# TIMBER SUPPLY AND ECONOMIC IMPACT OF MOUNTAIN PINE BEETLE SALVAGE STRATEGIES

by

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**Abstract**

To address the scale mountain pine beetle (MPB) outbreak in British Columbia, salvage has become fully integrated with timber supply strategies. The objective of this thesis is to assess the economic impact of different salvage strategies depending on different attack levels, decay rates, and stakeholder discount rates. The study area is located in N.E. British Columbia where the MPB has not yet reached its peak and where susceptible to attack stands account for 40% of the area. Salvage strategies were modelled with a timber supply model (Woodstock) which uses a linear programming type II optimization approach. Performance of the model was assessed over a range of indicators such as NPV, profit, salvage proportion, species composition, inventory levels, and non-recoverable volume. Sensitivity analyses were conducted on harvest flow, discount rate, and ending inventory. The model was very sensitive to the intensity of attack and less sensitive to the decay level. The high level of attack resulted in large volume losses, mostly as un-salvaged inventory.

Although allowable annual cut (AAC) uplifts have an economic benefit, they do not necessarily maximize the salvage of pine. Non-pine species are an important component of the salvage and these species are also essential for the future timber supply. If the objective is to ensure quality and quantity of the future forest, policies have to complement AAC uplifts by strongly encouraging the salvage of mainly pine-leading stands and management options that minimize the "by-catch" of non-pine species and minimize destruction of advanced regeneration during salvage. However, this has an opportunity cost for the private industry where the objective is to maximize profit. If the salvage strategy focuses on decreasing the impact on cash flows, achieving desirable ending inventory levels, avoiding salvage of stands after shelf-life, and reducing impact on non-attack species, then the current harvest level will likely lead to a mid-term timber supply fall-down. Using the fibre for bioenergy production is an alternative if managing for bioenergy can be integrated into harvest operations. However, unlike mill residues, the bioenergy supply has to fully account for harvest and transportation costs of dead wood to the mill.

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## Dedication

***To my parents***

***A mis padres***

## 1. Introduction

British Columbia, Canada, is currently experiencing the largest recorded mountain pine beetle (*Dendroctonus ponderosae*) outbreak in North America. This forest health epidemic is a catastrophic natural disturbance and is causing widespread mortality of lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.), the interior's most abundant commercial tree species (BCGOV 2005). Eng *et al.* (2006b) projected a total standing dead volume by 2005 of 450 million $m^3$, approximately 30% of the total provincial pine volume. The same authors project a total of ~950 million $m^3$ of killed pine by 2016, when the outbreak is supposed to reach its asymptote.

The mountain pine beetle (MPB) is an important ecological component of lodgepole pine forest dynamics and lodgepole pine has been an important raw material of the North American forest industry. The history and biology of the MPB and its interaction with the forest industry has been widely reviewed (e.g. Fahey *et al.* 1986, Koch 1996, Snellgrove and Fahey 1977, Safranyik *et al.* 1974, Safranyik and Wilson 2006). The level and intensity of the current outbreak has tremendous economic implications (Wagner *et al.* 2006).

The effects of the MPB are mainly concentrated on mature stands with a high density of lodgepole pine. There is also some evidence that MPB can attack trees with smaller diameters when larger diameter trees become scarce, potentially increasing the level of impact on the landscape (Bailey 2006, Hawkins 2006). The MPB carries blue stain fungi dominated by *Ophiostoma clavigerum* (Robinson-Jeffrey & Davidson) Harrington and *Ophiostoma montium* (Rumbold) von Arx (Kim *et al.* 2005). The beetle and the fungi produce minor physical defects like cavities and stains, but they eventually kill the tree.

The current MPB outbreak has serious implications for the sustainability of the forest industry. There are huge social and biological costs; Manning (1982, cited by Wagner *et al.* 2006) summarized five economic impacts: 1) impact on product values, 2) changes in forest management costs, 3) impact on allowable cut and value of output, 4) impact on resource flows, and 5) changes in protection costs.

The MPB outbreak is expected to result in the loss of 206 million $m^3$ of non-recovered merchantable volume by 2016 (Eng *et al.* 2006c). The merchantable volume of a forest is usually used for pulpwood, saw logs, and other high quality lumber products (e.g. poles, peelers). This merchantable loss is due to decay, blue stain, and checking (Lewis *et al.* 2006, Byrne *et al.* 2006, Work 1978). The low moisture content becomes a problem for wood processing (Giles 1986). Nielson and Wright (1984, cited by Giles 1986) presented a summary of the main difficulties for sawmill operations when processing attacked wood (See Appendix 1).

Besides the loss of value of the merchantable volume, Byrne *et al.* (2006) suggested that large losses are associated with handling. Work (1978, cited by Byrne *et al.* 2006) found that trees four years after death were 11% more susceptible to breakage than green trees. The process of falling, skidding, loading, hauling, decking and feeding mills involves handling the wood with large machinery. Each of these phases is associated with handling losses (Byrne *et al.* 2006). Dobie and Wright (1978) found that the operating costs for the first three stages of decay were similar, but were about 30% greater for the final, grey, loose-bark category. They also found that the difference in tree quality between the early stages of attack (green top) and the late stages (grey loose-bark) was about 11%, resulting in a negative net value for the latter. There are some estimations that incremental handling and administration costs will rise by 10 CAD$/$m^3$ for beetle salvaged timber (BCMOF 2001).

Following MPB attack there are three factors that affect the supply of potential products: 1) there is a diminishing rate of growth of the stand, 2) reduced shelf-life, and 3) how the different proportions of potential lumber products change during that shelf-life. The concept of shelf-life is related to food degradation. In the case of MPB attack, Thrower *et al.* (2005) define shelf-life as "the time that MPB-killed lodgepole pine wood is suitable for a specific use. Therefore, the shelf-life of the wood is inextricably linked to the product of interest". Some other authors use the concept of Time-Since-Death (TSD) to describe any potential merchantable use after lodgepole pine has been attacked (Lewis and Hartley 2006). Dobie and Wright (1978) and Snellgrove and Fahey (1977) were among the first to identify a relationship between lumber grades and time since attack.

Snellgrove and Fahey (1977) reported a near total loss of the highest lumber grade and an overall average loss in tree value of 69%, when comparing live pine trees with trees dead at least six years. A recent study concluded that five years after attack logs yielded 12.5% less lumber and 17.5% less value than green logs (Barrett and Lam 2007). Other studies have found that the decay level differs depending on the diameter (Fahey *et al.* 1986, Lewis *et al.* 2006, Snellgrove and Fahey 1977). Lewis and Hartley (2005) found that the rates of recovered lumber and chips decrease over time and are related to the climatic moisture regime (i.e. Wet Subzones and Dry Subzones). The percentage of recovered volume drops to zero for both lumber and chips 24 years after attack in Dry Subzones and after 18 years in Wet Subzones (Lewis and Hartley 2005). These two estimates of shelf-life were used by Eng *et al.* (2006a) for the provincial-level projection model of the current MPB outbreak. The shelf-life of attacked pine is a contentious issue and there is some evidence that it could be much shorter than these predictions (BCMOF 2007a, Pedersen 2004, Pousette and Hawkins 2006). The amount of volume and time required to salvage MPB-affected wood will depend not only on the quality of the raw material but also on the processing technology. Orbay and Goudie (2006) concluded that around 30% of the merchantable volume losses were due to poor log conditions and 70% due to actual sawing technology. There is a lack of information related to the shelf-life following attack and it is among the high priority research needs recognised by Byrne *et al.* (2006).

The projected levels of non-recoverable losses have increased the Province's interest in exploring opportunities of using this beetle-killed wood as source of energy. Due to climate change concerns and new energy policies, bioenergy has become important. Forest biomass could play an important role as a bioenergy supply and could have a positive economic impact for the forest industry. Indeed, new policies have been developed to support bioenergy initiatives both provincially and internationally. For example, BC has a new energy plan with a greater emphasis on efficiency, alternative energy, conservation, and innovation (Larson 2006). Although process residues (e.g. sawdust) are already widely used as bioenergy, mainly by the wood manufacturing industry, salvaging non merchantable wood is a different case. In the case of salvaged timber for bioenergy, the main concerns are the cost of production and transportation of this raw material to a processing facility. This is a key constraint in an industry where transportation and raw material costs are two of the highest items in the supply chain (Mani *et al.* 2006, Searcy *et al.* 2007, Sokhansanj and Turhollow 2004). Other studies show that without some external incentives, the production costs of bioenergy are too high to compete against traditional fossil fuels (Mani *et al.* 2006, Stennes and McBeath 2006).

The choice to use beetle-attacked wood for traditional sawn products or as a source of bioenergy is largely dependent upon the time after attack that wood retains (commercial) merchantable quality. How the forest industry minimizes the losses through salvage operations without affecting the medium term timber supply is a major concern. Pousette and Hawkins (2006) suggest that the current optimistic timber supply assumptions may result in a mid-term timber supply fall-down. Some authors suggest an alternative to mitigate these effects is by focusing the salvage strategies in lodgepole pine dominated stands with low levels of advance regeneration, thereby allowing non-pine stands or stands with advanced regeneration to contribute future volumes (Burton 2006, Griesbauer and Green 2006).

The current provincial policy is to salvage as much merchantable volume as possible. This policy is stated as the third objective on the BC Action plan: "Recover the greatest value from dead timber before it burns or decays, while respecting other forest values" (BCGOV 2005, BCGOV 2006). This policy is reflected by uplifts of the allowable annual cut (AAC) in most of the timber harvesting land base (THLB). Before August 2003, seven uplifts to mitigate MPB losses were approved in areas most affected by MPB. These uplifts represent more than 9% (6.8 million $m^3$/year) of the total AAC of the Province of British Columbia (BCMOF 2003).

New strategic and tactical planning has to be developed to mitigate the impacts of this outbreak and to support decision makers. These models have to reflect the decreased value of the timber products and the potential increase of new energy products. A decrease in the quality of the raw material, a lack of road infrastructure (Eng *et al.* 2006c), and an increase in the management costs requires that management activities be planned with greater care. A higher proportion of stands are becoming non-profitable for the traditional forest industry when pine lost its economic value, at least in the short- to med-term. To be successful in reducing economic and ecological impacts of mountain pine beetle, new strategic management approaches must be conceived (Wagner *et al.* 2006).

## 1.1. Objectives

The main objective of my thesis is to assess the economic impact of a MPB attack under different intensities of attack, different lengths of shelf-life and different salvage strategies. To accomplish this objective I will: (1) quantify the differences in volume, profit and type of product under different scenarios of attack, decay and salvage, (2) identify strategies that can maximize the salvage volume in the short-term without producing a fall-down in the medium term timber supply, (3) assess how a public salvage strategy might differ from a private salvage strategy, and (4) analyse the supply of non-recovered volume for possible bioenergy uses.

In this thesis, I analyse the impact of a MPB attack on a smaller scale compared to the provincial scale done by other authors (e.g. BCMOF 2003, BCMOF 2007a, Eng *et al.* 2006b, Eng *et al.* 2006c, Pousette and Hawkins 2006). My study examines harvest scheduling in an area where the outbreak has not yet reached its peak and where pine forms a lower composition of the forest than in previous studies. This allows me to analyze a more resilient forest, compared to other areas where the impact has been massive. I focus my analysis on different salvage strategies, the amount of salvage, the species salvaged (pine plus by-catch species), the inventory, and the economic implications. All analyses consider the short-term impact during attack and shelf-life (two decades) and the medium term impact after the shelf-life (five decades). I also address the conflict that may exists between a private salvage (industrial) strategy and a public salvage strategy that differ in the scale of salvage operations and the species that are being salvaged.

The thesis is organized as follows: The second chapter introduces the concepts of natural disturbances and uncertainty, and also the type of models used for timber supply analyses. In the third chapter I describe the methods including the study area and the management objectives. I also describe two base scenarios and four other scenarios to represent different intensities of attack and decay rates. The methods chapter continues with specific issues on modelling, a description of the inventory valuation method, and other assumptions. Finally, the methods chapter finishes with a mathematical formulation of the model, the sensitivity analysis, and the computer requirements used. In the fourth chapter I present my results and a discussion on how an equal harvest level can represent several salvage strategies, with different implications according to the scenarios modelled. The fifth chapter provides a general discussion, including limitations of the model and suggestions for further refinements. The thesis finishes with my concluding remarks.

## 2. Timber supply, forest stand-level models, and linear programming

Forecasting timber supply is a major issue in forest economics (Yoshimoto 2001). Timber supply is defined as “the quantity of timber available for harvest over time. Timber supply is dynamic, not only because trees naturally grow and die, but because conditions that affect tree growth, and the social and economic factors that affect the availability of trees for harvest, change through time” (BCMOF 2003). The forest industry has high capital requirements and has generally mid- to long-term capital returns and timber supply analyses are used to project the availability of sufficient raw material for future investments. To successfully maintain the forest industry, forest-level planning must ensure that there are always stands at the right stage of development and in sufficient number to yield the desired product mix coming from the forest (Gadow and Puumalainen 2000).

The classic forest management approach has been defined as “the human intervention into nature, extent, and timing of disturbance to forest ecosystems for the purposes of obtaining desired good and services” (Haeussler and Kneeshaw 2003). We have moved towards an ecosystem management approach that tries to incorporate the understanding of natural disturbances. The main message of natural disturbance studies is that the dynamics of ecosystems can not be understood without considering natural disturbances at different scales of time and space (Johnson *et al.* 2003). Thus, the representation of natural disturbances in timber supply models has been an important research topic. The main assumption is that timber harvest practices should mimic natural disturbances while retaining the range of natural variation in sustainable ecosystems (Armstrong *et al.* 1999). The problem is that not all natural disturbances can be emulated by harvesting and/or other anthropogenic activities. Therefore, the landscape pattern will always be a product of both natural disturbances and forest management practices (Johnson *et al.* 2003) and this needs to be reflected in timber supply analyses.

It is difficult to include natural disturbances in any type of timber supply modelling because they are difficult to predict in spatial distribution, temporal distribution, and/or intensity of impact. Therefore, decision making and planning must be carried out in an intrinsically stochastic environment. Forest management outcomes are often highly uncertain, and thus a ‘best practice’ may not exist (Bormann and Kiester 2004) and there is no single ‘optimal’ solution for these problems (Nelson 2003). Uncertainty is always present in natural systems and ignoring it can lead to poor management decisions (Regan *et al.* 2005).

Before proceeding, it is necessary to clarify the terminology related to uncertainty and natural disturbances. Zimmermann (2000) defined uncertainty as: “implies that in a certain situation a person does not dispose about information which quantitatively and qualitatively is appropriate to describe, prescribe or predict deterministically and numerically a system, its behaviour or other characteristic”. Related to natural resources management, Mowrer (2000) stated that uncertainty results: “from the inherent variability in the prediction of alternative states of nature and of natural processes over time”. Kangas and Kangas (2004) detailed several ways that uncertainty has been classified by previous authors. Ferson and Ginzburg (1996) distinguished two broad types of uncertainty: *objective* uncertainty arising from variability of the underlying stochastic system (*variability*) and *subjective* or epistemic uncertainty resulting from not having complete information about that system (ignorance). According to Ferson and Ginzburg (1996), *ignorance* can usually be reduced by additional study or by improving the techniques of measurement and *variability* is independent of an empirical study of it (e.g. temporal or spatial variability). Thus, natural disturbances are a type of *objective* uncertainty.

Risk is another concept often mixed with uncertainty. Risk is the case where we are able to estimate or assign occurrence probabilities to each state of nature (Davis and Johnson 1987). Risk has also been defined as the expected loss due to a particular hazard for a given area and reference period (United Nations 1992, cited by Gadow 2000). An expected loss is the product of the damage and its probability, where damage is the loss expressed in monetary terms (Gadow 2000). In forestry, the damage associated with natural disturbances is an increase of the harvest costs (salvage), a decrease in the log price (quality), and the cost of forgone opportunities. Mowrer (2000) defined risk as a function of two independent factors: potency (the severity of an adverse affect) and exposure (the likelihood of encountering the effect) and mentioned that human perceptions play an important role in risk evaluation.

