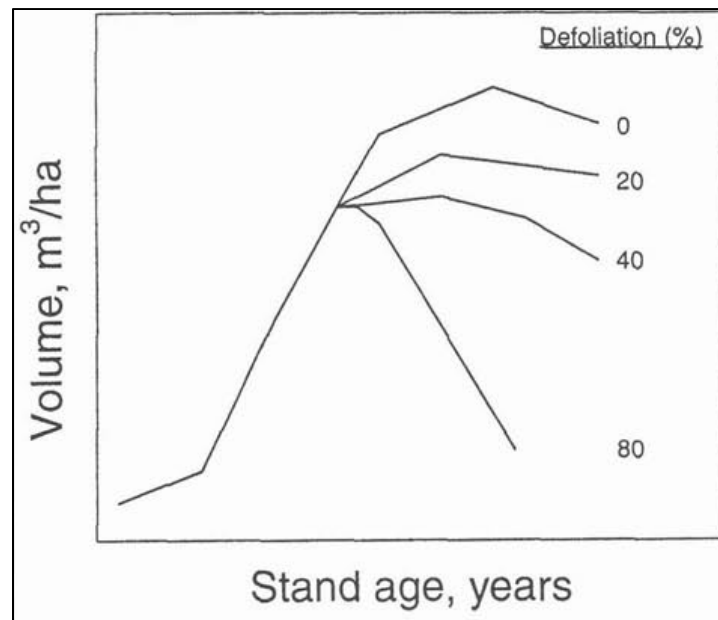


Figure 16 Stand growth curve with different levels of defoliation

Taken from Erdle & MacLean (1999, p. 144)

Forth, use forest estate model using stand-level forecasts as input to translate stand-level development into forest-level development (Erdle & MacLean, 1999).

Estimates of the growth loss and mortality from a spruce budworm outbreak depends on the four following components: spatial extent of the outbreak, annual defoliation levels, forest composition, and species-specific vulnerability to defoliation. The annual sequence of defoliation levels can affect tree growth and mortality of spruce budworm feeding (Gray & Mackinnon, 2006).

Repeated defoliations lead to tree mortality and wood loss. So, the number of years with defoliation and defoliation intensity (no defoliation = 0, light = 1, moderate = 2, and severe = 3) are two important parameters to find dead trees in a stand. We use a parameter called cumulative defoliation score (CDS) to study the defoliation history of a stand. Suppose there are four stands and based on the aerial survey detection, we have found the defoliation score (DS) for each stand. So, the CDS is the same as the defoliation score (it is assumed that the

outbreak has just started and there was no defoliation before time period one). Next year (time period 2), they again do the aerial survey and find the new defoliation score for each stand. The updated value of CDS is calculated as below:

$$CDS_t = CDS_{t-1} + DS_t \quad (1)$$

In Quebec, there is a methodology to calculate the percentage of dead trees due to the defoliation in a stand. Based on the proportion of dead trees, the available wood volume can be estimated annually for each stand. To find the rate of tree mortality, it is required to know the historical defoliation, the volume of balsam fir and white spruce, the total wood volume, and the number of years with defoliation in the stand. The following formulation is used to calculate the cumulative mortality rate (CMR) by spruce budworm in a stand:

$$CMR = \frac{1}{1 + e^{a - b \times CDS - c \times PBS - d \times \ln(YD)}} \times PBS \quad (2)$$

Where,

CDS: Cumulative defoliation score

PBS: Balsam fir and white spruce volume as a percentage of total wood volume in the stand

Ln: Natural logarithm

YD: Number of years with defoliation

a, b, c, d: Parameters with given values

Figure 17 shows the change of CMR as the CDS increasing over time based on the above-mentioned CMR formulation. The limit (red line) is defined by the proportion of the balsam fir and white spruce in a stand. Therefore, the CMR is changing from stand to stand over the forest even if they have the same CDS.

Based on the annual aerial surveys, the governments can find the defoliation score and consequently update the CDS and CMR. The difference between CMRs of two consecutive

periods indicates the tree mortality percentage during the period. Then, based on the available wood volume in the former period and the obtained proportion of tree mortality, the available wood volume can be updated for all stands.

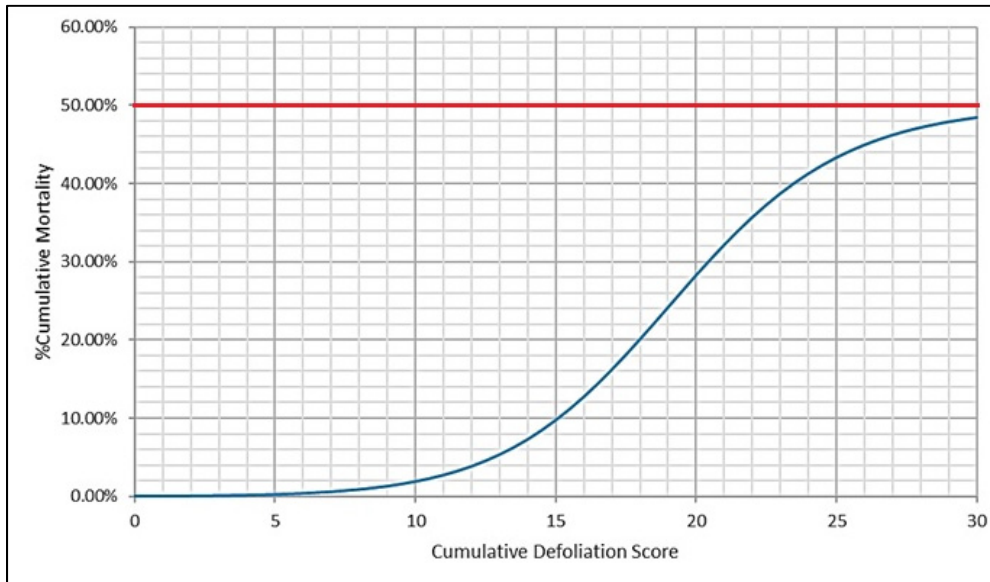


Figure 17 Changes of cumulative mortality rate of a stand based on the cumulative defoliation score and proportion of the balsam fir and white spruce in the stand

Stochastic optimization in forest management

An aspatial stochastic programming model developed to optimize the harvest schedule that accounts for the risk of fire (Martell, 1980). Lohmander (1983, 1987, 1988) used stochastic dynamic programming in discrete time to optimize the forest management at the stand level. The multi-period stochastic programming method has been well described by Birge and Louveaux (1997). Boychuk and Martell (1996) considered fire as an uncertain parameter in their forest-level timber management model and used multistage stochastic optimization to solve the model. D'amours et al. (2008) expressed that mixed integer linear programming and stochastic programming methods are better for tactical and strategic planning problems. Wei et al. (2014) employed multistage stochastic programming models to find optimal harvest schedules under the influence of wildfires. Kazemi Zanjani et al. (2013) proposed a two-stage

stochastic model for sawmill production planning. Zhu chen et al. (2017) used mixed-integer linear programming (MILP) and a two-stage stochastic programming to deal with the uncertainty associated with severity and propagation of SBW infestation over time.

Research contributions and organization

In the strategic forest management models literature review, we first review the well-known strategic forest management models. We found two mistakes in the Model II which can lead to different decision variables and objective value under certain conditions. These are the principal contributions of our first work. Having revised the model, we applied it to a case study in Gaspésie to validate our revised model.

Then, we start designing a forest value chain under uncertainty wherein the uncertain parameter is a well-known natural disturbance in the Eastern Canada called spruce budworm outbreak. From reviewing the literature, we found a lot of simulation models in strategic level in the realm of spruce budworm outbreak; however, we did not find a forest value chain at tactical level considering wood supply uncertainty due to the spruce budworm outbreak in previous studies. It drove us to develop a model mitigating the economic impacts of spruce budworm in the forest value chain. The main contributions of this model are classification of woods based on their level of infestation (i.e., quality), considering different levels of outbreak intensity which can lead to change in the wood quality (It has been assumed that changes in the outbreak intensity level will change the tree infestation level for all stands), and using multi-stage stochastic optimization technique to solve the model. The developed model has been applied to the Côte-Nord forest supply chain case study.

The last part of the literature review studies the integration of two control methods to mitigate the wood losses due to the spruce budworm outbreak. The principal contributions are using harvesting and spraying methods to deal with wood loss in the value chain, deriving transition matrices for sprayed and non-sprayed cells to predict the defoliation in the following year, forecasting the wood loss based on an empirical formula taken from the government of Quebec,

and designing a deterministic model with constraints as close as possible to the real world. Finally, we applied the model to forest area located in the Bas-Saint-Laurent region.

The main contributions of the thesis and the accomplished work in each one has been demonstrated in Figure 18. First, it answers to: What if we overlook the minimum number of periods between two regeneration harvests? How to deal with the upcoming errors which overlooking the minimum number of periods between two regeneration harvests? Afterwards, we focus on the tactical forest management and answer to the following questions: What is the effect of different levels of outbreak intensity on the wood values? How can the multistage stochastic model mitigate the economic impacts of SBW defoliation using harvesting? Finally, we have answered the questions including: What are the most important factors affecting the defoliation due to SBW? What is the mathematical relationship between historical defoliation and tree mortality? How can spraying and harvesting control methods mitigate the economic impact?

Design of Forest Supply Chain Under Uncertainty: The impact of Spruce Budworm Infestation on the Wood Supply

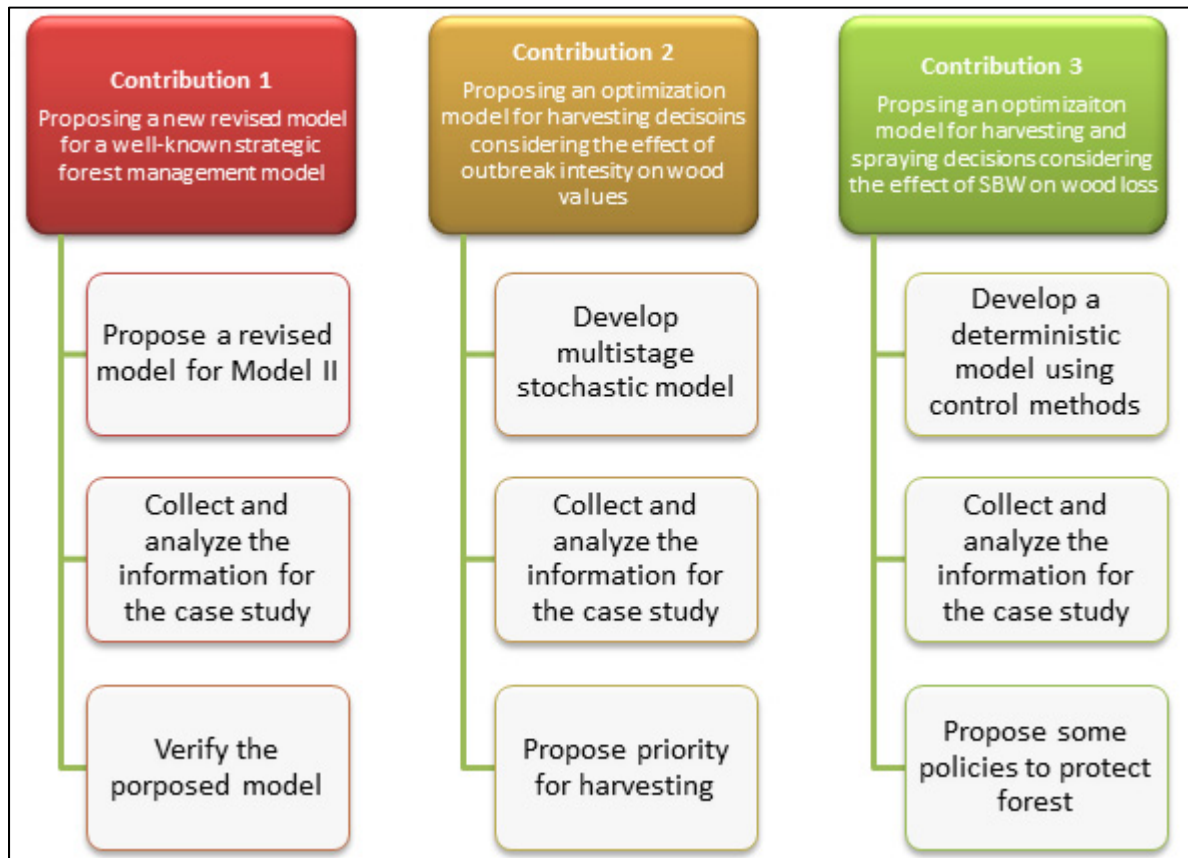


Figure 18 The main contributions of the thesis

Firstly, we review the strategic forest management models and in the existing literature. Having studied the advantages and disadvantages of the strategic forest management models and tree mortality after four to five years of sustained attack, we decided to study the impacts of spruce budworms on the forest at tactical level. Then, the following sections expand on the impact of spruce budworm on the wood supply chain and how destructive it can be. Then, we study different stages in a spruce budworm life cycle and when the most apparent damages can be seen in the forest. It further investigates the ideal condition for spruce budworm to disperse in the forest and how far they can move yearly. Next, we delve into the most effective parameters

on the relationship between spruce budworm and wood loss. Finally, the formulation used in Quebec to calculate tree mortality in a stand and how it can be used to estimate the wood loss will be explained.

There were limitations in our studies which can be considered as an opportunity for future studies. Some of them were common in all papers such as wood pricing and harvesting cost.

- **wood pricing:** There are different agents defining the value or price of the wood particularly diameter, length, moisture, quality, free market, etc. Changes in every agent can change the wood value. Moreover, the data was not simply accessible and sometimes you may find different prices for the same wood quality due to free market and location of the wood supplier. Therefore, we assumed wood values throughout this study. Note that you can use stochastic optimization technique to define wood price scenarios, but it complicates the problem further, prevents you from solving larger problem, and increases the runtime.
- **harvesting cost:** It can vary based on harvesting method, stand age, stand volume, and whether it is needed to build an access road. In addition, level of planning (tactical or strategic) can also change the required silvicultural treatments costs, for example, in strategic forest management, it is required to have an estimation for precommercial thinning, commercial thinning, and clear-cut harvesting; however, in tactical forest management, only clear-cut harvest might take into account. Sometimes the unit of measurement can be controversial decision as I faced this challenge through reviewing our first paper by reviewers.
- **growth model:** There are different type of species in the forest and they have different growth models varying by different variables like soil, local climate, light, fertility, density, etc. In our first paper, we just studied balsam fir with a given density. It can be interesting if a study verifies whether the proposed revised model provides significant difference in the objective value and decision variables. Note that in the second and third papers, we ignore the growth model as it is a tactical forest management; however, it would be more realistic if it is included in the models.

Some limitations were related to a specific paper. For example, in our second paper, finding data related to wood infestation like volume, wood loss (however we found a good formulation for wood loss because of spruce budworm defoliation while I was working on the last paper) and wood price were indeed challenging. Moreover, it was rare to find studies in this realm at tactical level. The other limitation was obtaining the probability of change in the outbreak intensity. It is obvious that the outbreak intensity is changing throughout the time, but it was difficult to find the data on it to derive the probabilities of change in the outbreak intensity.

Chapter 1

In the first article, we worked on a widely used strategic forest management models called Model II. We observed two mistakes in the original formulation while overlooking the minimum number of periods between regeneration harvests. The first is a mistake in the area constraints and the second in calculating one important parameter of the model representing discounted net revenue per hectare between periods. We provide a revised model together with comments on the computations of a parameter used in the model formulation. Then, in order to validate the problem identified, we solve the Model II with realistic data to address the modeling mistakes and explain how our revised formulation works with the same data. We also describe situations where the mistakes may have a larger impact. This study led to our first paper which has been submitted to Forest Science journal in 2018. It is under revision for two years and no final decision has been made yet.

Chapter 1 How the minimum number of periods between regeneration harvests induces modeling mistakes in the well-known Model II forest management	
Problem	<ul style="list-style-type: none"> • Overlooking the minimum number of periods between regeneration harvests leads to errors in the Model II
Hypothesis	<ul style="list-style-type: none"> • New revised model can provide a correct formulation for Model II
Methodology	<ul style="list-style-type: none"> • Collecting and analyzing data for Gaspésie case study • Comparing the results of the original and revised model
Contribution	<ul style="list-style-type: none"> • Propose a revised model for Model II • Apply the revised model to Gaspésie region • Present the result of the work at 18th Symposium on System Analysis in Forest Resources (SSAFR) • Publish a paper on CIRRELT Publication

Chapter 2

In this article, we considered the effect of changes of outbreak intensity on wood values throughout the forest as the wood infestation can change the lumber quality. Salvage harvesting considered as an action to mitigate the economic and environmental damages. We propose a multistage stochastic mixed-integer programming model for harvest scheduling under various outbreak intensities. The objective is to maximize revenues of wood value minus logistic costs while satisfying demand for wood in the industry. Results show that when there is an outbreak throughout the forest, the first priority for salvage harvesting is to focus on forest areas with the lowest level of infestation.

Chapter 2 Salvage Harvest planning for Spruce Budworm Outbreak using Multi-stage Stochastic Programming	
Problem	<ul style="list-style-type: none"> • To mitigate the economic impacts of SBW infestation on the value of the wood • To maximize revenues of wood value minus logistic costs while satisfying demand for wood in the industry • To decide which cell and when it should be harvested
Hypothesis	<ul style="list-style-type: none"> • Stochastic solution provides a reliable solution compared to a deterministic one • Silvicultural control methods such as pre-emptive and salvage harvesting can mitigate the economic impacts of SBW infestation
Methodology	<ul style="list-style-type: none"> • Collecting and analyzing data for Côte-Nord case study • Developing a multi-stage stochastic optimization model
Contribution	<ul style="list-style-type: none"> • Design a forest supply chain under the uncertainty of outbreak intensity • Apply the model to Côte-Nord region • Present the result of the work at 13th International Conference CIGI QUALITA • Publish a paper on Canadian Journal of Forest Research

Chapter 3

The third article considers two control methods such as spraying biological insecticide and harvesting, against SBW defoliation to mitigate the economic impact on the forest. In each period, the wood volume for each stand is estimated based on its characteristics, history of the defoliation, and whether it has been sprayed or not. The case study was located in the Bas-Saint-Laurent region in Quebec. This study provides a deterministic model addressing the questions of where and when should be harvested or sprayed to maximize revenues of harvested wood minus logistic costs and value of standing trees at the end of the planning

horizon while satisfying demand for wood in the industry and minimizing the forest protection costs. The results show the priority for stands to be harvested or sprayed. It also implies that spraying is not economical; however, it helps keep trees alive for future and have higher total volume.

Chapter 3 The integration of spraying and harvesting to minimize the wood losses during an outbreak of Spruce Budworm	
Problem	<ul style="list-style-type: none"> • To mitigate the economic impacts of SBW defoliation on wood supply in forest value chain • To maximize revenues of harvested wood minus logistic costs and value of standing trees at the end of the planning horizon while satisfying demand for wood in the industry and minimizing the forest protection costs • To make decision on which cell and when it should be harvested or sprayed
Hypothesis	<ul style="list-style-type: none"> • Integration of silvicultural and chemical control methods against SBW defoliation is more efficient • Dynamic wood volume because of defoliation reflects more realistic model • Use of deterministic model is more tractable than stochastic one
Methodology	<ul style="list-style-type: none"> • Collecting and analyzing data for Bas-Saint-Laurent case study • Developing a tractable deterministic model
Contribution	<ul style="list-style-type: none"> • Develop a forest supply chain model integrating the harvesting and spraying to mitigate wood losses from SBW defoliation • Apply the model to Bas-Saint-Laurent region • Submit a paper to Canadian Journal of Forest Research

The work presented in this thesis has led to the publication and submission of three articles presented in detail in chapter 1 (CIRRELT Publication), chapter 2 and 3 (Canadian Journal of

Forest Research). Furthermore, our research findings and contributions were submitted and presented to international conferences including 18th Symposium on System Analysis in Forest Resources (SSAFR), 13th International Conference CIGI Qualita, and Expo-conference.

CHAPTER 1

HOW THE MINIMUM NUMBER OF PERIODS BETWEEN REGENERATION HARVESTS INDUCES MODELING MISTAKES IN THE WELL-KNOWN MODEL II FOREST MANAGEMENT PLANNING MODEL

Siamak Mushakhian^a, Mustapha Ouhimmou^b, Mikael Rönnqvist^c, Jean-Martin Lussier^d

^{a,b} Department of Systems Engineering, École de technologie supérieure, Suite A-3586, 1100 Notre-Dame St. W., Montreal H3C 1K3, Canada

^c Department of mechanical Engineering, Université Laval, Suite 1504, 1065 avenue de la Médecine, Pavillon Adrien-Pouliot, Quebec City G1V 0A6, Canada

^d Canadian Wood Fiber Center 1055 du P.E.P.S. Street, P.O. Box 10380, Quebec City G1V 4C7, Canada

Paper published in CIRRELT publication, October 2019

Abstract

The Model II is widely used in forest management models and different variants of it are implemented in various software. Overlooking the minimum number of periods between regeneration harvests can cause some modeling mistakes. We have observed two mistakes in the original formulation. The first is a mistake in the area constraints and the second in calculating one important parameter of the model representing discounted net revenue per hectare between periods. In this paper, we provide a slightly revised model together with comments on the computations of a parameter used in the model formulation. Then, in order to validate the problem identified, we solve the Model II with realistic data to address the modeling mistakes and explain how our revised formulation works with the same data. We also describe situations where the mistakes may have a larger impact and explain why they have not been identified earlier.

Keywords: Forest management planning, timber harvest, harvest scheduling, linear programming, Model II

1.1 Introduction

One of the most important models for forest management is the so-called Model II (Johnson and Scheurman 1977). Many variants of this model have been implemented in numerous planning systems within companies and government organizations. One of the main uses of the model is to evaluate the net present value (NPV) of a given forest under different silviculture treatment scenarios and discount rates over a set of time periods representing long-term planning. This model is straightforward and has been referenced in articles since its introduction without any revisions. It has also been implemented in various planning systems and it can be assumed that it is a standard tool to make evaluations of discounted forest values. However, a direct implementation of the original formulation may provide erroneous solutions under certain conditions on parameter values. The main reason is that a number of variables are created incorrectly when a minimum number of periods between regeneration harvests are used. Another mistake is in how the objective function coefficients are calculated. These mistakes may or may not have an impact depending on the silviculture options available and used. Also, as the model is often used for NPV values and not for operational planning, there is no actual need to analyze the actual harvest decision in detail. Hence, there has been little reason to verify or find that some variables have erroneous values. We describe the mistakes and propose a new formulation, which is tested on some illustrative examples.

Simple decision support systems cannot be created and applied universally because strategic planning of the forest value chain includes many different players in many different business contexts. Decision support for strategic planning helps decision makers assess the potential consequences of strategic business choices (Anthony 1965, Drucker 1995). For strategic planning, we should take decision makers' values, objectives, and their future business anticipations into account because these decisions will change the future by changing the flow of the resources and opportunities available to the company (Gunn 2005). At the strategic planning level, decisions, goals, and other constraints of decisions makers must be considered because they have a long-term impact on the company and its resources.

The goal of forest management strategy is to answer the following questions: what to supply, from where to supply to, to which market, and for what use to create value and jobs for local communities. It also has impacts on sustainability, carbon sequestration, wildlife habitat, ecology, controlling invasive species, and social values (like employment). Sustainable long-term supply is often depicted in terms of level flow or nondeclining yield. D'Amours et al. (2016) have stated that renewability is the key feature of the forest as a supplier of raw materials.

There are three specific parts in the forest management linear models: the process of forest growth and management, the sustainability of forest products, and the requirement to provide certain types of forest cover. Four distinctive modeling approaches are found for forest growth and management, including the well-known Model I and Model II (Johnson and Scheurman 1977) and Model III, which is less common (Garcia 1990); however, it forms the base of popular packages like FOLPI (Gunn 2007), and John and Tóth (2015) proposed a new model for spatial forest harvest scheduling called Model IV.

Woodstock software is capable of generating linear programming matrices by the use of a generalized Model II formulation which is markedly more powerful than other harvest scheduling models based on Model II, like MUSYC (Multiple-Use/Sustained Yield Calculation). FORPLAN (FORest PLANning model) version 2 proposes the capabilities of the generalized Model II (Remsoft 1994).

A combination of Model I and Model II has been used as an optimization model to explore how different management regimes would affect the ability of forests to sequester carbon (Backéus et al. 2005). Martin et al. (2017) compared the efficiency of the spatial Model I and Model II and pointed out that Model I outperformed the Model II.

An optimization approach has been applied through a timber supply model which is an extension of the Model II formulation to estimate the cost of overlapping tenure constraint on forest management agreement areas in Northern Alberta (Nanang and Hauer 2006). A novel

approach has been represented to simultaneously maximize carbon sequestration in both forest and wood products and abated emissions from product substitution using Remsoft Spatial Planning System (Hennigar et al. 2008). Note that Woodstock is on the basis of an optimized forest treatment scheduling using a model II LP formulation (Hennigar et al. 2008). Nanang and Hauer (2008) examined the long-term impacts of access road development, which is an important factor in determining harvesting and hunter preferences and non-timber benefits, and they used an extension of the Model II formulation. Model II was used for optimal harvest scheduling in a case study in Spain (Diaz-Balteiro et al. 2009). Model II has been utilized in the forestry portion of the FASOM-GHG model which has been modified to simulate the effects of optional and mandatory participation in carbon offset sales programs (Latta et al. 2011). Model II has been applied in the forest sector model of a linked land-use and forest sector models which have been proposed to find how carbon offset sales can affect private forest owners' land-use and forest management decisions in Western Oregon (USA) (Latta et al. 2016). In order to analyze the impact of operational-level flexibility on long-term wood supply, a hierarchical planning, i.e. strategic, tactical, and operational, has been developed. The authors used a software called SilviLab to formulate the strategic-level model as a Model II linear program (Gautam et al. 2017). Model II has been used in a goal programming to analyze the long-term impact of policy and industry changes at the landscape level (Corrigan and Nieuwenhuis 2017).

The contribution of the paper is important as the Model II is used in many systems. It is difficult to know if any implementation has found and revised the modeling errors or not. However, we have not found any published article that addresses this, and it is important for other researchers and users of the system to understand how they are impacted by the mistakes or how to identify if the implementation may provide erroneous results. This paper identifies and proposes a few modeling mistakes in the Model II formulation given in Johnson and Scheurman (1977). Model II is one of the most well-known forest management models, but the original formulation has two mistakes which may overestimate the objective function and mislead the forest manager or researchers over optimal harvest decisions in a specific context. The first mistake occurs in the first set of the area constraints, wherein some additional decision variables are created.

These decision variables may take nonzero values and provide wrong information about the objective function and harvest decisions. The second mistake can be found in the way to calculate one of the key parameters of the model. This parameter will be explained in detail in the following sections.

The rest of this paper is organized as follows. Section 1.2 describes the forest management models, especially Model II in details with the mathematical formulation. In Section 1.3, we pose questions to Model II and propose a new mathematical formulation. In order to validate our new formulation, a problem would be represented with practical data and the results would be analyzed in Section 1.4. Finally, conclusions are drawn in Section 1.5.

1.2 Forest management models

In literature, four modeling approaches can be found for forest management planning, including the well-known Model I and Model II (Johnson and Scheurman 1977), Model III, which is less common (Garcia 1990), and John and Tóth (2015) proposed a new model for spatial forest harvest scheduling which is called Model IV. In Model I (Johnson and Scheurman 1977), the integrity of each age-class in the first period is kept throughout the planning horizon (see Model I in Figure 1.1). However, in Model II (Johnson and Scheurman 1977), the integrity of each age-class in the first period is kept until it is regeneration harvested and forms a new age-class until they are again regeneration harvested (see Model II in Figure 1.1). In Model III (Garcia 1990), in each period, the land in an age-class can be harvested or become one age-class older (see Model III in Figure 1.1). The aggregation of all stands in Model II is similar to the Model III; however, the network contains fewer nodes and arcs. Model I can be used to model either aggregated or individual stands (Gunn 2007). In the previous models, one decision variable is required for every applicable prescription for each forest management unit. The mentioned models are aspatial and also depend on static volume and revenue coefficients that must be calculated before starting optimization. Finally, John and Tóth (2015) introduced a new model which is called Model IV, using different equations and Boolean algebra for spatial forest harvest scheduling.

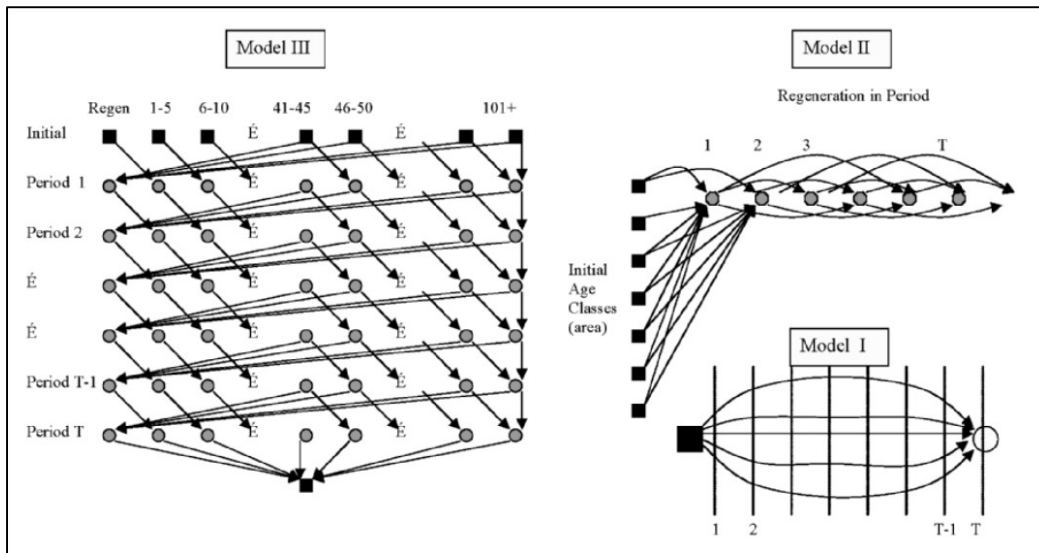


Figure 1.1 Models I, II, and III
 Taken from Gunn (2007, p.329)

1.2.1 Model II

Forest management planning aims to schedule timber harvest and investment on an area of timberland under even-aged management. The goal is to maximize the volume or value produced from its timberland while encountering constant or decreasing prices in the volume of timber output (Johnson and Scheurman 1977). The manager may come across land availability limits for harvesting in each time period when the whole area is managed under one silvicultural treatment regime. A silvicultural treatment regime is any sequence of silvicultural practices such as planting, pre-commercial thinning, commercial thinning, and fertilization. In addition to area constraints, it may also consider flow constraints (harvest fluctuation and sustainability).

Seven simplifying assumptions have been stated as follows:

1. The forest has one type-site consisting of different age-classes.
2. The area of forestland is fixed during the planning horizon.
3. The number of years representing each time period in the planning horizon is consistent with the years of each age-class.

4. For regeneration harvest, we use clear-cutting.
5. Regeneration occurs in the same period as regeneration harvest.
6. Yield estimates take into account all uncertainties such as fire, insect, and diseases implicitly.
7. The only out-of-pocket costs that should be paid are the silvicultural treatment costs.

In Model II, each age-class forms a management unit that is harvested. Having regeneration harvested, a new age-class is formed till they are again regeneration harvested. Each activity describes a possible management regime for a certain management unit from the time a unit is regenerated until it is regeneration harvested or left as ending inventory at the end of the planning horizon. A management regime includes two parts (Johnson and Scheurman 1977):

1. A regeneration harvest at some time during the planning horizon or an ending inventory at the end of the planning horizon.
2. An associated silvicultural treatment regime.

We require two sets of area constraints:

1. One set on the areas that can be regeneration harvested from, or put aside as ending inventory in, each age-class that exists at the start of planning horizon (See Figure 1.2 and Constraint 2) (Johnson and Scheurman 1977). Figure 1.2 indicates that the areas cut from each age-class through different time periods plus the areas left as ending inventory from that age-class are equal to the total number of areas in that age-class at the beginning of planning horizon. For instance, Figure 1.2b indicates that the total area from age-class one (on the assumption that there is no minimum number of periods between regeneration harvests) at the beginning of the planning horizon can be harvested in different periods starting from one to N , and put aside as ending inventory.

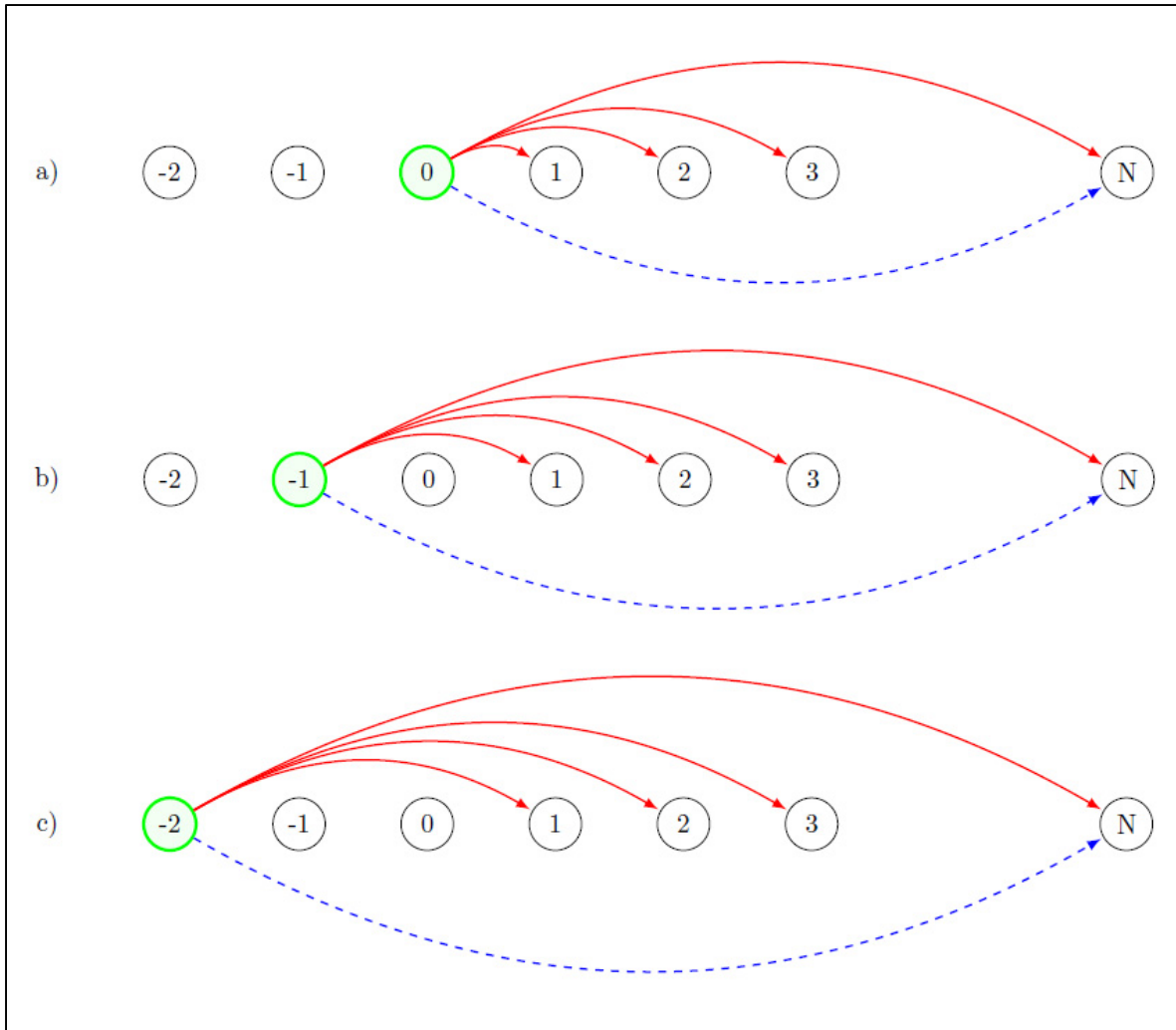


Figure 1.2 Balance constraint for areas regenerated or put aside as ending inventory at the start of the planning horizon for three different age-classes: 0, 1, and 2 can be seen in a, b, and c, respectively

2. The second set is on the areas that can be regeneration harvested from, or put aside as ending inventory in, each age-class that is created throughout the planning horizon (See Figure 1.3 and Constraints 3) (Johnson and Scheurman 1977). Figure 1.3 illustrates that the areas cut from areas regenerated in period j plus the areas left as ending inventory from areas regenerated in period j are equal to the total number of areas regenerated in period j (j can vary between the first period and the end of the planning horizon). For example, in period j , different age-classes may be harvested, so these areas can be harvested in the following future periods and also put aside as ending inventory.

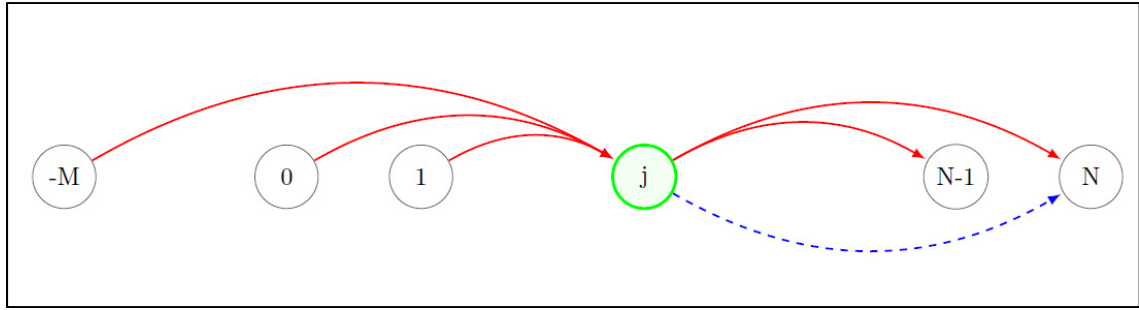


Figure 1.3 Balance constraint for areas regenerated or put aside as ending inventory throughout the planning horizon

1.2.2 Mathematical formulation

The mathematical form of Model II is summarized as follows:

$$\max \sum_{j=1}^N \sum_{i=-M}^{j-Z} D_{ij} x_{ij} + \sum_{i=-M}^N E_{iN} w_{iN} \quad (1.1)$$

Subject to

$$\sum_{j=1}^N x_{ij} + w_{iN} = A_i, \quad i = -M, \dots, 0 \quad (1.2)$$

$$\sum_{k=j+Z}^N x_{jk} + w_{jN} = \sum_{i=-M}^{j-Z} x_{ij}, \quad j = 1, 2, \dots, N \quad (1.3)$$

$$x_{ij} \geq 0, \quad i = -M, \dots, N, j = 1, 2, \dots, N \quad (1.4)$$

$$w_{iN} \geq 0, \quad i = -M, \dots, N \quad (1.5)$$

Constraint (1.2) expresses the land availability constraint for the beginning of the planning horizon (see Figure 1.2). The balance constraint for areas regenerated in period j can be found in Constraint (1.3) (see Figure 1.3). Constraint (1.4) and (1.5) show the non-negativity.

Authors defined the sets, data, and variables as follows, where:

N Number of periods in the planning horizon

x_{ij} Areas regenerated in period i and regeneration harvested again in period j

- w_{iN} Areas regenerated in period i and put aside as ending inventory in period N
- A_i Number of hectares present in period one that were regenerated in period i ($i = -M, \dots, 0$), with each A_i being a constant at the beginning of the planning horizon (period 1)
- M Number of periods before period zero in which the oldest age-class present in the period one was regenerated
- Z Minimum number of periods between regeneration harvests (reasonably it is greater than one, i.e., $Z \geq 1$)
- D_{ij} Discounted net revenue per hectare from areas regenerated in period i and regeneration harvested again in period j . It can be written as shown below:

$$D_{ij} = \sum_{k=\max(i,1)}^j \frac{P_{ikj}V_{ikj} - C_{ikj}}{\gamma^k} \quad (1.6)$$

Where

- P_{ikj} Unit price of the volume harvested in period k on areas regenerated in period i and regeneration harvested again in period j
- V_{ikj} Volume per hectare harvested in period k on areas regenerated in period i and regeneration harvested again in period j
- C_{ikj} Silvicultural treatment costs per hectare in period k on areas regenerated in period i and regeneration harvested again in period j
- γ^j Discount rate for period j
- E_{iN} Discounted net revenue per hectare during the planning horizon from areas regenerated in period i and put aside as ending inventory in period N plus discounted net value per hectare of leaving these areas as ending inventory. It can be written as shown below:

$$E_{iN} = \sum_{k=\max(i,1)}^N \frac{P_{ikN}V_{ikN} - C_{ikN}}{\gamma^k} + \frac{P'_{iN}}{\gamma^N} \quad (1.7)$$

Where

- P_{ikN} Unit price of the volume thinned in period k on areas regenerated in period i and put aside as ending inventory in period N
- V_{ikN} Volume per hectare thinned in period k on areas regenerated in period i and put aside as ending inventory in period N
- C_{ikN} Silvicultural treatment costs per hectare in period k on areas regenerated in period i and put aside as ending inventory in period N
- P'_{iN} Net value per hectare of leaving areas regenerated in period i as ending inventory in period N

1.3 Methods

In this section, we first present the modeling mistakes in Model II and then propose our new model to overcome these mistakes.

1.3.1 Mistake in the first set of area constraints

In accordance with the definition of Z , the minimum number of periods between regeneration harvests, it is not allowed to harvest an area unless at least Z periods have been passed since the last regeneration harvest. Unfortunately, Constraint (1.2) has been mistakenly written in Johnson and Scheurman (1977). In the original formulation, there are a number of extra variables generated that should be forced to be 0 due to the requirement of periods between regeneration harvests. If the coefficients of variables in the objective function are negative except for the additional decision variables, it is possible that those extra decision variables take values and if this is the case, we have an erroneous solution. There are a number of situations when this may happen, including partial cutting and thinning operations, where costs exceed revenue from sales.

In order to prove our claim and provide further clarification, consider the following example where we would like to schedule harvests for the next four time periods ($N = 4$) from a forest that now has three different age-classes aged 0, 1, and 2 (i.e., $A_0 = 300$, $A_{-1} = 200$, and $A_{-2} = 100$) ($M = 2$). There is a minimum of three time periods between regeneration harvests ($Z = 3$).

Now we want to expand the objective function and first set of area constraints and take a closer look at them. As mentioned above, an area cannot be harvested unless a minimum of Z periods has passed since the last regeneration. However, you can find variables in the constraints which are contrary to this law (x_{-11} , x_{01} , and x_{02}).

$$\max \sum_{j=1}^4 \sum_{i=-2}^{j-3} D_{ij} x_{ij} + \sum_{i=-2}^4 E_{i4} w_{i4} \quad (1.8)$$

$$\begin{aligned} &= D_{-21} x_{-21} + \\ &\quad D_{-22} x_{-22} + D_{-12} x_{-12} + \\ &\quad D_{-23} x_{-23} + D_{-13} x_{-13} + D_{03} x_{03} + \\ &\quad D_{-24} x_{-24} + D_{-14} x_{-14} + D_{04} x_{04} + D_{14} x_{14} + \\ &\quad E_{-24} w_{-24} + E_{-14} w_{-14} + E_{04} w_{04} + E_{14} w_{14} + E_{24} w_{24} + E_{34} w_{34} + E_{44} w_{44} \end{aligned} \quad (1.9)$$

First area constraint

$$\sum_{j=1}^4 x_{ij} + w_{i4} = A_i, \quad i = -2, \dots, 0 \quad (1.10)$$

$$x_{-21} + x_{-22} + x_{-23} + x_{-24} + w_{-24} = A_{-2}, \quad i = -2 \quad (1.11)$$

$$x_{-11} + x_{-12} + x_{-13} + x_{-14} + w_{-14} = A_{-1}, \quad i = -1 \quad (1.12)$$

$$x_{01} + x_{02} + x_{03} + x_{04} + w_{04} = A_0, \quad i = 0 \quad (1.13)$$

As aforementioned, if the coefficients of variables in the objective function are negative except for the additional decision variables, it is possible that those extra decision variables take values. To clear it up, suppose the following values for parameters D_{ij} and E_{iN} in Tables 1.1 and 1.2 for the above-mentioned example.

Table 1.1 Values for parameters D_{ij}

		Next Harvesting Period (Period j)			
		1	2	3	4
Most Recent Harvesting Period (Period i)	-2	1	1	1	1
	-1	0	-1	-1	-1
	0	0	0	-1	-1
	1	0	0	0	1
	2	0	0	0	0
	3	0	0	0	0
	4	0	0	0	0

Table 1.2 Values for parameters E_{i4}

Period i	-2	-1	0	1	2	3	4
E_{i4}	1	-1	-1	1	1	1	1

We solved the model and the results can be found in Tables 1.3 and 1.4. Light gray cells indicate the forbidden periods for the harvesting of each age-class according to the definition of the Z parameter. While the rule has been violated by x_{-11} and x_{01} , 200 and 300 are their values, respectively. The objective value is 300.

The repercussion will not be limited to this one. In addition to that, those values would be ignored for future harvest planning. For instance, when a management unit is regeneration harvested in period 1 ($x_{-11}=200$), it can be harvested in period 4 or taken into account as an

ending inventory while it has been overlooked, likewise for the other unallowable variable ($x_{01} = 300$).

Table 1.3 Outcomes for decision variables x_{ij} for original formulation

		Next Harvesting Period (Period j)			
		1	2	3	4
Most Recent Harvesting Period (Period i)	-2	100	0	0	0
	-1	200	0	0	0
	0	300	0	0	0
	1	0	0	0	100
	2	0	0	0	0
	3	0	0	0	0
	4	0	0	0	0

Table 1.4 Outcomes for decision variables w_{i4} for original formulation

Period i	-2	-1	0	1	2	3	4
w_{i4}	0	0	0	0	0	0	100

To correct the mistake, the revised formulation for the first set of area constraints is:

$$\sum_{j=1}^N x_{ij} + w_{iN} = A_i, \quad i = -M, \dots, 1 - Z \quad (1.14)$$

$$\sum_{j=Z+i}^N x_{ij} + w_{iN} = A_i, \quad i = 2 - Z, \dots, 0 \quad (1.15)$$

We solved the example again by considering the new formulation. The outcomes can be found in Tables 1.5 and 1.6. As it can be seen, there is no breach of rule for harvesting. The objective value is -4200.

Table 1.5 Outcomes for decision variables x_{ij} for revised formulation

		Next Harvesting Period (Period j)			
		1	2	3	4
Most Recent Harvesting Period (Period i)	-2	100	0	0	0
	-1	0	0	0	200
	0	0	0	300	0
	1	0	0	0	100
	2	0	0	0	0
	3	0	0	0	0
	4	0	0	0	0

Table 1.6 Outcomes for decision variables w_{i4} for revised formulation

Period i	-2	-1	0	1	2	3	4
w_{i4}	0	0	0	0	0	300	300

1.3.2 Mistake in calculation of D_{ij}

The model uses the objective function coefficients D_{ij} and E_{iN} . To find the miscalculation of D_{ij} parameter tangibly, consider the following example with given parameters: $N = 7$, $M = 1$, $Z = 3$. The objective function is as below:

$$\max \sum_{j=1}^7 \sum_{i=-1}^{j-3} D_{ij} x_{ij} + \sum_{i=-1}^7 E_{i7} w_{i7} \quad (1.16)$$

$$\begin{aligned} &= D_{-12} x_{-12} + \\ &\quad D_{-13} x_{-13} + D_{03} x_{03} + \\ &\quad D_{-14} x_{-14} + D_{04} x_{04} + D_{14} x_{14} + \\ &\quad D_{-15} x_{-15} + D_{05} x_{05} + D_{15} x_{15} + D_{25} x_{25} + \\ &\quad D_{-16} x_{-16} + D_{06} x_{06} + D_{16} x_{16} + D_{26} x_{26} + D_{36} x_{36} + \\ &\quad D_{-17} x_{-17} + D_{07} x_{07} + D_{17} x_{17} + D_{27} x_{27} + D_{37} x_{37} + D_{47} x_{47} + \\ &\quad E_{-17} w_{-17} + E_{07} w_{07} + E_{17} w_{17} + E_{27} w_{27} + E_{37} w_{37} + E_{47} w_{47} + E_{57} w_{57} + \\ &\quad E_{67} w_{67} + E_{77} w_{77} \end{aligned} \quad (1.17)$$

At each time period, two sets of timber flows are needed, including input (areas regenerated in previous time periods and going to be regeneration harvested again in this period) and output (areas may be regenerated in future or put aside as an ending inventory) flows. Figure 1.4 presents input and output flows in the aforementioned example ($N = 7, M = 1, Z = 3$). For example, in Figure 1.4c, there are two timber inflows from areas regenerated harvested three and four periods ago (period -1 and 0, respectively) and three timber outflows, two of which will be regenerated again in periods 6 and 7, and the third outflow is related to areas left as ending inventory. Note that thinned volume obtained from stand thinnings of regeneration harvested areas are not shown in Figure 1.4.

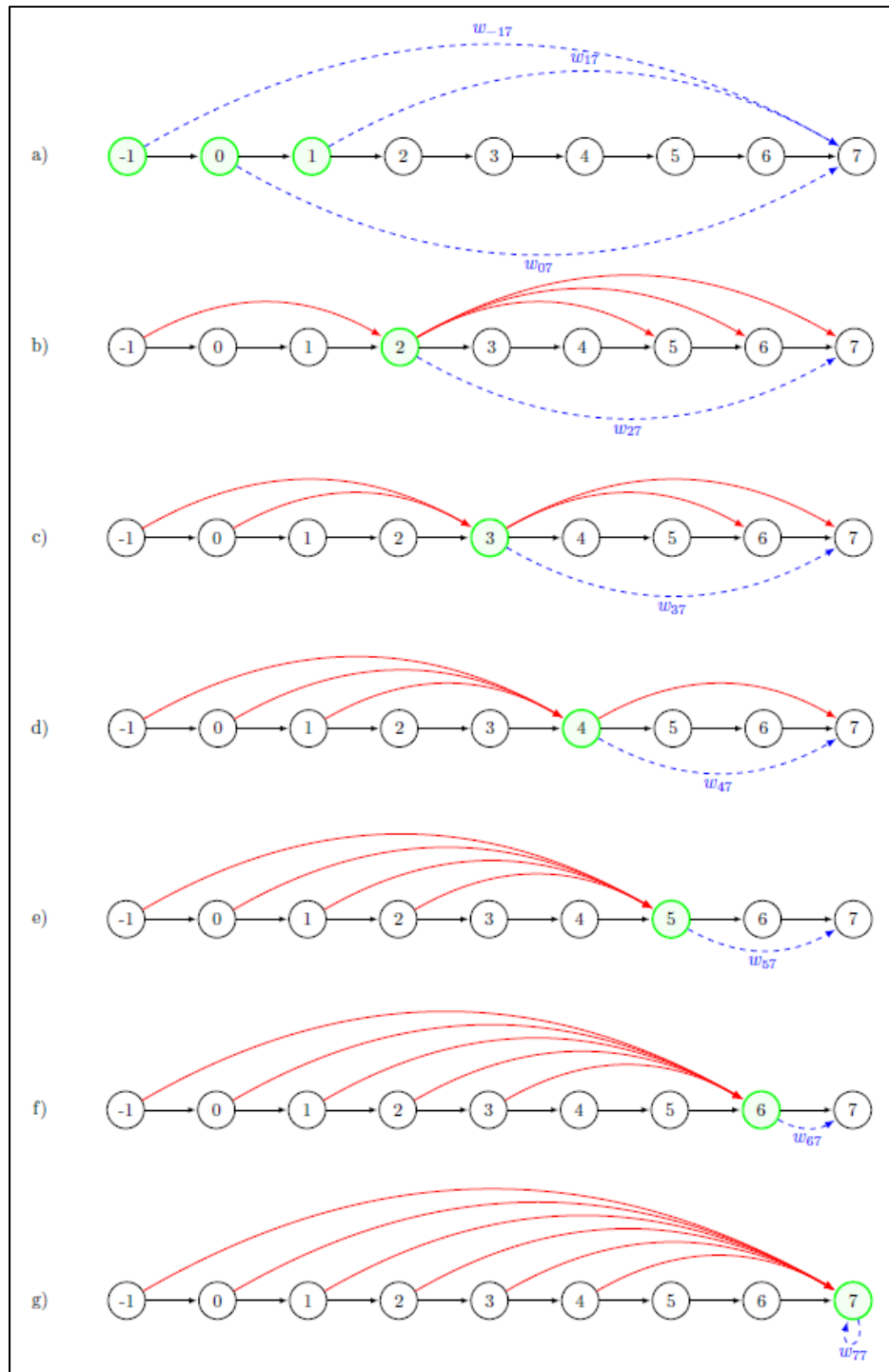


Figure 1.4 Timber flows for different time periods in an example with $N=7$, $M=1$, and $z=3$. Solid lines show the regenerated areas and dotted lines indicate the areas put aside as an ending inventory

To represent the mistake which we will come across while we are calculating the coefficients with the use of original formulation, consider the following equations and figures:

$$D_{-12} = \sum_{k=\max(-1,1)}^2 \frac{P_{-1k2}V_{-1k2} - C_{-1k2}}{\gamma^k} \quad (1.18)$$

$$= \frac{P_{-112}V_{-112} - C_{-112}}{\gamma} + \frac{P_{-122}V_{-122} - C_{-122}}{\gamma^2}$$

$$D_{-13} = \sum_{k=\max(-1,1)}^3 \frac{P_{-1k3}V_{-1k3} - C_{-1k3}}{\gamma^k} \quad (1.19)$$

$$= \frac{P_{-113}V_{-113} - C_{-113}}{\gamma} + \frac{P_{-123}V_{-123} - C_{-123}}{\gamma^2} + \frac{P_{-133}V_{-133} - C_{-133}}{\gamma^3}$$

$$D_{-14} = \sum_{k=\max(-1,1)}^4 \frac{P_{-1k4}V_{-1k4} - C_{-1k4}}{\gamma^k} \quad (1.20)$$

$$= \frac{P_{-114}V_{-114} - C_{-114}}{\gamma} + \frac{P_{-124}V_{-124} - C_{-124}}{\gamma^2} + \frac{P_{-134}V_{-134} - C_{-134}}{\gamma^3} + \frac{P_{-144}V_{-144} - C_{-144}}{\gamma^4}$$

$$D_{-15} = \sum_{k=\max(-1,1)}^5 \frac{P_{-1k5}V_{-1k5} - C_{-1k5}}{\gamma^k} \quad (1.21)$$

$$= \frac{P_{-115}V_{-115} - C_{-115}}{\gamma} + \frac{P_{-125}V_{-125} - C_{-125}}{\gamma^2} + \frac{P_{-135}V_{-135} - C_{-135}}{\gamma^3} + \frac{P_{-145}V_{-145} - C_{-145}}{\gamma^4} + \frac{P_{-155}V_{-155} - C_{-155}}{\gamma^5}$$

$$D_{-16} = \sum_{k=\max(-1,1)}^6 \frac{P_{-1k6}V_{-1k6} - C_{-1k6}}{\gamma^k} \quad (1.22)$$

$$\begin{aligned}
&= \frac{P_{-116}V_{-116} - C_{-116}}{\gamma} + \frac{P_{-126}V_{-126} - C_{-126}}{\gamma^2} + \frac{P_{-136}V_{-136} - C_{-136}}{\gamma^3} \\
&+ \frac{P_{-146}V_{-146} - C_{-146}}{\gamma^4} + \frac{P_{-156}V_{-156} - C_{-156}}{\gamma^5} + \frac{P_{-166}V_{-166} - C_{-166}}{\gamma^6}
\end{aligned}$$

Note that the number of the first and last regeneration periods is constant; however, the middle-harvested period (k) varies in the formulation. According to the definition of Z , some timber flows (only the harvested volume and not the thinned volume of stand thinnings) are impossible; bold segments of the formulas refer to this point. Figure 1.5 illuminates the possible and impossible timber flows. For instance, as discovered in Figure 1.5d, D_{-15} is consisted of five timber flows such as V_{-115} , V_{-125} , V_{-135} , V_{-145} , and V_{-155} ; however, in accordance with the definition of the Z parameter, some timber flows are impossible, like V_{-115} , V_{-135} , and V_{-145} . You should be aware that the mistake is not limited to impractical timber flows. In addition, there is an overlap between one fragment of the D_{-12} and D_{-15} . The fragments are as below:

$$\frac{P_{-122}V_{-122} - C_{-122}}{\gamma^2} \quad \& \quad \frac{P_{-125}V_{-125} - C_{-125}}{\gamma^2}$$

These two segments calculate the same timber flow and discount it for two periods. In other words, there is a timber flow in D_{-15} which has been computed in D_{-12} . Furthermore, two overlaps can be found between D_{-16} , D_{-12} , and D_{-13} .

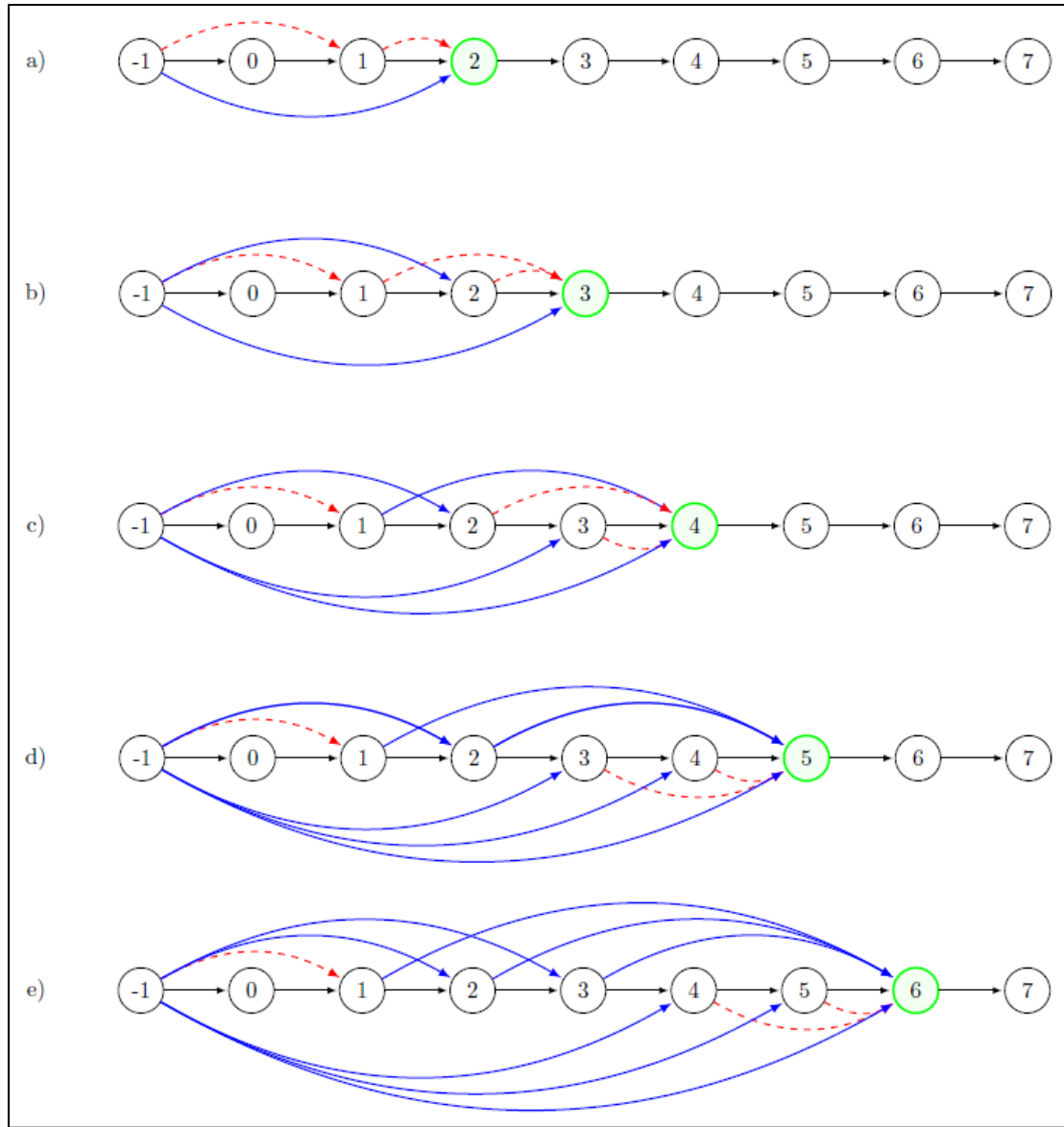


Figure 1.5 Timber flows used in calculation of discounted net revenue. Solid and dotted lines show the possible and impossible timber flows, respectively

To analyze the profitability of investment, NPV, which is the difference between the present value of cash inflows and outflows discounted by the discount rate, is used in capital budgeting. The coefficient D_{ij} is the discounted net revenue per hectare from areas regenerated in period i and regeneration harvested again in period j . However, in accordance with the definition of Z , some timber flows (V_{ikj}) are impossible. Moreover, there is an overlap between different D_{ij} in the objective function, i.e., the V_{ikj} is counted multiple

times in the D_{ij} which results in an overestimation in the calculation of the net present value (NPV). Therefore, in order to correct the formula, D_{ij} should be broken into two segments to consider both revenues from harvested volume (D'_{ij}) and thinned volume (D''_{ij}) as below:

$$D'_{ij} = \frac{P'_{ij}V'_{ij} - C'_{ij}}{(1 + \gamma)^j} \quad j = 1, 2, \dots, N \text{ \& } i = -M, \dots, j - Z \quad (1.23)$$

$$D''_{ij} = \sum_{k=\max(i,1)}^j \frac{P''_{ikj}V''_{ikj} - C''_{ikj}}{\gamma^k} \quad (1.24)$$

$$D_{ij} = D'_{ij} + D''_{ij} \quad (1.25)$$

Where

P'_{ij} Unit price of the volume harvested in period i and regeneration harvested in period j

V'_{ij} Volume per hectare harvested in period i and regeneration harvested in period j

C'_{ij} Silvicultural treatment costs per hectare in period i and regeneration harvested in period j

P''_{ikj} Unit price of the volume thinned in period k on areas regenerated in period i and regeneration harvested again in period j

V''_{ikj} Volume per hectare thinned in period k on areas regenerated in period i and regeneration harvested again in period j

C''_{ikj} Silvicultural treatment costs per hectare in period k on areas regenerated in period i and regeneration harvested again in period j

1.3.3 Full-revised Model II

Mathematically, the fully revised Model II would be illustrated as below:

$$\max \sum_{j=1}^N \sum_{i=-M}^{j-Z} D_{ij} x_{ij} + \sum_{i=-M}^N E_{iN} w_{iN} \quad (1.26)$$

Subject to

$$\sum_{j=1}^N x_{ij} + w_{iN} = A_i, \quad i = -M, \dots, 1 - Z \quad (1.27)$$

$$\sum_{j=Z+i}^N x_{ij} + w_{iN} = A_i, \quad i = 2 - Z, \dots, 0 \quad (1.28)$$

$$\sum_{k=j+Z}^N x_{jk} + w_{jN} = \sum_{i=-M}^{j-Z} x_{ij}, \quad j = 1, 2, \dots, N \quad (1.29)$$

$$x_{ij} \geq 0, \quad i = -M, \dots, N, j = 1, 2, \dots, N \quad (1.30)$$

$$w_{iN} \geq 0, \quad i = -M, \dots, N \quad (1.31)$$

$$D'_{ij} = \frac{P'_{ij} V'_{ij} - C'_{ij}}{(1 + \gamma)^j} \quad j = 1, 2, \dots, N \text{ \& } i = -M, \dots, j - Z \quad (1.32)$$

$$D''_{ij} = \sum_{k=\max(i,1)}^j \frac{P''_{ikj} V''_{ikj} - C''_{ikj}}{\gamma^k} \quad (1.33)$$

$$D_{ij} = D'_{ij} + D''_{ij} \quad (1.34)$$

Where

P'_{ij} Unit price of volume harvested in period i and regeneration harvested in period j

V'_{ij} Volume per hectare harvested in period i and regeneration harvested in period j

- C'_{ij} Silvicultural treatment costs per hectare in period i and regeneration harvested in period j
- P''_{ikj} Unit price of volume thinned in period k on areas regenerated in period i and regeneration harvested again in period j
- V''_{ikj} Volume per hectare thinned in period k on areas regenerated in period i and regeneration harvested again in period j
- C''_{ikj} silvicultural treatment costs per hectare in period k on areas regenerated in period i and regeneration harvested again in period j

1.4 Results

As a case study, we use a forest located close to Causapsal, in the Gaspésie Region. The stand type is a stand dominated by balsam fir (*Abies balsamea*) with a small component (< 15%) of White spruce and White birch (*Betula papyrifera*) on an average site quality (Site Index = 17 for balsam fir). We will consider that the forest stand within the management unit is managed following an even-aged regime based on the shelterwood system. This is common for balsam-fir located in the Gaspésie and the Bas-St-Laurent Regions of Quebec. This regime consists of a partial cutting done to support the establishment and growth of regeneration under the canopy of the residual stand and a few years later the rest of the dominant canopy are removed by a final cut while protecting the advanced regeneration. Balsam fir is very adaptable to this regeneration system since these species are grown by regular seed rain and seedlings are highly shade tolerant. For regenerating this stand type with this regeneration method, only a partial opening of the canopy is required with no soil preparation and no plantation. Consequently, regeneration costs are much lower than for the plantation regeneration system. If the logging is done properly at the final harvest, the young balsam fir stands would be very dense requiring a precommercial thinning to avoid growth stagnation over time.