When are natural disturbances significant enough to be considered in the planning process? Ecologists generally recognize the traditional meaning of disturbance as an event that is massively destructive and rare, but they also consider disturbances to be normal events in the course of ecosystem dynamics (Rykiel 1985). For White and Pickett (1985) a disturbance is "any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment". The disruption includes any environmental fluctuations and destructive events, whether or not these are perceived as 'normal' for a particular system (White and Pickett 1985). What constitutes disturbance, as opposed to normal fluctuation, is dependent on the scale of observation as well as the level of biological organization being considered (Baker 1992). Natural disturbances can be classified by the type of origin: *biotic* (e.g. biological mechanisms, pests and disease occurrence, and change in soil productivity) and *abiotic* (e.g. wildfires, wind throw, snow, floods, hurricanes, volcanic eruptions, and landslides). For the purposes of this study, natural disturbance is a catastrophic event that results in significant losses. For the forest manager, these disturbances are mostly unpredictable and largely uncontrollable and affect the sustainability of timber and other outputs (Armstrong *et al.* 1999).

Several authors have included natural disturbances as sources of uncertainties in timber supply analyses (Armstrong 2004, Klenner *et al.* 2000, Peter and Nelson 2005, Reed and Errico 1987). It is up to the modeller whether to explicitly include uncertainty in the model or not. Scenario analysis has been extensively used to include uncertainty in decision making processes. Based on probabilities of uncertain events, alternative scenarios of these events are evaluated to determine the most reasonable management alternative (Mowrer 2000) and to answer *what if* questions related to a particular path (Gadow 2000). von Gadow and Puumalainen (2000) noted that scenario planning can reduce uncertainty by anticipating the future in a systematic way, thus reducing the likelihood of unexpected events. Brumelle *et al.* (1990) stated that the use of sensitivity analysis or experimentation with multiple scenarios is an informal method to introduce uncertainty into the forest-management decision framework. The use of 'optimistic' versus 'pessimistic' scenarios provide the decision maker with a sense of the possible range of outcomes associated with specific solutions, but without an explicit assessment of their likelihood (Brumelle *et al.* 1990).

A wide variety of models have been used for timber supply analyses and all these models have a high level of complexity. The analyst has to fully understand the model behaviour and its results, plus clearly communicate this to the public (Nelson 2005). A good model has to represent a complex problem in a simple way and in reasonable time and therefore is a balance between complexity and solution time.

Timber supply models can be classified into two types: *simulation* and *optimization*. Some of the advantages of simulation models mentioned by Nelson (2005) are: they are easy to understand and use, can work with large size problems with fast solution times, and can track many stand attributes. However, the simulation models only assess a reduced proportion of all possible strategies, require user inputs to guide the solution, and they do not produce optimal solutions (Nelson 2005).

Timber supply models can also be *deterministic* or *stochastic*, have *continuous* or *integer (mixed-integer)* variables, and be *linear* or *non-linear*. In a deterministic model the value assigned to each parameter is a known constant (Hillier and Lieberman 2001) and variables are not subject to random fluctuations, so that the system is at any time entirely defined by the initial conditions chosen[a]. In stochastic models some or all of the parameters are random and defined by known probability distributions (Nelson 2005). Continuous models can have fractional decision variables (Davis *et al.* 2001) but when spatial analysis is required, some of the decision variables are forced to be binary (Nelson 2005). The models are linear when there is a linear relationship between the decision variables and non-linear when they involve other relationships (i.e. products, power, and logarithms) (Davis *et al.* 2001).

[a] http://www.biology-online.org/dictionary/Deterministic_model (visited 15/01/2008)

Optimization models can use either *exact* or *heuristic* solution techniques. The best solution technique is exact because it finds the optimum. When problems increase in size and have long solution times, heuristics are the preferred method because they provide results with less computational effort (Davis *et al.* 2001). One problem with heuristics is that they neither guarantee optimality nor provide any indication of how close their solutions are to being optimal (Reeves 1993, cited by Crowe and Nelson 2005). Harvest scheduling problems that include spatial requirements are usually integer problems and heuristics have become powerful tools to solve them (Nelson 2003). Finally, Bettinger and Chung (2004) conclude that strategic plans that attempt to develop broad (non-spatial) strategies related to harvest levels, habitat levels, and economic expectations, will most likely continue to utilise linear programming (LP) because of its ability to find an exact solution in a reasonable time.

Linear programming is widely used for forest estate planning. LP has been used in forest planning systems starting with TimberRAM (Navon 1971), MAX-MILLION (Ware and Clutter 1971), FOLPI (García 1984), and FORPLAN (Johnson *et al.* 1986, Johnson and Stuart 1986). These early computer LP-based models were followed by MELA (Siitonen 1993), GAYA-LP (Naesset *et al.* 1997), SPECTRUM (Camenson *et al.* 1996), and WOODSTOCK (Walters 1994).

Johnson and Scheurman (1977) presented two LP formulations for harvest scheduling that are widely used. The two general formulations are: Model type I and Model type II. Later on, a third model was simultaneously developed by García (1984), Reed and Errico (1986), and Gunn and Rai (1987). This last model was called Model type III by Gunn (1991) and by Boychuk and Martell (1996). García (1990) named the Model types A, B, and C for the Model types III, II and I, respectively and Reed and Errico (Reed and Errico 1989) described Model type III as LP1, demonstrating that it could be equivalent to a Model type II (LP2). All three models usually have an objective function that maximizes Net Present Value (NPV) or total volume to be harvested.

These three LP models are essentially equivalent in their power for describing and solving strategic forest planning problems (García 1990). The decision of which formulation to use depends on the problem being addressed and on the interests of the analyst and stakeholders (Davis *et al.* 2001). In Appendix 2, I describe the basic mathematical formulation of the three LP harvest scheduling models.

Some of the main differences are that Model type I defines decision variables that follow the life history of a hectare over all planning periods while Model type II defines decision variables that follow the history of a hectare over the life of a stand growing on that hectare, from its birth (in one planning period) through its death (in a subsequent planning period) (Sessions *et al.* 1996). Model type I preserves intact the area of each treatment unit throughout the planning horizon (Johnson and Scheurman 1977). In Model type II, regenerated stands are detached from the existing stands and new decision variables are defined for them. Therefore, a hectare may pass through several decision variables as stands are born, live, and die (Sessions *et al.* 1996).

One of the disadvantages of Model type II is that it is hard to keep track of the stands because they can be merged after any treatment or activity occurs (Gunn and Rai 1987, Johnson and Scheurman 1977, Sessions *et al.* 1996). Thus, it is difficult to track individual stands over the planning horizon, thus making spatial analysis difficult. The opportunity of merging and creating new management units through the time is also one of the biggest advantages of the Model type II, because it allows us to explore more choices in the future and to create new management types. This aggregation is optional and in Model type II it is also possible to maintain the identity of the stand if so desired (García 1990).

Model type II and III can be represented as flow of areas through a network, but the network of Model type II is less detailed (Gunn 2007). There are two essential differences between Model type II and III. The Model type III includes a state variable to describe the period-to period transitions of the forest and areas above a certain age can be classified as one collector age-class (Boychuk and Martell 1996, García 1984, Reed and Errico 1989). If that certain age is equal to the oldest possible age that a stand can reach over the planning horizon and if you transform or eliminate the state variable, the differences vanish and the two model types become identical (Reed and Errico 1989).

Extensions of these models for uncertainty, natural disturbances and other complex variables are common. Hoganson and Rose (1987) built a stochastic linear programming model based on Model type I. Johnson *et al.* (1986) described how to deterministically include fires or stochastic losses in a Model type II. A Model type III approach was used by Reed and Errico to consider losses due to fire (1986) and to assess the effect of pest hazards (1987), and by Gunn and Rai (1987) for long-term planning in a integrated industry structure. Then, Gassmann (1989) and Boychuk and Martell (1996) formulated a multistage stochastic programming model based on Model type III. The use of stochastic programming to study forest planning, even when there are few analysis areas, can result in very large LP formulations that make this technique impractical for many forest planning problems (Sessions *et al.* 1996).

## 3. Methods

This chapter describes the study area and the forest management objectives. I then describe the base scenarios and the attack scenarios, follow by a description and mathematical formulation of the decision model. This chapter ends with a description of the sensitivity analysis to be conducted and the computer requirements.

### 3.1. Study area

The study area is Tree Farm License 48 (TFL 48). It is held by Canadian Forest Products Ltd. and consists of five supply blocks in the western half of the Dawson Creek Forest District (Baker 2001). The four main commercial species of the study area are sub-alpine fir (also called balsam fir) (*Abies lasiocarpa*), spruce (*Picea glauca* or white spruce, *P. engelmannii* or Engelmann spruce, and their crosses), trembling aspen (*Populus tremuloides*), and lodgepole pine (*Pinus contorta*). A large proportion of these species exist in mixed-wood stands comprising two or more species (Benskin 2007).

The easternmost part of the TFL is characterized by flat or gently rolling terrain, while the southern and western parts are more rugged, lying within the Rocky Mountains. The four biogeoclimatic zones located in the TFL are the Boreal White and Black Spruce (BWBS), Sub-Boreal Spruce (SBS), Engelmann Spruce-Subalpine Fir (ESSF) and Alpine Tundra (AT) (Benskin 2007).

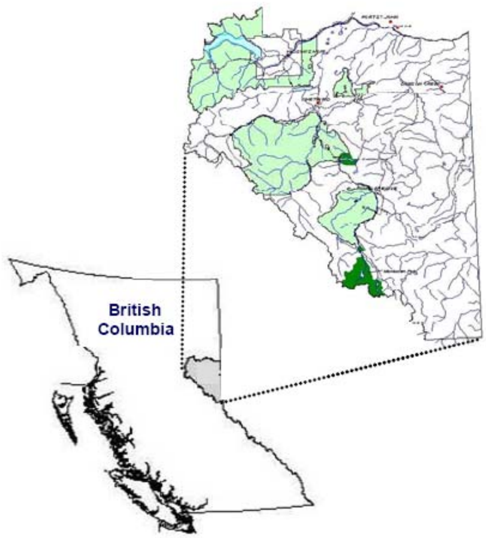


**Figure 3.1. Illustration showing the location of the study area within northeastern British Columbia (not to scale). Source: CANFOR Ltd.**

All baseline data were taken from the following project: "Exploring opportunities for mitigating the ecological impacts of current and future mountain pine beetle outbreaks through improved planning: A focus on Northern BC" (Seely *et al.* 2007). This spatial database includes a description of all polygons (ecological and economical), the respective yield curves, and stand successional options (Nelson *et al.* 2006, Seely *et al.* 2007).

TFL 48 is approximately 651,000 ha of which about 53% (345,480 ha) is defined as the timber harvesting land base (THLB). Only the THLB area will be considered in this study. I assume that the stands susceptible to Mountain Pine Beetle attack will have lodgepole pine as one of three main species with a percentage > 25% and an age greater than 40 years (Seely *et al.* 2007). Therefore, 142,809 ha (41%) are considered as susceptible to attack. The number of polygons and the THLB area by attack susceptibility are summarized in Table 3.1. These polygons were grouped to build the management units that form the basis of the Type II LP decision model, which is described later in this chapter.

**Table 3.1. Area distribution of the Timber Harvesting Land Base of TFL #48.**

| Description | # of polygons | Area (ha) | Percentage of THLB area |
|---|---|---|---|
| Polygons with pine percentage > 25% and age greater than 40 years, susceptible to attack | 36,791 | 142,809 | 41% |
| Other polygons, including young pine, spruce, mixed wood, deciduous, and sub-alpine fir stands | 49,835 | 199,050 | 58% |
| Missing data * | 872 | 3,620 | 1% |
| Total | 87,498 | 345,480 | 100% |

* Missing data correspond to polygons without a BEC classification or without the harvest system information to build the cost component.

### 3.2. Forest management objectives

The model represents four consecutive attacks during the first four planning periods. BCMOF (2003) describes two approaches for modelling the mountain pine beetle attack: 1) the area approach and 2) the volume approach. These approaches constrain the model to a certain level of area attacked or to a certain level of volume attacked (e.g. MPB will "kill" 50% of the area or 50% of the volume, respectively). For this study the attack will be restricted by a percentage of the area of susceptible stands in each respective period.

Following the labels shown in Figure 3.2, a 'Pine Natural Stand' is a susceptible to attack and can follow two management options: 1) **attack** or 2) **non-attack**. An attacked stand can follow two management options: 1) **salvage** or 2) **decay**. These options following an attack are repeated for the first four periods. If the attack scenario does not represent an outbreak of 100%, some of the susceptible stands can age as non-attacked stands. These stands can be harvested and regenerated as 'Managed Stands' or remain as standing inventory. An attacked stand can also remain as standing inventory, following the last decay transition.

The salvage treatment uses the same volume yield curve as the natural stands, but uses different merchantability rates for the percentage of various products recovered. The decay treatment represents a virtual thinning (with no cost) that 'harvests' the periodic increments of the lodgepole pine after attack without affecting the other species. The decay transition eliminates the periodic growth of pine if an attacked stand is not salvaged, while maintaining the growth and age of other species. Pine is also allowed to age, but not to grow volume. In Figure 3.2 each 'Salvage *e_k*' and 'Decay *e_k*/2' treatment is coded according to the period of attack (*e*) and the current period (*k*), because the time-since-attack defines the different recovery rates for pine. A 'Decay' treatment occurs every second period instead of every period to reduce the size of the model. This modeling issue is detailed in Section 3.8.

An attack event is time dependent. This means that it is related to a period in the planning horizon and not to the age of the stand (other than susceptible stands are older than 40 years). The advantage of this time dependency is that the decay rate starts after each attack period, regardless of the age of the attacked stand.

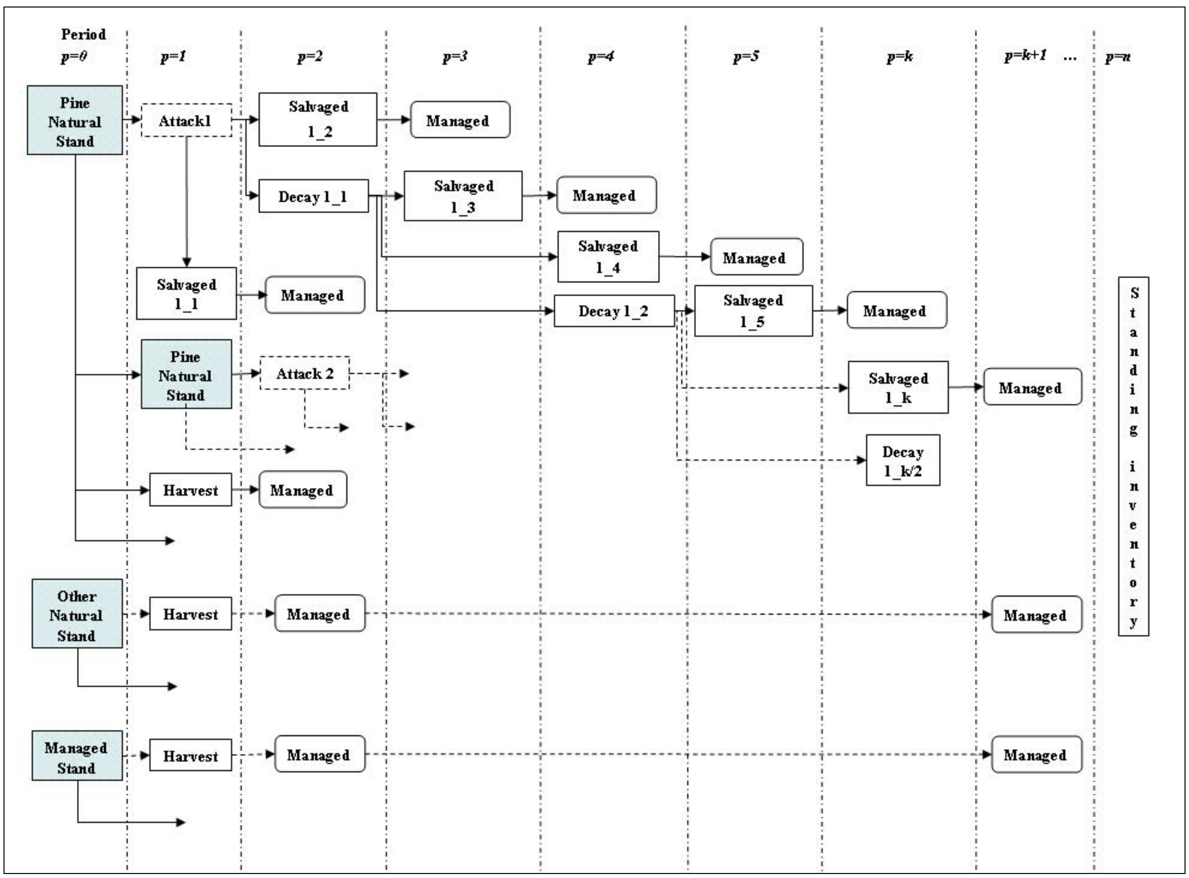


**Figure 3.2. Flow chart for the transition of pine stands susceptible to attack by MPB (Pine natural stand) and other non-susceptible stands (Other Natural stand and Managed stand). Columns are 2-year periods.**

All natural and non-susceptible stands ('Other Natural Stands' and 'Managed stands') and salvaged stands undergo a transition to a managed stand state upon harvest. Natural and non-susceptible stands can also remain as standing inventory depending on the scenario and on the harvest ages defined for these types. The stands that are currently classed as 'Managed Stands' are not susceptible to attack and remain in the 'Managed Stands' category following harvest.