1.4.1 Precommercial thinning

Silvicultural treatment is an operational plan (a sequence of actions, including precommercial thinning (PCT), commercial thinning (CT), shelterwood, selection, buffer, clear-cut, and do nothing) which explains the forest management goals for an area.

In general, stands naturally regenerated are needed to be pre-commercially thinned. In Canada, there are no marketable wood materials during the pre-commercial thinning; it is a cost generator with no intermediate income for the landowner. To minimize the cost, PCT should be performed within the first four years of the stand (Forest and Range 2004). Pre-commercial thinning is only conducted in even-aged forests around 15 years old. The trees are too small to be used in the mills and they are always left on site because their decomposition enriches the soil (Forêts, Faune et Parcs Gouvernement du Québec 2003). Precommercial thinning is assumed to be applied at the age of 10. The treatment reduces the canopy of competing hardwoods and regulates the spacing of the softwoods. We assume that the treatment is a prerequisite for obtaining the yields in this study.

Estimating the actual costs of pre-commercial thinning, labor, and equipment costs which vary depending on different issues should be known (De Franceschi and Boylen 1987). Hedin (1982) took into account the PCT costs of \$19.80 per hour based on brushsaw ownership, operating costs, and labor union wage. He also supposed that 15 hours should be spent to thin a hectare, i.e. \$297 per hectare. In this research, the cost estimate is based on the rates applied by the Ministry of Forests, Wildlife and Parks of Quebec (Gouvernement du Québec 2019). It is calculated with the following function:

$$\text{Precommercial thinning} = 156.33 + (630.28 * \log(DI) - 5095) * TP \quad (1.35)$$

Here,

- **DI:** Initial density per hectare, the count of all stems with a stump height diameter (15 cm) greater than 1.5 cm
- **TP:**
 - Target composition of the poplar: 0.7705
 - Target composition of the softwood: 1.0000
 - Target composition of mixed forest with softwood tendency: 1.1004

In our study, we assume an average tree density (DI) of 19,000 $\frac{\text{trees}}{\text{ha}}$ (equals to the average density observed for the fir-dominated ecoregion before PCT treatment in Laflèche and Tremblay (2008)), and a target stand composition dominated by softwoods (TP = 1), then the PCT cost is estimated to be 1,272.97 $\frac{\$}{\text{ha}}$.

1.4.2 Commercial thinning, shelterwood, and growth curve

The growth rate is influenced by numerous variables, such as soil, local climate, light, fertility, and the care you provide. Each tree has its own growth rate curve concluding three phases. In the beginning, the tree is growing, and the growth rate is increasing. Gradually, the growth rate decreases until the tree stops growing. Finally, the phase of decay starts, and the growth rate reduces further to negative levels.

The goal of the commercial thinning is to cut some trees to make more space for the remaining trees and increase their growth and favour the development of advanced regeneration while providing an intermediate supply of timber before the final harvest. The

treatment increases the average tree volume by 24% in comparison to untreated stands (Pelletier and Pitt 2008) (see Figure 1.6).

Based on the results from Pelletier and Pitt (2008) commercial thinning has no effect on the cumulative merchantable volume production (thinning + standing volumes) in comparison to untreated stands. Table 1.7 represents the empirical yield tables for balsam fir stand with and without commercial thinning (Pothier and Auger 2011).

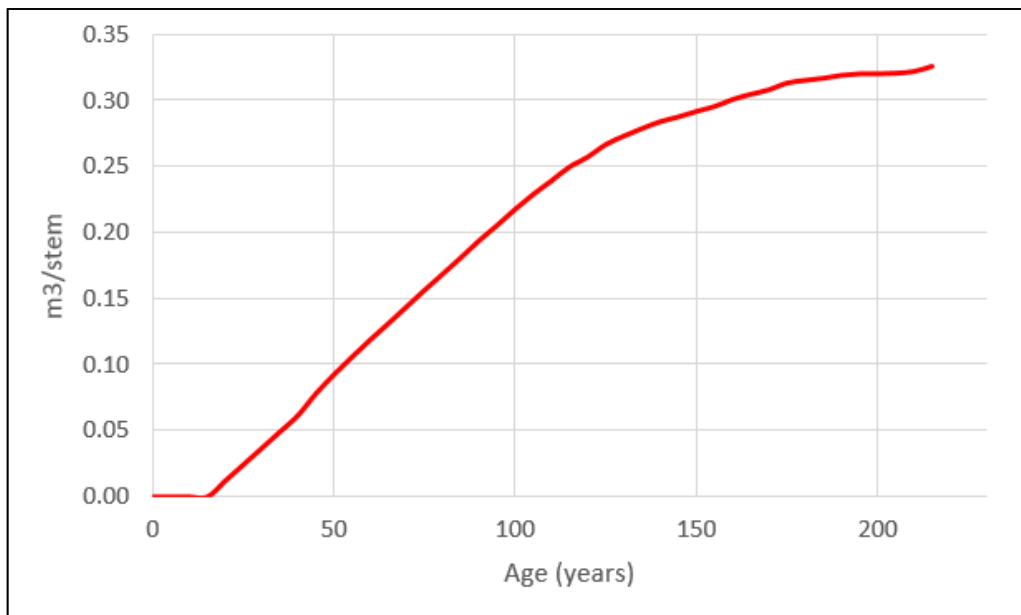


Figure 1.6 The stem volume growth for balsam fir trees

Table 1.7 Balsam fir stand volume with and without commercial thinning

Age Class	Age	Mean tree Volume (m ³ /tree)	Volume (m ³ /ha)	Volume after CT (m ³ /ha)
1	5	0	0	0
2	10	0	0	0
3	15	0	0	0
4	20	0.01	21.1	21.1
5	25	0.02	42.2	42.2
6	30	0.04	63.3	31.7
7	35	0.05	84.6	53.0
8	40	0.08	106.0	74.4
9	45	0.10	139.6	108.0
10	50	0.11	166.5	134.9
11	55	0.13	187.3	155.7
12	60	0.15	202.7	171.1
13	65	0.16	213.1	181.5
14	70	0.18	219.6	188.0
15	75	0.19	222.5	190.9
16	80	0.21	222.4	190.8
17	85	0.22	220.0	188.4
18	90	0.24	215.7	184.1
19	95	0.26	210.2	178.6
20	100	0.27	203.7	172.1
21	105	0.28	196.6	165.0
22	110	0.30	189.3	157.7
23	115	0.31	181.9	150.3
24	120	0.32	174.7	143.1
25	125	0.33	168.1	136.5
26	130	0.34	162.0	130.4
27	135	0.35	156.2	124.6
28	140	0.35	151.4	119.8
29	145	0.36	147.0	115.4
30	150	0.36	143.0	111.4

Commercial thinning is usually done in stands between 30 and 80 years old, with no regeneration objective (Forest Practices Branch, Ministry of Forests, British Columbia, Canada 1999). In this study, commercial thinning is implemented at age 30 and a 50% crown thinning is prescribed, including the effect of skidding trails. Partial harvest is done with a harvester and a forwarder. After commercial thinning the standing volume is assumed to be equal to the volume of an unthinned stand, minus the volume remove at the moment of the thinning (see Table 1.7 and Figure 1.7). This follows the results from Pelletier and Pitt (2008).

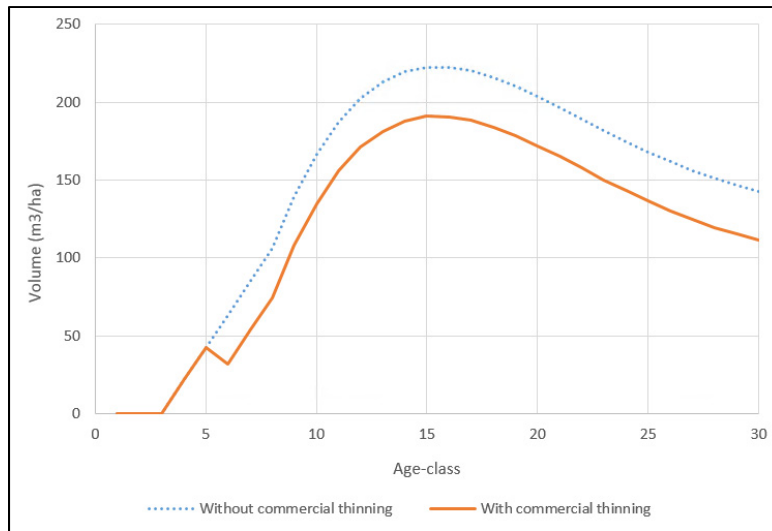


Figure 1.7 The stand growth curve for balsam fir with and without commercial thinning

Figure 1.8 illustrates how the road-side harvest costs for commercial thinning and final harvest for softwood stands change by mean volume of the tree (m^3). The commercial thinning is assumed to be done with a cut-to-length system, with a harvester and a forwarder. The cost functions are based on the average productivity observed in Eastern Canada by FPInnovations (Meek 2016, personal communication).

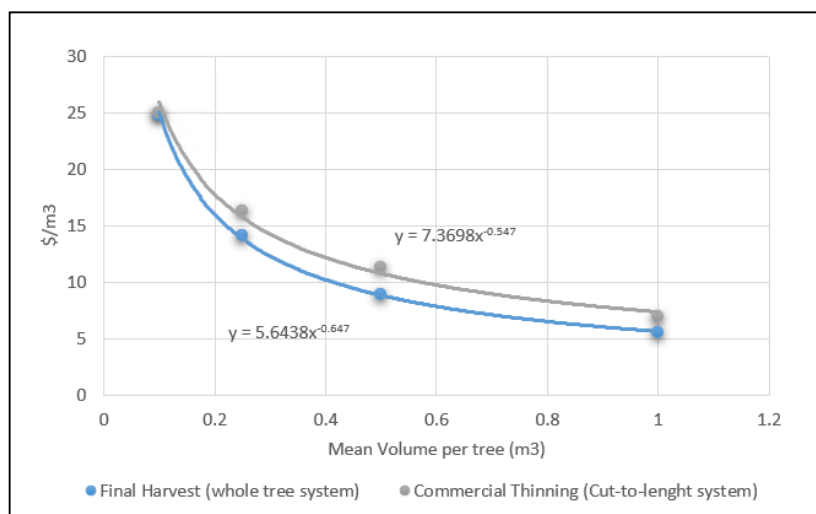


Figure 1.8 The road-side harvest (commercial thinning and final harvest) costs for softwood stands

Taken from Meek (2016, personal communication)

1.4.3 Final harvest

All merchantable trees in the stand are harvested in the final harvest. Moreover, non-merchantable trees are protected using careful logging techniques. The final harvest is done with a feller-buncher and a skidder. Harvest scheduling is determined by optimization and the harvested volume is equal to the volume of the remaining trees in the stand after the commercial thinning (see Table 1.7 and Figure 1.7). Stands are eligible to final harvest when the average tree volume is higher than 0.2 m^3 to ensure that the production of chips for pulpwood does not exceed $50 \frac{\text{kg}}{\text{m}^3}$. Considering the mean tree volume estimation in Table 1.7, the minimum number of periods between two final harvests is 25 years for a stand treated with the above silviculture regime.

To estimate the stand yield after commercial thinning in relation with age-class, we used the empirical yield model from Natura-2014 (Pothier and Auger 2011, Auger 2017) which has been estimated by the Chief forester of Quebec by using forest inventory plots to initiate the model and modified with the assumptions presented in section 1.4.2. The results can be found in Table 1.7 and Figure 1.7.

Table 1.8 represents the treatment costs incurred between two consecutive final harvests. For example, if a stand is going to be harvested at age 60, there would be a PCT cost (\$1272.97) at age 10, a CT cost (\$1420) at age 30, and finally a final harvest cost at age 60 (\$3329).

Table 1.8 Silvicultural treatment costs between two consecutive regeneration harvests

Age Class	Age	Mean Tree Volume (m ³ /tree)	PCT Cost (\$/ha)	CT Cost (\$/ha)	Final Harvest Cost (\$/ha)
1	5	0	0	0	0
2	10	0	1272.97	0	0
3	15	0	0	0	0
4	20	0.01	0	0	2052
5	25	0.02	0	0	2621
6	30	0.04	0	1420	1512
7	35	0.05	0	0	2097
8	40	0.08	0	0	2214
9	45	0.10	0	0	2756
10	50	0.11	0	0	3085
11	55	0.13	0	0	3263
12	60	0.15	0	0	3329
13	65	0.16	0	0	3313
14	70	0.18	0	0	3234
15	75	0.19	0	0	3109
16	80	0.21	0	0	2961
17	85	0.22	0	0	2793
18	90	0.24	0	0	2612
19	95	0.26	0	0	2439
20	100	0.27	0	0	2265
21	105	0.28	0	0	2101
22	110	0.30	0	0	1953
23	115	0.31	0	0	1810
24	120	0.32	0	0	1691
25	125	0.33	0	0	1575
26	130	0.34	0	0	1482
27	135	0.35	0	0	1397
28	140	0.35	0	0	1328
29	145	0.36	0	0	1268
30	150	0.36	0	0	1213

1.4.4 Harvest revenue

The price of timber depends on different agents such as type of tree, length, diameter, and quality. Quality is one of the chief agents of price change. In this research, a single price table was estimated for both woods from commercial thinnings and final harvests. Table 1.9 shows the average price (\$) in relation to the average tree volume in the stand (m^3). The estimation has been done in two steps: market search and bucking simulation.

1.4.5 Market Search

We had a search for mill prices at www.prixbois.ca which is a wood marketing tool from the Fédération des producteurs forestiers du Québec. The tool provides roadside prices for logs while considering the trucking cost from the forest to the mill. In our analysis, we

supposed that the logs are cut in the area of Causapcal (Quebec). Prixbois calculates the road distance and hauling cost from the forest to the mills. The analysis was initially done for 8, 12, 14, and 16-foot logs. However, according to the tool, there is a regional market only for 8- and 12-foot logs. Therefore, if only 8-foot logs are produced, the best price is from JDIrving (Kedgwick, NB) while if a combination of 8- and 12-foot logs are produced, the only mill accepting this assortment is Damabois (Cap Chat).

1.4.6 Bucking simulation

The unit price per unit volume ($\frac{\$}{m^3}$) depends on the number of logs of each sort that can be obtained in the bucking operation. This, in turn, depends on the tree size and taper. A bucking simulator was developed based on the taper equation from Ung et al. (2013) which calculates the number and size of each log based on the average taper profile, given species, and the DBH.

Selling prices ($\frac{\$}{m^3}$) of merchantable volume (from a stump height of 30 cm and a top diameter of 9cm, based on the volume equation from (Perron 2003)) were calculated for a range of DBH. Two scenarios were compared:

1. Only producing 8-foot logs and selling them to JDIrving.
2. The production of a combination of 8- and 12-foot logs sold to Damabois.

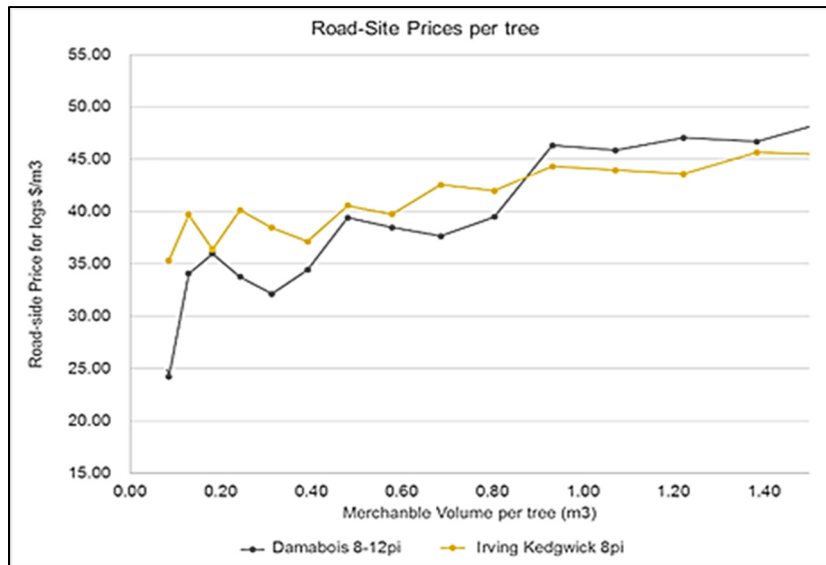


Figure 1.9 Comparison of selling price of merchantable volume with different length

Figure 1.9 illustrates that for trees with merchantable volume lower than 1 m^3 selling 8-foot logs to JDIrving is the most profitable option. So, to obtain a good estimation for the price of wood in each age-class, a linear regression has been done to find the best-fitting line (Figure 1.10). Table 1.9 shows the income received from final harvest in relation to the age-class.

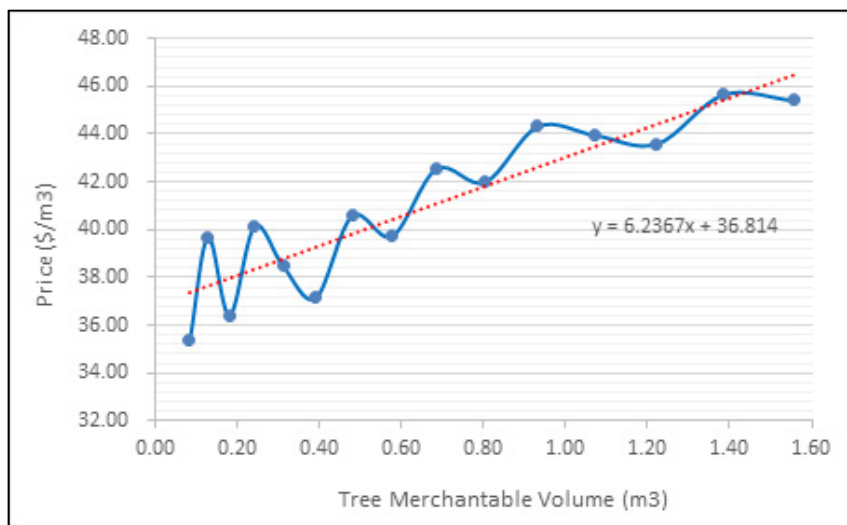


Figure 1.10 Price table for balsam fir in the Causapschal region

Table 1.9 Final harvest income at each age class

Age Class ▾	Age ▾	Volume after CT (m3/ha) ▾	Price (\$/m3) ▾	Revenue (\$/ha) ▾
1	5	0	0	0
2	10	0	0	0
3	15	0	0	0
4	20	21.1	36.9	778
5	25	42.2	37.0	1560
6	30	31.7	37.0	1172
7	35	53.0	37.1	1966
8	40	74.4	37.3	2773
9	45	108.0	37.4	4039
10	50	134.9	37.5	5061
11	55	155.7	37.6	5858
12	60	171.1	37.7	6454
13	65	181.5	37.8	6864
14	70	188.0	37.9	7128
15	75	190.9	38.0	7257
16	80	190.8	38.1	7271
17	85	188.4	38.2	7198
18	90	184.1	38.3	7052
19	95	178.6	38.4	6857
20	100	172.1	38.5	6624
21	105	165.0	38.6	6365
22	110	157.7	38.7	6095
23	115	150.3	38.7	5822
24	120	143.1	38.8	5551
25	125	136.5	38.9	5305
26	130	130.4	38.9	5074
27	135	124.6	39.0	4854
28	140	119.8	39.0	4672
29	145	115.4	39.0	4503
30	150	111.4	39.1	4351

1.4.7 Forest age class distribution

In this study, we use a typical age class distribution from the Gaspésie Region; it is compiled from the estate model used by the Chief Forester of Quebec for the Forest Unit No. 11161 (Forestier en chef, Woodstock File from the Chief Forester of Quebec for Forest Unit 11161). Figure 1.11 shows the percentage of total area of the Forest Unit No. 11161 in different age classes.

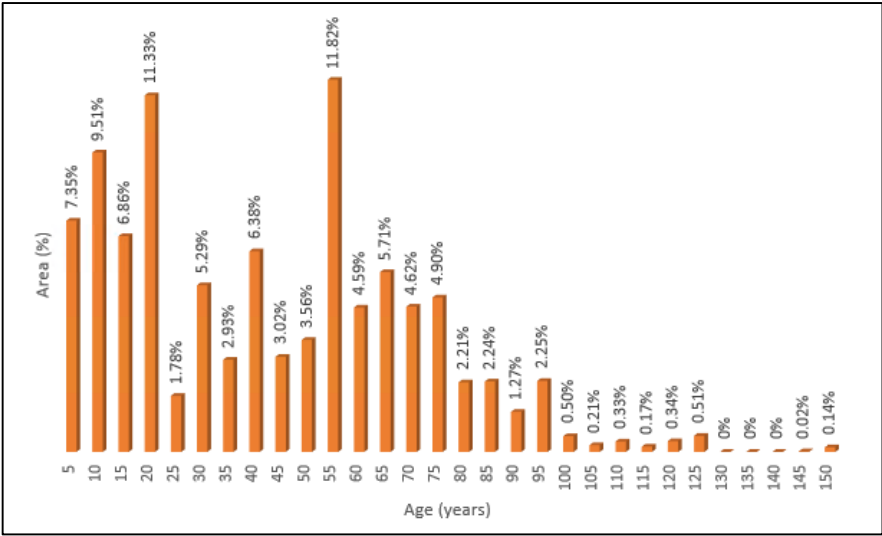


Figure 1.11 The age class distribution for Forest Unit No. 11161

The total area for the Forest Unit No. 11161 is 619,683 ha. In this study, it is assumed that there is a forest with 30 different age-classes. Therefore, we would have the area for each age class as given in Table 1.10.

Table 1.10 The age class distribution taken from Woodstock file from the Chief Forester of Quebec for Forest Unit 11161

Age (years)	Area (ha)	Age (years)	Area (ha)
5	45,517	80	13,691
10	58,954	85	13,861
15	42,485	90	7,877
20	70,210	95	13,971
25	11,016	100	3,092
30	32,809	105	1,312
35	18,151	110	2,050
40	39,511	115	1,033
45	18,730	120	2,119
50	22,056	125	3,152
55	73,269	130	0
60	28,419	135	0
65	35,395	140	0
70	28,607	145	104
75	30,390	150	890

1.4.8 Comparison of the models

To compare the results of the original and proposed models, the following assumptions are used:

- the length of each planning period is 5 years.
- the age-class distribution at the beginning of the planning horizon (A_i) can be found in Table 1.10.
- the minimum number of periods between regeneration harvests is 5 ($Z = 5$), in other words, when the stand is 25 years old.
- the planning horizon is 10 periods (50 years).
- PCT is implemented at age 10, in other words, two planning periods after the regeneration harvest and it would cost \$1272.97.
- CT is implemented at age 30 (6 periods after the regeneration harvest) and a 50% crown thinning is prescribed.
- the silvicultural treatment (CT and final harvest) costs can be found in Table 1.8.
- the estimation of the unit price of the wood is presented in Table 1.9.
- trees older than 150 years old are considered as dead with no value.
- the annual interest rate is assumed to be 1.5% and constant throughout the planning horizon.
- to calculate the net value per hectare of leaving areas regenerated in period i as ending inventory in period N (P'_{iN}), we calculate the value of standing trees which is assumed to be equal to the potential income from wood volume available in the stand. We used the following formula to calculate P'_{iN} :

$$P'_{iN} = \frac{(P_{iN} - C_{iN})V_{iN}}{\gamma^N} \quad (1.36)$$

P_{iN} Unit price of volume harvested in period i and regeneration harvested in period N (put aside as ending inventory)

V_{iN} Volume per hectare harvested in period i and regeneration harvested in period N (put aside as ending inventory)

C_{iN} Silvicultural treatment costs per hectare in period i and regeneration harvested in period N (put aside as ending inventory)

According to the aforementioned assumptions and data, D_{ij} and E_{i10} values can be found in Table 1.11 and Table 1.12, respectively. Gray cells in Table 1.11 indicate the impossible values for D_{ij} based on the definition of Z parameter.

Table 1.11 Values for parameters D_{ij} obtained from revised formulation

		Next Harvesting Period (Period j)									
		1	2	3	4	5	6	7	8	9	10
Most Recent Harvesting Period (Period i)	-30	0	0	0	0	0	0	0	0	0	0
	-29	2,919	0	0	0	0	0	0	0	0	0
	-28	3,009	2,715	0	0	0	0	0	0	0	0
	-27	3,111	2,799	2,526	0	0	0	0	0	0	0
	-26	3,216	2,894	2,604	2,349	0	0	0	0	0	0
	-25	3,341	2,991	2,692	2,422	2,185	0	0	0	0	0
	-24	3,469	3,108	2,783	2,504	2,253	2,033	0	0	0	0
	-23	3,591	3,227	2,891	2,588	2,329	2,096	1,891	0	0	0
	-22	3,732	3,340	3,002	2,690	2,408	2,167	1,950	1,759	0	0
	-21	3,854	3,472	3,107	2,793	2,502	2,240	2,016	1,814	1,636	0
	-20	3,966	3,585	3,229	2,890	2,598	2,328	2,084	1,875	1,687	1,522
	-19	4,055	3,689	3,335	3,004	2,689	2,417	2,165	1,938	1,744	1,569
	-18	4,110	3,772	3,432	3,102	2,794	2,501	2,248	2,014	1,803	1,622
	-17	4,130	3,823	3,509	3,192	2,886	2,600	2,327	2,091	1,874	1,677
	-16	4,098	3,842	3,556	3,264	2,970	2,684	2,418	2,164	1,945	1,743
	-15	4,010	3,812	3,574	3,308	3,036	2,763	2,497	2,249	2,013	1,810
	-14	3,859	3,730	3,546	3,325	3,077	2,825	2,570	2,323	2,093	1,873
	-13	3,623	3,590	3,470	3,299	3,093	2,863	2,628	2,391	2,161	1,947
	-12	3,304	3,370	3,339	3,228	3,068	2,877	2,663	2,444	2,224	2,010
	-11	2,907	3,073	3,135	3,106	3,003	2,854	2,676	2,477	2,274	2,069
	-10	2,414	2,705	2,859	2,916	2,889	2,793	2,655	2,490	2,304	2,115
	-9	1,838	2,246	2,516	2,659	2,713	2,688	2,598	2,470	2,316	2,144
	-8	1,194	1,710	2,089	2,340	2,474	2,524	2,500	2,417	2,298	2,154
	-7	519	1,111	1,591	1,943	2,177	2,301	2,348	2,326	2,248	2,137
	-6	-123	483	1,033	1,480	1,808	2,025	2,141	2,184	2,164	2,092

[illegible]

Table 1.12 Values for parameters E_{i10}

Period i	-30	-29	-28	-27	-26	-25	-24	-23	-22	-21
E_{i10}	0	0	0	0	0	0	0	0	0	0
Period i	-20	-19	-18	-17	-16	-15	-14	-13	-12	-11
E_{i10}	1522	1569	1622	1677	1743	1810	1873	1947	2010	2069
Period i	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1
E_{i10}	2115	2144	2154	2137	2092	1783	1676	1524	1331	-97
Period i	0	1	2	3	4	5	6	7	8	9
E_{i10}	-303	-551	-821	-1080	-1110	-1282	-1332	-664	-618	0
Period i	10									
E_{i10}	0									

If we solve the problem with two different formulations, the original one and our suggested formulation, there would be a gap between the objective values. The objective value for original and proposed formulations are 1,351,867,304.26 and 1,347,442,815.31, respectively. The new NPV is 0.33% less than the original formulation - the original formulation overestimates the objective function, that is:

$$\frac{(1,347,442,815.31 - 1,351,867,304.26)}{1,351,867,304.26} = -0.33\%$$

Although the gap between two models is small, the value is 4.42 million dollars. Clearly, the original model provides an erroneous solution. Tables 1.13 and 1.14 indicate the outcomes of decision variables if we solve the problem with original formulation. Tables 1.15 and 1.16 demonstrate the new values for the decision variables if we use the proposed formulation.

According to the definition of the Z parameter, some cells must not take a value (gray cells in Tables 1.13 and 1.15); however, as it can be found in the Table 1.13, the value of x_{-11} is equal to 45,517 which is impossible. The proposed formulation has modified this error and the value of x_{-11} is equal to 0 instead of 45,517. Therefore, in addition to the difference between the objective values, there is a difference between the decision variables of the compared models.

Note that it is hard to estimate the impact on general problems as the type of harvest operations included plays a role.

Table 1.13 Original formulation - Outcomes for decision variables x_{ij}

[illegible]

[illegible]

Table 1.16 Outcomes for decision variables w_{i10} for revised formulation

Period i	-30	-29	-28	-27	-26	-25	-24	-23	-22	-21
w_{i10}	0	0	0	0	0	0	0	0	0	0
Period i	-20	-19	-18	-17	-16	-15	-14	-13	-12	-11
w_{i10}	0	0	0	0	0	0	0	0	0	0
Period i	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1
w_{i10}	0	0	0	0	0	0	0	0	0	45,517
Period i	0	1	2	3	4	5	6	7	8	9
w_{i10}	0	258,344	0	0	0	0	0	0	0	143,162
Period i	10									
w_{i10}	171,649									

1.5 Concluding remarks

Models are considered as the basic tools of strategic forest planning by most foresters because they examine the long-term consequences of forest-management inputs (Gunn 2007). In this paper, we focused on Model II and how the minimum number of periods between regeneration harvests, i.e, Z parameter, leads to modeling mistakes. The first mistake appears in the first set of area constraints where additional decision variables are included. These variables have no contribution to the objective function; however, in specific contexts, they could take nonzero values. The second mistake is when computing the D_{ij} parameter where overlaps and impossible timber flows could be found in the formulation.

As far as we know in the literature, these mistakes have not been identified and presented by any researcher, since Model II was suggested by Johnson and Scheurman (1977). An illustrative example is given with realistic parameters to verify the modeling errors. The case

study from a real forest also supports the findings. Some well-known software, such as Woodstock, FORPLAN, TigerMoth, and SilviLab are based on variants of Model II formulation. We have not verified that these applications use the formulation that was published in the original article by Jonhson and Scheurman (1977). Furthermore, we have not verified that the models referenced to Jonhson and Scheurman (1977) included the mistakes or that the mistakes were a publication error. It is, however, important to provide information to avoid the mistakes in new models and they can be corrected, if necessary, in the old models. It can be very difficult to identify these errors in particular if the models are only used for computing forest NPV values and it is not necessary to study the detailed harvest plan where the additional variables can be identified.

1.6 Acknowledgments

We gratefully thank the FORAC Research Consortium for its financial support.

CHAPTER 2

SALVAGE HARVEST PLANNING FOR SPRUCE BUDWORM OUTBREAK USING MULTI-STAGE STOCHASTIC PROGRAMMING

Siamak Mushakhian^a, Mustapha Ouhimmou^b, Mikael Rönnqvist^c

^{a,b} Department of Systems Engineering, École de technologie supérieure, Suite A-3586, 1100 Notre-Dame St. W., Montreal H3C 1K3, Canada

^c Department of mechanical Engineering, Université Laval, Suite 1504, 1065 avenue de la Médecine, Pavillon Adrien-Pouliot, Quebec City G1V 0A6, Canada

Paper published in Canadian Journal of Forest Research, April 2020

Abstract

Forest supply chain planning must deal with many natural disturbance uncertainties such as fires, insects, and windthrows. One important consideration is wood infestation by invasive insects as it causes environmental and economic harm. An example of invasive insects in Eastern Canada is the spruce budworm (*Choristoneura fumiferana* (Clemens)) which is one of the most destructive insects in North America's conifer stands. In 2017, more than 5 million ha of forest were defoliated by spruce budworm in Quebec. Repeated defoliation causes tree mortality, reduction of growth rates, and reduced lumber quality. Consequently, different wood qualities with greatly varied values are found in the forest. Changes in the outbreak intensity impact wood values throughout the forest. One of the common actions to mitigate the economic and environmental damages is salvage harvesting. However, because of the large uncertainties and lack of detailed information, it is a difficult problem to model. We propose a multistage stochastic mixed-integer programming model for harvest scheduling under various outbreak intensities. The objective is to maximize revenues of wood value minus logistic costs while satisfying demand for wood in the industry. Results show that when there is an outbreak throughout the forest, the first priority for salvage harvesting is to focus on forest areas with the lowest level of infestation.