All yield curves for the stand types were obtained from Nelson *et al.* (2006) and were derived from the FORECAST Ecosystem Simulation Program (Kimmins *et al.* 1999). All yield curves are described in Appendix 3. The yield curves are derived from individual stem information which allows the breakdown of volume by species and diameter class. These yield curves and successional transitions are based on the 'High-productive-100 scenario' modeled for the project (Seely *et al.* 2007). In the 'High-productive-100 scenario' salvaged stands are regenerated with an emphasis in pine and managed for high productivity, including fertilization. The differences between the current study and the model of Nelson *et al.* (2006) are the intensity of attack, the attack length, the estimation of merchantable volume for attacked stands, and use of an optimization model rather than a simulation model. All yield curves represent the merchantable volume per hectare with a 15% reduction for non-productive areas (OAFs 1 = Operational Adjustment Factors). A total of nine log products are considered based on species and size. All four species are divided into two diameter classes (< 30 cm dbh and >= than 30) to allocate volume to pulp, large sawlogs, small sawlogs, and peelers, based on the assumptions used in Peter (2004) and the prices provided for the interior BC by the Ministry of Forests and Range (BCMOF 2007b) (Table 3.2).

**Table 3.2. Assumptions of product yield based on species and dbh with corresponding price.**

| Species | Dbh | Product distribution assumption | Percentage of volume | Price * (CAD$/m$^3$) |
|---|---|---|---|---|
| White, Engelmann and Hybrid Spruce | >= 30 cm | Peeler grade | 20 % | 72 |
| | | Large diameter saw logs | 30 % | 53 |
| | | Small diameter saw logs | 50 % | 43 |
| | < 30 cm | Small diameter saw logs | 100 % | 43 |
| Lodgepole Pine | >= 30 cm | Large diameter saw logs | 50 % | 53 |
| | | Small diameter saw logs | 50 % | 43 |
| | < 30 cm | Small diameter saw logs | 100 % | 43 |
| Sub-alpine Fir | >= 30 cm | Large diameter saw logs | 25 % | 53 |
| | | Small diameter saw logs | 25 % | 43 |
| | | Pulpwood | 50 % | 32 |
| | < 30 cm | Small diameter saw logs | 50 % | 43 |
| | | Pulpwood | 50 % | 32 |
| Trembling Aspen | all | Pulpwood | 100 % | 37 |

* The statistics of the BCMOF are presented with only one price for the saw log category. Therefore, this price was assigned for large diameter saw logs and an average between this price and pulpwood was used as price for the small diameter saw logs.

The model also considers a by-product, called **waste**, to account for the losses of the beetle attack. Waste is defined as all merchantable pine volume that is not assigned to other products during decay. It is a proportional discount of each pine product when an attack stand starts to decay. Thus, the volume of all pine products volume plus the waste volume sum up to the same total volume as an un-attacked stand at the point of attack. Waste is not associated with breakage and non-merchantable stems (e.g. small dbh or tops) since the model only considers net merchantable volume. There is no market price assigned for this by-product but its volume (standing and harvested if it is salvaged) and its production costs are included to assess the impact of the beetle attack and its potential opportunity as a bioenergy source. Waste is not included in the objective function as a merchantable product, nor is it included in ending inventory valuation. The production costs for waste are the same as for pine, including the hauling to the mill.

I next describe two base scenarios and four scenarios that I use to model different assumptions about attack trends and decay rates. In all scenarios I use 2-year planning periods and a planning horizon of 64 years (32 periods). For the rest of the thesis, all volume of any product from spruce, pine, and fir is grouped as coniferous and aspen is grouped as deciduous.

### 3.3. Base case scenarios

The harvest flow constraint consists of meeting the allowable annual cut (AAC) for the TFL 48. The AAC has been modified in response to the mountain pine beetle epidemic and updated inventories. The AAC has been increased three times since 2001 and the last rationale was approved in 2007 (Benskin 2007). In the base case scenario, the AAC calculated in 2001 allowed the harvest of 525,000 $m^3$/year for coniferous-leading stands and 55,000 $m^3$/year for deciduous-leading stands (Baker 2001). Since then, a first uplift modified these volumes to 729,000 $m^3$/year and 85,000 $m^3$/year for the first decade, then decreasing them to 558,000 $m^3$/year and 85,000 $m^3$/year for conifer and deciduous stands, respectively (CANFOR Ltd. 2005). The latest approved uplift consists of 800,000 $m^3$/year and 100,000 $m^3$/year for coniferous-leading stands and deciduous-leading stands, respectively (Benskin 2007).

**Scenario 1. Base Case with uplift and no attack.** The uplift of 800,000 $m^3$/year for coniferous and 100,000 $m^3$/year for deciduous (Benskin 2007) is assumed for 10 years (5 periods) and after that the harvest levels drop to 525,000 $m^3$/year for coniferous and to 55,000 $m^3$/year for deciduous, as per the rationale of 2001. For the model, this represents 1,600,000 $m^3$/period for coniferous and 200,000 $m^3$/period for deciduous during the first decade and 1,050,000 $m^3$/period for coniferous and 110,000 $m^3$/period for deciduous during the rest of the planning horizon.

**Scenario 2. Base Case without uplift and no attack.** This scenario uses the harvest level established in 2001 for the whole planning horizon. Therefore, this scenario uses a steady harvest flow of 525,000 $m^3$/year for coniferous and to 55,000 $m^3$/year for deciduous, equivalent to 1,050,000 $m^3$/period for coniferous and to 110,000 $m^3$/period for deciduous. The objective of this scenario is to compare the effect of the uplift *per se*.

### 3.4. Attack scenarios

These scenarios vary according to two main factors: intensity of attack (area attacked per period) and shelf-life or decay rates (merchantable volume for pine) following attack. Eng *et al.* (2006b) projected that 79% of Dawson Creek forest district will be impacted by the MPB over the next decade. The attacked area is projected to peak between years

2009-2010. This corresponds to the second planning period in the model presented here. This information defines the level of attack in terms of intensity and distribution over time. Two intensities of attack were defined: a) high attack, corresponding to an attack of 100% of the area susceptible to attack and b) medium attack, corresponding to an attack of 60% of the area susceptible to attack. The intensity and the distribution of attack over time are summarized in Table 3.3 and Figure 3.3.

**Table 3.3. Intensity of attack (% area of susceptible stands) during the first four periods.**

| Year | Period | Attack | Medium | Projected * | High |
|---|---|---|---|---|---|
| 2007-2008 | 1 | 1 | 9 % | 13 % | 19 % |
| 2009-2010 | 2 | 2 | 32 % | 37 % | 42 % |
| 2011-2012 | 3 | 3 | 16 % | 21 % | 26 % |
| 2013-2014 | 4 | 4 | 3 % | 8 % | 13 % |
| | | Total | 60% | 79% | 100% |

* From Eng *et al.* (2006b)

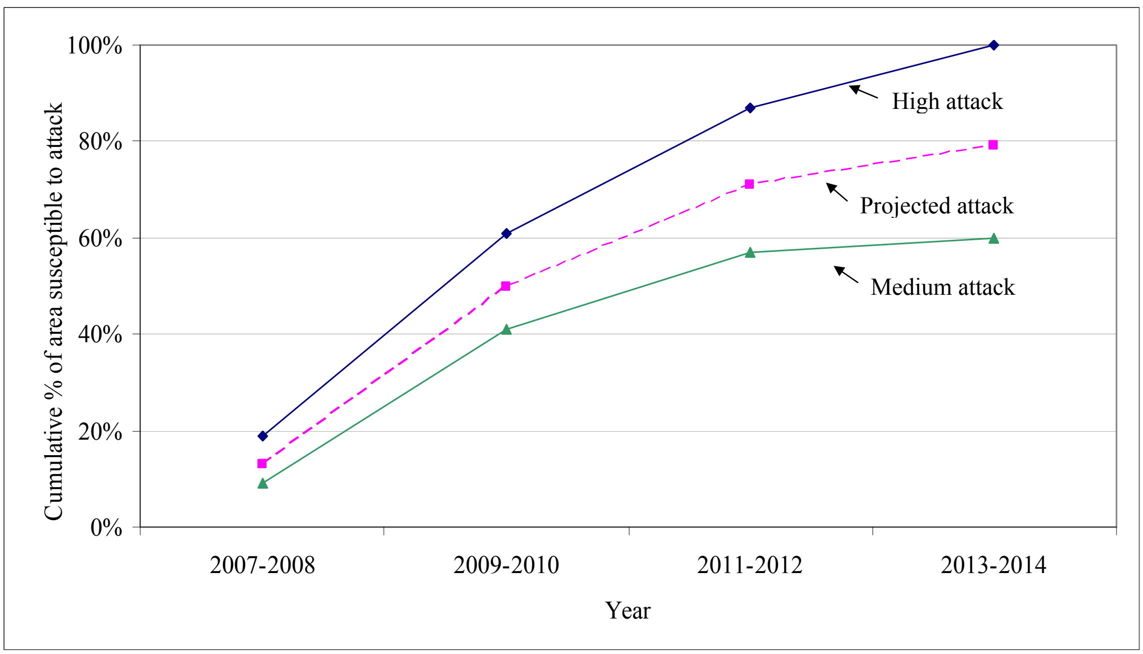


**Figure 3.3. Cumulative impact of attack intensities. The 'Projected attack' curve is based on Eng *et al.* (2006b) projections.**

The second factor that defines a scenario is the decay rate or shelf-life. Since no recent information regarding decay rates of beetle-killed logs is available, I assumed an equal recovery rate for all diameter types and products. Two different decay levels will be investigated for the attack scenarios: the first, named fast decay, uses a shelf-life of 6 years; the second, named slow decay, uses a shelf-life of 10 years. The salvage can start during the same period as the attack. For example, for the fast decay this means that in the same year of attack, 90% of the pine volume can be recovered and 10% turns into waste. During the second and third period after attack the merchantable level of recovery is 60% and 30%, respectively. The recovery rate for period 4 (six years after attack) is zero and from then on there is no recovery of merchantable pine volume. Thus, after period 4, all pine is considered waste for the fast decay. In the slow decay rate, the merchantable volume drops to zero by period 6, 10 years after the attack. The decay rate equally applies to all attacked stands and it starts during the same period a respective attacks occurs (i.e. period 1, 2, 3, or 4 of the planning horizon). The two levels of decay and the recovered portion of merchantable pine over time are summarized in Table 3.4.

**Table 3.4. Proportion of merchantable pine volume recovery during salvage, depending on decay rate and time since attack.**

| Periods after attack | Fast decay | | Slow decay | |
|---|---|---|---|---|
| | % recovery | % waste | % recovery | % waste |
| 0 | 90 | 10 | 90 | 10 |
| 1 | 60 | 40 | 72 | 28 |
| 2 | 30 | 70 | 54 | 46 |
| 3 | 0 | 100 | 36 | 64 |
| 4 | | | 18 | 82 |
| 5 | | | 0 | 100 |

The attack intensities and decay rates identify the following scenarios, sorted from the best to the worst case (Table 3.5).

**Scenario 3. With uplift, Medium attack & Slow decay.** Uses Scenario 1 harvest flow with an attack of 60% of the area susceptible and a slow decay (i.e. long shelf-life) of 10 years.

**Scenario 4. With uplift, Medium attack & Fast decay.** Uses Scenario 1 harvest flow with an attack of 60% of the area susceptible and a fast decay (i.e. short shelf-life) of 6 years.

**Scenario 5. With uplift, High attack & Slow decay.** Uses Scenario 1 harvest flow with an attack of 100% of the area susceptible and a slow decay (i.e. long shelf-life) of 10 years.

**Scenario 6. With uplift, High attack & Fast decay.** Uses Scenario 1 harvest flow with an attack of 100% of the area susceptible and a fast decay (i.e. short shelf-life) of 6 years.

**Table 3.5. Summary of attack scenarios, depending on the attack intensity and decay rate.**

| Decay Rate / Attack Intensity | Slow (10 years) | Fast (6 years) |
|---|---|---|
| Medium (60%) | Scenario 3 | Scenario 4 |
| High (100%) | Scenario 5 | Scenario 6 |

## 3.5. Decision model

The timber supply model in this study uses Linear Programming (LP). I used the Remsoft® Spatial Planning System (Woodstock version 2007.04) to develop the model and as the LP matrix builder. I used the software MOSEK® to solve the LP model. The Woodstock interpreter generates LP matrices using a Model type II formulation. Although the Remsoft® package includes some tools to analyze spatial constraints (e.g. Stanley), they are not used in this thesis.

The objective function maximizes the Net Present Value (NPV) for different intensities of attack, shelf-life, and rate of decay of the different products. As in the traditional model II LP, the objective function maximizes the discounted net income plus the valuation of the standing inventory at the end of the planning horizon.

I was able to take advantage of the Model type II structure by collapsing common areas from similar stands passing through an action in a period. The current formulation allows all attacked, natural, and managed stands to merge into a unique managed type of stand after salvage or harvest if they have different ages but belong to the same management unit. The method of merging stands from the same management unit is also used to merge attack stands when the recovery of pine is zero (see salvage and decay balance in

Section 3.8.). If a management unit is not salvaged in one period it is 'forced' to age passing through a decay transition that subtracts the growth of dead pine. Therefore, following an attack a management unit is forced to be either salvaged or decayed during subsequent planning periods.

Although the focus of this study is on the short- to mid-term implications, the planning horizon is longer to buffer against the artefacts of model behaviour at the end of the planning horizon. The planning horizon was set to 64 years and is divided in 32 two–year periods. Period one represents years 2007-2008. This planning horizon is sufficiently long for some of the young managed stands to reach harvest age.

The model includes strict equality constraints for the harvest flow. This is a simplification of what is likely to happen in reality, but it helps isolate changes in the salvage strategy and the type of stands selected depending on the different scenarios. These restrictions are relaxed in the sensitivity analysis to explore possible impacts related to the harvest flow.

There are four factors that control the stands available for harvest: a) a minimum harvest age, b) a maximum harvest volume per period, c) an ending inventory valuation, and d) a minimum ending inventory. Because TFL48 is an old-growth surplus forest (see age class distribution in Figure 4.13a, p. 63), the minimum harvest age and the ending inventory valuation are less relevant. The harvest age is less relevant because the majority of the forest is available for harvest from the beginning to the end of the planning horizon and the ending inventory valuation is less relevant because there is little economic incentive to postpone the harvest to gain more volume or better quality products. These are the reasons why a minimum ending inventory constraint becomes important in this type of analysis.

The model includes a minimum, green standing inventory at the end of the planning horizon (i.e. ending inventory excluding the standing waste inventory or dead trees). After initial exploration, this minimum level was arbitrarily set at 49,250,000 $m^3$ for all six scenarios. This value is based on the standing inventory that a high attack scenario could reach once the shelf-life had expired for the last attack period (i.e. after period eight for slow decay). The minimum ending inventory level was modified during the sensitivity analysis, as I explain later.