Keywords: Salvage harvesting, Infestation, Spruce Budworm, Wood supply, Stochastic programming

2.1 Introduction

The forest industry is very important from both environmental and economic perspectives and in particular for countries such as Canada, Chile, Finland, New Zealand, and Sweden (Rönnqvist et al. 2015). For example, in 2017, production in the forest sector contributed around \$25 billion to Canada's real gross domestic product (GDP) through 210 000 direct and 107 000 indirect jobs (Natural Resources Canada 2018a) (note that all monetary values are expressed in Canadian dollars). However, damage by invasive species incurs billions of dollars in cost for forest owners such as government, industries, and private citizens (Aukema et al. 2011). Revenue losses, prevention and control investments, and environmental mitigation efforts have cost Canada hundreds of millions of dollars during the last years (Natural Resources Canada 2017). Between 1990 to 2017 forest insects such as spruce budworm (*Choristoneura fumiferana* (Clemens)), forest tent caterpillar (*Malacosoma disstria* Hubner), and mountain pine beetle (*Dendroctonus ponderosae* Hopkinss, 1902) annually defoliated, on average, around 11 million ha of forest in Canada (National Forestry Database 2019). In 2017 only, spruce budworm (SBW) infested over 5 million ha in Quebec (National Forestry Database 2019). At a rough estimate, annual timber harvest volume losses from forest insect outbreaks are around half of the annual harvest level in Canada (MacLean 2004).

Reduction in the wood supply for the forest is one major direct impact of insect outbreaks. Another is the increased fuel levels of deadwood for fires. One of the challenges in forest management and planning is natural disturbances, which results in uncertainty (Rönnqvist et al. 2015) that is difficult to deal with in the forest value chain (Gunn 2007). Natural processes like fire, insects, and windthrows are the main sources of uncertainty complicating forest management and can profoundly change forest ecosystems. Forest ecosystems can be adversely affected by invasive species such as SBW in Eastern Canada (MacLean et al. 2002) and the mountain pine beetle (MPB) in Western Canada. Reduction in the insect mortality can

increase the flammability of wood, fire intensity, and burned area which together can have a dire effect on the availability and quality of the timber resources (D'Amours et al. 2016). One of the main challenges for forestry companies is to ensure that they have access to reliable sources of wood and fiber (quantity and quality).

There are different approaches to reduce the negative impacts of insect outbreaks. Removing trees, applying chemical treatments, and employing biological control (e.g., the use of other living organisms to stop the invasive species) are measures to mitigate economic and environmental damages (Hof 1998; Blackwood 2010; Büyüктаhtakın et al. 2011; Epanchin-Niell and Wilen 2012; Kovac 2014; E.Y. Kibis, I.E. Büyüктаhtakın, R.G. Haight, N. Akhundov, K. Knight, and C. Flower, unpublished data). Despite more than 50 years of research related to SBW, there are few management options, including spraying insecticide to prevent defoliation and conducting salvage harvesting of dead trees in the 3- to 5-year period when they are still valuable. Alternatives also include altering species composition by planting jack pine (*Pinus banksiana* Lamb) or hardwood species (which are not susceptible to SBW) or species with low susceptibility such as black spruce (*Picea mariana* (Mill.) B.S.P.), using precommercial thinning at the stand level or harvest planning at the landscape level, and idly accepting the growth reduction and mortality and doing nothing (MacLean 1996; MacLean et al. 2000).

It is difficult to control the periodicity of outbreaks (Royama et al. 2005) and epicenter location of SBW outbreaks through preventive management actions (Bouchard and Auger 2014); however, reducing host species can decrease the risk of future outbreak damage (Bouchard and Auger 2014). Salvage harvesting and modifying the harvest schedule (replanning) can partially mitigate the wood supply impacts of an SBW outbreak (Hennigar et al 2013). Replacing host species with nonhosts, especially on large scale, can be very expensive and have negative impacts on the biodiversity conservation, as host species are a crucial habitat for some plant and animal species in the boreal forest (Bouchard and Auger 2014).

Considering the impact of salvage harvesting and scheduling on the following years, planning under uncertainty should be used, which is more difficult than using deterministic planning. There are several sources of uncertainties. Some information can be estimated with good quality, or replanning can be done to take it into consideration when estimated data change considerably. Such examples are supply and demand estimation and prices of raw material and final products. Kazemi Zanjani et al. (2010) modeled uncertainty in the quality of the raw material and products demand. Shahi and Pulkki (2015) developed a simulation-based optimization supply chain model under the stochastic demand for supplying sawlogs to sawmills. Abasian et al. (2018) considered the uncertainty of demand and prices of the final products in a forest supply chain. Others factors such as fires, insect outbreaks, windthrows are much more difficult to estimate and there are few operations research models that consider these directly in wood supply models.

Zhu chen et al. (2017) used mixed-integer linear programming (MILP) and a two-stage stochastic programming to deal with the uncertainty associated with severity and propagation of SBW infestation over time. The authors maximized the total profit from the harvested volume less the total cost of harvesting processes. They assumed the volume percentage in each forest stand and the change in inventories based on the transition matrix over the planning horizon. However, one of the main reasons for a change in the phase of infestation is the dynamic population of SBW (outbreak intensity).

The MPB outbreak in Columbia (BC), Canada, led to a reduction in the annual allowable cut (AAC) by approximately 12 million m^3 below pre-outbreak levels beginning in 2009 (British Columbia Ministry of Forests and Range 2007). Mahmoudi et al. (2009) stated due to the severe infestation of the MPB in BC, there were huge volumes of deadwood that exceeded the capacity of the lumber industry. One way to deal with this surplus wood is to use it for bioenergy. Perez and Dragicevic (2010) used a spatially explicit model integrating geographic information systems (GISs) and agent-based modeling to simulate MPB outbreaks. Mathey and Nelson (2010) showed that increasing harvest levels as a management strategy can perform well economically in comparison with other strategies, although it would lead to a very young

growing stock with low proportion of old forest. Dhar et al. (2016) confirmed that in BC, when management strategies like salvage logging are used in response to MPB outbreak the impact is more significant on variables such as midterm timber supply, forest growth, forest structure and composition, vegetation diversity, forest fire, climate change, and ecosystem resilience.

Uncertainty is present on network parameters such as demand, price, wood supply, infestation level, outbreak intensity. The combination of assumed random parameters constitutes a scenario. Stochastic optimization (Brige and Louveaux 1997) directly accounts for scenarios in the planning. It is an extension of a deterministic model and considers many scenarios instead of only one average scenario. Two-stage stochastic optimization can be used if the behavior of random parameters remains stationary over time; otherwise, multi-stage stochastic optimization is needed to solve the problem (Abasian et al. 2018). D'amours et al. (2008) suggested that MILP and stochastic programming methods are useful for tactical and strategic planning problems.

In this paper, we focus on harvest planning and modeling associated with SBW infestations. It is difficult to get both relevant and accurate data on the infestation level and its spread. Moreover, as the spread is highly uncertain, it is also difficult to model the planning problem accurately. The main contributions of the paper are as follows. First, we propose a deterministic model that considers the effect of the dynamics of outbreak intensity on the infestation level of SBW. This is used as a basis for a multistage stochastic programming model. Second, we analyze and propose mitigation strategies for how to best salvage an SBW infested area using real data in a case study.

This paper is organized as follows. Section 2.2 describes the problem. In Section 2.3, we present deterministic and multistage stochastic models for the proposed problem. To validate our models, we solve the proposed models with real data, and the results are analyzed in Section 2.4. Concluding remarks are provided in Section 2.5.

2.2 Problem definition

After 4 to 5 years of sustained attack of SBW, the result is complete defoliation. If the infestation does not kill the entire tree within 3-5 years, it will kill the crown of the tree. Consequently, it increases tree mortality and decreases growth rate and wood quality. Decay in dead trees results in a rapid reduction in the quality of salvageable volume (Hennigar et al. 2013). Fir (*Abies* Mill) can be salvaged for lumber for 1-3 years after death (Basham and Belyea 1960, Basham 1986) and spruce (*Picea* A. Dietr) can be salvaged for pulpwood up to 3-5 years after death (Sewell and Maranda 1979). In this paper, we consider seven levels of infestation associated with lumber quality in the model. It is assumed that salvage harvesting can be implemented within a 4-year period.

Reduction in the wood supply for the forest companies is the greatest direct impact of insect outbreaks. It can also affect the communities relying on the forest companies (Natural Resources Canada 2017). In Quebec, the last major SBW outbreak, which lasted between 1967 and 1992, it is estimated to have devastated 12.9 million ha of commercial forests (Davidson 2011).

Cyclical SBW outbreaks have affected forests in Eastern Canada for a long time (Royama et al. 2005). Approximately every 35 to 40 years, there is an outbreak of SBW in Eastern Canada (Natural Resources Canada 2018b, Royama et al. 2005). Figure 2.1 represents the intensity dynamics of an insect outbreak over time. Both reduction in the available resources for SBW resulting from damaged trees and increases in SBW mortality caused by natural enemies can end an outbreak (Natural Resources Canada 2018b). Reduction in host species can affect local budworm dispersal success (Nealis 2016) and natural enemies (Royama 1984, Eveleigh et al. 2007); consequently, it might have an effect on the frequency and intensity of budworm outbreak cycles. It is difficult to control the periodicity of SBW outbreaks (Royama et al. 2005). Although mitigation strategies can be controlled by the management, SBW outbreak pattern (severity, timing, and duration of defoliation) is out of their control (Hennigar et al. 2013). Therefore, a set of future possible scenarios can be created based on these uncontrollable

factors. In this paper, the intensity dynamics of the outbreak is considered to be the uncertain parameter. There are three levels of outbreak intensity (light, moderate, and severe) with an associated probability.

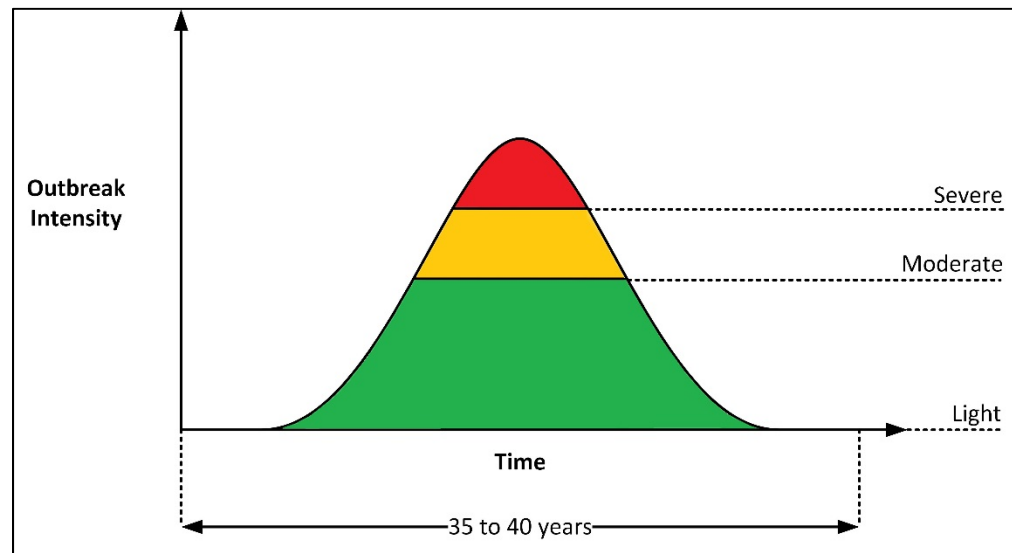


Figure 2.1 Intensity dynamics of an insect outbreak

Taken from James et al. (2015, p. 298)

Measures such as spraying of biological insecticide, salvage harvesting, and strategic replanning help mitigate the wood supply impacts of defoliation by SBW (Hennigar et al. 2007). Salvage harvesting is applied to save volume that would otherwise be lost as a result of SBW outbreak (Hennigar et al. 2013). Hennigar et al. (2007) also showed that the combination of optimized salvage and harvest scheduling can decrease future harvest reductions by up to 12%. Chang et al. (2012) showed that combining SBW control and replanning of harvest scheduling and salvage strategy under moderate and severe outbreak can mitigate the negative economic impact between 1% and 18% depending on the level of control implemented. In the short term, salvage and replanning can reduce wood supply losses up to 20% (Hennigar et al. 2013). However, the overall wood supply benefit over the long term is insignificant. Landscape-level forest management has influenced insect outbreak characteristics such as duration, frequency, and severity of SBW outbreak, but empirical evidence remains elusive (Robert et al. 2012, Robert et al. 2017).

Figure 2.2 shows the impact of an outbreak in Quebec that started in 2006 and has defoliated more than 5 million ha (National Forest Database 2019). Hennigar et al (2013) have shown that defoliation impacts continue well beyond the period of actual defoliation occurrence.

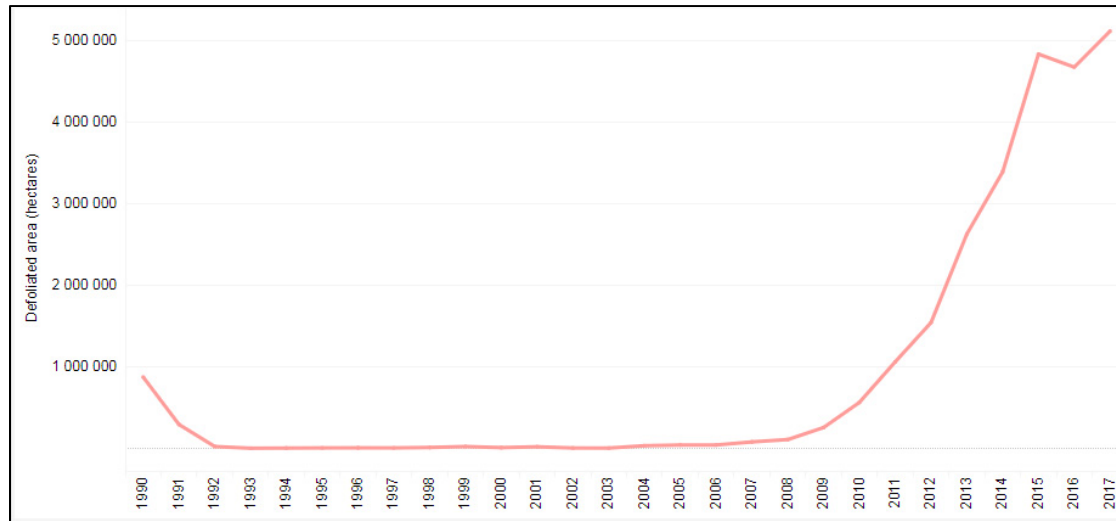


Figure 2.2 Area of moderate to severe defoliation by spruce budworm between 1990 and 2018 in Quebec, Canada.

Invasive species depreciate the value of wood in the forest which incurs losses for the owners and increases harvesting and production costs. However, the value of wood is not necessarily null. For example, dead trees can be used for producing pulp; however, the process needs much more infested wood to make 1 ton of newsprint, as well as more chemicals in the pulp-making process. Indeed, to remove stains in the wood from budworm and ensure an acceptable paper quality, the poor-quality fiber must be bleached, so the process is also more expensive than the process for normal trees. Furthermore, the harvesting cost per usable unit is higher because the companies are paying the same amount for lower wood volume with lower quality.

In this paper, we study a fir and spruce (host species for SBW) forest infested with SBW with a given wood volume that is constant during the planning horizon. Each level of infestation is given a particular wood quality and consequently a particular wood price. It is assumed that the wood price is constant during the planning horizon. The infestation level will be changed

based on the outbreak intensity of the year. To satisfy the industrial wood demand in each time period and prevent from a diminution in value of standing trees in the forest, we must determine where and when salvage harvesting should be applied. However, the harvested volume cannot be greater than the AAC, which is the annual volume of timber that can be harvested on a sustainable basis within a defined forest area (Bouchard et al. 2017). Salvage harvesting would incur costs in the value chain. It is assumed that salvage harvesting would remove 100% of the volume, (i.e., clear-cut) and there is no more tree in the harvested area for the rest of the planning horizon. The objective is to maximize the value obtained from the harvested volume and the value of remaining standing trees in the forest minus the logistic costs associated with harvesting and transportation.

2.3 Mathematical models

To address the stated planning problem, we propose a deterministic and a multistage stochastic programming model of SBW infestation in the forest. We first divide the forest into cells and further characterize the forest trees into seven levels based on their infestation level. Each cell can only have one infestation level. Infestation level 1 represents susceptible or healthy trees, Infestation level 7 represents the highest infestation level. Trees in each infestation level move to the next lowest or next infestation level or remain at the same level in the following periods based on the outbreak intensity.

We represent the temporal propagation of SBW infestation under different levels of outbreak intensity (low, medium, and high) as illustrated in Figure 2.3, in which numbers correspond to tree infestation levels (1 to 7). If the intensity of the outbreak is low, all infestation levels change to the next lowest infestation level except level 1, in other words, infestation levels 2-7 become levels 1-6 and there is no change in level 1. If the intensity is medium, none of the tree infestation levels change. Finally, if the intensity is high, all infestation levels change to the next infestation level except for the last level (i.e., stands with infestation level 7 stay in level 7).

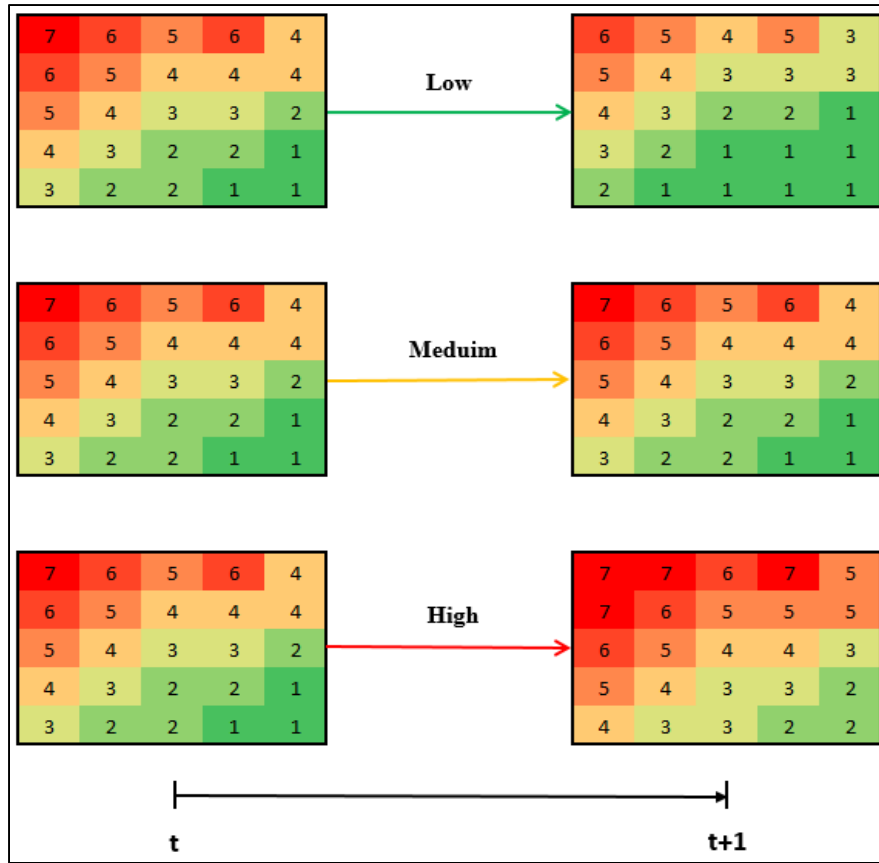


Figure 2.3 Spruce budworm infestation under different outbreak intensity levels (low, medium, and high). Numbers correspond to seven infestation levels; level 1 is the lowest infestation level, and level 7 is the highest.

To satisfy the demand required by forestry companies at each time period, some cells are harvested. It is assumed that each cell can be harvested only once during the planning horizon. We use the developed multistage stochastic programming model to analyze when and where salvage harvesting should be implemented considering the scenario with the same probability (low, medium and high).

Next, we develop a deterministic model in which all uncertainty is ignored. This model is then used as a basis to formulate the multistage stochastic programming model. This first deterministic model maximizes the total value (harvested wood and standing trees) obtained from the forest and finds the optimal harvesting decisions defining which stand should be

harvested and when it should be harvested based on the outbreak intensity level while considering constraints on wood inventory, demand, and forest sustainability.

2.3.1 Deterministic model

The notations of sets, parameters, and decision variables used in this model are as follows:

Sets and Indices:

- I Set of all cells in the forest ($i \in I$)
- P Set of all infestation levels ($p \in P$)
- T Set of all time periods ($t \in T$)

Parameters:

- m_p Market price of the wood in infestation level p
- m'_p Standing tree value in phase infestation level p , $m'_p \leq m_p$
- d_t Demand of wood from industry in time period t
- b Purchasing price of wood from market, $m_p \leq b$
- AAC Annual allowable cut
- I_{1ip} Initial inventory of wood available in cell i in infestation level p at the beginning of the planning horizon
- M a large number

Decision Variables:

$$X_{ti} = \begin{cases} 1, & \text{If cell } i \text{ is harvested during time period } t \\ 0, & \text{otherwise} \end{cases}$$

- I_{tip} Inventory of wood available in cell i , in infestation level p at the beginning of time period t
- L_{tip} Harvested volume from cell i , in infestation level p in time period t
- Z_t Volume of wood purchased from external market at time period t

A deterministic model is formulated in accordance with the outbreak intensity level shown in Figure 2.3. The objective function of this model is to maximize the total profit (revenue minus cost) obtained from harvesting and the value of standing trees in the forest while subtracting the cost incurred by buying wood from the market to satisfy the demand. We assume that the cost of harvesting is not affected by the infestation level; hence, the harvesting cost can be assumed as a constant. Therefore, the objective is formulated as

$$\begin{aligned}
 Z = & \sum_{t=1}^T \sum_{i=1}^I \sum_{p=1}^P m_p \times L_{tip} \\
 & + \sum_{i=1}^I \sum_{p=1}^P m'_p \times I_{(T+1)ip} \\
 & - \sum_{t=1}^T b \times Z_t
 \end{aligned} \tag{2.1}$$

Each cell can be harvested only once during the planning horizon.

$$\sum_{t=1}^T X_{ti} \leq 1, \quad \forall i = 1, \dots, I \tag{2.2}$$

As we assumed that there is only one level of infestation in each cell, there is only one level with wood volume in our data. For example, the structure of wood inventory for a cell in infestation level 4 is presented in Table 2.1.

Table 2.1 An example of the structure of the inventory for a cell in infestation level 4.

Infestation Class	1	2	3	4	5	6	7
Inventory in cell i	0	0	0	100	0	0	0

At each time period, the demand can be satisfied by harvested volume from the forest or by wood purchased from the external market.

$$\left(\sum_{i=1}^I X_{ti} \times \left[\sum_{p=1}^P I_{tip} \right] \right) + Z_t \geq d_t, \quad \forall t = 1, \dots, T \quad (2.3)$$

The harvested volume should not be greater than AAC in each time period.

$$\sum_{i=1}^I X_{ti} \times \left[\sum_{p=1}^P I_{tip} \right] \leq AAC, \quad \forall t = 1, \dots, T \quad (2.4)$$

The inventory of wood in infestation level p in each cell in the next time period is dependent on the harvesting decision and the outbreak intensity. Therefore, according to each outbreak intensity level, we represent specific balance control constraints. For example, when there is a low outbreak intensity in the forest, all infestation levels will go to the next lowest infestation level in the next period except for infestation level 1. So, in the next period, there is no infestation level 7 in the forest (See Figure 2.3).

$$I_{(t+1)i(p-1)} = (1 - X_{ti}) \times I_{tip}, \quad \forall i = 1, \dots, I, p = 3, \dots, P, t = 1, \dots, T \quad (2.5)$$

$$I_{(t+1)i1} = (1 - X_{ti}) \times (I_{ti1} + I_{ti2}), \quad \forall i = 1, \dots, I, t = 1, \dots, T \quad (2.6)$$

$$I_{tiP} = 0, \quad \forall i = 1, \dots, I, t = 2, \dots, T + 1 \quad (2.7)$$

Medium outbreak intensity in the forest does not change the state of the forest; therefore, we have

$$I_{(t+1)ip} = (1 - X_{ti}) \times I_{tip} \quad \forall i = 1, \dots, I, p = 1, \dots, P, t = 1, \dots, T \quad (2.8)$$

When there is a high outbreak intensity in the forest, all infestation levels will move up to the next infestation level in the next period except for level 7. Therefore, in the next time period, there is no infestation level 1 in the forest (see Figure 2.3), so we have

$$I_{(t+1)i(p+1)} = (1 - X_{ti}) \times I_{tip}, \quad \forall i = 1, \dots, I, p = 1, \dots, P - 2, t = 1, \dots, T \quad (2.9)$$

$$I_{(t+1)iP} = (1 - X_{ti}) \times (I_{ti(P-1)} + I_{tiP}), \quad \forall i = 1, \dots, I, t = 1, \dots, T \quad (2.10)$$

$$I_{ti1} = 0, \quad \forall i = 1, \dots, I, t = 2, \dots, T + 1 \quad (2.11)$$

Non-negativity constraints are as follows.

$$X_{ti} \in \{0,1\} \quad \forall i = 1, \dots, I, t = 1, \dots, T$$

$$I_{tip} \geq 0 \quad \forall i = 1, \dots, I, p = 1, \dots, P, t = 1, \dots, T$$

$$L_{tip} \geq 0 \quad \forall i = 1, \dots, I, p = 1, \dots, P, t = 1, \dots, T$$

$$Z_t \geq 0 \quad \forall t = 1, \dots, T$$

The beginning of the planning horizon is at $T = 1$, and the first decision is made at this moment.

2.3.2 Multistage stochastic programming model

To include uncertainty through multiple scenarios, we formulate a multistage stochastic programming model. The uncertainty in this model is outbreak intensity in the forest within

each period t . The outbreak intensity level can change the infestation levels and consequently change the quality and value of the wood in the following periods.

We develop a scenario tree to represent the harvesting decisions and stochastic spread over time. Figure 2.4 represents nine possible scenarios over two planning periods. Node 0 (root node) represents the first decision stage. It is associated with the initial absence of observations. The scenario tree divides into branches corresponding to different realizations of the random outbreak intensity. Node L, M, and H show the state of the forest under low, medium, and high outbreak intensity throughout the forest, respectively. Figure 2.5 shows how the forest will change under a specific level of intensity. For example, the infestation level 4 (in the top right corner of the initial forest state in Figure 2.5) moves to the next lowest level, (i.e., level 3). However, if there is a high outbreak intensity throughout the forest, the infestation level will move to next phase (i.e., level 5). Finally, if there is a moderate outbreak intensity, there is no change in the infestation level, and it remains in level 4.

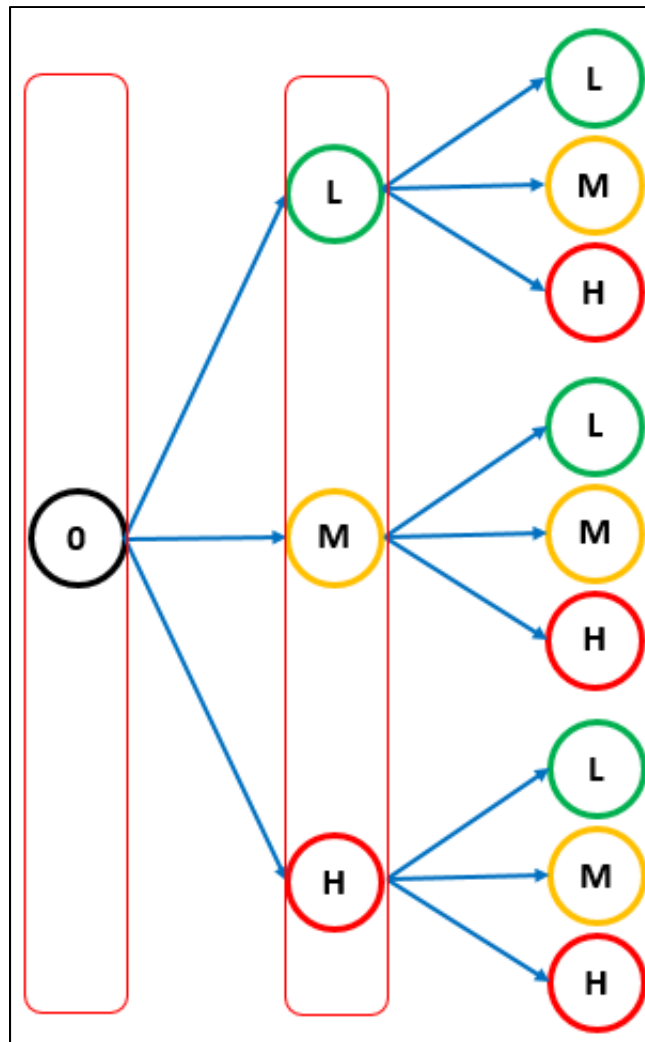


Figure 2.4 Scenario tree over two planning periods. Node 0 (root node) represents the first decision stage; nodes L, M, and H represent low, medium, and high outbreak intensity, respectively.

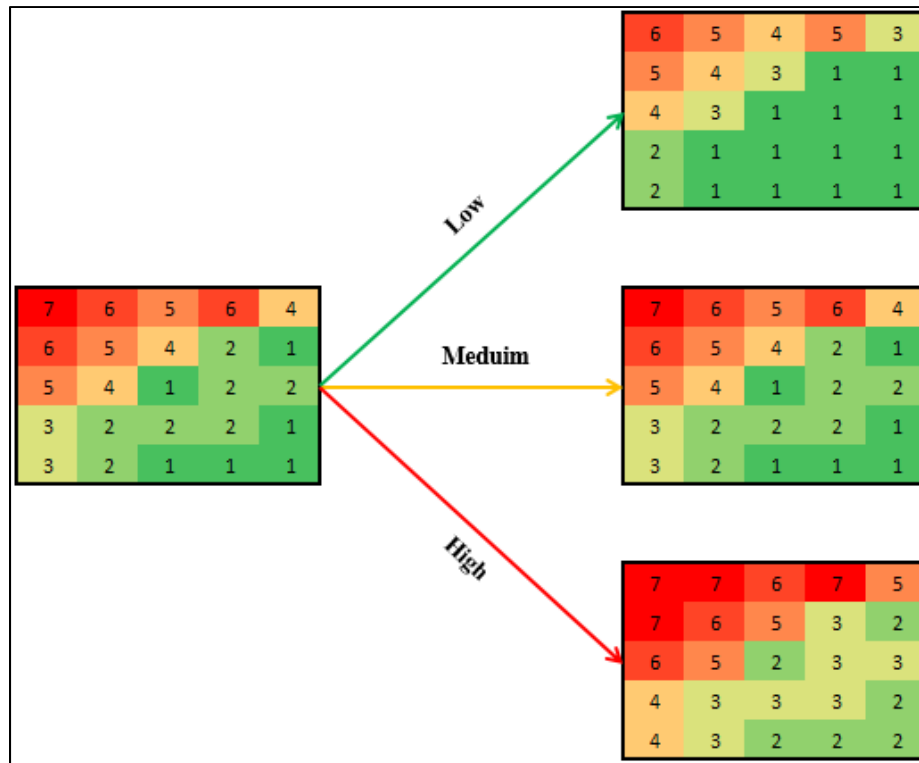


Figure 2.5 State of the forest under different outbreak intensity levels (low, medium, and high). Numbers correspond to seven infestation levels; level 1 is the lowest infestation level, and level 7 is the highest.

The notations of sets, parameters, and decision variables used in this model are presented in the List of symbols.

Sets and Indices:

S Set of all scenarios in scenario tree ($s \in S$)

Parameters:

S Number of scenarios

I_{1ip} Initial inventory of wood available in cell i , in infestation level p at the beginning of the planning horizon

π_s Probability for scenario s

Binary Decision Parameters in the Discrete Scenario Tree:

a_{stp} If the inventory of wood in infestation level p in time t under scenario s goes to the next phase of infestation in next time period

b_{stp} If the inventory of wood in infestation level p in time t under scenario s stays at the same phase of infestation in next time period

c_{stp} If the inventory of wood in infestation level p in time t under scenario s goes to the next lowest phase of infestation in next time period

Decision Variables:

$$X_{sti} = \begin{cases} 1, & \text{If cell } i \text{ is harvested during time period } t \text{ under scenario } s \\ 0, & \text{otherwise} \end{cases}$$

I_{stip} Inventory of wood available in cell i , in infestation level p at the beginning of time period t under scenario s

L_{stip} Harvested volume from cell i , in infestation level p in time period t under scenario s

Z_{st} Volume of wood which should be purchased from markets at time period t under scenario s

With the decision variables defined, we can formulate a mathematical program to maximize the expected total profit obtained from the harvesting process and the value of standing trees in the forest while subtracting the expected cost of buying wood from the market to satisfy the demand by considering all scenarios.

$$Z = \sum_{s=1}^S \pi_s Z_s \quad (2.12)$$

$$\begin{aligned}
Z_s = & \sum_{t=1}^T \sum_{i=1}^I \sum_{p=1}^P m_p \times L_{stip} \\
& + \sum_{i=1}^I \sum_{p=1}^P m'_p \times I_{s(T+1)ip} \\
& - \sum_{t=1}^T b \times Z_{st}
\end{aligned} \tag{2.13}$$

Each cell can be harvested only once during the planning horizon.

$$\sum_{t=1}^T X_{sti} \leq 1, \quad \forall i = 1, \dots, I, s = 1, \dots, S \tag{2.14}$$

At each time period, the demand should be satisfied by harvested volume from the forest or by wood supplied by the market.

$$\left(\sum_{i=1}^I \sum_{j=1}^J X_{sti} \times \left[\sum_{p=1}^P I_{stip} \right] \right) + Z_{st} \geq d_t, \quad \forall t = 1, \dots, T, s = 1, \dots, S \tag{2.15}$$

The harvested volume should not be greater than AAC in each period.

$$\sum_{i=1}^I \sum_{j=1}^J X_{sti} \times \left[\sum_{p=1}^P I_{stip} \right] \leq AAC, \quad \forall t = 1, \dots, T, s = 1, \dots, S \tag{2.16}$$

To control the flow of inventory of the wood in the forest, we use the (2.17) to (2.19):

$$\begin{aligned}
I_{s(t+1)i1} = & (1 - X_{sti}) \times (a_{st1} \times 0 + b_{st1} I_{sti1} + c_{st1} I_{sti2}), \\
& \forall i = 1, \dots, I, t = 1, \dots, T, s = 1, \dots, S
\end{aligned} \tag{2.17}$$

$$I_{s(t+1)ip} = (1 - X_{sti}) \times (a_{stp}I_{sti(p-1)} + b_{stp}I_{stip} + c_{stp}I_{sti(p+1)}), \quad (2.18)$$

$$\forall i = 1, \dots, I, p = 2, \dots, P - 1, t = 1, \dots, T, s = 1, \dots, S$$

$$I_{s(t+1)iP} = (1 - X_{sti}) \times (a_{stP}I_{sti(P-1)} + b_{stP}I_{stip} + c_{stP} \times 0), \quad (2.19)$$

$$\forall i = 1, \dots, I, t = 1, \dots, T, s = 1, \dots, S$$

The following constraints (2.20) to (2.23) represent the nonanticipative constraints ensuring that the scenarios with the same past will have identical decisions up to that period.

$$X_{sti} = X_{s'ti}, \quad \text{For all scenarios } s \text{ and } s' \text{ with identical past up to time } t \quad (2.20)$$

$$I_{stip} = I_{s'tip}, \quad \text{For all scenarios } s \text{ and } s' \text{ with identical past up to time } t \quad (2.21)$$

$$L_{stip} = L_{s'tip}, \quad \text{For all scenarios } s \text{ and } s' \text{ with identical past up to time } t \quad (2.22)$$

$$Z_{st} = Z_{s't}, \quad \text{For all scenarios } s \text{ and } s' \text{ with identical past up to time } t \quad (2.23)$$

Nonnegativity constraints are as follows.

$$X_{sti} \in \{0,1\} \quad \forall i = 1, \dots, I, t = 1, \dots, T, s = 1, \dots, S$$

$$I_{stip} \geq 0 \quad \forall i = 1, \dots, I, p = 1, \dots, P, t = 1, \dots, T + 1, s = 1, \dots, S$$

$$L_{stip} \geq 0 \quad \forall i = 1, \dots, I, p = 1, \dots, P, t = 1, \dots, T, s = 1, \dots, S$$

$$Z_{st} \geq 0 \quad \forall t = 1, \dots, T, s = 1, \dots, S$$

There are several constraints that are nonlinear in the above models. It is, however, possible to use a straight-forward approach and linearize these constraints. Instead of rewriting the entire models, the resulting linearizations are provided in Appendices I and II. These are the models used in all experiments.

2.4 Case study

In this section, we use an illustrative example, which will be the basis of the instances. The study area, suggested by a forest researcher at Ministère des Forêts, de la Faune et des Parcs (MFFP), is Côte-Nord located in the north of Quebec and is a well-known area for wood infestation with SBW. The forest is divided into 81 cells ($9 \text{ cells} \times 9 \text{ cells}$). Bouchard and Auger (2014) used a cell size of $15 \text{ km} \times 15 \text{ km}$ in their study, which is relatively close to the cell sizes used in similar analyses of SBW defoliation surveys. Therefore, in our paper, the cell size is assumed to be $15 \text{ km} \times 15 \text{ km}$ ($225 \text{ km}^2 = 22\,500 \text{ ha}$). An ordered pair shows the cell number and wood volume in each cell (See Figure 2.6). The generated wood volume was based on 230 random sample of stands in the area. The data are normalized and wood volume is generated using a continuous uniform distribution on the interval between the maximum and minimum normalized volumes ($[0.5, 0.87]$) obtained on the basis of samples from Government of Quebec (2019). One of the assumptions is that there is only one infestation level per cell. To have a realistic distribution of infestation throughout the forest, we use the volume percentage in a phase of infestation data in Zhu Chen et al. (2017) to generate an instance. According to the data, it is assumed that 54%, 6%, 14%, 7%, 8%, 6%, and 5% of the cells have infestation levels of 1, 2, 3, 4, 5, 6, and 7, respectively (See Figure 2.7). The volume percentage data in different phase of infestation are from FPIinnovations, which is a private, not-for-profit organization.

(1, 0.69)	(2, 0.60)	(3, 0.78)	(4, 0.78)	(5, 0.76)	(6, 0.65)	(7, 0.79)	(8, 0.85)	(9, 0.52)
(10, 0.63)	(11, 0.78)	(12, 0.71)	(13, 0.61)	(14, 0.73)	(15, 0.60)	(16, 0.80)	(17, 0.86)	(18, 0.58)
(19, 0.86)	(20, 0.69)	(21, 0.86)	(22, 0.50)	(23, 0.53)	(24, 0.79)	(25, 0.51)	(26, 0.64)	(27, 0.85)
(28, 0.64)	(29, 0.55)	(30, 0.73)	(31, 0.65)	(32, 0.62)	(33, 0.57)	(34, 0.71)	(35, 0.66)	(36, 0.59)
(37, 0.64)	(38, 0.84)	(39, 0.73)	(40, 0.53)	(41, 0.75)	(42, 0.80)	(43, 0.70)	(44, 0.65)	(45, 0.68)
(46, 0.67)	(47, 0.64)	(48, 0.52)	(49, 0.86)	(50, 0.64)	(51, 0.68)	(52, 0.67)	(53, 0.73)	(54, 0.55)
(55, 0.74)	(56, 0.64)	(57, 0.79)	(58, 0.77)	(59, 0.80)	(60, 0.57)	(61, 0.53)	(62, 0.54)	(63, 0.69)
(64, 0.70)	(65, 0.53)	(66, 0.75)	(67, 0.63)	(68, 0.76)	(69, 0.69)	(70, 0.78)	(71, 0.67)	(72, 0.57)
(73, 0.53)	(74, 0.56)	(75, 0.53)	(76, 0.60)	(77, 0.77)	(78, 0.74)	(79, 0.53)	(80, 0.61)	(81, 0.60)

Figure 2.6 Cell number and unit wood volumes throughout the forest. The first value in each ordered pair is the forest cell number (1-81), and the second value is the unit wood volume.

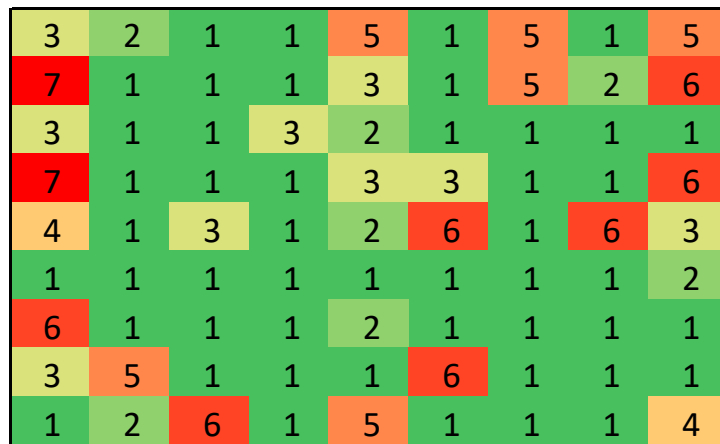


Figure 2.7 Infestation levels of the 81 forest stands

Generally, silvicultural treatment cost like harvesting also depends on different parameters such as the method of harvesting, building an access road, age, and wood volume. So, in

accordance with our discussion with experts, we assumed a mean value ($35 \frac{\$}{m^3}$) for harvesting. Table 2.2 represents the unit price of the harvested volume and standing trees in accordance with the infestation level per unit volume. Harvesting cost, on average, accounts for the difference between the price of harvested wood and the value of the standing tree in Table 2.2. Obtaining the realistic value for the price is challenging because the price of the wood is defined by various parameters such as age, diameter, length, moisture, and quality based on the infestation level. So, it is assumed that the market price of wood is 200 unit price per unit volume. Demand and AAC are considered as 1% and 8% of the total wood volume in the forest, respectively. There is a 4-year planning horizon with four decision-making stages and at each stage there are three outbreak intensity levels. Consequently, there are 81 (3^4) scenarios for the outbreak intensity. For simplicity, we assume that the probability of change in the outbreak intensity is equal.

Table 2.2 Unit price (CAN\$. m^{-3}) of harvested wood and standing trees according to the infestation level (1-7)

Infestation Wood type	1	2	3	4	5	6	7
Harvested wood	150	120	95	75	60	50	45
Value of standing tree	115	85	60	40	25	15	10

Based on the illustrative example, we have generated a set of instances. These are outlined in Table 2.3, and they have different planning horizon (2, 3, and 4 periods) and landscape sizes (5 cells \times 5 cells, 10 cells \times 10 cells, 15 cells \times 15 cells, and 20 cells \times 20 cells), respectively.

Table 2.3 Instances generated based on the case study, with different sizes and number of time periods

Instance	Size	No. of Periods
I1	5×5	2
I2	5×5	3
I3	5×5	4
I4	10×10	2
I5	10×10	3
I6	10×10	4
I7	15×15	2
I8	15×15	3
I9	15×15	4
I10	20×20	2
I11	20×20	3
I12	20×20	4

2.5 Results and discussion

The multistage stochastic optimization models were solved using CPLEX 12.8 (IBM, Armonk, N.Y., USA) on a desktop computer with an Intel Core i7 CPU processor and 64.0 GB of memory. A time limitation of 24 hours with 1% gap limit was imposed for solving the instances.

We start to describe results with the illustrative example. It is solved with both deterministic and multistage stochastic programming model. The deterministic model was solved with low, medium, and high outbreak intensity levels, respectively. The optimal salvage harvesting decisions and objective values are given in Table 2.4.

Table 2.4 Deterministic solution for three outbreak intensity levels

Intensity of Outbreak	X (Cell numbers harvested in each period)								Objective Value (Unite price)
	Period 1	Volume	Period 2	Volume	Period 3	Volume	Period 4	Volume	
Low	8, 25, 26, 27, 35, 49	4.397	2, 23, 24, 46, 56, 72, 74	4.395	3, 29, 32, 34, 60, 76, 79	4.395	1, 20, 33, 43, 48, 50, 54	4.396	6727.32
Medium	1, 7, 9, 18, 34, 48, 74	4.394	10, 21, 33, 44, 62, 65, 72	4.395	13, 15, 17, 25, 39, 73, 79	4.396	12, 22, 23, 45, 57, 75, 80	4.394	5391.08
High	21, 26, 49, 57, 67, 76	4.397	20, 25, 29, 35, 38, 40, 72	4.396	12, 27, 30, 34, 43, 71	4.397	11, 15, 46, 47, 73, 79, 80	4.396	2560.06

The optimal solution was very sensitive to the outbreak intensity. The overall net profit for the illustrative example ranged from \$2560 to \$6727. Figure 2.8 illustrates the harvesting decisions and the state of the forest in each period under different outbreak intensity levels (low, medium, and high) and consequently the state of the forest at the end of the planning horizon (time period 5). The first row of grids in Figure 2.8 illustrates the low outbreak intensity, in which it was assumed that the outbreak intensity was low. Harvesting decisions show that infestation level 1 takes priority over all other levels because it is known that the other infestation levels (2-7) will transition to the next lowest level in the next time period, which indicates appreciation in the value of wood in these levels, whereas there is no improvement in the value of wood for level 1, which has the maximum value. Therefore, a combination of cells in level 1 were chosen to be harvested while satisfying the demand and sustainable forest constraints. Sometimes, to comply with the AAC constraint, it is not possible to choose only from level 1 to satisfy all the constraints, so a cell of lower priority must be harvested. Under severe outbreak, in which it is assumed that there is a high outbreak intensity in each time period, the harvesting priority is the same as that of the light outbreak intensity (level 1 is the first priority because it has the most valuable woods); however, if the stands are not harvested, they will go to the next phase of infestation and there is a depreciation in their values. Severely infested stands have low priority and are harvested at the end if they are needed. Therefore, the harvesting policy is the same under low and high outbreak intensity with difference in the interpretation, whereas there is no specific policy for harvesting when the outbreak intensity is medium because it is assumed that there is no change in the infestation levels and consequently

there is no change in the value of the wood. Therefore, cells were chosen for harvesting to satisfy the demand and sustainable forest constraints.

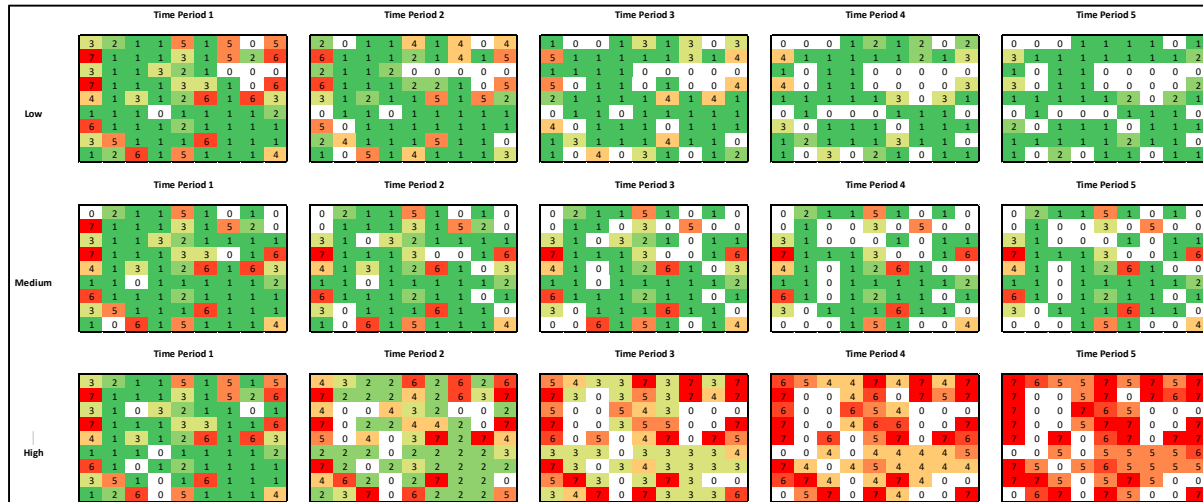


Figure 2.8 States of the forest and decisions under different outbreak intensity levels from the deterministic model. Level 0 indicates that the cell is harvested

Table 2.5 represents the multistage stochastic programming solution (harvesting decisions) for 81 scenarios during the 4-year planning horizon. The results illustrate that the solutions vary depending on the scenario and there is no single solution that fits all circumstances. At the beginning of the planning horizon, we did not have any information about the intensity of the outbreak which will occur. Therefore, we decided to cut cells 20, 61, 68, 71, 73, 76, and 79 to satisfy the industry demand. Then, according to the outbreak intensity occurred during the first period (state of the forest at the beginning of the second period), we made the harvesting decisions for the second period. For instance, if there was a high outbreak intensity in period one, we cut 13, 24, 27, 30, 31, and 43 in the second period, and if there is a low outbreak, we harvested cells 13, 31, 46, 51, 52, and 66; otherwise, we cut 6, 11, 13, 27, 43, and 46 in the second period. Therefore, the decisions for each period were affected by the observed information during the previous period. The objective value obtained under each scenario and the mean objective function of all scenarios are shown in Table 2.6.

Table 2.5 Optimal solution with the four-period stochastic program

Period, Scenario	Harvesting decisions	Period, Scenario	Harvesting decisions
1, 1-81	20, 61, 68, 71, 73, 76, 79	4, 22-24	6, 11, 24, 27, 30, 62
2, 1-27	13, 31, 46, 51, 52, 66	4, 25-27	6, 11, 24, 27, 30, 62
2, 28-54	6, 11, 13, 27, 43, 46	4, 28-30	24, 38, 49, 51, 80
2, 55-81	13, 24, 27, 30, 31, 43	4, 31-33	24, 30, 38, 49, 51
3, 1-9	6, 43, 49, 56, 58, 62	4, 34-36	24, 30, 38, 49, 51
3, 10-18	6, 43, 49, 56, 58, 62	4, 37-39	24, 30, 31, 38, 49
3, 19-27	38, 43, 49, 56, 58	4, 40-42	24, 30, 31, 38, 49
3, 28-36	31, 52, 56, 58, 62, 66	4, 43-45	24, 30, 31, 38, 49
3, 37-45	51, 52, 56, 58, 62, 66	4, 46-48	24, 30, 31, 38, 49
3, 46-54	51, 52, 56, 58, 62, 66	4, 49-51	24, 30, 31, 38, 49
3, 55-63	6, 52, 56, 58, 66, 80	4, 52-54	24, 30, 31, 38, 49
3, 64-72	6, 52, 56, 58, 66, 80	4, 55-57	11, 38, 46, 49, 51, 62
3, 73-81	11, 49, 58, 62, 66, 80	4, 58-60	11, 38, 46, 49, 51, 62
4, 1-3	11, 24, 27, 30, 38	4, 61-63	11, 38, 46, 49, 51, 62
4, 4-6	11, 24, 27, 30, 38	4, 64-66	11, 38, 46, 49, 51, 62
4, 7-9	11, 24, 27, 30, 38	4, 67-69	11, 38, 46, 49, 51, 62
4, 10-12	11, 24, 27, 30, 38	4, 70-72	11, 38, 46, 49, 51, 62
4, 13-15	11, 24, 27, 30, 38	4, 73-75	6, 38, 46, 51, 52, 56
4, 16-18	11, 24, 27, 30, 38	4, 76-78	6, 38, 46, 51, 52, 56
4, 19-21	6, 11, 24, 27, 30, 62	4, 79-81	6, 38, 46, 51, 52, 56

Table 2.6 The objective values obtained under each scenario

Scenario	Objective Value (Unit price)	Scenario	Objective Value (Unit price)	Scenario	Objective Value (Unit price)
1	6690.25	28	6410.70	55	6049.49
2	6423.34	29	6156.76	56	5677.36
3	5369.45	30	5159.60	57	4758.59
4	6431.66	31	6156.76	58	5677.36
5	6177.72	32	5791.05	59	5249.20
6	5187.69	33	4878.70	60	4438.72
7	6046.34	34	5671.68	61	5126.14
8	5049.18	35	4757.52	62	4315.66
9	4242.07	36	4033.14	63	3695.23
10	6423.34	37	6163.06	64	5545.65
11	6169.40	38	5797.35	65	5117.49
12	5172.24	39	4890.41	66	4307.01
13	6173.38	40	5791.05	67	4994.43
14	5807.67	41	5369.31	68	4183.95
15	4898.73	42	4565.24	69	3563.52
16	5694.23	43	5260.23	70	4117.89
17	4771.16	44	4446.40	71	3470.20
18	4037.74	45	3822.01	72	3011.24
19	6037.69	46	5672.17	73	4943.73
20	5671.98	47	5244.01	74	4103.65
21	4759.63	48	4433.53	75	3453.64
22	5548.92	49	5120.95	76	4001.17
23	4636.57	50	4310.47	77	3351.21
24	3914.27	51	3690.04	78	2891.30
25	4554.79	52	4244.41	79	3319.64

Scenario	Objective Value (Unit price)	Scenario	Objective Value (Unit price)	Scenario	Objective Value (Unit price)
26	3819.71	53	3596.72	80	2809.26
27	3273.54	54	3137.76	81	2488.92
Average of Objective Value (Unit price)					
4842.96					

Comparison between the deterministic model and the stochastic model was measured on the Value of the Stochastic Solution (VSS) (Birge and Louveaux 1997). Normally, the VSS measures the importance of using a stochastic model and considering uncertainty in planning. VSS represents the goodness of the expected solution value when expected values are replaced by random values. VSS is defined as $VSS = RP - EEV$, where RP is the result of here-and-now (or recourse problem) solution and EEV is the result of the expected value problem solution. To obtain the EEV, we first found the expectation of uncertainty realizations in each stage, which was, in this case, the medium outbreak intensity, and then solve the deterministic model, which is called the EV problem, to get the optimal decision variables. The optimal deterministic harvesting decisions are shown in Table 2.4. Then, we applied this policy (fixing the harvesting decisions) in each period and evaluated the EV problem solution across all scenarios while observing the random intensity level. In other words, we knew the value of random decision variables and then applied them to each scenario one by one to find the objective value. Finally, as we obtained the objective values for all scenarios, we calculated the expectation of the objective values. In this case, we calculated 4723.66; however, the multistage stochastic solution gave 4842.96 (see Table 2.6), so

$$VSS = 4842.96 - 4723.66 = 119.30 \quad (2.24)$$

Consequently, the loss by not considering the random variation is a unit price of 119.30. In other words, 119.30 or 2.53% is the possible gain from solving the stochastic model and consider uncertainty when the decision-maker is planning forest harvesting activities dealing

with SBW. This 2.53% saving, when applied to a large-scale problem, can be equivalent to millions of dollars at the regional and the national level where forest industry is an important key player.

Table 2.7 gives the comparison of computational performance of the instances in Table 2.3 of the multistage stochastic optimization model. In most instances, the solution gaps are much tighter than the imposed limits. We found that the mean computational solution time increases as the size of the problem increases temporally and spatially. Note that because of the complexity and size of the model, four-period instances with landscape sizes 25 cells \times 25 cells and larger were not solvable (memory excess problems) and required a much more advanced computer and more memory. Therefore, only the results for instances from 5 cells \times 5 to 20 cells \times 20 for three different planning horizons (2, 3, and 4) are presented in Table 2.7.

Table 2.7 Comparison of performances of instances with different sizes of the multistage model

Instance	No. of Periods	AAC	Gap (%)	CPU Time (s)	Constraints	Variables	Binary Variables
I1	2	6%	0.61%	4	24,600	8,343	450
I1	2	7%	0.06%	4	24,600	8,343	450
I1	2	8%	0.04%	4	24,600	8,343	450
I2	3	6%	0.30%	10	111,630	35,181	2,025
I2	3	7%	0.75%	11	111,630	35,181	2,025
I2	3	8%	0.36%	11	111,630	35,181	2,025
I3	4	6%	0.52%	41	449,832	135,999	8,100
I3	4	7%	0.85%	40	449,832	135,999	8,100
I3	4	8%	0.70%	43	449,832	135,999	8,100
I4	2	6%	0.00%	12	98,250	33,318	1,800
I4	2	7%	0.05%	10	98,250	33,318	1,800
I4	2	8%	0.99%	11	98,250	33,318	1,800
I5	3	6%	0.31%	40	445,830	140,481	8,100

Instance	No. of Periods	AAC	Gap (%)	CPU Time (s)	Constraints	Variables	Binary Variables
I5	3	7%	0.49%	40	445,830	140,481	8,100
I5	3	8%	0.34%	39	445,830	140,481	8,100
I6	4	6%	0.48%	271	1,796,532	543,024	32,400
I6	4	7%	0.46%	255	1,796,532	543,024	32,400
I6	4	8%	0.68%	217	1,796,532	543,024	32,400
I7	2	6%	0.00%	24	221,000	74,943	4,050
I7	2	7%	0.30%	19	221,000	74,943	4,050
I7	2	8%	0.10%	20	221,000	74,943	4,050
I8	3	6%	0.25%	95	1,002,830	315,981	18,225
I8	3	7%	0.57%	94	1,002,830	315,981	18,225
I8	3	8%	0.23%	97	1,002,830	315,981	18,225
I9	4	6%	0.38%	1,159	4,041,032	1,221,399	72,900
I9	4	7%	0.58%	615	4,041,032	1,221,399	72,900
I9	4	8%	0.33%	635	4,041,032	1,221,399	72,900
I10	2	6%	0.00%	36	392,850	133,218	7,200
I10	2	7%	0.01%	41	392,850	133,218	7,200
I10	2	8%	0.04%	32	392,850	133,218	7,200
I11	3	6%	0.19%	229	1,782,630	561,681	32,400
I11	3	7%	0.44%	239	1,782,630	561,681	32,400
I11	3	8%	0.35%	203	1,782,630	561,681	32,400
I12	4	6%	0.09%	4,342	7,183,332	2,171,124	129,600
I12	4	7%	0.10%	3,405	7,183,332	2,171,124	129,600
I12	4	8%	0.92%	4,625	7,183,332	2,171,124	129,600

2.6 Concluding remarks

In this paper, we have proposed a linear multistage stochastic programming model to determine the harvesting decisions considering a forest with SBW outbreak. The uncertainty dealt is related to the SBW intensity. The model is novel and includes the volume to be harvested depending on the infestation level. This is enabled through a linearization approach of an underlying nonlinear model. The proposed approach is applied to maximize the net profit from the harvesting and to have a higher quality forest at the end of the planning horizon. Our numerical results indicate that the stochastic programming model is an efficient approach to solve this type of uncertainty problems. As the problem size increases spatially and temporarily, the number of constraints and variable increase exponentially. However, the size of the problem solved can represent actual cases in which the forest is divided into large areas. This is often the case, as planning with SBW areas typically is aggregated. Our results provides a simple rule for harvesting decisions to maximize the profit: the lower the infestation level is in each cell, the higher priority it harvesting priority is.

There were some limitations in our study with the first being wood pricing. There are different agents defining the value or price of the wood, particularly diameter, length, and moisture. Changes in every agent change the quality of the wood and consequently the wood value. Obtaining such data is difficult, even for an expert (based on our experience). The second limitation in our study was harvesting cost. Harvesting cost can vary based on harvesting method, building of an access road, age and volume of the tree. In this case, we assumed a mean value for harvesting cost. The third limitation was finding the probability of change in the outbreak intensity. It is obvious that outbreak intensity changes over time, but it was difficult to find data to derive the probability of change in the outbreak intensity.

Future research should consider the characteristics and properties that are even more realistic. Using a transition matrix like Zhu Chen et al. (2017) used and biological models to model the spread instead of three outbreak intensity levels as an uncertain parameter are avenues for future research to explore. Furthermore, the interaction of spread depending on the infestation

of adjacent cells and the spread of the SBW through the forest are also of interest. The impacts of insects on forest carbon dynamics can also be considered.

2.7 Acknowledgement

We are grateful for the financial support from the FORAC Research Consortium at Université Laval (Québec, Canada).

CHAPTER 3

THE INTEGRATION OF SPRAYING AND HARVESTING PLANNING TO MINIMIZE WOOD LOSSES DURING AN OUTBREAK OF SPRUCE BUDWORM

Siamak Mushakhian^a, Mustapha Ouhimmou^b, Mikael Rönnqvist^c, Julion Montecinos^d

^{a,b,d} Department of Systems Engineering, École de technologie supérieure, Suite A-3586, 1100 Notre-Dame St. W., Montreal H3C 1K3, Canada

^c Department of mechanical Engineering, Université Laval, Suite 1504, 1065 avenue de la Médecine, Pavillon Adrien-Pouliot, Quebec City G1V 0A6, Canada

Paper submitted for publication, October 2020

Abstract

Spruce budworm (*Choristoneura fumiferana*) outbreak is a well-known major natural disturbance in Eastern Canada. It is the most destructive insect in North America's conifer stands. Wood supply reduction and log quality degradations are key direct impacts of insect outbreaks. There are different control methods to protect forests against insects and diseases. Silvicultural control methods such as salvage harvesting and pre-emptive harvesting are used to mitigate these impacts and to satisfy the forestry companies' demand. Chemical methods like spraying biological insecticide (*Bacillus thuringiensis* ssp. *kurstaki*) are used to maintain trees alive during large-scale infestation for later harvest. The estimation of wood volume for each stand is continuously updated based on its characteristics, history of the defoliation, and whether it has been sprayed or not. This study proposes a deterministic optimization model addressing the questions of where and when forest stands should be harvested or sprayed to maximize revenues of harvested wood during the planning horizon and the value of standing trees at the end of the planning horizon minus the logistic and forest protection costs while satisfying industry demand for wood. The results from a case study in the Bas-Saint-Laurent region in the province of Quebec show that harvesting is highly beneficial to save wood volume and higher levels of harvesting lead to higher net profit from harvested wood and higher value from standing trees. Furthermore, spraying is an effective way to control the spruce budworm outbreak but the marginal spraying cost per saved volume unit is increasing exponentially. The results also show that it is possible to characterize the potential defoliated stands for harvesting

and spraying by feature attributes and defoliation history. For example, when balsam fir (*Abies balsamea*) and white spruce (*Picea glauca*) constitute more than 70% of the stand volume, these stands have top priority for harvesting. In addition, stands in which the proportion of volume to the area is more than 30 get the priority for spraying.

Keywords: Harvesting, defoliation, spruce budworm, wood loss, spraying

3.1 Introduction

Governments, industries, and private forest owners incur billions of dollars by the cost of damage of invasive species (Aukema et al. 2011). Over the years Canada incurred billions of dollars by timber losses, prevention and control costs, and environmental mitigation efforts. Reduction in the wood supply is the greatest direct economic impact of insect outbreaks which cost forest companies heavily (Natural Resources Canada 2017).

We consider the problem to plan the logistics actions when an area has been affected by spruce budworm (*Choristoneura fumiferana*). Today, there are a few models and methods that accurately can describe how the spruce budworm (SBW) outbreak affects the forest. We aim to develop more accurate models to recover as much of the forest value as possible.

At a rough estimate, annual timber harvest volume losses from forest insect outbreaks are about half the annual harvest level in Canada (MacLean 2004). Uncontrolled moderate or severe budworm outbreaks can reduce the timber harvest supply between 29 and 43 million m^3 from 2017 to 2067 (Liu et al. 2019). Therefore, one of the main challenges for forestry companies is to ensure that they have access to reliable sources of wood and fiber (quantity and quality). Invasive species, on the one hand, depreciate the value of wood in the forest which generates losses for the owners and on the other hand, increase harvesting and production costs. For example, recently dead trees can be used for producing pulp; however, the process needs more infested wood (as compared to standard quality wood) to make one ton of newsprint plus adding more expensive chemicals in the pulp making process.

Spruce budworm is the most destructive defoliator in North America. In the 1970s, the spruce budworm outbreak peaked at 52 million hectares in Northeastern Ontario, Western Quebec, central New Brunswick, and Maine (Kettela 1983). Their main hosts are balsam fir (*Abies balsamea*) (BF) and white spruce (*Picea glauca*) (WS) and to a lesser extent red spruce (*Picea rubens*) and black spruce (*Picea mariana*) (Natural Resources Canada 2020). Repeated defoliation by spruce budworm leads to large-scale mortality, reduction of growth rate, and reduced lumber quality (Government of British Columbia 2015). It can also change the future age-class structure and productivity (MacLean 2019). The spruce budworm outbreak has repercussions for the whole forest industry such as wood supply reduction, higher cost of timber supply, shortage of high-quality sawlogs, more low-grade woods, higher risk of forest fires, sawmill shutdowns or layoffs, and job loss. For example, in 2014, the lack of lumber supply because of spruce budworm infestation was a factor for Resolute Forest Company to shut down two mills in Quebec (Resolute Forest Products 2014).