The model contains 9 landscape class themes[b] that describe management units of the forest for the Woodstock model (Table 3.6). Theme 1 (Block) represents an administrative spatial subdivision of the forest and has a role in the attack distribution. Themes 2, 3, 4, 6, and 8 collectively define yield curves. These themes are the Pine Category, the Non-Pine Leading Species Code, the Site Quality, the Actions[c], and the Decay, respectively. The Actions define the successional pathway that a management unit might follow and the decay theme defines changes in state after attack. Themes 5 and 7 (BEC zone and Cost class, respectively) are used to calculate harvest and silviculture costs. Theme 9 (Age Class) is used to define age-classes for the stands. A total of 10 age classes (20 years each) were created to classify the initial forest. The last class of the Age Class theme merges all stands with ages higher than 150 or 200 years, depending on their respective yield curves. This aggregation decreases the number of management units. The current age and the area are the last two attributes that complete the definition of the management units.

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[b] Landscape theme is defined in Spatial Woodstock ® as map layers in a GIS system or fields in a forest inventory database in that they describe various aspect of the forest, such as physical or administrative features (REMSOFT 2006).

[c] In Spatial Woodstock ® an action is defined as any silviculture treatment, harvest, administrative activity or naturally occurring event that causes a development or management type to undergo a transition that changes the condition of the forest (REMSOFT 2006).

**Table 3.6. Landscape themes used to define the forest.**

| Theme | Class Name | Description | Classes |
| --- | --- | --- | --- |
| THEME 1 | Block | Spatial administrative blocks within TFL48 | MZ1, MZ2, MZ3, MZ4, MZ5 |
| THEME 2 | Pine Category | Percentage of pine | P0: non pine or non susceptible<br>P1: < 25%<br>P2: [ 25% : < 50% ]<br>P3: [ 50% : < 75% ]<br>P4: >= 75% |
| THEME 3 | Non-Pine Lead Species | Other species composition stands | S1: spruce species<br>BL2: sub-alpine fir<br>AE3: deciduous leading, represented by aspen<br>AEMXD5: deciduous leading mixed wood<br>SMXC6: conifer leading mixed wood<br>$O_i$ other stands with $i \in$ {code for other non-pine yield curves} |
| THEME 4 | Site Quality | Site productivity | SQ0: not determinant<br>SQ1: poor<br>SQ2: med-good |
| THEME 5 | BEC zone, subzone, variant | Biogeoclimatic classification. Associate with silviculture costs per hectare (CAD$/ha) | BWBSmw1, BWBSwk1, BWBSwk2, SBSwk2, ESSFmv2, ESSFmv4, ESSFwk2, ESSFwc3, and CADU: for deciduous<br>NoClass: not defined |
| THEME 6 | Actions | Define the transitions that stands follow | NA: pine natural stands<br>YG: young pine stands (<40 years) not susceptible for attack<br>NA0: stands with other yield curves<br>NA1: Other non-pine leading species stands with FORECAST AU between 11000 and 12000.<br>AT: attacked stands in period one<br>AT2: attacked stands in period two<br>AT3: attacked stands in period three<br>AT4: attacked stands in period four<br>MA: managed stands<br>MAY: future managed young pine stands |
| THEME 7 | Cost Class | Sum of tree-to-truck cost (harvesting cost) and hauling cost (e.g. C21 = 21 CAD$/m$^3$) | C21: [19 – 23]; C26: [24 – 28]; C31: [29 – 33]; C36: [34 – 38]; C41: [39 – 43]; C46: [44 – 48]; C51: [49 – 53]; C999: not defined |
| THEME 8 | Decay | Defines changes in the stage after attack (e.g. D2: first period after attack) | D1, D2, D3, D4, D5, D6, …, D27, D28, D29, D30, D31, D32 |
| THEME 9 | Age Class | Age class definitions | AC010:[ 1 - 20 ] => Age class: 10<br>AC030:[ 21 - 40 ] => Age class: 30<br>AC050:[ 41 - 60 ] => Age class: 50<br>AC070:[ 61 - 80 ] => Age class: 70<br>AC090:[ 81 - 100 ] => Age class: 90<br>AC110:[ 101 - 120 ] => Age class: 110<br>AC130:[ 121 - 140 ] => Age class: 130<br>AC150:[ 141 - 160 ] => Age class: 150<br>AC170:[ 161 - 180 ] => Age class: 170<br>AC190:[ 181 - 200+] => Age class: 190<br>AC00: Reclassification of regenerated stands |

Harvest and transportation cost information was provided by CANFOR Ltd. The Cost Class theme is the variable cost per cubic meter and is the sum of: a) the tree-to-truck cost (harvest cost) and b) the hauling cost. The tree-to-truck cost includes three types of harvest systems: 1) cable, 2) ground and 3) mixed (50/50). The ground harvest system is assigned to 87% of the area. This cost depends on the harvest system and the species composition (Table 3.7). The hauling cost is a complex variable that depends on the distance from the source to the mill, the type of road, and the species (coniferous or deciduous) (Table 3.8). Following the methodology used by Nelson *et al.* (2006), the tree-to-truck and hauling costs were weighted by the species proportion per polygon. In addition, the hauling distance and the associated cost were weighted by each type of road (three forest road classes plus one highway class). Although the species composition per stand changes over time, the model uses a fixed stand composition at the harvest age to weight the costs. The average hauling cost is 7.31 CAD$/m$^3$, for an average distance of 90 km. Since each polygon of the TLHB potentially has a distinct cost structure, it is difficult to include them in any other way than as a range within the Cost Class theme. Therefore, the categories for the variable cost are considered as a range of costs in CAD$/m$^3$ (Theme 7 - Cost Class).

**Table 3.7. Tree-to-truck cost by harvest system and species.**

| Harvest System | Cable | Ground | | | | Average |
|---|---|---|---|---|---|---|
| Species | All | Spruce | Pine | Sub-alpine fir | Deciduous | All |
| CAD$/m$^3$ | $ 27.5 | $ 17.16 | $ 18.55 | $ 18.88 | $ 18.00 | $ 20.02 |

Source: CANFOR Ltd.

**Table 3.8. Hauling cost by species and road class.**

| Road Class | Conifer (CAD$/m$^3$/km) | Deciduous (CAD$/m$^3$/km) |
|---|---|---|
| Highway | $ 0.06 | $ 0.05 |
| Class 1 | $ 0.10 | $ 0.07 |
| Class 2 | $ 0.11 | $ 0.09 |
| Class 3 | $ 0.25 | $ 0.19 |

Source: CANFOR Ltd.

The silviculture cost is a cost per hectare and depends on the biogeoclimatic variant and the percentage of deciduous species. Eight curves are used with a lower price for deciduous leading stands (560 CAD$/ha) (i.e. yield curve # 43, 112, 11310, 313100, 12310, 323100). In addition, for the mixed wood yield curves # 11510 and 315100, I used a weighted average of the cost of deciduous with the average cost for the biogeoclimatic variant (872 CAD$/ha). These curves represent natural and managed stands dominated by aspen with less than 35% pine or spruce. For all other management units that were not linked to previously described yield curves, the silviculture cost was assigned based on the specific BEC subzones/variant as summarized in Table 3.9.

**Table 3.9. Silviculture costs per hectare by biogeoclimatic subzone/variant.**

| BEC code | Biogeoclimatic zone | Subzones | CAD$/ha |
|---|---|---|---|
| BWBSmw1 | Boreal White and Black Spruce | Moist warm | $ 1,779 |
| BWBSwk1 | Boreal White and Black Spruce | Wet cool | $ 1,320 |
| BWBSwk2 | Boreal White and Black Spruce | Wet cool | $ 1,320 |
| SBSwk2 | Sub-Boreal Spruce | Wet cool | $ 1,555 |
| ESSFmv2 | Engelmann Spruce–Subalpine Fir | Moist very cold | $ 1,358 |
| ESSFmv4 | Engelmann Spruce–Subalpine Fir | Moist very cold | $ 1,505 |
| ESSFwk2 | Engelmann Spruce–Subalpine Fir | Wet cool | $ 1,526 |
| ESSFwc3 | Engelmann Spruce–Subalpine Fir | Wet cold | $ 1,606 |
| Average BEC | | | $ 1,496 |
| Deciduous | | | $ 560 |
| Weighted average BEC-Deciduous (1:2) | | | $ 872 |

Source: CANFOR Ltd.

Profit includes the income minus the tree-to-truck, the hauling, and the silviculture costs, but does not include road construction, road maintenance, and administration costs. Other costs like the incremental harvest costs due to handling dead trees in attacked stands and spatial restrictions like green up delays and adjacency constraints are not included. The effects of including additional costs are discussed later in the thesis.

The profit calculations use market values to estimates revenues, shown in Table 3.2. The model does not consider the subdivision of the profit between stumpage and private return on investment. The model also assumes perfect elasticity for demand and constant product prices over the whole planning horizon, independent of the level of demand. Therefore, the uplift does not affect market prices. Given the case of a massive forest insect outbreak with ensuing uplifts, it is very likely that we will see an increase in the short-term supply that will lower the prices. I discuss this limitation later.

All scenarios maximize net present value using a 4% discount rate, calculated at the beginning of each period. In subsequent sensitivity analyses I use a 1% discount rate.

### 3.6. <u>Ending inventory valuation</u>

The ending inventory is considered as income in the objective function. The calculations of the ending inventory valuation are summarized in three stages:

1. Calculate the rotation age that maximizes the value for a **single rotation** with a 4% discount rate. This value is calculated for all yield curves using the weighted price-product per species and diameter class shown in Table 3.2, the harvest cost, and the regeneration cost. Since the forest is composed mainly of pre-established, natural stands, all regeneration costs were assumed to occur at the end of the rotation. Thus, management units have the regeneration costs applied right after the harvest and for the future value, the regeneration cost occurs again after each harvest. This results in a rotation age value and a corresponding future value. Stands with negative final values were not included in the ending inventory valuation.
2. At the end of the planning horizon three types of stands remain as ending inventory: (a) existing stands beyond the rotation age, (b) existing stands under the rotation age, and (c) stands regenerated during the planning horizon and under the rotation age. For all three types of stands the valuation was done using the present value of the current rotation plus the present value of a perpetual periodic series of future rotations. For type (a) stands, the valuation of the current rotation used the standing volume at the end of the planning horizon. However, for type (b) and (c) stands the valuation used the volume at the rotation age. Therefore, the present value was discounted by the planning horizon for stands (a) and by the planning horizon plus the remaining of the current rotation for stands (b) and (c). The starting point of the perpetual series is immediately following the end of the planning horizon for stands (a) and immediately after the next rotation for stands (b) and (c). The first rotation was calculated with the current yield curves and the perpetual rotations were calculated using the future managed yield curves for stands (a) and (b). In the case of the regenerated stands (c), the same yield curve was used for the current and future rotations.

3. The future value for each management unit was multiplied by the areas left as ending inventory. The attacked stands left as ending inventory were valuated using 50% percent of its pine volume for the current rotation, assuming that some re-stocking of the pine volume occurs. This was an arbitrary value chosen to reflect that attacked stands will be naturally restocked with pine in the future, but to a lesser extent than a natural, un-attacked stand with a same age and belonging to the same management unit.

### 3.7. Other assumptions and limitations

- The model represents the impact of a single-event disturbance spread over eight years (not a probability distribution of multiple disturbances over time).
- There is no objective to achieve a specific age class distribution for the future forest.
- The model uses a minimum harvest age but no maximum harvest age. Each management unit, once reaching the minimum harvest age, can be harvested at that point, the following periods, or can be retained as ending inventory.
- The susceptibility for attack is a model input defined using age and species composition criteria. All the attack-susceptible management units have the same probability of being attacked. The possibility that the model would chose which stands to attack to optimize the final solution was mitigated by imposing attack distribution constraints in the final model.
- Salvage activities can start in the same period as the respective attack occurs.
- 100% of pine mortality was assumed in attacked stands and the deterioration of all pine commences immediately.
- The model considers only one alternative for future managed stands (reflected in only one set of future yield curves).
- An assumption related to waste is that no special salvage activities occur to specifically harvest waste. The waste analysis focuses on waste volume distribution over time and its harvest cost. Waste income/cost was not included in the objective function. I assumed that waste will have a commodity price lower or

similar than pulp logs. Therefore, harvest decisions are driven by the other market valued products (logs).

### 3.8. Final model

The objective function and the intrinsic restrictions of the original optimization Model type II are based on Johnson and Scheurman (1977) (Equations [1], [2], and [3]). For the sake of clarity, the final model is presented as a simplified mathematical formulation. This simplification is in terms of the real number of variables that compose some of the components of the summation. Therefore, $X_{ij\ abcdefgh}$ is an existing area harvested that was regenerated in period *i* and harvested in period *j*, of a block *a*, with a pine category *b*, in a site quality *c*, of a BEC zone *d*, belonging to an action *e*, with a cost class *f*, in a decay transition *g*, and with an age class *h*. Similarly $X_{jk\ abcdefgh}$ is a new area regenerated during the planning horizon in period j and harvested again in period k with the same previous sub indexes for the landscape class description. For display purposes, the following formulas contain only the relevant sub indexes. The final model has a large number of accounting constraints to keep track of key variables (e.g. volume and areas per product, per species, per treatment, standing inventory, costs and revenues, etc.). These accounting constraints are not included in the formulation.

Equation [1] is the objective function that maximizes net present value, equation [2] ensures that the initial area at the beginning of the planning horizon is equal to the area harvested during the planning horizon or left as ending inventory. Equation [3] ensures that the area regenerated during the planning horizon is equal to the area subsequently harvested or left as ending inventory.

Objective Function:

$$MAX \quad \sum_{j=1}^{N} \sum_{i=-M}^{j-Z} D_{ij} X_{ij} + \sum_{i=-M}^{N} E_{iN} w_{iN} \qquad [1]$$

Subject to

Area Constraints: $$\sum_{j=1}^{N} x_{ij} + w_{iN} = A_i \qquad i = -M,\ldots,0 \qquad [2]$$

$$\sum_{k=j+Z}^{N} x_{jk} + w_{jN} = \sum_{i=-M}^{j-Z} x_{ij} \qquad j = 1,\ldots,N \qquad [3]$$

Where:

$x_{ij}\,(x_{jk})$ = hectares regenerated in period *i* (period *j*) and regeneration harvested in period *j* (period *k*)

$w_{iN}\,(w_{jN})$ = hectares regenerated in period *i* (period *j*) and left as part of the ending inventory in period *N*=32

$A_i$ = number of hectares present in period one that were regenerated in period *i*, $i = -M, \ldots, 0$, with each $A_i$ being a constant at the beginning of the planning horizon (period 1). As an example, $A_{-5}$ represents hectares regenerated six periods before period one

$M$ = number of periods before period zero in which the oldest age class present in period one was regenerated

$Z$ = minimum number of periods between regeneration harvests

$E_{iN}$ = discounted net revenue per hectare during the planning horizon from hectares regenerated in period *i* and left as ending inventory in period *N* plus discounted net value per hectare of leaving these hectares as ending inventory.

$D_{ij}$ = discounted net revenue per hectare from hectares regenerated in period *i* and regeneration harvested in period *j*.

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

$P_{ikj}$ = unit profit (price – hauling – tree-to-truck) of the volume harvested in period *k* on hectares regenerated in period *i* and regeneration harvested in period *j*.

$V_{ikj}$ = volume per hectare harvested in period *k* on hectares regenerated in period *i* and regeneration harvested in period *j*.

$C_{ikj}$ = Silviculture treatments costs per hectare in period *k* on hectares regenerated in period *i* and regeneration harvested in period *j*.

$\gamma^k$ = discount rate for period *k*.

Income and cost balance

Equation [4] is to ensure that the total un-discounted income is greater than the total un-discounted gross cost for each period.

$$\sum\sum_{p=1}^{9} \Pr_p V_{pk}\ X - C\,V_k X - \sum Silv_k\ X \geq 0 \qquad \forall\ k = 1,\ldots,32 \qquad [4]$$

Where:

$\Pr_p V_{pk}\ X$ Unit price *Pr* of product *p* multiplied by the volume *V* of product *p* harvested in period *k* of all hectares *X* harvested in period *k* (with X = $X_{ij}$ or $X_{jk}$).

$CV_k\ X$ Unit variable Cost *C* multiplied by the total volume *V* harvested in period *k* of all hectares *X* harvested in period *k* (with X = $X_{ij}$ or $X_{jk}$). This cost depends on the management unit and it is defined by theme 7 (cost class).