The absence of forest protection against insects and diseases leads to high economic and environmental damages. For example, during the severe spruce budworm outbreak in the 1970s-1980s in Nova Scotia, the decision about not using insecticide as a control method led to an average of 87% mortality in mature balsam fir stands (MacLean and Ostaff 1989). There are different techniques ranging from preventative and silvicultural measures to the use of physical, behavioral, chemical, biological control methods to manage pests effectively, economically, and environmentally (Government of British Columbia 2016). Removing trees, applying chemical treatments, and employing biological control (like the use of other living organisms to stop the invasive species) are control measures to mitigate the economic and environmental damages (Hof 1998; Blackwood 2010; Büyüktaktın et al. 2011; Epanchin-Niell and Wilen 2012; Kovac 2014). Spraying registered insecticides, salvage harvesting, removing susceptible stands, or reducing future susceptibility by planting or thinning are various forest protection tactics to deal with spruce budworm outbreaks (Hennigar et al. 2013). Monitoring and early detection can help reduce losses in areas where the outbreak might spread (Boulanger et al. 2017). The other possible management techniques called early intervention

strategy including detecting and controlling the hotspots along the leading edge of an outbreak (Johns et al. 2019).

Since 1952 varying degrees of insecticide have been applied in forests as forest protection programs aimed at reducing tree mortality caused by spruce budworm defoliation (Kettela 1975). Between 1970 and 1983, in New Brunswick, on average two million hectares of forest was sprayed each year at an average annual cost of \$7.7 million (this represents $7.7 \times 6.61 = \$50.9$ million in the value of today by taking into account the inflation) (to spray the same area the estimated cost would be between \$90 to \$160 million today) per year to prevent extensive tree mortality (Forest Protection Limited 1993). Marshall (1975) stated that the benefits of spraying exceed total operating costs. The spraying cost had a relatively low cost at that moment. A total of 3.9 million acres out of 15 million acres was sprayed at the total operating cost of \$3.2 million. Application of intensive protection measures would lead to the highest amount of volume saved and net present value (Slaney et al. 2010). The main purpose of insecticide application is to keep 50% or more of current foliage on trees to reduce timber losses during the outbreak (Carisey et al. 2004, Fuentealba et al. 2015). Dupont et al. (2017) showed that the more intensive spraying strategy is applied, the lower tree mortality will be in the forest; however, all intervention strategies have prevented and delayed tree mortality. In northern New Brunswick, treated areas with low but increasing spruce budworm population did not need any treatment in the following years and the larvae population decreased by over 90% in areas with moderate and higher populations (MacLean et al. 2019). Liu et al. (2019) showed greater efficacy of aerial spraying on annual defoliation reduction in the early stage of the outbreak. Fuentealba et al. (2019) compared the efficiency of different aerial spraying scenarios against spruce budworms. They presented that standard (spraying every year after the first year of moderate-severe defoliation) and intensive (applying biological insecticide every year) were the most efficient spraying strategies.

Re-optimized harvest scheduling and salvage harvest scheduling could reduce the spruce budworm impacts on the harvest reductions to 25% (from 35%) and 34% (from 46%) under normal and severe defoliation, respectively, according to Hennigar et al. (2007). Moreover,

under a severe outbreak with no protection the maximum reduction by re-optimizing the harvest schedule was 4% while salvage harvesting didn't have any effect and the combination of these approaches could reduce future harvest reductions by up to 12% (Hennigar et al. 2007). Mathey and Nelson (2010) showed that increasing harvest levels as management strategies improve both timber supply and economic returns. Salvage harvesting and re-planning can mitigate the wood supply losses by up to 20% in the short term (20 to 25 years) (Hennigar et al. 2013). The risk of future outbreak damage can be reduced by host species reduction (Bouchard and Auger 2014). Reduction in host species can affect local budworm dispersal success (Nealis 2016) and natural enemies (Royama 1984, Eveleigh et al. 2007). Mushakhian et al. (2020) used harvesting as a management strategy to deal with spruce budworm outbreaks and demonstrated that stands with the lowest level of infestation have the priority for salvage harvesting. Moll and Chinneck (1992) used linear programming to assess alternative regimes for spraying and harvesting strategies subject to wood loss due to fire.

One or several control methods might be coordinated to mitigate the negative impacts of insects on wood supply (Government of British Columbia 2016). Spraying biological insecticide, salvage harvesting, and strategic re-planning help mitigate the wood supply impacts of defoliation by SBW (Hennigar et al. 2007). Moreover, the combination of these techniques can reduce future harvest reductions by up to 12%. Chang et al. (2012) showed that aerial spraying mitigates the economic impacts of spruce budworm outbreak by up to 66% and a combination of spruce budworm control with replanning harvest scheduling and salvage strategy can reduce the negative impact further by up to 18% depending on the level of control implemented. Hennigar et al. (2013) demonstrated that foliage protection treatments can avoid harvest reduction up to 30% to 50% depending on the outbreak scenario.

There are different levels of defoliation in each stand in the forest and the transition probability matrix gives the probabilities of transitioning from one state to another. Four classes of cellular transition probability models have been developed to predict the spatial dynamics of gypsy moth defoliation (Zhou and Liebhold, 1995). To characterize defoliation initiation and termination, Liebhold and Elkinton (1989) used the two-state transition models. Zhou et al.

(2017) used transition probabilities to track the levels of infested volume inventory of forest stands under the phases of spruce budworm infestation. So, to evaluate the potential effect of insecticide spraying on tree mortality, transition matrices were used, with defoliation severity as the entity of evaluation.

In New Brunswick, Saskatchewan, and some other Canadian jurisdictions, Spruce Budworm Decision Support System (SBWDSS: MacLean et al. 2000, 2001) is used for spruce budworm protection planning and find out the wood supply benefits of protection. However, it can quantify the spruce budworm impacts on the forest, it cannot optimize management interventions like a new harvest scheduling, salvage harvesting, and spatially optimized spraying (Hennigar et al. 2007). Furthermore, management decisions on where and when to spray biological insecticides, salvage harvesting, and harvest rescheduling to mitigate the spruce budworm impacts require data on cumulative defoliation level of forest stands (Zhao et al. 2014). In the existing literature, the researchers usually used the simulation method to analyze the impact of spruce budworm on the forest and they did not consider the optimization characteristics in their models. There are three main contributions in this paper. First, a model formulation that integrates harvesting and spraying decisions on a detailed level is proposed and developed. Second, as a part of the modeling development, we derive and use transition probabilities for sprayed and non-sprayed stands to predict the defoliation in the following year considering the mathematical relationship between defoliation and wood loss into the model. Third, we apply the model on a case study and make detailed analysis for important practical insights. The objective function of the proposed model is to maximize the net present value of the harvested volume during the planning horizon and the value of standing trees at the end of the planning horizon minus the spraying and harvesting costs. The results of the model provide information on where and when harvesting and spraying should take place during the planning horizon to deal with spruce budworm outbreak impacts on the wood loss. Moreover, it also characterizes potential stands for harvesting and spraying.

The remaining parts of the paper are organized as follows. In Section 2, the problem is described. Section 3 describes the deterministic mathematical model. In Section 4, a case study

from the province of Québec is described and results are provided together with analysis. Concluding remarks are provided in Section 5.

3.2 Problem Definition

An outbreak of spruce budworm started in Quebec in 2006 and is steadily increasing and exacerbating the situation. Figure 3.1 shows the affected areas in hectares during the last ten years.

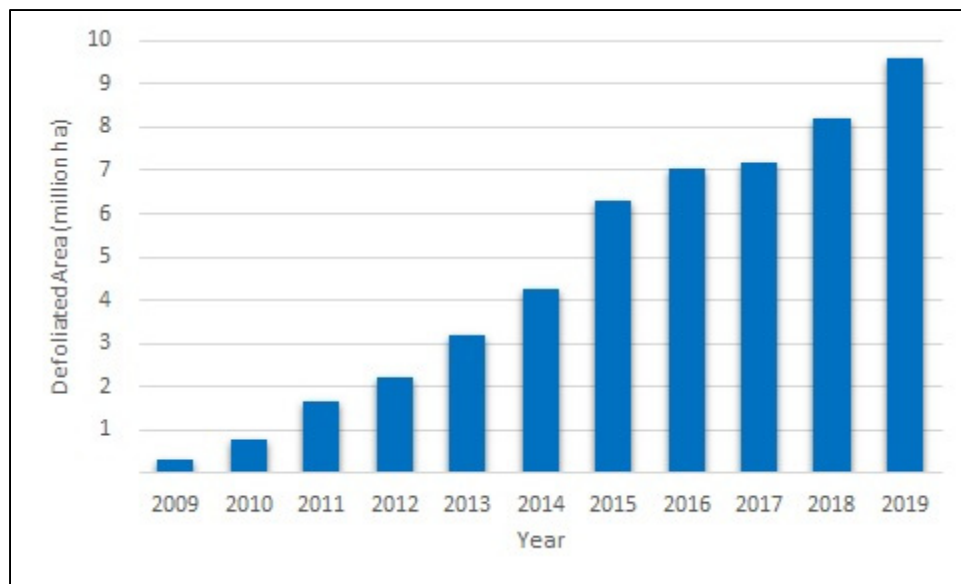


Figure 3.1 Total annual area defoliated by spruce budworm between 2009-2019.

Taken from Ministère des Forêts, de la Faune et des Parcs (2019a, p.5)

The forest protection department of the ministry of forests, wildlife, and parks (MFFP) does an annual aerial detection survey to assess the severity of the damage caused by forest pests, watch carefully existing outbreaks, detect new outbreaks, and find previously undetected outbreaks. In 2019, the government of Quebec spent 33 million dollars to control the spruce budworm outbreak. They sprayed 337,500 and 456,000 hectares of moderate to the serious defoliated forest in 2018 and 2019, respectively (Montreal Gazette 2019). Figure 3.2 shows the surveyed and non-surveyed areas in the province of Quebec Canada in 2019.

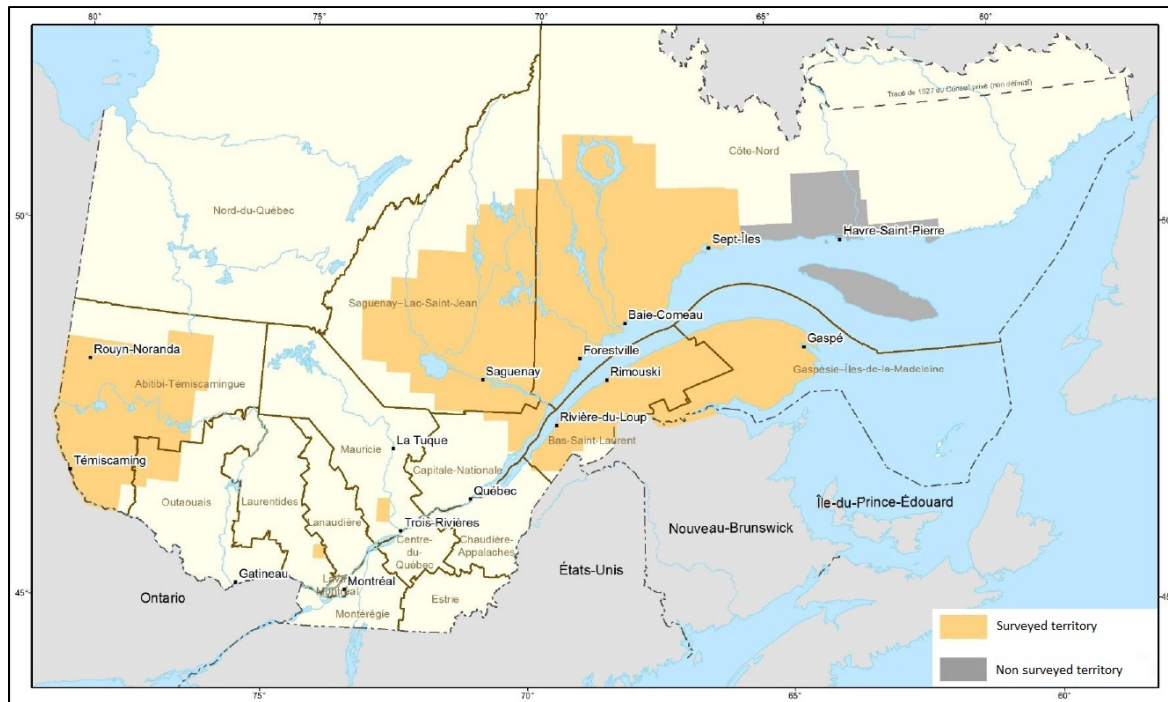


Figure 3.2 Areas covered by aerial detection surveys during 2019 in Quebec

Taken from Ministère des Forêts, de la Faune et des Parcs (2019b, p.13)

A widespread loss of leaves in a plant (like a tree) is called defoliation. Based on the aerial detection survey maps, the annual defoliation caused by the spruce budworm is categorized into four categories: no, light, moderate, and severe defoliation (Figure 3.3). The levels are defined as follows (each color corresponds to an infestation level in Figure 3.3):

- no defoliation: There is no foliage loss in the tree (Black)
- light defoliation: The foliage loss is in the upper third of the tree crown (Green).
- moderate defoliation: The foliage loss is in the upper half of the tree crown (Yellow).
- severe defoliation: The foliage loss is over the entire tree crown (Red).

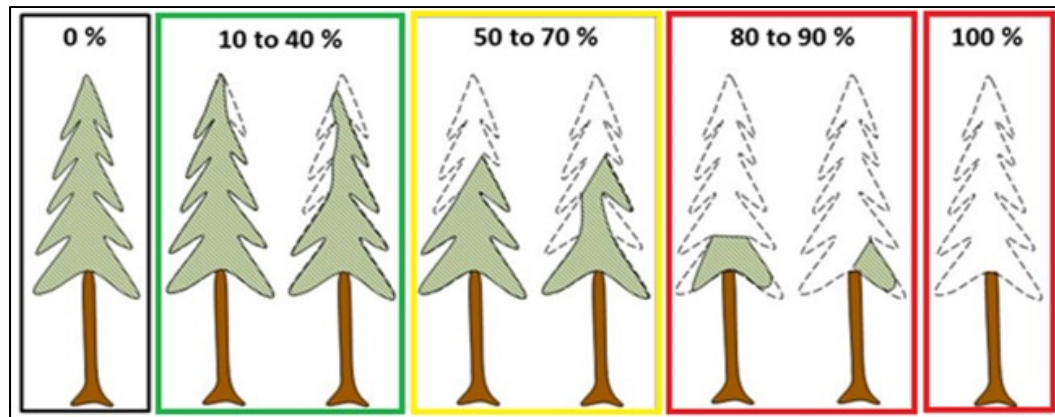


Figure 3.3 Classification of defoliation into 4 levels between 0%-100%

Taken from Lavoie et al. (2019, p. 5)

According to the above-mentioned classification, Figure 3.4 shows defoliation levels in different regions of Quebec in 2019.

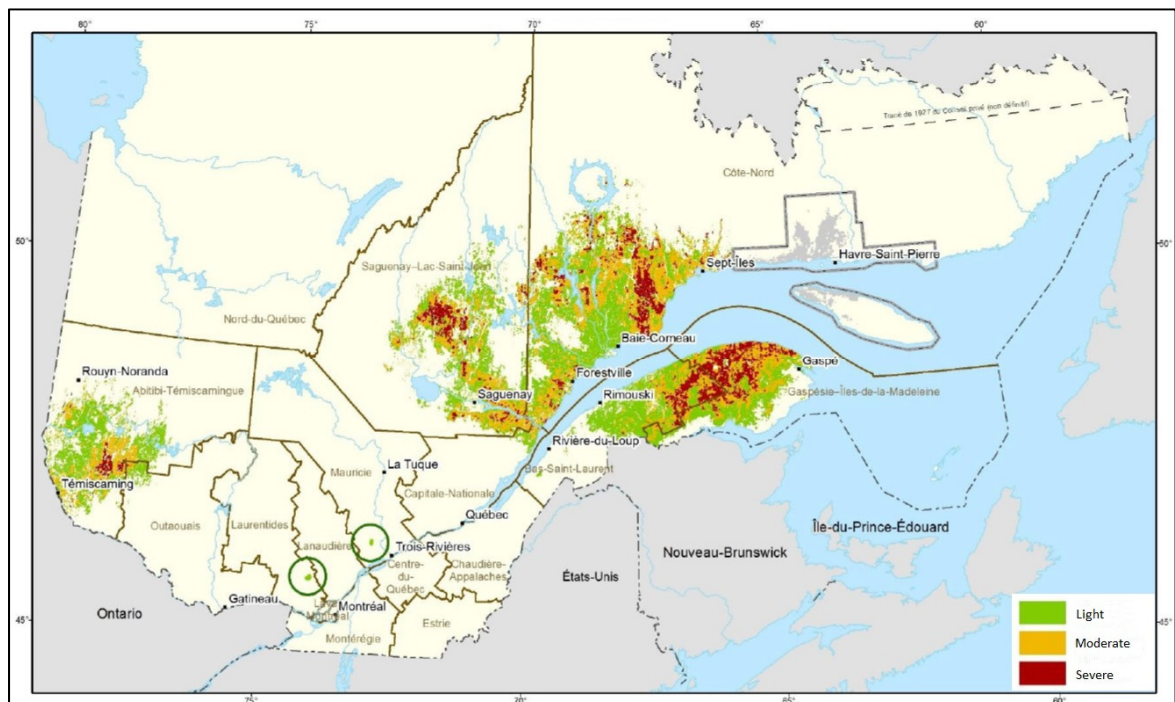


Figure 3.4 Levels of defoliation defined at surveyed areas in the province of Quebec during 2019. White: No defoliation, Green: light defoliation, Yellow: Moderated defoliation, and Red: Severe defoliation

Taken from Ministère des Forêts, de la Faune et des Parcs (2019b, p.13)

Sustainable forest management is one of the primary tools to ensure that forests can provide a wide range of goods and services over the long term. Each Canadian province estimates the maximum wood volume that can be harvested sustainably under its jurisdiction to find the annual allowable cut (Environment and Climate Change Canada 2018).

There is a cumulative effect of spruce budworm defoliation on growth and mortality (Chen et al. 2017). Blais (1958) observed the relationship between tree mortality and cumulative defoliation. Alfaro et al. (1982) studied the effect of western spruce budworm defoliation on Douglas-fir radial growth and tree mortality. MacLean et al. (1996) assessed the effect of cumulative defoliation caused by spruce budworm on growth rates and growth reduction. Colford-Gilks et al. (2012) indicated that initial balsam fir basal area, % tolerant hardwood basal area, cumulative defoliation, and spruce budworm outbreak zone significantly influenced fir-spruce mortality. Chen et al. (2017) used statistical models to evaluate the influence of cumulative spruce budworm defoliation on the net growth, mortality, and ingrowth of spruce-fir stands.

Repeated defoliations over years lead to tree mortality and wood loss. So, the number of years with defoliation and defoliation score (no defoliation = 0, light defoliation = 1, moderate defoliation = 2, and severe defoliation = 3) are two important parameters to find dead trees in a stand. We use a parameter called Cumulative Defoliation Score (CDS) to study the historical defoliation of a stand. To calculate the CDS, we should add the current Defoliation Score (DS) obtained from recent aerial survey to the historical defoliation of the last year (CDS_{t-1}). So, we have:

$$CDS_t = CDS_{t-1} + DS_t$$

Balsam fir and white spruce are the main hosts for spruce budworms, so high proportion of such species in a stand lead to higher tree mortality in the stand. Hennigar et al. (2008) showed consistent differences in defoliation level among host species of spruce budworm in all sampled stands. The defoliation of balsam fir and white spruce was evidently higher than red

spruce and black spruce. Zhang et al. (2018) found that fir defoliation is remarkably lower as hardwood proportion increases in the stands.

In Quebec, there is a methodology to calculate the percentage of dead trees due to the defoliation in a stand. Based on the proportion of dead trees, the available wood volume can be estimated annually for each stand. To find the rate of tree mortality, it is required to know the historical defoliation, the volume of balsam fir and white spruce, the total wood volume, and the number of years with defoliation in the stand. The following formulation is used to calculate the Cumulative Mortality Rate (CMR) by spruce budworm in a stand (private communication with Mr. Sylvain Dallaire and Mr. Frédéric Leblanc at Ministère des Forêts, de la Faune et des Parcs):

$$CMR = \frac{1}{1 + e^{a - b \times CDS - c \times PBS - d \times \ln(YD)}} \times PBS$$

Where,

CDS: Cumulative defoliation score,

PBS: Balsam fir and white spruce volume as a percentage of total wood volume in the stand,

Ln: Natural logarithm,

YD: Number of years with defoliation,

and a, b, c, d are parameters with given values.

Figure 3.5 shows the change of CMR as a function of the cumulative defoliation score. The limit line (red line) is defined by the proportion of the balsam fir and white spruce in a stand. Therefore, the CMR is changing between stands even if they have the same CDS.

Based on the annual aerial surveys, we can find the defoliation score and consequently update both CDS and CMR values of stands. The difference between CMRs of two consecutive periods indicates the tree mortality percentage during the period. Then, based on the available wood volume in the former period and the obtained proportion of tree mortality, the available

wood volume can be updated for the stand. Hennigar et al. (2013) gave higher protection priority to stands which might have higher volume loss caused by spruce budworm.

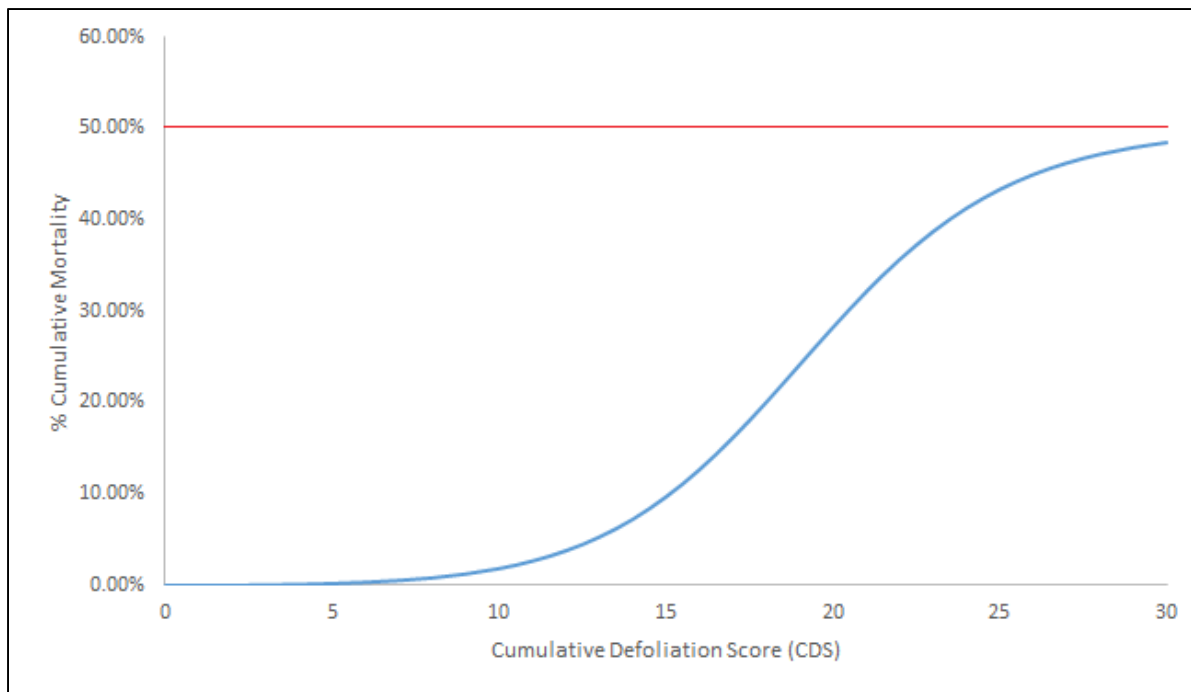


Figure 3.5 Changes of cumulative mortality rate (blue line) of a stand based on the cumulative defoliation score and proportion of the balsam fir and white spruce in the stand (red line)

There are four control methods to protect the forest ecosystems against pests: physical (like using traps), biological (like predatory and parasitic insects), chemical (like using synthetic and naturally derived pesticides), silvicultural (such as preemptive harvesting, salvage harvesting). Application of these protection approaches in the forest can lead to lower infestation and hopefully lower defoliation in the area. Dupont et al. (2017) compared six different aerial spraying of biological insecticide scenarios and showed a link between intervention intensities and defoliation levels of host species. Therefore, pest management can affect the CDS, and consequently the wood volume in stands.

To find how the defoliation will be changed in the following year, transition probabilities matrices are used, one for stands which have been sprayed and one for stands not sprayed.

Assuming that we have S defoliation states (1, 2, ..., S), the transition probability matrix is given by

$$P = \begin{bmatrix} P_{1,1} & \cdots & P_{1,S} \\ \vdots & \ddots & \vdots \\ P_{S,1} & \cdots & P_{S,S} \end{bmatrix} \quad (3.3)$$

Note that $P_{i,j} \geq 0$ and for all i , we have

$$\sum_{j=1}^S P_{i,j} = 1 \quad (3.4)$$

Each stand can be made up of different defoliation levels. Now, as an example, suppose that there is a stand composed of 10%, 20%, 30%, and 40% ($A_0 = 10\%$, $A_1 = 20\%$, $A_2 = 30\%$, $A_3 = 40\%$) from defoliation level 0, 1, 2, and 3, respectively and it has not been sprayed and the transition matrix for the non-sprayed stands is given in Table 3.1. The summation of all proportions of defoliation levels is equal to one (sum of each row is 100%). These proportions are changing based on the state transition matrices.

Table 3.1 Transition matrix for non-sprayed stands

From \ To	0	1	2	3
0	15%	40%	30%	15%
1	5%	35%	35%	25%
2	5%	15%	55%	25%
3	0%	15%	35%	50%

The defoliation score of the stand is defined as the weighted average of the stand proportions multiplied by a predetermined weight associated with the level of defoliation (0, 1, 2, and 3). To simplify the modeling and runtime reduction, it is assumed that defoliation levels can take

any whole number between 0 and 3. Therefore, for the given example, the defoliation score in the next year would be:

$$\begin{aligned}
 \text{Defoliation score} &= \sum_{s=0}^3 A_s \left(\sum_{s'=0}^3 s \times P_{ss'} \right) \\
 &= 10\%*(0*15\% + 1*40\% + 2*30\% + 3*15\%) + 20\%*(0*5\% + 1*35\% + 2*35\% + 3*25\%) + \\
 &30\%*(0*5\% + 1*15\% + 2*55\% + 3*25\%) + 40\%*(0*0\% + 1*15\% + 2*35\% + 3*50\%) \\
 &= 2.045
 \end{aligned}$$

The obtained defoliation score will be added to the CDS of the last time period to update the CDS and consequently the mortality rate of the stand.

3.3 Mathematical Model

We propose a deterministic mathematical model taking both harvesting and spraying decisions into account. Each stand consists of different proportions of defoliation levels that change according to the transition probabilities. With knowledge of the defoliation score, the CDS and CMR will be updated for each stand and the available wood volume can be computed. To satisfy the demand of wood volume for each time period some stands should be harvested. We consider tactical planning and hence it is assumed that each stand can be harvested only once during the planning horizon. Spraying can lead to lower defoliation level in a stand in the following year and therefore has an increased volume at the end of the planning horizon. The spraying process incur cost for the government and there is a limited budget available. In the model, we have two main decisions: when (time period) and which (stands) should be harvested and/or sprayed to maximize the total discounted revenue (from harvested wood during the planning horizon and the value of standing trees at the end of the planning horizon) obtained from the forest while minimizing the costs of harvesting and spraying. It is assumed that the full stand is harvested or sprayed.

The notations of sets, parameters and decision variables used in this model are as follows:

Sets:

I	Set of stands $\{1, \dots, M\}$
P	Set of defoliation states $\{0, \dots, 3\}$
T	Set of time periods $\{1, \dots, T\}$

Parameters:

Θ_{pq}^N	Transition probabilities from state p to q with no spraying
Θ_{pq}^S	Transition probabilities from state p to q with spraying
A_i	Area of stand i (ha)
V_{0i}	Initial volume in stand i (m^3)
d_{0i}	Initial defoliation score of stand i
s_{0ip}	Initial proportion of stand i in state p
A_p	Increase in defoliation score being in state p
D_t^{Max}	Maximum demand in period t , i.e., Annual Allowable Cut (AAC) in the region (m^3)
C_{ti}^F	Wood procurement cost to the mill gate from stand i in period t ($\frac{\$}{m^3}$)
C_{ti}^S	Cost of spraying stand i in period t ($\frac{\$}{ha}$)
B_t	Budget of spraying in period t (\$)
Γ^t	Discount rate in period t
P^{ST}	Average market value of standing timber (\$)
P^{SL}	Average market price of softwood lumber (\$)
$g(d_{ti})$	Piecewise linear function describing the available wood volume in stand i at period t depending on the cumulative defoliation score d_{ti} (Figure 3.6)

Variables:

$x_{ti} = \begin{cases} 1, & \text{if stand } i \text{ is sprayed in period } t \\ 0, & \text{otherwise} \end{cases}$	
$y_{ti} = \begin{cases} 1, & \text{if stand } i \text{ is harvested in period } t \\ 0, & \text{otherwise} \end{cases}$	

s_{tip}	Proportion of stand i in state p in period t
z_{tip}^N	Proportion of stand i in state p in period t which has not been sprayed
z_{tip}^S	Proportion of stand i in state p in period t which has been sprayed
d_{ti}	Cumulative defoliation score of stand i in period t
v_{ti}	Available wood volume to harvest in stand i in period t
hv_{ti}	Harvested wood volume in stand i in period t

Model:

$$\max z = \sum_{t \in T} \left[\left(\sum_{i \in I} (P^{SL} \times hv_{ti} - C_{ti}^S A_i x_{ti} - C_{ti}^F hv_{ti}) \right) / (1 + \Gamma^t) \right] \\ + \left[\sum_{i \in I} P^{ST} \times v_{Ti} \right] / (1 + \Gamma^T)$$

s. t.

$$s_{tiq} = \sum_{p \in P} \Theta_{pq}^S z_{tip}^S + \sum_{p \in P} \Theta_{pq}^N z_{tip}^N, \quad \forall i \in I, q \in P, t \in T \quad (3.5)$$

$$z_{tip}^S \leq x_{ti}, \quad \forall i \in I, p \in P, t \in T \quad (3.6)$$

$$z_{tip}^N \leq 1 - x_{ti}, \quad \forall i \in I, p \in P, t \in T \quad (3.7)$$

$$z_{tip}^S \leq s_{(t-1)iq}, \quad \forall i \in I, p \in P, t \in T \quad (3.8)$$

$$z_{tip}^N \leq s_{(t-1)iq}, \quad \forall i \in I, p \in P, t \in T \quad (3.9)$$

$$\sum_{p \in P} z_{tip}^S + \sum_{p \in P} z_{tip}^N = 1, \quad \forall i \in I, t \in T \quad (3.10)$$

$$d_{ti} = d_{(t-1)i} + \sum_{p \in P} A_p s_{tip}, \quad \forall i \in I, t \in T \quad (3.11)$$

$$\sum_{t \in T} y_{ti} \leq 1, \quad \forall i \in I \quad (3.12)$$

$$v_{t''i} = \left(1 - \sum_{t=1}^{t''} y_{ti} \right) g(d_{t''i}), \quad \forall i \in I, t'' \in T \quad (3.13)$$

$$hv_{ti} = y_{ti} \times v_{(t-1)i}, \quad \forall i \in I, t \in T \quad (3.14)$$

$$\sum_{i \in I} hv_{ti} \leq D_t^{Max}, \quad \forall t \in T \quad (3.15)$$

$$\sum_{i \in I} C_{ti}^S A_i x_{ti} \leq B_t, \quad \forall t \in T \quad (3.16)$$

$$x_{ti}, y_{ti} \in \{0,1\} \quad (3.17)$$

$$s_{tip}, z_{tip}^N, z_{tip}^S, ds_{ti}, v_{ti}, hv_{ti} \geq 0 \quad (3.18)$$

The objective function is to maximize the total discounted revenue from harvested volume during the planning horizon and the discounted value of standing trees in the forest at the end of the planning horizon minus the discounted costs incurred by harvesting and spraying. Constraint (1) describing how the proportions of a stand will change according to the transition probabilities depending on whether the stand has been sprayed or not. Constraints (2) and (3) expresses whether the stand (and consequently its proportions) can be sprayed or not. Constraints (4) and (5) state that the proportions of sprayed or non-sprayed stand cannot be more than the proportions before any spraying decision is made. Constraint (6) express that the sum of all proportions (sprayed or not sprayed) must be 1. The update of the cumulative defoliation score is shown in constraint (7). Constraint (8) shows that each stand can be harvested only once during the planning horizon. The total available wood volume in each stand is updated by constraint (9). The harvested volume is described in constraint (10). Constraint (11) indicates the maximum demand from forestry companies (i.e., annual allowable cut (AAC)). Constraint (12) states the limited budget for spraying. Finally, constraints (13) and (14) represent non-negativity constraints. There are two nonlinear constraints (9 and 10) in the above model, and we use piecewise linear approximation of them in the model. The approach to linearize them is given in Appendix I.

Note that the model does not take the stand growth model and adjacency constraints for stands into account. Figure 3.6 illustrates the gradual wood reduction in a stand based on changes in the cumulative mortality in Figure 3.5.

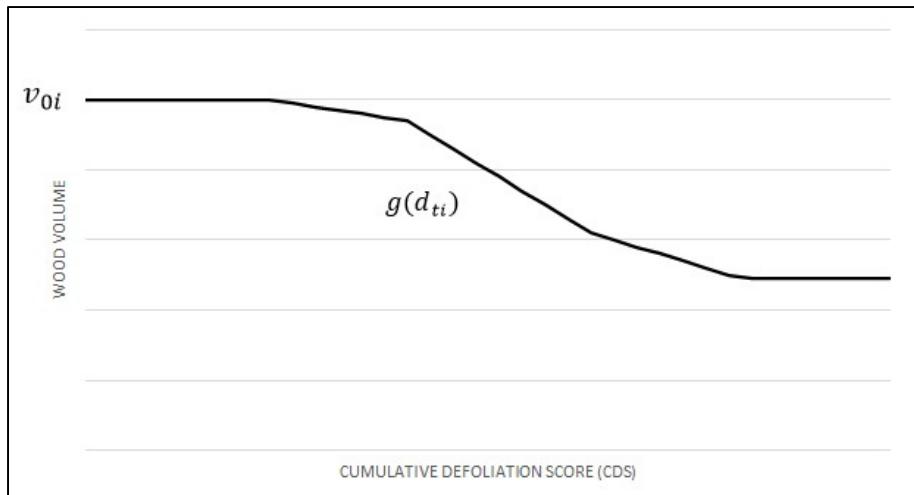


Figure 3.6 Piece-wise linear function describing the available wood volume in a stand based on the CDS

3.4 Case study

The study area is located in Bas-Saint-Laurent region in Quebec (Figure 3.7). Forests in this region are dominated by balsam fir and spruce species. The affected areas by the spruce budworm remained almost the same, going from 1,197,034 ha in 2018 to 1,186,782 ha in 2019. Table 3.2 presents the defoliated areas based on defoliation level. The defoliation level is mainly “light” and “moderate” (Ministère des Forêts, de la Faune et des Parcs 2019) (see Figure 3.7). On the other hand, one can observe that moderate and severe levels have slightly increased while light level have decreased.

Table 3.2 Affected areas (ha) by the spruce budworm in Bas-Saint-Laurent during the last two years

Year	Defoliation Class			Total
	Light	Moderate	Severe	
2018	686,034	323,016	177,732	1,186,782
2019	575,252	390,131	231,651	1,197,034

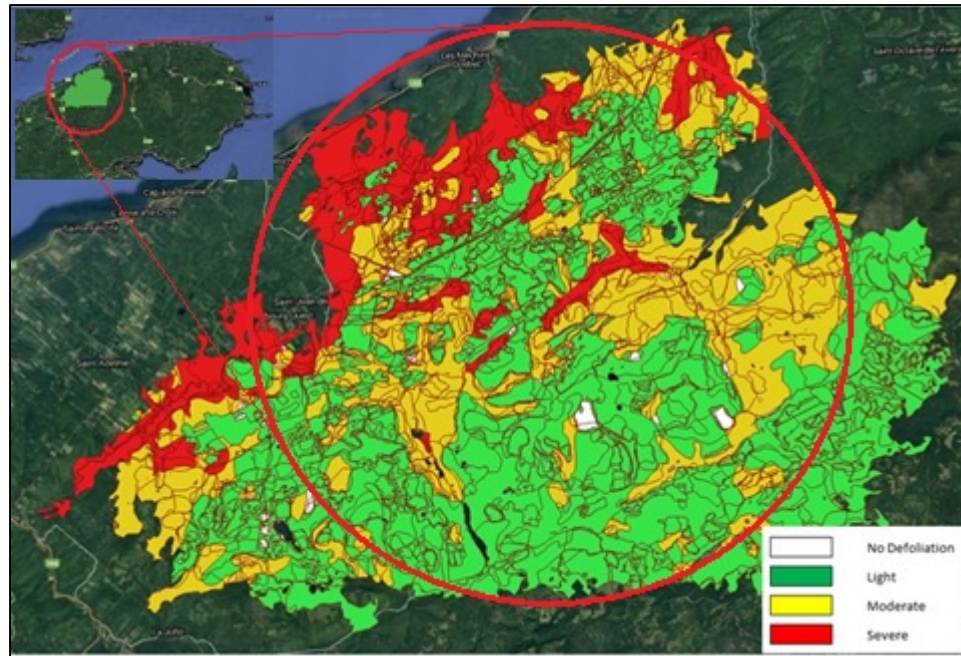


Figure 3.7 The study region in Bas-Saint-Laurent in Quebec and the extent of different defoliation levels in the region in 2018

The forest data is provided by Ministère des Forêts, de la Faune et des Parcs (MFFP) and Société de protection des forêts contre les insectes et maladies (SOPFIM). There were three datasets including feature attributes of stands, defoliation scores in the forest, and sprayed areas in the forest. The polygons of the provided shapefiles were not the same as they were provided by different departments. So, to decide on the defoliation score for the available stands and find whether the stand has been sprayed or not, it is necessary to find the overlaps between defoliation and spraying polygons with feature attributes polygons. Therefore, we have developed an algorithm to find the overlap between stand polygons and defoliation polygons. If there is an overlap of more than 50%, the defoliation score of the stands is the same as the defoliation polygon. For example, if 60% of the stand area is covered by a defoliation polygon of moderate level (2), the defoliation level for this stand is assumed to be equal to 2. The same algorithm is used to find whether the stand has been sprayed in a particular year or not. For instance, if the area coverage of the spraying polygon is 51%, the stand is assumed to be a sprayed stand. The outcomes will be used in calculation of the transition matrices. Furthermore, to run the optimization model, it is required to find the proportions of defoliation

score in each stand. So, the area coverage of different defoliation levels would be the proportions of the defoliation score. As an example, a stand can be made up of 40%, 30%, 20%, and 10% from no-defoliation, light, moderate, and severe defoliation, respectively.

Having processed the data, there were 16,371 stands with feature attributes such as wood volume (for each species), surface area, historical defoliation levels, historical spraying areas, and proportions of different defoliation levels.

The transition probabilities, depending on whether the stand has been sprayed or not in the last year, explain how the defoliation state will change in the following year. Historical data (from 2014 to 2018) for defoliation levels and spraying areas have been used to estimate the transition matrices. The frequency of changes from one defoliation score (initial year) to another defoliation score (following year) is counted during the study period (from 2014 to 2018) and then it is divided by the total number of changes from the initial defoliation score to find the probabilities matrix. Based on whether the stand has been sprayed in the initial year or not, the transition probabilities are categorized into sprayed or non-sprayed transition matrices, respectively.

Assuming the defoliation states are 0, 1, 2, and 3, then the state transition matrices are given by Table 3.3.

Table 3.3 Transition matrices of defoliation levels for sprayed and non-sprayed stands

		To From	0	1	2	3
Non-sprayed stands	0		14.60%	15.50%	41.50%	28.30%
	1		6.20%	33.00%	34.20%	26.70%
	2		4.60%	33.60%	36.80%	25.00%
	3		0.80%	27.70%	35.00%	36.50%
Sprayed stands	0		14.60%	15.50%	41.50%	28.30%
	1		1.00%	70.70%	21.30%	7.00%
	2		2.00%	88.80%	7.10%	2.20%
	3		0.00%	98.20%	1.80%	0.00%

It is highly probable that the defoliation level remains at the same level or goes to a lower level when stands are sprayed because spraying kill some of the spruce budworms and reduce their population in the next year. The transition probabilities for sprayed stands from state 0 is assumed to be equal to the transition probabilities for non-sprayed stands due to limited recorded data. It is reasonable because normally non defoliated stands are not sprayed.

To test the model, we select a limited region situated in the north of Bas-Saint-Laurent with 500 stands, total area of 4,377.2 ha, and total volume of 72,530.36 m^3 (see Figure 3.8). The smaller study region was selected to obtain shorter runtime as we run multiple instances of the model during this study.

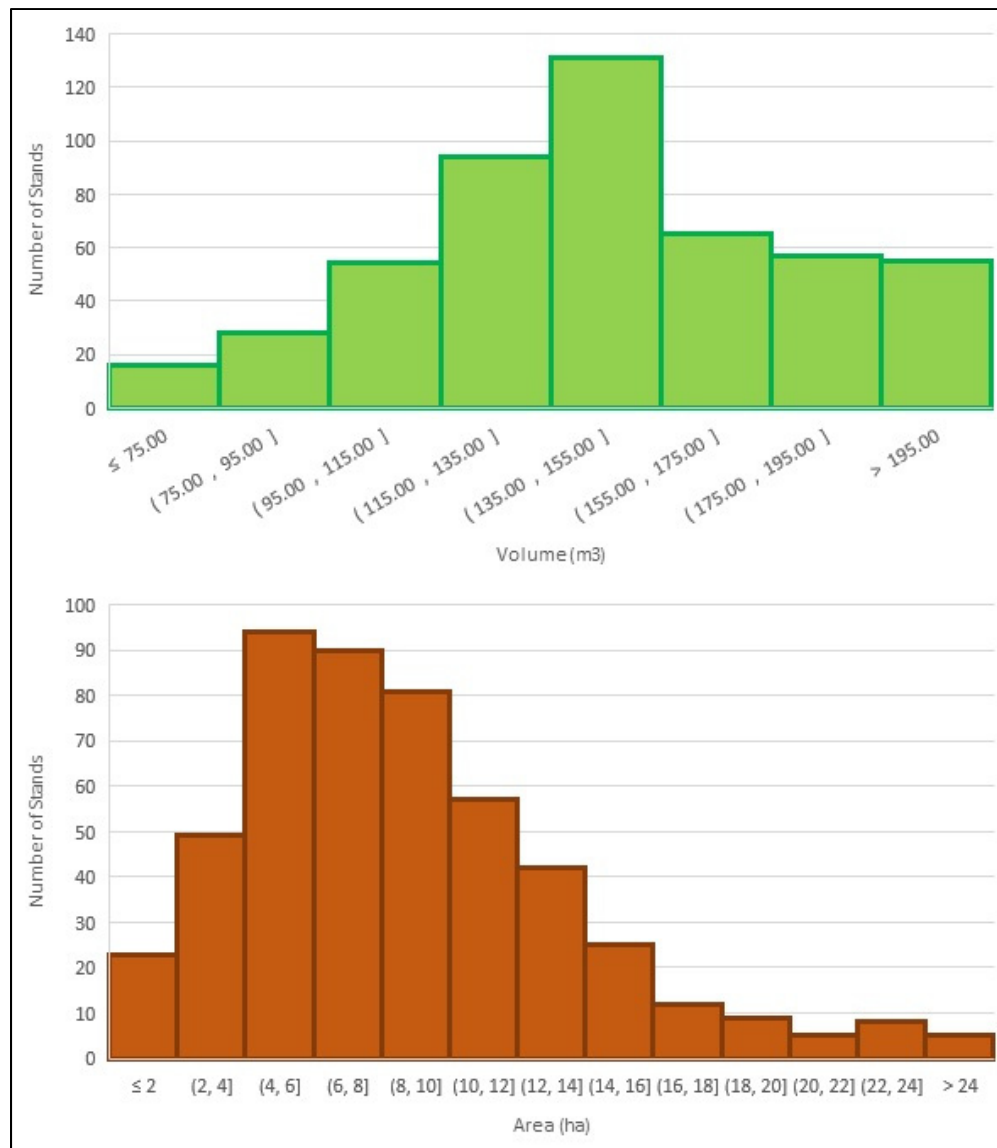


Figure 3.8 Distribution of available wood volume in stands at the beginning of the planning horizon and surface area of stands in the smaller study region

To characterize the potential stands for harvesting and spraying and to define policies for them, we study stratification parameters such as age, height, density, slope, drainage, etc. (Ministère des Forêts, de la Faune et des Parcs, 2008).

The age class parameter provides information on both the age of the trees and the stand structure. There are different stand structures like regular (even-aged or uneven-aged),

irregular (even-aged or uneven-aged) and staged (stands composed of two age classes) structures in this study (see Figure 3.9). Age classes 30 to 90 are used for even-aged forests and they constitute 71% of the study area. The uneven-aged stand structures are shown by JIN, VIN, JIR, VIR, where "J" expresses that young stems are the dominant players in the stand with a maximum age of 80 years and "V" refers to the old stems when they are over 80 years old (Ministère des Forêts, de la Faune et des Parcs, 2019). This stand structure is responsible for 28% of the study area. "IN" and "IR" refer to regular and irregular structure, respectively. The staged structure is composed of two distinct height classes (at least 5 meters) and the age class is formed of two age classes (like 5050, 5090, 7070) where the first number is related to the stage with the largest basal area. These two age classes can be identical, consecutive, or non-consecutive. For example, 5090 states that the main stage is 50 years, and the second stage is 90 years (Ministère des Forêts, de la Faune et des Parcs, 2008).

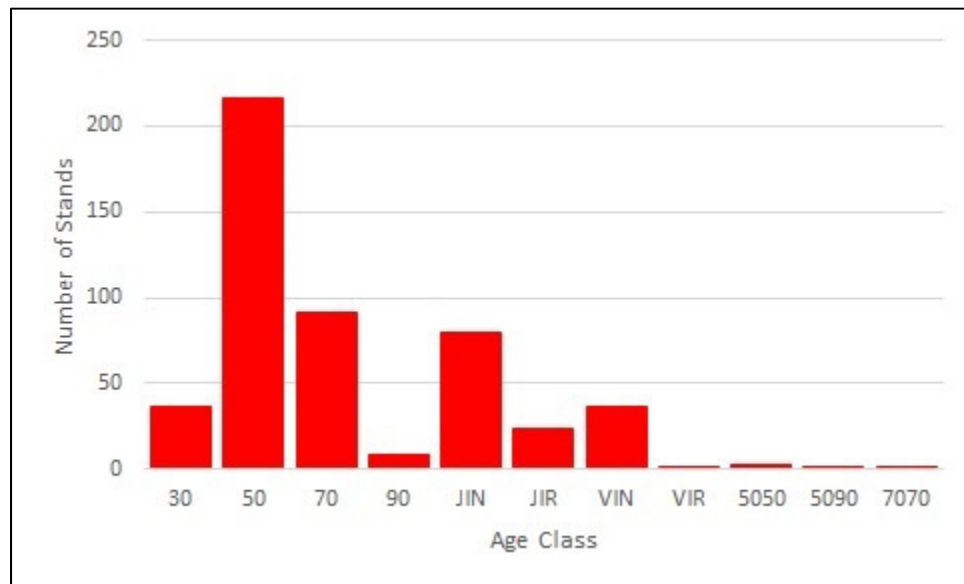


Figure 3.9 Distribution of stand age in the study area

Proportion of the balsam fir and white spruce in a stand and cumulative defoliation score are the most important features in the cumulative mortality rate of a stand. Figure 3.10 illustrates the number of stands with different proportions of balsam fir and white spruce.

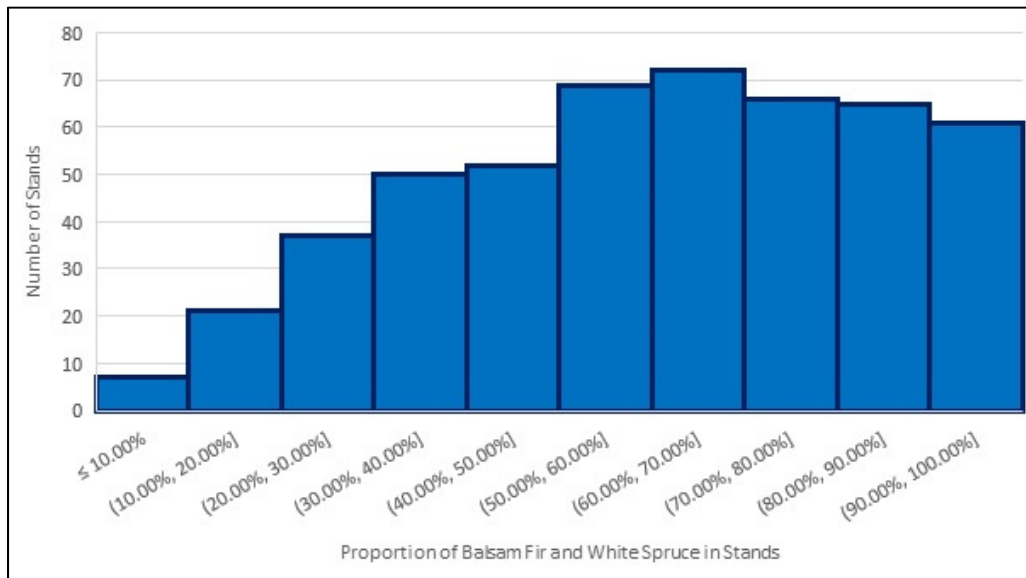


Figure 3.10 Distribution of proportion of balsam fir and white spruce in stands (%) in the smaller study area

The density class is determined by canopy projection and it is classified according to percentage of cover density. If the cover density (%) is greater than 80%, between 60% to 80%, between 40% to 60%, and between 25% and 40%, it is classified as class A, B, C, and D, respectively (Ministère des Forêts, de la Faune et des Parcs, 2008). Figure 3.11 illustrates the proportion of density classes in the study region.

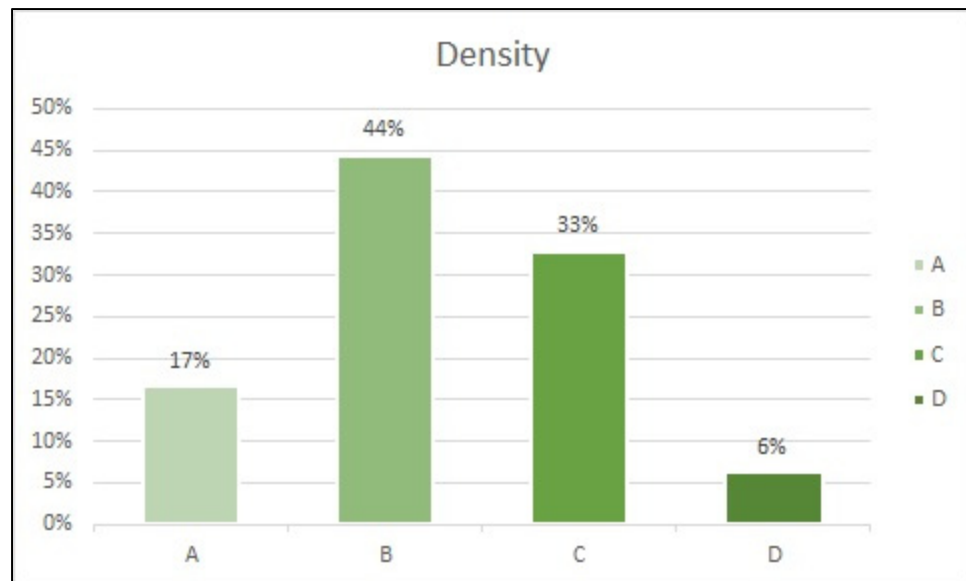


Figure 3.11 Distribution of density classes in the smaller study area

The exact location of the smaller study region, the proportions of defoliation score, and cumulative defoliation score in the region are shown in Figure 3.12.

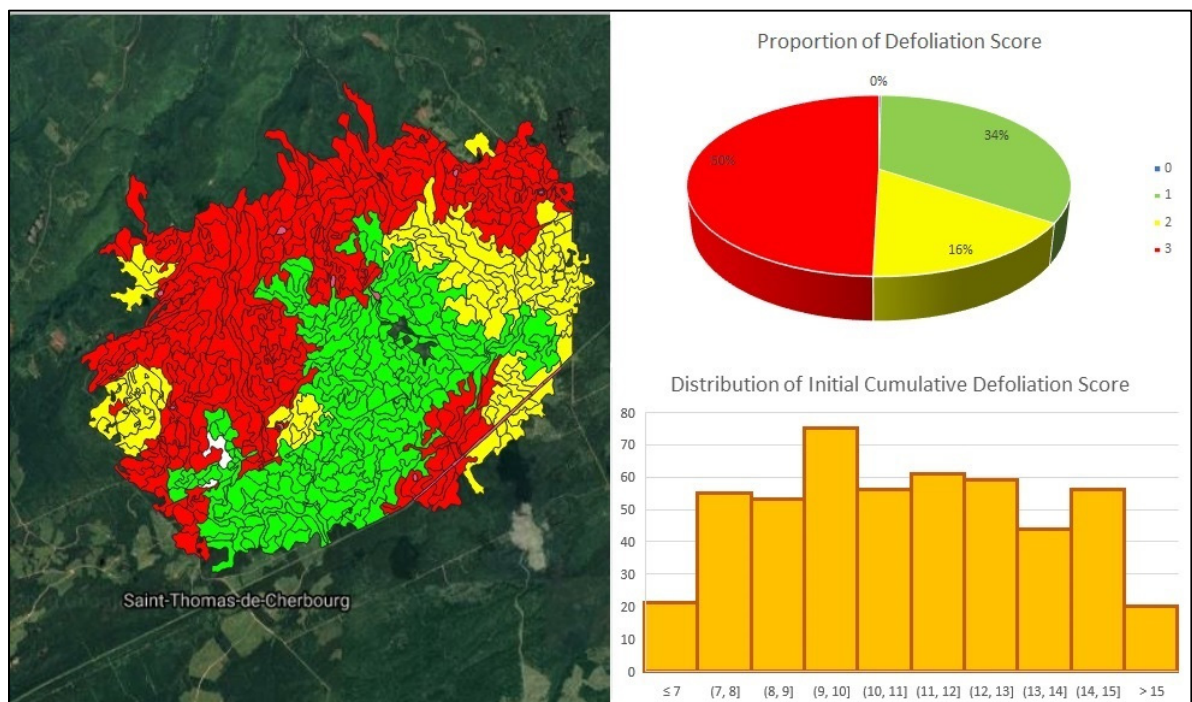


Figure 3.12 The geographical location of the smaller study area, the proportion of defoliation scores and the distribution of historical defoliation in 2018 in the smaller study area

The cost of wood for Bas-Saint-Laurent region is estimated to be $61.24 \left(\frac{\$}{\text{m}^3}\right)$ including the supply costs (harvest and purchase of timber) and government transfers (Government of Quebec 2016). Based on the recent report of SOPFIM for 2019, the spraying cost is assumed to be $42.06 \left(\frac{\$}{\text{ha}}\right)$ (La Société de protection des forêts contre les insectes et maladies 2020). The value of the wood is varying according to the species, diameter, length, moisture, quality, infestation, etc. The average market value of standing timber (MVST) and market price of softwood lumber (MPSL) for this region are assumed to be $12 \left(\frac{\$}{\text{m}^3}\right)$ and $100 \left(\frac{\$}{\text{m}^3}\right)$, respectively (Government of Quebec 2016). The planning horizon is 5 periods, and the length of each planning period is one year. The annual discount rate is assumed to be 1% and constant throughout the planning horizon.

3.5 Results and Discussion

The model was solved using CPLEX 12.8 solver on a desktop computer running with Intel(R) Xeon(R) CPU and 192 GB of memory. A time limitation of 12 hours with a 2% MIP gap (the relative difference between the integer solution found and the proven best possible objective solution value) limit was used as a convergence criterion.

The results show that it is no longer economic to use insecticide to reduce the wood loss caused by spruce budworm. Although spraying insecticide over defoliated stands can reduce the wood loss, the incurred costs outweigh the benefits. Harvesting gets the priority as a control method against spruce budworm. An increase in the harvesting level leads to an increase in the total wood volume because it stops stands from further defoliation and help reduce the spraying cost in the system. Results on the average defoliation score show that stands with cumulative defoliation score within 15 to 20 have been harvested because of high rate of wood loss (steeper slope in the cumulative mortality rate curve) while stands with CDS close to this range have been sprayed to prevent them from big wood loss.

We have made a sensitivity analysis to find a relation between total wood volume (the total wood volume refers to the sum of harvested wood volume during the planning horizon plus standing volume in the stands at the end of the planning horizon.), total spraying cost, and annual allowable cut (AAC). The AAC is the annual amount of timber that can be harvested on a sustainable basis within a defined forest area and usually ranges between 1% to 2% of the total volume. The variation of total spraying cost and total volume is shown in Figure 3.13 while AAC varies between 0 and 4% (4% of the total wood volume of the forest at the beginning of the planning horizon). When AAC increases, the total volume increases and the increase in the harvesting level can also help the system save spraying cost. For example, suppose that the government aims to have 56,000 m^3 (vertical blue dotted line in Figure 3.13) as total wood volume in the scenario where harvesting is not allowed, therefore a large area should be sprayed at a cost of almost \$500,000 which is about 10 times higher than the spraying cost when AAC is 4%. As the stands are harvested, there is no more wood loss throughout the forest, hence harvesting can reduce wood losses and spraying costs in the system.

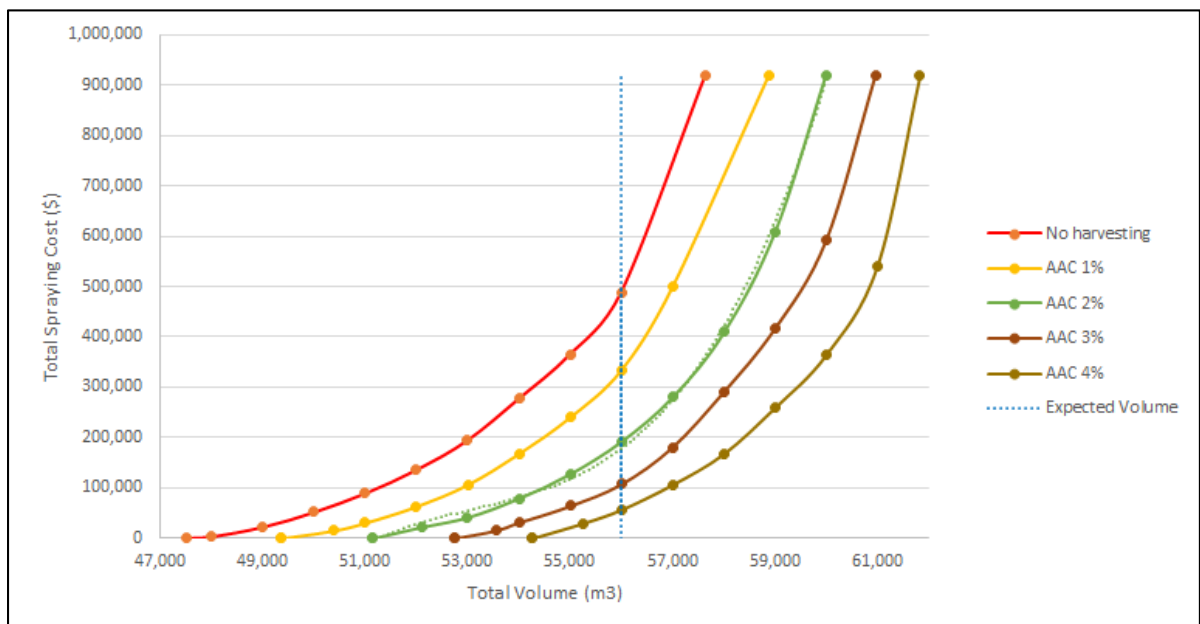


Figure 3.13 Variation of total spraying cost and total volume by changing the harvesting level (AAC)

The results show a rapid nonlinear increase in the spraying cost per saved volume (the spraying cost increases faster than the value of recovered wood volume). The green dotted line in Figure 3.13 illustrates the fitted equation for spraying cost prediction based on the expected total wood volume while AAC is 2%. In fact, each curve lies between two extremes of the highest and lowest total volume with the highest and lowest spraying cost, respectively. From now on, the highest extreme is referred as “All spraying” scenario and the lowest extreme as “No spraying” scenario. Table 3.4 shows the changes of total spraying cost in terms of total volume. As the total volume increases, higher spraying cost should be paid to save the same amount of volume. For example, to increase the total volume from 53,000 m³ to 54,000 m³, the government incurs \$37,537; however, to save the same amount of volume at 58,000 m³ volume level, they have to spend around \$200,000 for spraying because they have to spray larger area.

The fitting curve to predict the total spraying cost for a given total volume when AAC is 2% can be estimated by the following equation, where x and y are the total volume and total spraying cost, respectively:

$$y = 0.000002 x^3 - 0.3397 x^2 + 18,090.9 x - 321,490,182 \quad (3.17)$$

Table 3.4 Variation of total spraying cost in relation to changes in total volume when AAC is 2%

Total volume (m ³)	Total Spraying cost (\$)	Incremental increase in total spraying cost (\$)
51,144.52	0.00	
52,103.55	22,186.63	22,186.63
53,000.42	41,736.48	19,549.85
54,000.56	79,273.74	37,537.26
55,007.57	128,417.84	49,144.10
56,000.23	192,475.68	64,057.84
57,000.89	280,969.46	88,493.78
58,000.34	409,289.41	128,319.95
59,000.13	608,753.10	199,463.69
59,989.74	918,683.74	309,930.64

Table 3.5 shows the runtime and gap limits for solving different instances of the optimization model. “No spraying” scenario means that there is no budget for spraying and all spraying decisions are equal to zero; consequently, the total volume is in the bare minimum. “All spraying” scenario means that there is unlimited spraying budget, and all the stands are sprayed in each period. So, all the spraying decisions in each period are assumed to be equal to one and the total volume is the maximum value. “Optimal” scenario refers to a problem where there is adequate spraying budget to spray all stands at each period and harvesting and spraying decisions are the optimum level. In the other scenarios, it is assumed that the spraying budget can cover spraying expenses for all stands during the planning horizon and it is expected to obtain a certain amount of total volume (from 55,000 to 61,000 m^3).

Table 3.5 Terminating conditions for different scenarios when harvesting level is 4%

Scenario	No Spraying	Optimal	55,000	56,000	57,000	58,000	59,000	60,000	61,000	All Spraying
Runtime	27 s	7 min	12 h	12 h	12 h	12h	12 h	12 h	12 h	30 s
Gap	2%	2%	3.29%	5.15%	9.07%	15.02%	20.00%	28.58%	52.02%	2%

Figure 3.14 illustrates the variation of objective values by changing the total volume and AAC. It helps us understand whether the benefits of spraying outweigh the spraying cost in our case study. It is obvious that reducing wood losses needs more spraying (Figure 3.13). Although it increases the total volume in the forest, it increases the spraying cost and the incurred cost outweigh the economic benefits. According to Figure 3.14, the optimal decision takes place where there is no spraying in the forest, and it is no longer economic to use insecticides to reduce wood losses. In other words, in this specific study, spraying cost is not covered entirely by the value of recovered wood (wood could be harvested during the periods or considered as standing tree at the end of planning horizon). At the same time, it shows elevating the harvesting level improves the objective value and total volume which is in line with the outcome of Mathy and Nelso (2010). For example, when there is no harvesting in the forest ($AAC = 0$), at the total volume of 56,000 m^3 (blue dotted line in Figure 3.14), the objective

value is about \$200,000; however, if the AAC elevates to 4%, the objective value will go up to \$1,000,000 which is 5 times higher than the no harvesting one.