$Silv_k$ Silviculture cost *Silv* per hectare harvested in period *k*. This cost depends on the management unit and it is defined by theme 5 (BEC or deciduous stands).

Maximum and minimum harvest flow

Equation [5] establishes the minimum and maximum harvest level for coniferous stands. For all scenarios the minimum and the maximum are the same, but these restrictions are relaxed for the sensitivity analysis. Equation [6] establishes the minimum and maximum harvest level for deciduous stands. In this equation the sub index for volume accounts only for product 9, corresponding to pulpwood of trembling aspen (Table 3.2).

$$\sum\sum_{p=1}^{8} V_{pk}\ X \geq hrvcon_k \quad ; \quad \sum\sum_{p=1}^{8} V_{pk}\ X \leq hrvcon_k \ ; \quad with\ hrvcon_{1,\ldots,5} = 1{,}600{,}000 \wedge hrvcon_{6,\ldots,32} = 1{,}050{,}000 \quad [5]$$

$$for\ Scenarios\ 1,3,4,5, and\ 6 \quad and \quad hrvcon_{1,\ldots,32} = 1{,}050{,}000\ \ for\ Scenario\ 2$$

$$\sum V_{9k}\ X \geq hrvdec_k \quad ; \quad \sum V_{9k}\ X \leq hrvdec_k \ ; \quad with\ hrvdec_{1,\ldots,5} = 200{,}000 \wedge hrvdec_{6,\ldots,32} = 110{,}000 \quad [6]$$

$$for\ Scenarios\ 1,3,4,5, and\ 6 \quad and \quad hrvdec_{1,\ldots,32} = 110{,}000\ \ for\ Scenario\ 2$$

Where:

| | |
|---|---|
| $V_{pk}\ X$ | Volume *V* of product *p* harvested in period *k* of all hectares *X* harvested in period *k* (with X = $X_{ij}$ or $X_{jk}$) with p=1,…,8 for coniferous and with p=9 for deciduous. |
| $hrvcon_k\ (hrvdec_k)$ | Harvest flow for coniferous *hrvcon* and deciduous *hrvdec* established in period *k*, with or without uplift depending on the scenario. |

Attack intensity

Equation [7] establishes the intensity of attack. Since the model maximizes the NPV, stands will not be attacked nor follow required successional pathways unless the model is constrained to do so.

$$\sum_{i=-M}^{0} X_{ije} - TASatk * p_j = 0 \qquad e = Attack\ 1,2,3,4 \quad for\ \ j = 1,2,3,4, \quad respectively \qquad [7]$$

Where:

| | |
|---|---|
| $X_{ije}$ | Area regenerated in period *i* (existing stands) and regeneration ‘harvested’ in period *j* as attacked stands *e*. |
| $TASatk$ | Total area susceptible for attack = 142,809 ha. |
| $p_j$ | Intensity of attack per period and per scenario (Table 3.3). |
| $-M = -94$ | Maximum age of original stands. Since stands were grouped in age classes (theme 9) *i* = -94, -84, -74, -64, -54, -44, -34, -24, -14, -4. |

Attack distribution

Equation [8] ensures that the difference between proportions of attack among all classes of selected themes is less or equal than 10%. Without this constraint the model will select the worst stands for attack to minimize the revenue losses (i.e. most expensive and worst site quality). For example, in equation [8], the difference of area attacked over the four periods between block 1 and block 2 must be less or equal than 10%. For the scenarios with 100% of attack this constraint is redundant.

$$\frac{1}{ASatk_{a}} * \sum_{j=1}^{4} \sum_{i=-M}^{0} X_{ij\,ae} - \frac{1}{ASatk_{a'}} * \sum_{j=1}^{4} \sum_{i=-M}^{0} X_{ij\,a'e} \leq 0.1 \qquad \begin{array}{l} with \quad e = attack\ 1, 2, 3, 4. \\ \forall \quad a \neq a', \quad a, a' \in \{landscape \quad class\} \wedge \\ \forall\ landscape \quad class \in \{theme\ 1,2,3,4,5,7,9\} \end{array} \qquad [8]$$

Where:

| | |
|---|---|
| $X_{ij\,ae} \quad (X_{ij\,a'e})$ | For landscape class 1: Area of Block *a (a')* that was originally regenerated in period *i* (existing stands) and regenerated in period *j* as attacked *e* stands. |
| $ASatk_{a}\ (ASatk_{a'})$ | Total area susceptible for attack for class *a (a')* element of landscape class 1. |
| $landscape\ \ class$ | Forest subdivision based on themes 1,2,3,4,5,7, and 9 for block, pine category, non-pine lead specie, site quality, BEC, cost class, and age class, respectively. |

Salvage and decay balance

The salvage and decay balance constraints ensure that all the attacked area that was not salvaged during a certain period will go through a decay stage to maintain the same level of pine volume, but allowing the growth of the other species. The salvage transition occurs every period. The decay transition occurs every two periods in order to decrease the size of the model. The decay transition is the virtual thinning and should not be confused with the decay rates for the salvaged pine that is related to the salvage transition. When the recovery rate for attacked pine is zero, there is no time-dependent effect remaining (i.e. shelf-life) and all attack stands can be merged. For un-salvaged stands after the shelf-life, this merge consists of rejoining all four attacked stands (created in periods 1-4) into one attacked stand. Therefore, only areas from the same management unit but classified in different attack periods can be merged. This produces a minor underestimation of the volume of pine waste (one or two periodic increments of some attack stands) and should not affect the results.

Equations [9] and [10] represent the balance constraints for an attack that occurred in period 1. In equation [9] the summation of the total area attacked in period 1 must be equal to the total area salvaged in period 1, plus the total area salvaged in period 2, and plus the total area that goes through a decay transition in period 2. Hence, everything that is not salvaged passes through a decay transition. In the same way, equation [10] ensures that all the area that passed through a decay transition in period 2 must be equal to the total area salvaged in period 3, salvaged in period 4, and the total area that goes through a decay transition in period 4. This is successively repeated over the whole planning horizon and independently repeated for the four attack actions that start in period 1, 2, 3, and 4, respectively.

$$\sum_{i=-M}^{0} X_{i1AT} - \sum X_{11SV_1} - \sum X_{12SV_1} - \sum X_{12DC_1} = 0 \qquad [9]$$

$$\sum X_{12DC_1} - \sum X_{13SV_1} - \sum X_{14SV_1} - \sum X_{14DC_1} = 0 \qquad [10]$$

$$with\ \{AT_1 = Attack1;\ SV_1 = Salvage\ for\ Attack1;\ DC_1 = Decay\ for\ attack1\} \in e$$

$$\forall\ \ Attack1,\ Attack2,\ Attack3,\ Attack4.$$

Where:

| | |
|---|---|
| $X_{i1AT_1}$ | Area regenerated in period *i* (existing stands) and regeneration 'harvested' in period 1 as attack-1 stands. |
| $X_{11SV_1}\left(X_{12SV_1}\right)$ | Area regenerated as attack-1 in period 1 and salvaged in period 1 or period 2. |
| $X_{12DC_1}$ | Area regenerated as attack-1 in period 1 and decayed in period 2. |

Minimum ending inventory

Constraint [11] ensures a minimum standing inventory at the end of the planning horizon. The sum of the standing volume after period 32 of all existing stands (that were not harvested or attacked) and all regenerated stands during the planning horizon must be greater or equal than a predefined value.

$$\sum_{i=-94}^{0} w_{iN}\, V_N + \sum_{j=1}^{32} w_{jN}\, V_N - MINEI \geq 0 \qquad [11]$$

Where:

| | |
|---|---|
| $w_{iN}\ V_N$ | Hectares regenerated in period *i* (original stands) and left as part of the ending inventory period $N = 32$. |
| $w_{jN}\ V_N$ | Hectares regenerated in period *j* (regenerated stands during the planning horizon) and left as part of the ending inventory in period $N = 32$. |
| $MINEI$ | The minimum ending inventory ($m^3$). |

## 3.9. Sensitivity analysis

Two types of sensitivity analysis are conducted; one for the ending inventory linked to the harvest flow and one for the discount rate. As mentioned before, an initial sensitivity analysis was conducted to define the final model and scenarios. From this analysis it was concluded that the model had to be constrained in the distribution of the attack over time and over the types of stands. These constraints were used so that the model would not concentrate the beetle attacks on only the most expensive stands or stands with the poorest site quality that would otherwise be retained as ending inventory. The decision to link the harvest flow, the ending inventory valuation, and the minimum ending inventory was necessary because the ending inventory valuation was not sufficient for conserving the forest structure. The minimum ending inventory is necessary because the valuation of the future forest is highly penalized by the discounted rate and the model ends with lower inventory than desirable. This led to a sensitivity analysis between the ending inventory and the harvest flow.

Finally, I use two discount rates to evaluate the model from the point of view of different stakeholders. All six scenarios were run with an initial 4% discount rate to reflect a private or business as usual (BAU) salvage strategy perspective. A second set of runs were done with 1% discount rate to reflect a public perspective. For this second set of runs the ending inventory valuation was recalculated using the same 1% discount rate.

### 3.10. Computer requirements

All computations were done on a personal computer with a Pentium(R) D (3.01 GHz) processor and 2.0 GB of RAM. The processing time varied due to the different processes that can be independently done for one model. The model processing in Spatial Woodstock can be divided in several stages. For instance, the longest process occurs when creating the new development types (all the variables that represent all landscapes units through time) but this process has to be done only once. The second longest process occurs when building the matrix, followed by building the solution reports and graphs. The software allows editing the Right Hand Side (RHS) of the matrix, allowing substantial time saving by not re-building the whole matrix. The solver time was one of the lowest components, usually in less than one minute. Finally, conversion of the results to the defined reports and graphs depends on the number of desired outputs.

## 4. Results

I first present some generalized results related to the model. Following this, I present the results of the seven main indicators: net present value, unit profit, inventory, harvest flow, salvage strategy, waste as a potential bioenergy source, and age class distribution. The final section of this chapter reports results from the sensitivity analysis.

From the original 86,626 polygons, the model was reduced to 5,581 management units. The model created 126,518 new development types to represent the different management units over the planning horizon. The matrix was composed of 146,154 rows; 559,605 columns and had a density of 0.000044. The matrix building process took approximately 75 minutes.

Although I will refer to mid-term supply issues and sustainability, the determination of the long-term AAC was beyond the scope of this study. In order to have a yield approximation of the future forest I calculated the long-term sustained yield (LTSY) using all future yield curves. The result was a LTSY of approximately ~700,000 $m^3$/year (1,400,000 $m^3$/period) for coniferous and of ~ 200,000 $m^3$/year (400,000 $m^3$/period) for deciduous. The weighted average rotation was 88 years with a weighted average merchantable volume of 220 $m^3$/ha. Although the uplift (800,000 $m^3$/year) is higher than the LTSY for coniferous, all analyzed scenarios are below the LTSY when we consider the average volume harvested per period for the whole planning horizon. For deciduous, the harvest level is never higher than the LTSY. Also, all scenarios including the ones with high intensity of attack were feasible for the AAC flow requirements (with or without uplift).

### 4.1. Net present value

The maximization of the NPV shows the overall economic impact of a MPB attack (Table 4.1). As expected, the highest NPV is for the scenario that included the uplift but no attack (Scenario 1). The base Scenario 2, which does not include the AAC uplift and is not attacked, has one of the lowest NPV.

The intensity of attack and the shelf-life have an impact on overall value. In Table 4.1 there is only a 3% drop for Scenarios 3 and 4, with respect to Scenario 1. In the case of the high intensity of attack (Scenarios 5 and 6), the drop in value is 12% and 14% for slow and fast decay, respectively. The base case without uplift has a similar NPV to the high intensity attack scenarios, with less than 3% difference among them.

**Table 4.1. Objective function value per scenario and their proportion with respect to the base case Scenario 1.**

| Scenario | Description | NPV (CAD$) | % NPV of Scenario 1 |
|---|---|---|---|
| 1 | Base – SFMP#3 w/ Uplift & No Attack | 411,562,443 | 100% |
| 2 | Base – SFMP#3 & No Attack | 366,919,534 | 89% |
| 3 | Attack 60% - Slow Decay | 399,877,318 | 97% |
| 4 | Attack 60% - Fast Decay | 399,822,280 | 97% |
| 5 | Attack 100% - Slow Decay | 361,125,437 | 88% |
| 6 | Attack 100% - Fast Decay | 354,635,678 | 86% |

### 4.2. Unit profit

Figure 4.1 shows the unit gross profit (undiscounted cash flow) over time for the six scenarios. The overall trend is decreasing gross profit over the planning horizon as expected with a maximization NPV objective function. For the two base-scenarios (Scenarios 1& 2) and the two scenarios with medium intensity of attack (Scenarios 3 & 4), there is little difference in unit gross profit. These four scenarios start with a gross profit close to 23 CAD$/m$^3$ and finish close to 10 CAD$/m$^3$. Scenarios 5 and 6 show similar behaviour between each other, but different from the other scenarios. These two scenarios show a lower gross profit over the first 12 years, then increasing over the other scenarios for approximately ten years, and ending with a lower gross profit of 5 CAD$/m$^3$. This reflects the higher salvage intensity for Scenarios 5 and 6 with a lower initial profit, mainly because of the delay of the harvest of the stands with a higher composition of spruce compared to the other scenarios.

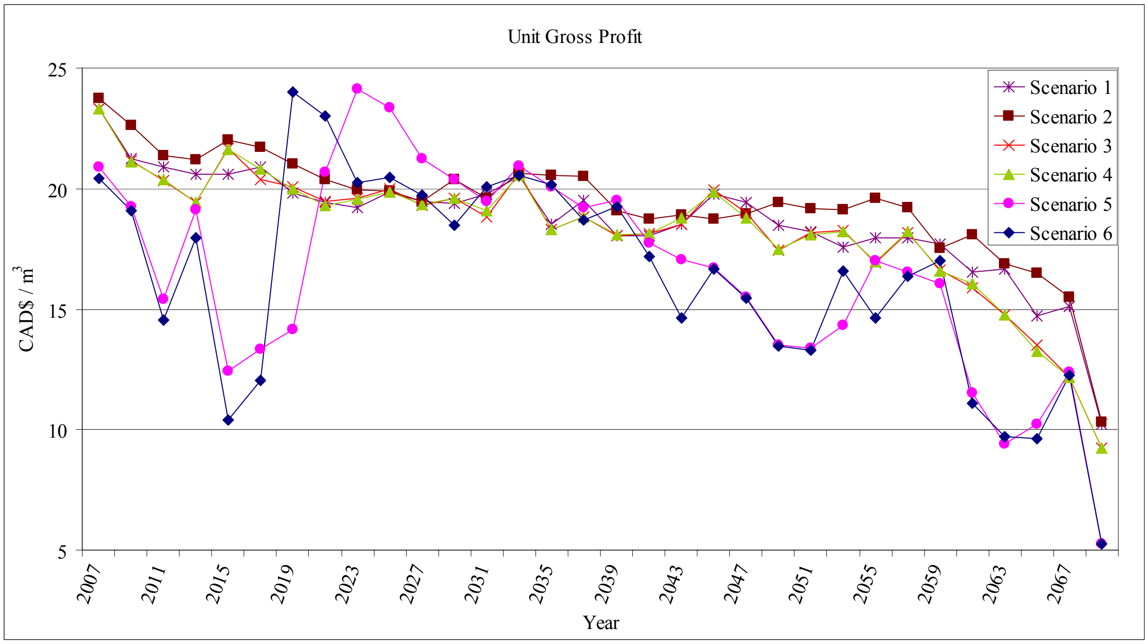



**Figure 4.1. Unit gross profit by scenario over the planning horizon.**

All Scenarios present an average gross income of 46 CAD$/m$^3$ over the whole planning horizon. The scenarios with high intensity attack (Scenarios 5 and 6) present an overall average cost of 29 CAD$/m$^3$. This average cost is 2 CAD$/m$^3$ higher than the base cases and medium intensity attack scenarios.