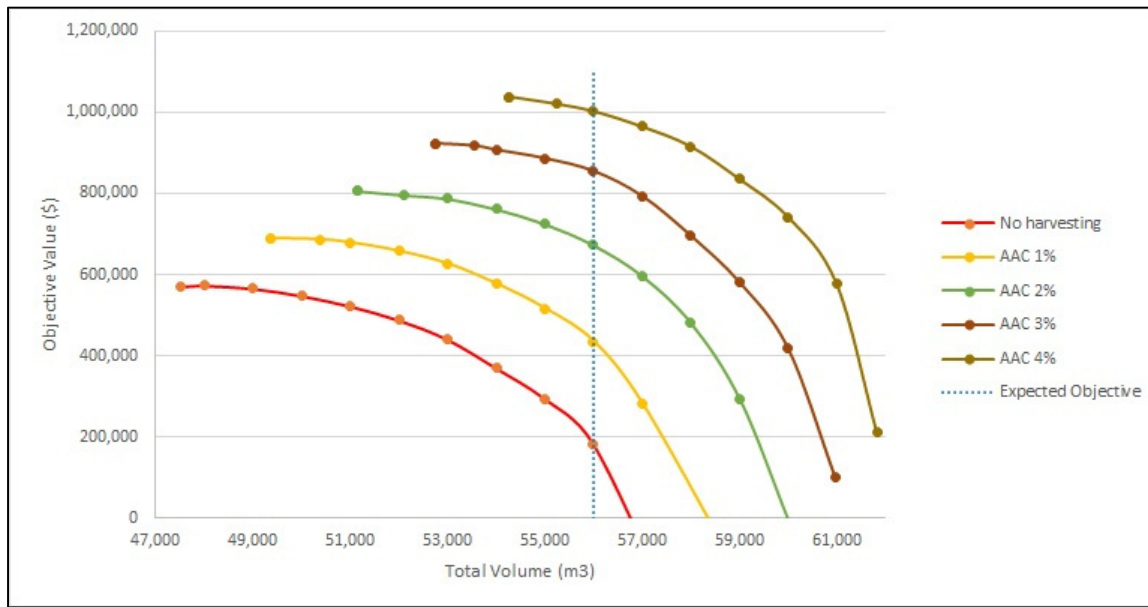


Figure 3.14 Variation of objective value when varying total volume and AAC

Next, we evaluate the decisions depending on stratification parameters like proportion of BF and WS species in the stands, cumulative defoliation score, density, and stand age (4% AAC). Generally, the average defoliation score is increasing in stands during an outbreak (Figure 3.15). According to Figure 3.5, the rate of wood loss is at the highest level while the CDS is between 15 and 20. Therefore, stands with CDS close to the given range get priority for spraying to prevent them from big wood losses (Figure 3.15a) and on the other hand, stands in the given range of CDS take priority for harvesting (see Figure 3.15b) to stop losing wood, in other words, save the wood from further defoliation.

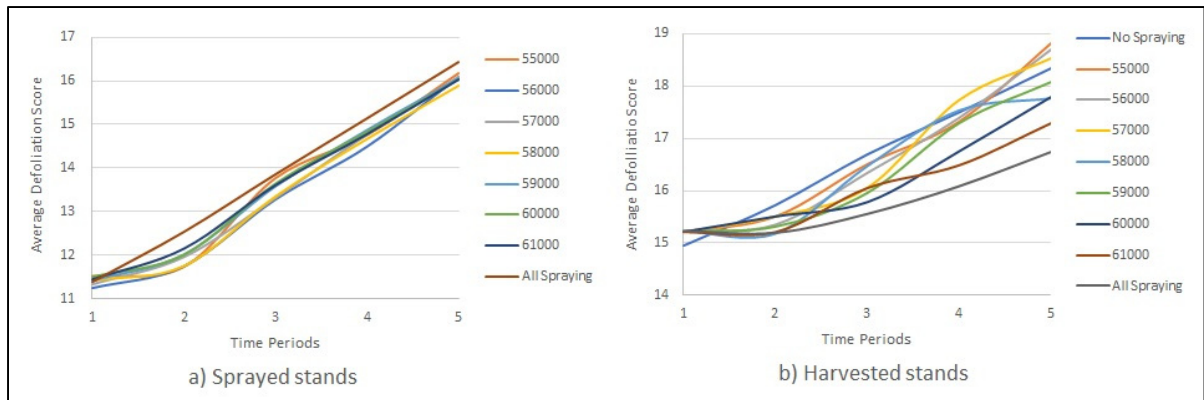


Figure 3.15 Changes in the average defoliation score in sprayed and harvested stands when AAC is 4% (legend shows the amount of total volume expected to find at the end of the planning horizon)

An important parameter is the proportion of BF and WS in the stands. Based on our results, stands made up of more than 70% (with an average of 81%) of BF and WS have top priority for harvesting while the harvesting level was 4%. If this proportion increases, the limit line on CMR graph will increase and consequently, the CMR slope and rate of wood loss will increase. On the other hand, harvesting these stands, can reduce the average proportion of BF and WS throughout the forest (Figure 3.16). Bouchard and Auger (2014) also stated that the host species reduction can reduce the risk of future outbreak damage. After harvesting the risky stands, the remaining stands with high proportion of BF and WS get priority for the spraying.

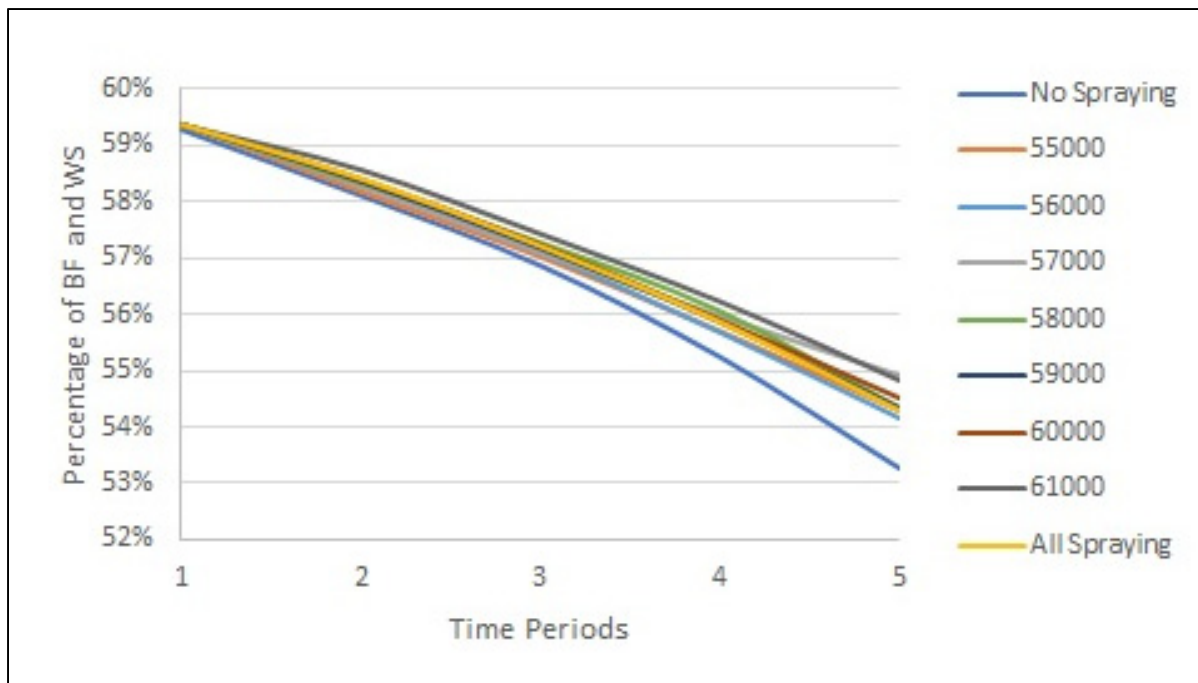


Figure 3.16 Changes in the average proportion of balsam fir and white spruce in standing stands during the planning horizon when AAC is 4% (legend shows the total volume)

When it comes to the defoliation score, the model chooses stands with defoliation scores between 15 to 20 for harvesting because they are in the growth phase of CMR graph (see Figure 3.5); however, stands with defoliation scores within a range of 11.5 to 16.5 have been elected for spraying to delay their entrance to the growth phase.

The comparison of stand age classes for “No spraying” and “All spraying” scenarios (AAC = 4%) indicates that age classes 50, 70, and JIN will be given priority for harvesting over the other classes (Figure 3.17).

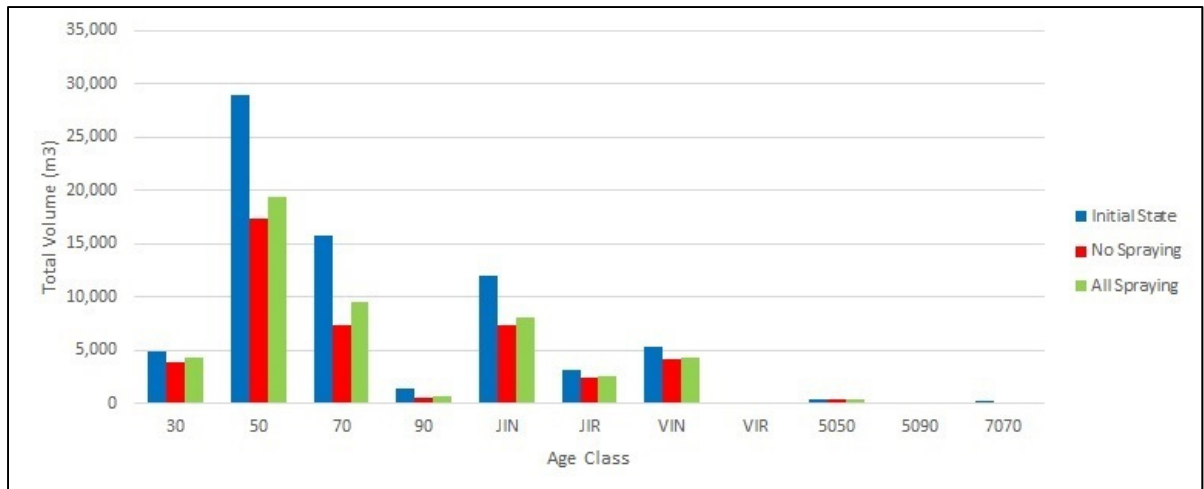


Figure 3.17 Comparison of age classes

Figure 3.18 provides a comparison of initial density classes with “No spraying” and “All spraying” scenarios when AAC is 4%. Density classes B and C constitutes large proportion of the harvested volume.

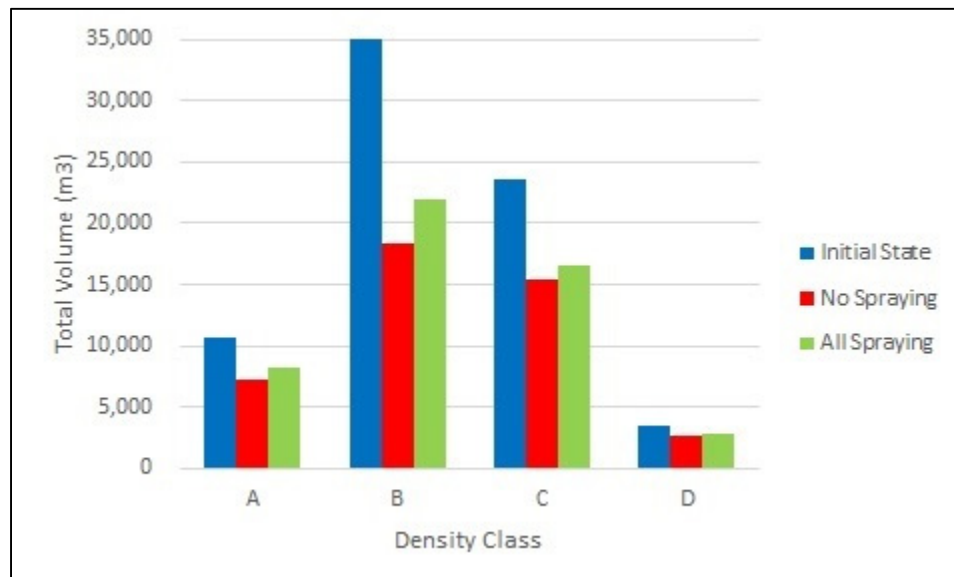


Figure 3.18 Comparison of density classes

One of the other parameters showing the volume density in a stand area is the ratio of the volume (m^3) to the area (ha). Figure 3.19 illustrates the changes of the density ratio during the

planning horizon for different levels of harvesting while the expected total volume is 56,000 m^3 .

To find the expected volume (56,000 m^3), the higher the harvesting level is, the smaller area should be sprayed to meet the expected volume. Therefore, the density ratio is increasing as the harvesting level increases (Figure 3.19), in other words, we can draw conclusion that if we are going to spray a stand, the density ratio should be high to justify the economic point of view of the spraying action.

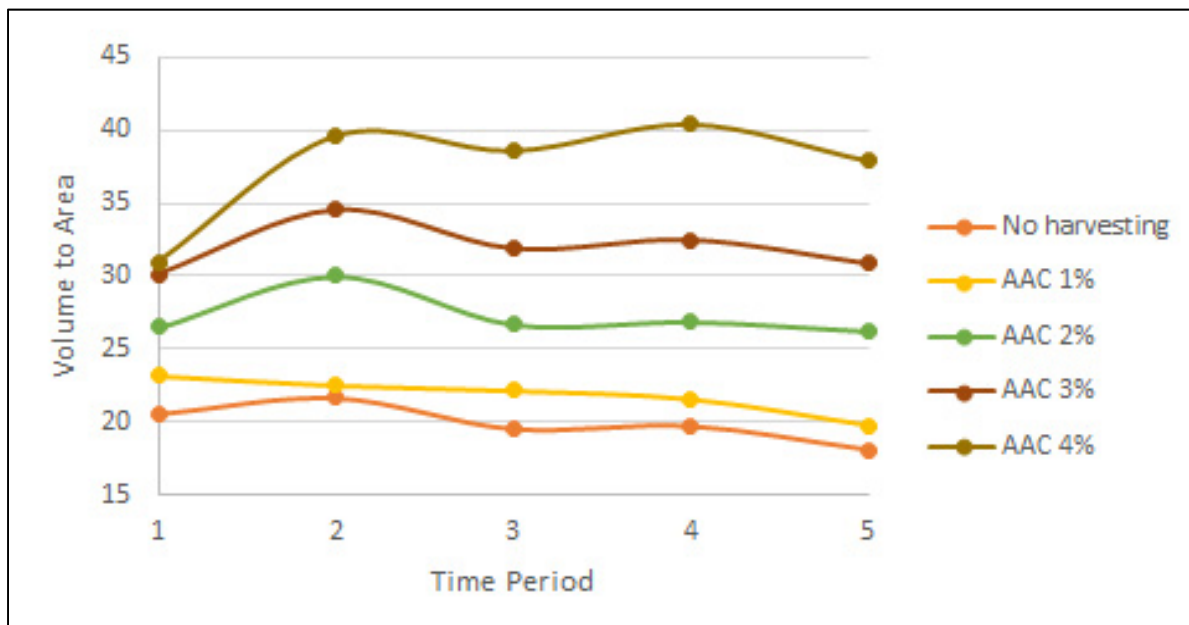


Figure 3.19 Variation of volume to area ratio (on average) by AAC for harvested and sprayed stands while the expected total volume is 56,000 m^3

3.6 Concluding remarks

Spruce budworm outbreak is one of the well-known natural disturbances in the Eastern Canada and wood loss and quality degradation are the major direct impacts of the outbreak. Stochastic optimization is one way to deal with uncertainty caused by natural disturbances. However, when the number of stands or period increases, the size of the problem increases exponentially.

Due to complexity, intractability, and long runtime of a stochastic programming model, we have proposed a deterministic model taking the wood losses into account based on cumulative defoliation score (CDS) and proportion of balsam fir and white spruce in the stands through forest. Two control methods, spraying and harvesting, have been used to deal with spruce budworm defoliation and mitigate the economic impacts of the outbreak. The results show that harvesting is highly beneficial when it comes to saving wood volume; however, if the objective is to save more woods, there is a need to perform spraying throughout the forest and the marginal cost of spraying per saved volume unit is increasing rapid. Moreover, results express that the higher the harvesting level will be, the higher net present value of harvested and standing volume can be obtained from the forest. Based on the harvesting decisions, we can draw conclusion that the harvesting priority goes for density classes B and C, and age classes 50, 70, and JIN. The proposed model does not take growth model into account and defoliation reduces the total volume during the planning horizon. According to the cumulative mortality curve, when cumulative defoliation score is between 15 and 20, the slope of mortality rate is steep, so stands within this range get the priority for harvesting and stands close to this range have high priority for spraying. Finally, stands with more than 70% of BF and WS are chosen for harvesting because in accordance with the cumulative mortality curve, the proportion of BF and WS defines the limiting point and consequently the slope of mortality rate. Therefore, the average of proportion of the BF and WS would decrease throughout the forest meaning lower slope for wood loss.

In this paper, we assumed that based on the tree mortality rate, there is a wood loss in the stand volume; however, tree mortality does not mean exactly wood loss. Dead trees can be salvage harvested and some volume can be recovered. So, salvage harvesting costs and benefits can be studied in future works. In addition, it was assumed that tree mortality is for all species in the stand; however, it is recommended to consider tree mortality only for vulnerable species to spruce budworm.

Results of the case study show that it is no longer economic to spray insecticide to reduce wood loss. To come to a firm conclusion, it has been suggested that different price levels could be

considered for different age classes, the spraying cost should be assumed to be 70 \$/ha instead of 40\$/ha, and finally, the analysis timeframe can be expanded to more than 5 years to find the effect of spraying on a longer planning horizon and consider the non-declining constraints.

For future research, we plan to develop heuristic solution methods to be able to solve larger sized MIP problems. Using the feature attributes of adjacent stands to find a better prediction for defoliation score in the following years can also be taken into account. Moreover, adding adjacency constraints for harvesting and spraying decisions can improve the practicality of the model.

3.7 Acknowledgement

We thank Mathieu Bouchard (MFFP), Sylvain Dallaire (MFFP), Frédéric Leblanc (BMMB), Cédric Fournier (MFFP), and Nicolas Girard (SOPFIM) for providing data. We also thank Simon Fortier (MFFP) and Louis Morneau (MFFP) for useful discussions. This work was supported by NSERC and FORAC Research Consortium at Université Laval (Québec, Canada).

CONCLUSION

This research aimed to find more about spruce budworm and then look for and evaluate control methods to deal with economic impacts of wood losses due to the spruce budworm outbreak. So, firstly, we studied the strategic forest management planning models to assess the economic impacts of the spruce budworm outbreak on the forest. We know that four to five years of sustained attack of spruce budworms can result in a large tree mortality, reduced growth rate, and reduced lumber quality in the forest. So, we study the impact of spruce budworms on the forest in tactical level with a planning horizon of 5 years.

While studying the strategic forest management planning models, we faced with some modeling mistakes in Model II. We have observed two mistakes in the original formulation. Having proposed a revised mathematical model for Model II, it was validated by solving the Model II with realistic data to address the modeling mistakes and explaining how our revised formulation works with the same data. I believe that it contributed to research in this domain.

In the second part of the thesis, we took outbreak intensity into consideration in our modeling to deal with spruce budworm outbreak and mitigate the economic impacts of it. During an insect outbreak, repeated defoliation can lower the lumber quality. So, different wood qualities with much-varied values can be found in the forest. Changes in the outbreak intensity impact wood values throughout the forest. We have developed a multistage stochastic mixed-integer programming model for harvest scheduling under various outbreak intensities to answer to the following questions: Which stands should be harvested? When they should be harvested? to maximize revenues of wood value minus logistic costs while satisfying industry demand for wood. Results show that stands with the lowest level of infestation get priority for harvesting during the outbreak. Wood pricing based on the quality was the strength of this model.

This model was at the tactical level. If we want to integrate it with the strategic forest management models, we must include the forest stand growth curve in our modeling. Based on our knowledge, there are different growth curves for different defoliation levels and

spraying strategies including the effect of defoliation and spraying on the stand volume. Therefore, more spraying decisions are expected to find at the strategic forest management level due to cost-benefit analysis.

To integrate our tactical model with an operational level, it is highly recommended to study the spruce budworm life cycle carefully and collaborate with entomologists and meteorologists to decide on the appropriate time for spraying and harvesting. Knowing the spruce budworm population, geographical information of the stands like elevation, average degree-days, soil drainage, and wind direction can help the system to have a better prediction of the defoliation in the stands. Moreover, monitoring the immigration of spruce budworms with satellite can also help in this matter.

The last part of the thesis studies two common control methods against spruce budworm outbreak and how they can mitigate the economic impacts of the outbreak. The main research questions are: Which stands should be harvested or sprayed? When they should be harvested or sprayed? Which treatment method is more efficacious? Which stands have priority for harvesting or spraying? We have developed a deterministic model maximizing revenues of harvested wood during the planning horizon minus logistic cost and maximizing the value of standing trees at the end of the planning horizon minus forest protection cost while satisfying industry demand for wood. One of the greatest advantages of this model is that it considers the wood loss and tree mortality into account based on feature attributes of the stand, defoliation history, and whether it has recently been sprayed or not. The developed model has been applied to a case study located in the Bas-Saint-Laurent region in Quebec. The results show that the efficacious treatment method is harvesting. Stands with more than 70% of balsam fir and white spruce or with defoliation score between 15 to 20 take high priority for harvesting. Results also imply that spraying is not economical to save wood; however, it can keep trees alive and lead to more total wood volume in the following years. Stands with high density ratio have top priority for spraying. In addition, stands with cumulative defoliation score close to the turning point of CMR curve have priority for spraying. Finally, the outcomes show that density classes B and C, and age classes 50, 70, and JIN have higher priority for harvesting.

FUTURE WORKS

In the last chapter, we improved the model by integrating two control methods against spruce budworms. There were some simplifying assumptions which can be improved in future models to tackle the real problem.

No one can cast doubt on the efficacy of spraying on spruce budworms and defoliation reduction; however, based on our results, we found that it is no longer economic to use against spruce budworms. I believe that there are two reasons: First, deriving transition matrices to find how the defoliation levels change in the next period without considering the impact of surrounding stands' feature attributes and geographical and meteorological parameters such as wind direction, temperature, and elevation during the immigration stage of budworms. The second reason is ignoring the impact of spraying on the wood volume. Lack of having a reliable mathematical formulation to quantify the effect of spraying on defoliation reduction and recovery of wood volume.

Therefore, studying the impact of surrounding cells attributes on the immigration and emigration of spruce budworms to/from the surrounding cells can be interesting. There are various parameters that can have impact on immigration and emigration of spruce budworms such as available food for budworms (percentage of balsam fir and white spruce), spraying, wind direction, temperature, elevation. Using machine learning technique can help researchers find appropriate weights for each parameter and provide a better defoliation prediction in the next year.

Spraying keeps the trees alive for the following years and it can prevent them from further defoliation and wood loss while our model only considers the tree mortality. It is recommended to include growth rate in the modeling in addition to mortality rate. Therefore, the model would be closer to the real application and probably find more about spraying in the outcomes. I know that it would be challenging but considering some simplifying assumptions can improve the results of the model.

Furthermore, finding a mathematical relationship between spraying strategies and defoliation level is difficult but obtaining this relationship can help the system consider the effect of spraying on the forest stands and make a better estimation of available wood volume in a stand. Decision variables of the model indicates which stands should be sprayed or harvested and when they should be sprayed or harvested. It would be great if researchers impose adjacency constraints for spraying and harvesting because if the model is going to be implemented in practice (operational level), we might incur higher spraying and harvesting costs due to different geographical locations of the spraying and harvesting decisions. The spray airplane should fly to a stand for spraying and then stop spraying and move to another area for spraying which increases the spraying cost in the system. Similar process can occur for harvesting teams and they must build new access roads to reach to specified stand for harvesting.

Stochastic optimization is one way to deal with uncertainty caused by natural disturbances like spruce budworm outbreak; however, when the number of stands or periods increases, the size of the problem increases exponentially. Due to complexity, intractability, and long runtime of a stochastic programming model, we have proposed a deterministic model. To solve the model for longer planning horizon, it is recommended to consider other techniques such as scenario reduction, dynamic programming, approximate dynamic programming, or metaheuristic algorithms to solve larger size models and reduce the runtime.

APPENDIX I

LINEARIZATION EQUATIONS IN THE DETERMINISTIC MODEL

Note that constraint set (2.3) is nonlinear, but it can be equivalently represented with the following linear inequalities:

$$L_{tip} \leq I_{tip} + (1 - X_{ti}) \times M, \quad \forall i = 1, \dots, I, p = 1, \dots, P, t = 1, \dots, T \quad (\text{I-1})$$

$$L_{tip} \geq I_{tip} - (1 - X_{ti}) \times M, \quad \forall i = 1, \dots, I, p = 1, \dots, P, t = 1, \dots, T \quad (\text{I-2})$$

$$L_{tip} \leq X_{ti} \times M, \quad \forall i = 1, \dots, I, p = 1, \dots, P, t = 1, \dots, T \quad (\text{I-3})$$

$$\left(\sum_{i=1}^I \sum_{p=1}^P L_{tip} \right) + Z_t \geq d_t, \quad \forall t = 1, \dots, T \quad (\text{I-4})$$

Constraint (2.4) can be rewritten as below:

$$\sum_{i=1}^I \sum_{p=1}^P L_{tip} \leq AAC, \quad \forall t = 1, \dots, T \quad (\text{I-5})$$

Since (2.5) and (2.6) are nonlinear, we can linearize them as follows:

$$I_{(t+1)i(p-1)} \leq I_{tip} + X_{ti} \times M, \quad \forall i = 1, \dots, I, p = 3, \dots, P, t = 1, \dots, T \quad (\text{I-6})$$

$$I_{(t+1)i(p-1)} \geq I_{tip} - X_{ti} \times M, \quad \forall i = 1, \dots, I, p = 3, \dots, P, t = 1, \dots, T \quad (\text{I-7})$$

$$I_{(t+1)i(p-1)} \leq (1 - X_{ti}) \times M, \quad \forall i = 1, \dots, I, p = 3, \dots, P, t = 1, \dots, T \quad (\text{I-8})$$

$$I_{(t+1)i1} \leq (I_{ti1} + I_{ti2}) + X_{ti} \times M, \quad \forall i = 1, \dots, I, t = 1, \dots, T \quad (\text{I-9})$$

$$I_{(t+1)i1} \geq (I_{ti1} + I_{ti2}) - X_{ti} \times M, \quad \forall i = 1, \dots, I, t = 1, \dots, T \quad (\text{I-10})$$

$$I_{(t+1)i1} \leq (1 - X_{ti}) \times M, \quad \forall i = 1, \dots, I, t = 1, \dots, T \quad (\text{I-11})$$

Constraint (2.8) is reformulated as below in order to make it linear.

$$I_{(t+1)ip} \leq I_{tip} + X_{ti} \times M, \quad \forall i = 1, \dots, I, p = 1, \dots, P, t = 1, \dots, T \quad (\text{I-12})$$

$$I_{(t+1)ip} \geq I_{tip} + X_{ti} \times M, \quad \forall i = 1, \dots, I, p = 1, \dots, P, t = 1, \dots, T \quad (\text{I-13})$$

$$I_{(t+1)ip} \leq (1 - X_{ti}) \times M, \quad \forall i = 1, \dots, I, p = 1, \dots, P, t = 1, \dots, T \quad (\text{I-14})$$

We can linearize (2.23) and (2.24) with equivalent linear inequalities:

$$I_{(t+1)i(p+1)} \leq I_{tip} + X_{ti} \times M, \quad \forall i = 1, \dots, I, p = 1, \dots, P - 2, t = 1, \dots, T \quad (\text{I-15})$$

$$I_{(t+1)i(p+1)} \geq I_{tip} + X_{ti} \times M, \quad \forall i = 1, \dots, I, p = 1, \dots, P - 2, t = 1, \dots, T \quad (\text{I-16})$$

$$I_{(t+1)i(p+1)} \leq (1 - X_{ti}) \times M, \quad \forall i = 1, \dots, I, p = 1, \dots, P - 2, t = 1, \dots, T \quad (\text{I-17})$$

$$I_{(t+1)iP} \leq (I_{ti(P-1)} + I_{tiP}) + X_{ti} \times M, \quad \forall i = 1, \dots, I, t = 1, \dots, T \quad (\text{I-18})$$

$$I_{(t+1)iP} \geq (I_{ti(P-1)} + I_{tiP}) - X_{ti} \times M, \quad \forall i = 1, \dots, I, t = 1, \dots, T \quad (\text{I-19})$$

$$I_{(t+1)iP} \leq (1 - X_{ti}) \times M, \quad \forall i = 1, \dots, I, t = 1, \dots, T \quad (\text{I-20})$$

APPENDIX II

LINEARIZATION EQUATIONS IN THE MULTI-STAGE STOCHASTIC MODEL

Because of the nonlinearity of the constraint (2.15), it should be equivalently represented with the following linear inequalities:

$$L_{stip} \leq I_{tip} + (1 - X_{sti}) \times M, \quad \forall i = 1, \dots, I, p = 1, \dots, P, t = 1, \dots, T, s = 1, \dots, S \quad (\text{II-1})$$

$$L_{stip} \geq I_{stip} - (1 - X_{sti}) \times M, \quad \forall i = 1, \dots, I, p = 1, \dots, P, t = 1, \dots, T, s = 1, \dots, S \quad (\text{II-2})$$

$$L_{stip} \leq X_{sti} \times M, \quad \forall i = 1, \dots, I, p = 1, \dots, P, t = 1, \dots, T, s = 1, \dots, S \quad (\text{II-3})$$

$$\left(\sum_{i=1}^I \sum_{j=1}^J \sum_{p=1}^P L_{stip} \right) + Z_{st} \geq d_t, \quad \forall t = 1, \dots, T, s = 1, \dots, S \quad (\text{II-4})$$

Constraint (II-5) will be substituted for (2.16) in order to linearize the above inequality:

$$\sum_{i=1}^I \sum_{j=1}^J \sum_{p=1}^P L_{stip} \leq AAC, \quad \forall t = 1, \dots, T, s = 1, \dots, S \quad (\text{II-5})$$

Note that the constraints (2.17) to (2.19) are nonlinear, so we need to linearize them with equivalent inequalities as below:

$$I_{s(t+1)i1} \leq (a_{st1} \times 0 + b_{st1}I_{sti1} + c_{st1}I_{sti2}) + X_{sti} \times M, \quad \forall i = 1, \dots, I, t = 1, \dots, T, s = 1, \dots, S \quad (\text{II-6})$$

$$I_{s(t+1)i1} \geq (a_{st1} \times 0 + b_{st1}I_{sti1} + c_{st1}I_{sti2}) - X_{sti} \times M, \quad \forall i = 1, \dots, I, t = 1, \dots, T, s = 1, \dots, S \quad (\text{II-7})$$

$$I_{s(t+1)i1} \leq (1 - X_{sti}) \times M, \quad \forall i = 1, \dots, I, t = 1, \dots, T, s = 1, \dots, S \quad (\text{II-8})$$

$$I_{s(t+1)ip} \leq (a_{stp}I_{sti(p-1)} + b_{stp}I_{stip} + c_{stp}I_{sti(p+1)}) + X_{sti} \times M, \quad \forall i = 1, \dots, I, p = 2, \dots, P - 1, t = 1, \dots, T, s = 1, \dots, S \quad (\text{II-9})$$

$$I_{s(t+1)ip} \geq (a_{stp}I_{sti(p-1)} + b_{stp}I_{stip} + c_{stp}I_{sti(p+1)}) - X_{sti} \times M, \quad \forall i = 1, \dots, I, p = 2, \dots, P - 1, t = 1, \dots, T, s = 1, \dots, S \quad (\text{II-10})$$

$$I_{s(t+1)ip} \leq (1 - X_{sti}) \times M, \quad \forall i = 1, \dots, I, p = 2, \dots, P - 1, t = 1, \dots, T, s = 1, \dots, S \quad (\text{II-11})$$

$$I_{s(t+1)ip} \leq (a_{stp}I_{sti(p-1)} + b_{stp}I_{stiP} + c_{stp} \times 0) + X_{sti} \times M, \quad \forall i = 1, \dots, I, t = 1, \dots, T, s = 1, \dots, S \quad (\text{II-12})$$

$$I_{s(t+1)ip} \geq (a_{stp}I_{sti(p-1)} + b_{stp}I_{stiP} + c_{stp} \times 0) - X_{sti} \times M, \quad \forall i = 1, \dots, I, t = 1, \dots, T, s = 1, \dots, S \quad (\text{II-13})$$

$$I_{s(t+1)ip} \leq (1 - X_{sti}) \times M, \quad \forall i = 1, \dots, I, t = 1, \dots, T, s = 1, \dots, S \quad (\text{II-14})$$

APPENDIX III

LINEARIZATION EQUATIONS IN THE DETERMINISTIC MODEL

Note that constraint (3.9) is nonlinear and can be equivalently represented with the following linear inequalities:

$$v_{t''i} \leq \left(1 - \sum_{t=0}^{t''} y_{ti}\right) \times M, \quad \forall i \in I, t'' \in T \quad (\text{III-1})$$

$$v_{t''i} \leq g(ds_{t''i}), \quad \forall i \in I, t'' \in T \quad (\text{III-2})$$

$$v_{t''i} \geq g(ds_{t''i}) - \left(\sum_{t=0}^{t''} y_{ti}\right) \times M, \quad \forall i \in I, t'' \in T \quad (\text{III-3})$$

Constraint (3.10) is reformulated as below in order to make it linear.

$$hv_{ti} \leq y_{ti} \times M, \quad \forall i \in I, t \in T \quad (\text{III-4})$$

$$hv_{ti} \leq v_{(t-1)i}, \quad \forall i \in I, t \in T \quad (\text{III-5})$$

$$hv_{ti} \geq v_{(t-1)i} - (1 - y_{ti}) \times M, \quad \forall i \in I, t \in T \quad (\text{III-6})$$

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