Figure 4.2, Figure 4.3, and Figure 4.4 show the decomposition of the unit profit previously shown in Figure 4.1. The unit gross income (Figure 4.2) reflects the differences in the value of different species and different product composition. This value is mainly influenced by spruce and pine, because aspen produces only one product (i.e. has the same income over time) and sub-alpine fir is only a minor component during the second half of the planning horizon. The unit gross harvest and hauling cost (Figure 4.3) represents on average 85% of the total cost. This cost shows an increasing trend over time, likely reflecting the harvest of more distant stands. The unit gross harvest and hauling costs do not reflect any cost difference in harvesting attack or non-attack stands. This is not the case for the silviculture cost (Figure 4.4). Since the silviculture cost is calculated per hectare it does reflect incremental costs of salvaging attacked stands with less volume than natural stands. Although the silviculture cost accounts on average only for 15% of the costs, during some of the salvage periods it shows increases of more than

100% for Scenario 6 compared to Scenarios 1 and 4. In both costs types Scenario 6 presents the highest peaks and the highest variation along the planning horizon.

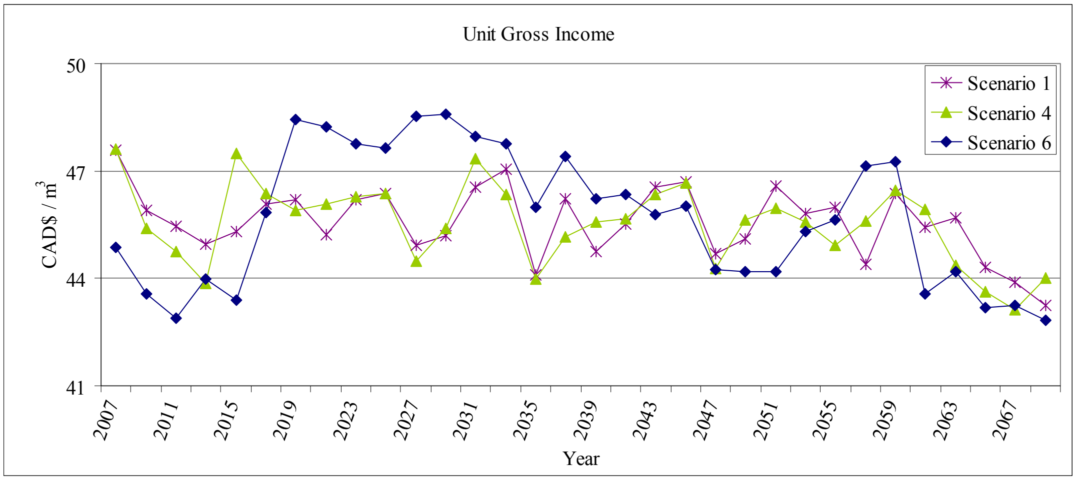



**Figure 4.2. Unit gross income for base Scenario 1 and fast decay scenarios with medium (Scenario 4) and high (Scenario 6) intensity attack.**

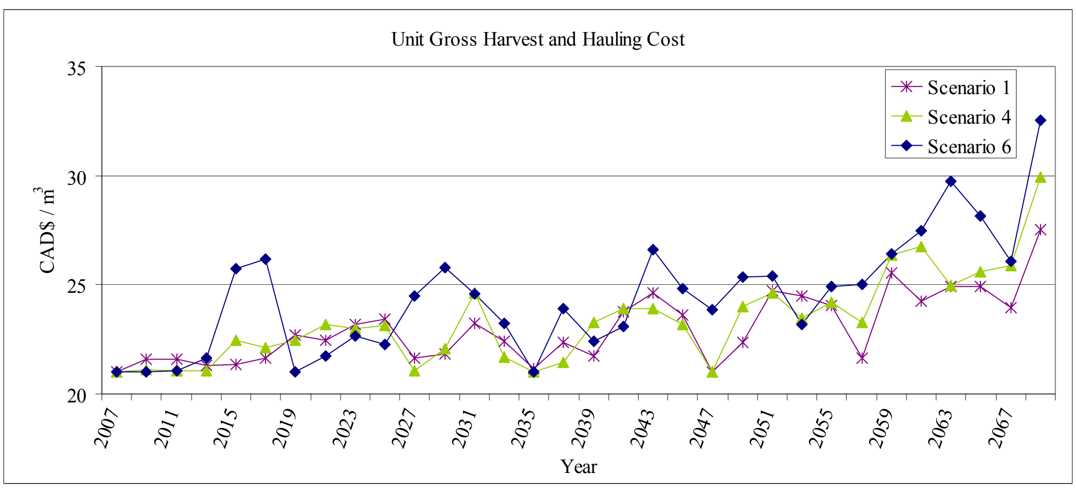



**Figure 4.3. Unit gross harvest and hauling cost for base Scenario 1 and fast decay scenarios with medium (Scenario 4) and high (Scenario 6) intensity attack.**

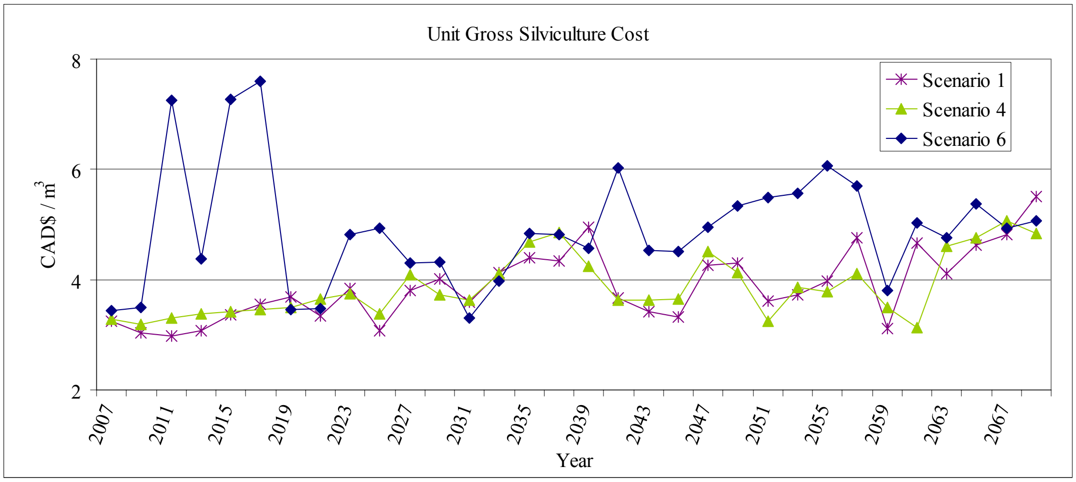



**Figure 4.4. Unit gross silviculture cost for base Scenario 1 and fast decay scenarios with medium (Scenario 4) and high (Scenario 6) intensity attack.**

## 4.3. Inventory

Since the model is set up to maximize profit, any AAC uplift means it will harvest or salvage as much as possible to reduce the loss of volume. However, the harvest flow has a close interaction with the ending inventory and the species harvested.

**Table 4.2. Standing inventory and volume distribution of attacked pine (thousands of cubic meters)**

| Scenario | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Total initial standing inventory (TISI) | 71,523 | | | | | |
| Initial pine inventory susceptible to attack (IPISA) | 22,821 | | | | | |
| Attacked pine volume (AV) (% respect to IPISA) | | | 12,982 (57%) | 13,000 (57%) | 23,556 (103%) | 23,605 (103%) |
| Salvaged pine volume (% respect to AV) | | | 3,293 (25%) | 3,265 (25%) | 7,498 (32%) | 6,912 (29%) |
| Salvaged pine waste during shelf-life (% respect to AV) | | | 437 (4%) | 385 (3%) | 3,130 (13%) | 2,722 (12%) |
| Standing pine waste volume after decay * (% respect to AV) | | | 9,250 (71%) | 9,350 (72%) | 12,928 (55%) | 13,970 (59%) |
| Total ending inventory without waste (% respect to TISI) | 67,404 (94%) | 69,730 (97%) | 54,856 (77%) | 54,832 (77%) | 49,250 (69%) | 49,250 (69%) |

* This standing waste is calculated after the recovered volume of useful pine drops to zero (i.e. period 6 for fast decay and period 8 for slow decay or 2 and 4 periods after last attack, respectively).

In Table 4.2, both base-scenarios (1 and 2) have an ending inventory within 6% of the initial inventory. There is no apparent difference depending on the shelf-life between Scenarios 3 and 4, and Scenarios 5 and 6. In contrast, there is an important difference in the intensity of attack. In the case of medium intensity, the ending inventory is close to 55 million $m^3$, which is 23% lower than the initial value. In the case of a high intensity attack, the ending inventory is below 50 million $m^3$, 31% lower than the initial inventory.

The attacked volume also differs between the two intensities of attack. At a medium intensity this represents an attack over 85,686 ha (60%) of pine-leading stands, affecting ~13 million $m^3$. At a high intensity this represents an attack over 142,890 ha (100%) of pine leading stands, affecting ~23.5 million $m^3$. These volumes represent 18% and 33% of the original inventory (~71.5 million $m^3$), respectively. In the case of the medium intensity attack, this volume corresponds to nearly the same proportion of area attacked (i.e. 57% of volume for 60% of the area attacked). This result reflects one of the important differences between area regulated models and volume regulated models. In volume regulated models, the percentage of volume tends to be less than the percentage of area attacked. In the case of a high intensity attack (Scenarios 5 and 6), the attacked pine volume is 3% higher than the initial inventory because the model grows the forest while the attack occurs in the first four periods.

With respect to the salvage volume there are also some important differences. The amount of pine salvaged in a high intensity attack scenario is more than double the volume salvaged in a medium intensity attack. In addition to the volume salvaged, there is a difference in the proportion of salvaged pine compared to the volume of attacked pine, which is related to the efficiency of the salvage strategy. Only 25% of pine is salvaged in a medium attack and around 30% in a high attack. This means there are more than 9 million of $m^3$ of un-recovered pine for the medium intensity, 13 million of $m^3$ of un-recovered pine for the high intensity with slow decay, and 14 million of $m^3$ of un-recovered pine for the high intensity with fast decay. Finally, about 3.2 million $m^3$ and 7 – 7.5 million $m^3$ are salvaged as merchantable volume for the medium intensity and the high intensity scenarios, respectively (Table 4.2).

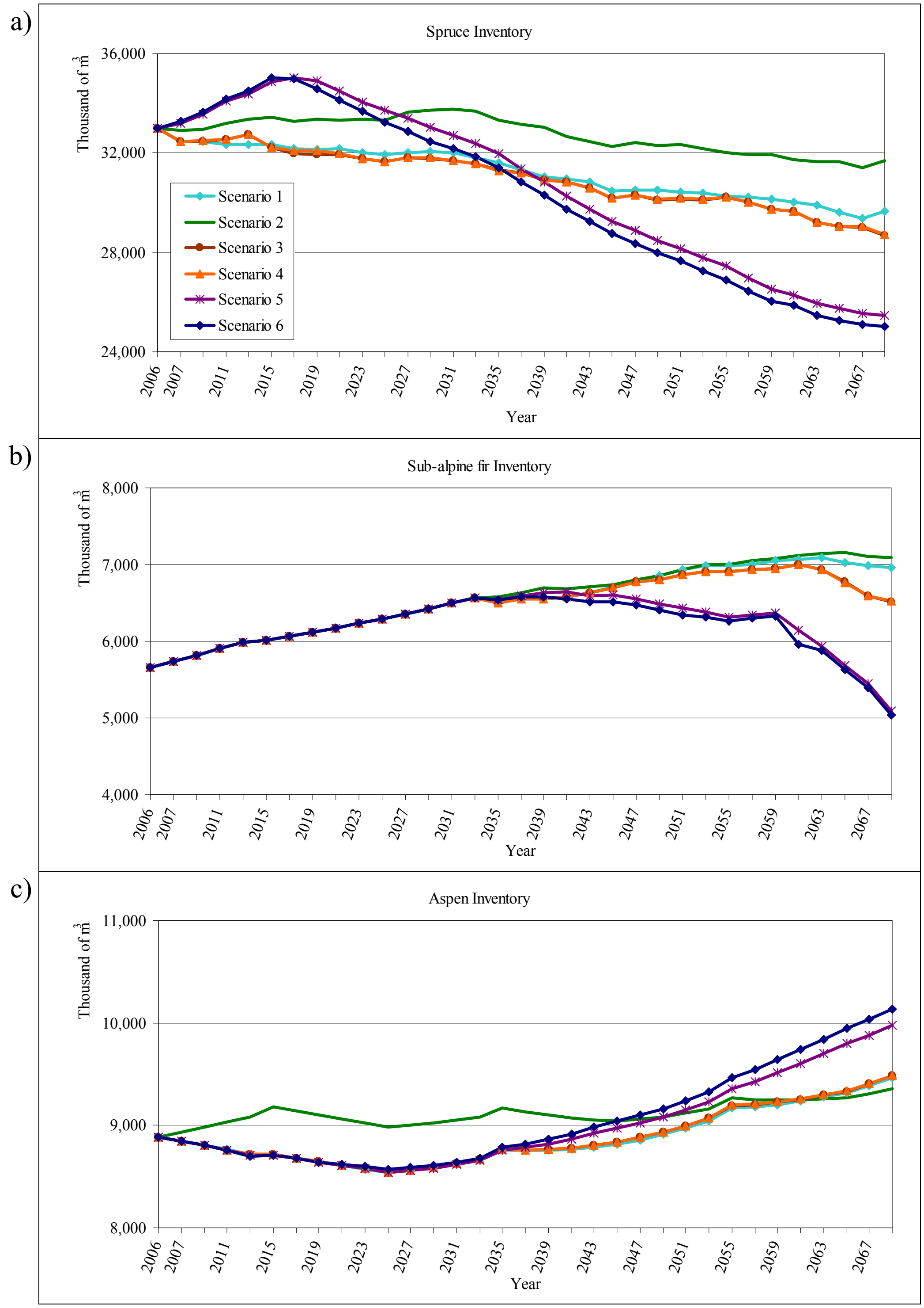



**Figure 4.5. Inventory distribution over time for a) spruce, b) sub-alpine fir, and c) aspen. The year 2006 is before the first planning period and the following years are the first year of each two-year period.**

Figure 4.5 and 4.6 show the distribution of the inventory over the planning horizon. For the spruce inventory in Figure 4.5a, there are different trends depending on the scenario.

The most stable spruce inventory over time is obtained for the base scenario 2 (no uplift nor attack). Scenario 2 ended 4% lower than the initial inventory compared to ~12% for Scenarios 1, 3, and 4, and ~24% for Scenarios 5 and 6. Spruce inventory shows a steady decrease for the base scenario with uplift and the scenarios with a medium intensity of attack (3 and 4). Even though Scenarios 5 and 6 show an increase of the spruce inventory early in the planning horizon, there is a significant steady drop following year 2017. This increase can be explained because during these early periods most of the supply is coming from salvaged pine stands, as I will show later. However, when the pine supply is over, most of the supply comes from spruce stands. This result shows how dependent the supply is on spruce when pine no longer provides any merchantable volume. Scenario 1 (with uplift and no attack) also shows a decrease in spruce inventory. This is because the model prefers to harvest higher valued spruce and use less valued species (sub-alpine fir) to satisfy ending inventory constraints.

Sub-alpine fir inventory shows similar trends for all scenarios until year 2033 (Figure 4.5b). This steady increase means that sub-alpine fir is growing and it does not contribute significant to the harvest flow. There is a break after year 2033 and again Scenario 5 and 6 show a decrease, ending with a lower inventory (10%) than the initial. This is not the case for the other four scenarios that finish with a higher ending inventory of 124% for the base scenarios and 115% for the medium attack scenarios. The decrease of the inventory for the high intensity of attack scenarios (5 and 6) reflects that sub-alpine fir becomes important when the other coniferous species (pine and spruce) become scarce. This secondary importance of sub-alpine fir might be explained by the lower overall price of sub-alpine fir relative to the other coniferous species.

Aspen inventory levels show no major changes following beetle attack for all six scenarios, though a modest increase is observed at the end of the planning horizon (Figure 4.5c). As opposed to the other species, the highest increase is shown for the high intensity of attack scenarios (5 and 6). The higher increases for Scenarios 5 and 6 after year 2035 is likely related to the faster growth of new managed stands salvaged at the beginning of the planning horizon. Although there is an uplift of 18% for the first 10 years it does not seem to have an impact on the aspen inventory and all scenarios end up with a higher inventory than the initial one (between 105% and 114% higher). This result suggests that the deciduous AAC could be higher.

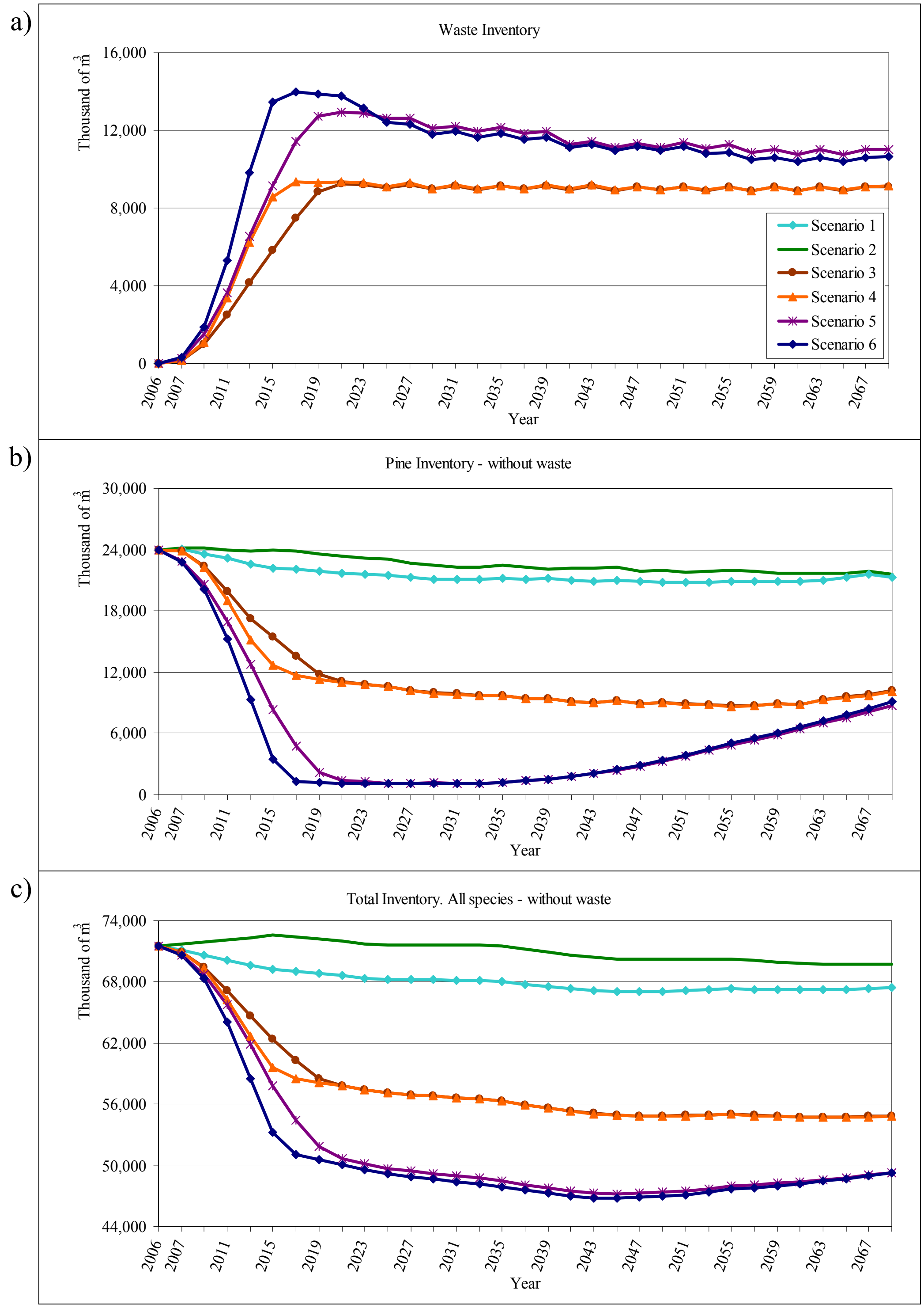



**Figure 4.6. Inventory distribution over time for a) waste, b) pine without waste, and c) all species without waste. The year 2006 is before the planning period and the following years are the first year of each two-year period.**

Figure 4.6a and 4.6b show the effect of the MPB attack on pine inventory divided into waste as dead non-recoverable volume and pine as green plus dead recoverable merchantable volume, respectively. The pine inventory - without waste (Figure 4.6b) reflects MPB losses, whether salvaged or not. Figure 4.6b shows the decline in the merchantable pine inventory between years 2007 and 2022 for Scenarios 3, 4, 5, and 6. This decline stabilizes after year 2022 and the high and medium intensity attack scenarios show a clear difference for the rest of the planning horizon, probably due to more managed stands with faster growth rates. During the first eight periods (2007-2022) the differences in pine inventory represent the different levels of decay. Scenarios 4 and 6, with a fast decay produce a faster drop than Scenarios 3 and 5. Thus, a faster level of decay results in a faster decrease of pine inventory and a faster increase of waste inventory (Figure 4.6a). In addition, these results demonstrate that the loss of pine inventory between both levels of decay is not necessarily transferred to a higher level of salvage but rather to a higher level of waste.

There is no decay assumed for waste, so if waste is not harvested as a by-product of the salvage activities, its inventory remains constant. That is why the waste inventory remains relatively constant for medium attack scenarios 3 and 4. There is little salvage occurring after year 2022, when shelf-life is over for all attack scenarios.

Finally, Figure 4.6c shows the overall impact on the total inventory (all species – no waste) of a MPB attack. The intensity of attack has a significant impact over the total inventory.

## 4.4. Harvest flow

As mentioned, only one harvest flow was assessed in order to reduce the number of scenario results. A total of 40,320,000 m$^3$ were harvested in all attack scenarios, including 36,350,000 m$^3$ for the coniferous (spruce, pine, and fir) and 3,970,000 m$^3$ for deciduous (aspen). However, there were differences in the ending inventory, the amount of salvaged volume and the amount of waste volume for each scenario. I will next present the results about the relative importance of the different species harvested, how relevant the salvage supply is to the system, the species proportion of the salvaged volume, what type of stands are salvaged, and what type of stands are left.

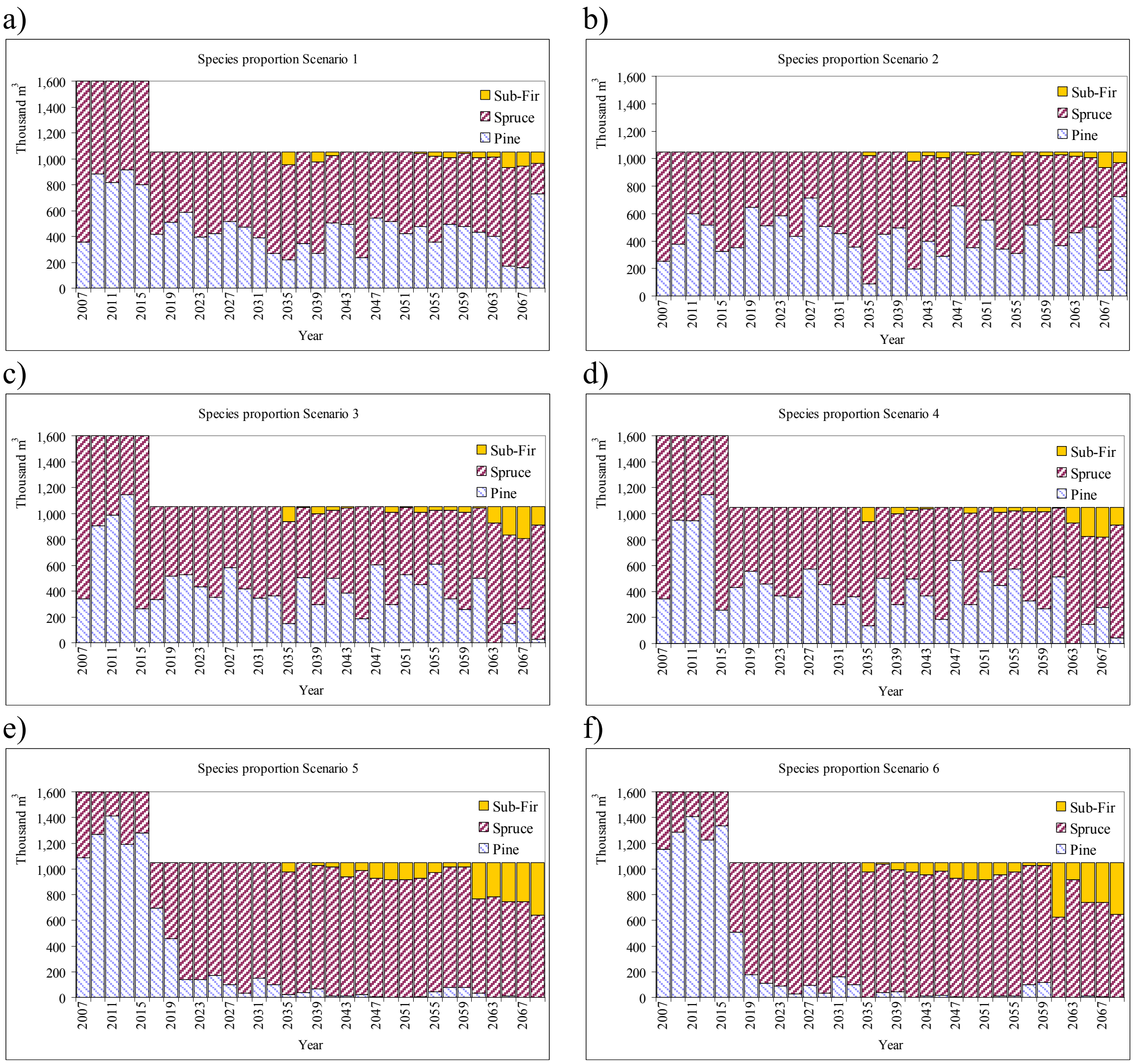



**Figure 4.7. Species composition of the coniferous harvest flow by scenario: a) Scenario 1, b) Scenario 2, c) Scenario 3, d) Scenario 4, e) Scenario 5, and f) Scenario 6.**

Figure 4.7 shows the coniferous harvest distribution by species for each scenario. For Scenario 1 and Scenario 2, pine and spruce are generally balanced over the planning horizon (Figure 4.7a and 4.7b). The same occurs with Scenarios 3 and 4, with a slight increase in the pine volume harvested during part of the shelf-life, between years 2009 and 2014 (Figure 4.7c and 4.7d). This balance changes dramatically with the high intensity attack scenarios (Figure 4.7e and 4.7f). The average percentage of spruce for

Scenario 1, 2, 3, and 4 is between 53% and 60% during the uplift (first 10 years) and between 56% and 61% after the uplift. On the other hand, the average for Scenarios 5 and 6 is around 21% during the uplift and 84% after the uplift. There is a high concentration of the pine harvest during the early periods, and it is closely related to the assumed shelf-life. After the shelf-life, pine harvest drops to nearly zero. During the shelf-life, almost all pine volume is coming from salvage activities, as I will explain later. Therefore, a medium intense outbreak does not seem to have a great impact in the species distribution over time, showing a similar pine-spruce proportion as the non-attacked scenarios. This is not the case for a high intensity attack.

In all scenarios sub-alpine fir became important in the late stages of the planning horizon. Sub-alpine fir has the greatest proportion in scenarios with a high intensity of attack (Scenarios 5 and 6) (Figure 4.7e and 4.7f) and this can be explained by the low value of sub-alpine fir relative to the other species.

The total impact on the forest estate can be defined as the sum of the merchantable volume harvested, the salvage of waste, and the loss of standing inventory as non-recoverable pine. Table 4.3 presents the impact in terms of total volume and the average volume per year for conifers for all attack scenarios. In all scenarios, these average volumes are similar or higher than the estimated LTSY presented at the beginning of this chapter.

**Table 4.3. Total impact in terms of loss of coniferous' volume per scenario.**

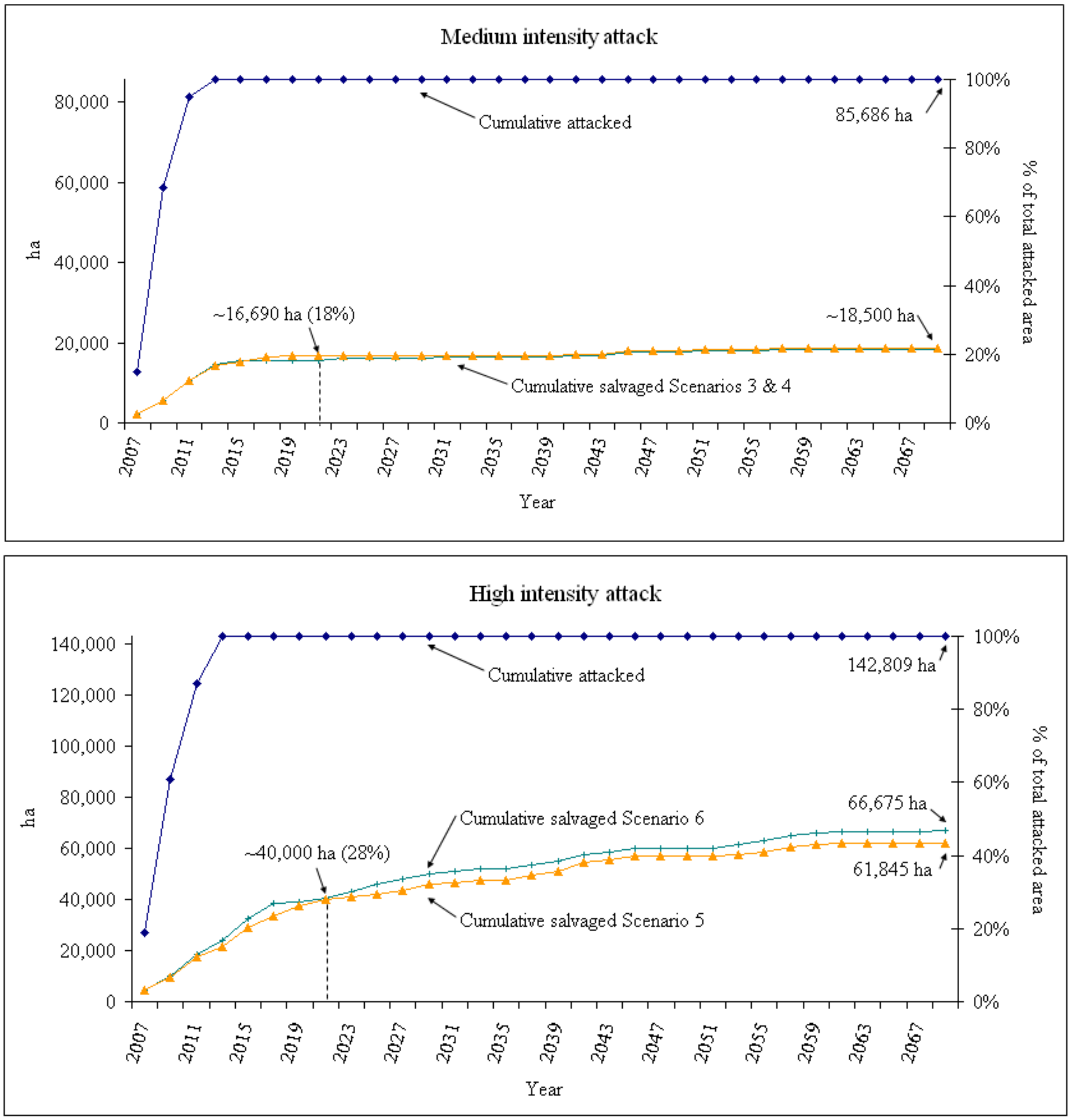
| Cubic meters for Coniferous | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 |
|---|---|---|---|---|
| Total merchantable harvested | 36,350,000 | 36,350,000 | 36,350,000 | 36,350,000 |
| Salvage of waste | 438,000 | 385,000 | 3,130,000 | 2,722,000 |
| Standing non-recoverable pine | 9,250,000 | 9,350,000 | 12,930,000 | 13,970,000 |
| Total impact | 46,038,000 | 46,085,000 | 52,410,000 | 53,042,000 |
| Estimated LTSY ($m^3$/year) | 700,000 | 700,000 | 700,000 | 700,000 |
| Average impact ($m^3$/period) | 1,439,000 | 1,440,000 | 1,638,000 | 1,658,000 |
| **Average impact ( $m^3$/year)** | **719,000** | **720,000** | **819,000** | **829,000** |

## 4.5. Salvage strategy

Figure 4.8 shows the area affected by the outbreak and the area salvaged over the planning horizon. In the case of the medium intensity of attack –Figure 4.8a– 60% of the area is attacked, corresponding to approximately 86,000 ha. In this case the overall salvage covers only 21% of the area and 18% of the area is salvaged within the pine shelf-life. In the case of the high intensity of attack –Figure 4.8b– 100% of the area susceptible to attack was affected, corresponding to ~143,000 ha. Less than half of this area was salvaged during the planning horizon (43%). During the shelf-life, around 40,000 ha were salvaged, corresponding to 28% of the total affected area.

In order to explain the impact of the salvage area on the total harvest flow, I present results focusing on the salvaged stands (Salvaged) versus the combined volumes from non-attack, natural and managed harvested stands (Non-attacked). Managed stands contributed very little to the overall harvest flow, with the bulk of the volume coming in the last planning periods. The relative unimportant role played by the managed stands is largely due to the state of the forest, a planning horizon that is only one rotation, and because managed stands are not susceptible to attack.

a)



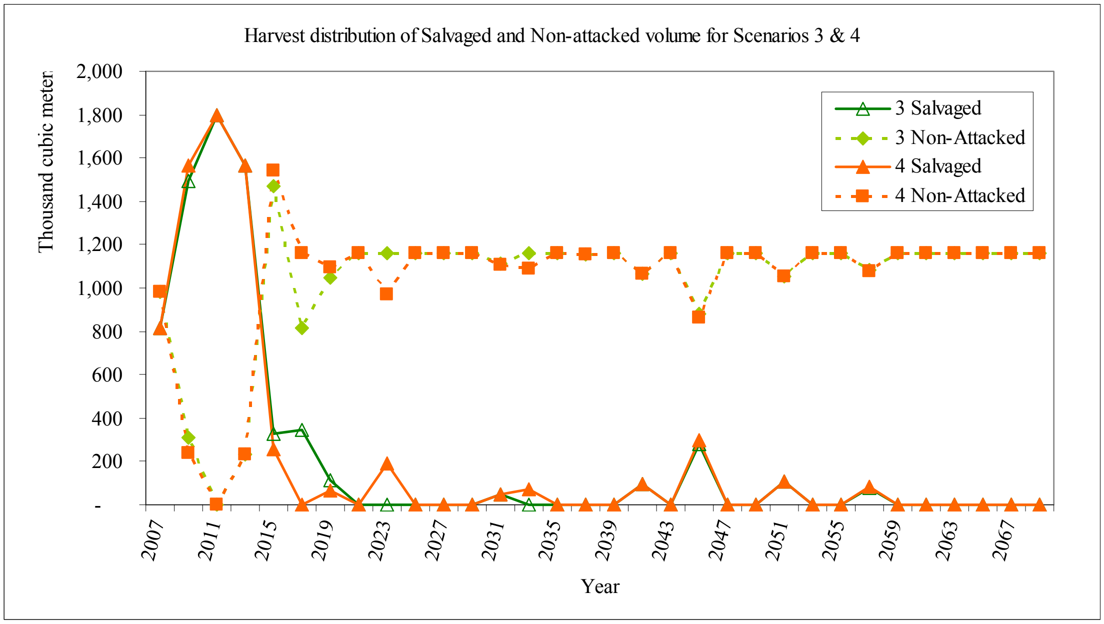

b)



**Figure 4.8. Cumulative area attacked and cumulative area salvaged for Scenarios 3 and 4 (a) and for Scenarios 5 and 6 (b). The value marked in years 2021-2022 (period 8) is the amount and percentage of area salvaged during the pine shelf-life.**

Figure 4.9 shows the differences between the four scenarios where salvage occurred. In all four scenarios the salvage activities cover the major proportion of volume requirements during the early periods. While salvage strategies in a medium intensity attack (Scenarios 3 and 4) are still dominant during the first 16 years (until year 2022), they are lower compared to high attack scenarios. Differences between medium and high intensity attack scenarios can also be seen in relation to shelf-life, with shelf-life becoming less important under medium intensity attack scenarios. The shelf-life of attacked trees extends to year 2022 in Scenario 3 (slow decay) and to year 2018 in Scenario 4 (fast decay) but there is no salvage in either of these final years, because the model switches to non-attacked stands.

a)




b)

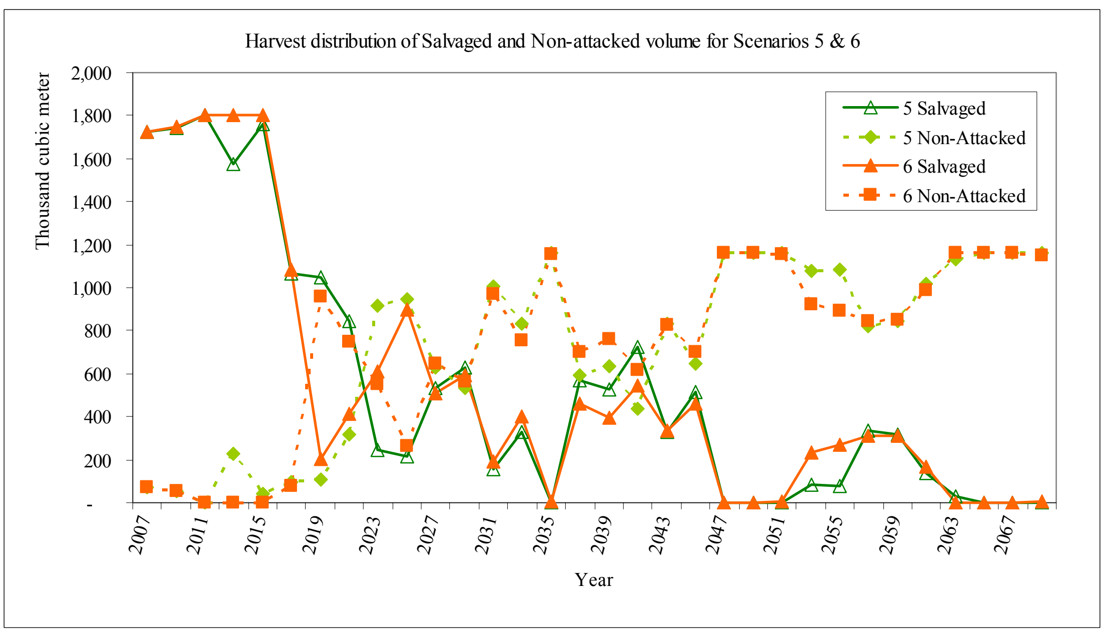



**Figure 4.9. Total harvest distribution (coniferous and deciduous) per year by the type of management action in salvaged stands (Salvaged) and natural, non-attacked or managed stands (Non-Attacked): a) Scenarios 3 and 4, b) Scenarios 5 and 6.**

Salvage activities that occur after the shelf-life result in green volume composed of spruce, fir, aspen, and in the case of pine, only waste. The results show that once we go beyond the shelf-life of pine trees, salvage volumes drop nearly to zero for scenarios that assume a medium intensity attack. In contrast, with a high intensity, attacked stands provide an important amount of volume over the whole planning horizon. Since my assumption was that natural regenerated merchantable volume of pine in attacked stands will not be available during this planning horizon, all green merchantable volume is obtained from the harvest of non-pine species. The model uses these stands to satisfy the harvest, even though they do not supply any merchantable pine volume, and this could ultimately lead to shortages in the mid-term.

There are some important differences between the species that comprise the early salvage volume. Figure 4.10 shows the proportion of green (spruce, fir, and aspen) and dead merchantable pine volume that is available for salvage over the active shelf-life. The figure shows only the first eight periods of the planning horizon because these are where shelf-life takes place, representing a slow decay of five periods after the fourth or last attack occurs (i.e. since salvage can occur during the same period of the attack, the shelf-life for the fourth attack lasts between period 4 and 8 for the slow decay scenarios). Scenario 6 (high intensity attack-fast decay) has the lowest proportion (31%) of green volume. That is, for every two $m^3$ of dead pine, one $m^3$ of green species is harvested as by-catch. For all other scenarios this proportion is higher, rising to a maximum ratio of 1:1 for the medium attack and slow decay (Scenario 3, Figure 4.10). This means that a high intensity of attack scenario salvages more than 7 million $m^3$ of merchantable dead pine and almost 4 million $m^3$ of green volume during the shelf-life (between years 2007 - 2022). On the other hand, a medium intensity of attack scenario salvages more than 3 million $m^3$ of dead pine merchantable and almost 3 million $m^3$ of green volume.

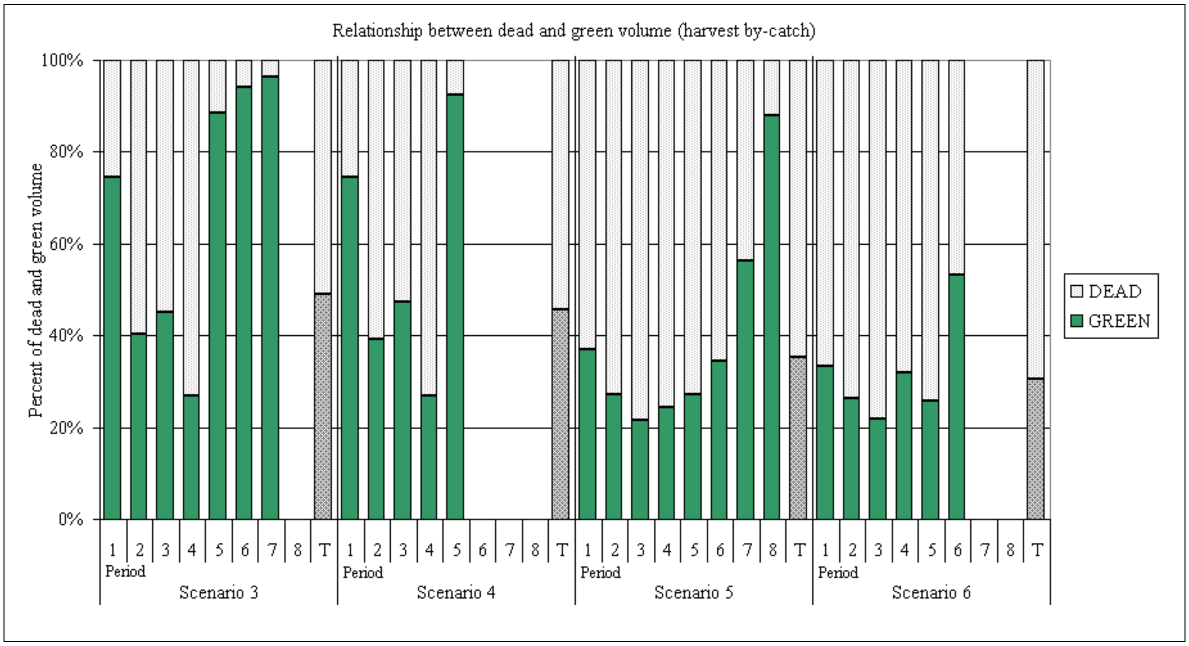



**Figure 4.10. Dead and green harvest merchantable volume relationship from salvaged stands. Scenario 3 and 5 are represented until period 8 (slow decay = length of shelf-life). Scenario 4 and 6 are represented until period 6. 'T' represents the total proportion over the 6 or 8 analysed periods, depending on the scenario.**

The last component of the salvage strategy to be analyzed is the type of pine stands that are salvaged and the stands that remain un-salvaged. These results are reported according to the landscape classifications used for the pine stands, described in Table 3.6. Table 4.4 shows a summary for Scenario 3 and Scenario 6 according to the area attacked, the area salvaged, and the proportion of each landscape class. Each landscape category is independent and therefore they all sum to the total attacked area and 100% salvage. Table 4.4 shows a shift in the salvage strategy depending on the intensity of attack and future supply requirements. For example, with respect to the pine category the highest proportion of pine in Scenario 6 (38%) comes from P4 (percentage of pine >=75%). On the other hand, the highest proportion of pine in Scenario 3 (53%) comes from P2 (percentage of pine >=25% & <50%). In both cases the highest proportion of salvage with respect to the total area attacked comes from P2, with 46% and 60% for Scenarios 3 and 6, respectively.

**Table 4.4. Area attacked, area salvaged, and their relative proportion for the landscape classifications for Scenarios 3 and 6. The landscape classifications are Pine category, Non-pine leading species, Site quality, Cost class, and Seral stage.**

| | **Area Attacked (ha) (a)** | | **Area Salvaged (ha) (b)** | | **Salvaged relative to total area attacked (%) (b ÷ a)** | | **Salvaged relative to total area salvaged (%) (b ÷ c)** | |
|---|---|---|---|---|---|---|---|---|
| Lclass* \ Scenario | 3 | 6 | 3 | 6 | 3 | 6 | 3 | 6 |
| P2 | 21,340 | 33,085 | 9,810 | 19,815 | 46% | 60% | 53% | 30% |
| P3 | 31,280 | 49,075 | 3,140 | 21,810 | 10% | 44% | 17% | 33% |
| P4 | 33,060 | 60,650 | 5,690 | 25,050 | 17% | 41% | 31% | 38% |
| S1 | 65,315 | 112,810 | 17,040 | 50,280 | 26% | 45% | 91% | 75% |
| Bl2-Ae3 | 20,370 | 30,000 | 1,600 | 16,395 | 8% | 55% | 9% | 25% |
| Sq1 | 55,850 | 87,440 | 8,795 | 29,000 | 16% | 33% | 47% | 43% |
| Sq2 | 29,830 | 55,370 | 9,845 | 37,675 | 33% | 68% | 53% | 57% |
| C21 | 27,340 | 51,035 | 14,925 | 33,425 | 55% | 65% | 80% | 50% |
| C26 | 36,130 | 56,830 | 3,715 | 27,260 | 10% | 48% | 20% | 41% |
| C31 | 13,040 | 20,510 | - | 4,745 | - | 23% | - | 7% |
| C36+ | 9,175 | 14,435 | - | 1,250 | - | 9% | - | 2% |
| Adult ** | 12,930 | 19,385 | - | 5,140 | - | 27% | - | 8% |
| Mature | 49,505 | 84,690 | 9,080 | 36,660 | 18% | 43% | 49% | 55% |
| Old-G | 23,250 | 38,735 | 9,560 | 24,880 | 41% | 64% | 51% | 37% |
| **Total area** | **85,685** | **142,809** | **(c) 18,639** | **66,680** | **22%** | **47%** | **100%** | **100%** |

* Lclass: Landscape class.
** Adult: Age class 50-70; Mature: Age class 90-110-130; Old-G: Age class 150-170-190.

The stands with spruce as a non-pine leading species (S1) were the principal component in the all salvage operations. The high intensity of attack scenario tends to rely more on stands with other non-pine leading species (i.e. Bl2-Ae3: sub-alpine fir and deciduous leading, represented by aspen). For Scenario 6, Bl2-Ae3 represents 25% of the total salvaged area; however, it represents 55% of the total attacked area. In contrast, only 8% of the total attacked area is salvaged in Scenario 3 for this type of non-pine leading species, representing 9% of the total salvaged area.

In terms of site quality, there is no apparent difference between the proportions of total area salvaged. However, there is a tendency towards a higher salvage proportion (53% and 57%) of the medium-good sites (Sq2) in both scenarios.

As expected, all scenarios concentrate the salvage operations in the less expensive stands (C21, C26), with a small proportion or zero in stands with a harvest cost of 31 CAD$/$m^3$ or higher (C31, C36+).

The last landscape category shown in Table 4.4 is the age class. In both cases the salvage strategy is focused on mature and old growth stands. Adult stands did not become a significant part of the salvage strategy in any scenario. In Scenario 6, the adult class contributed 8% towards the total salvaged area and 0% in Scenario 3.

To complement the results in Table 4.4, Figure 4.11 illustrates the distribution of the landscapes categories over the planning horizon. These values are relative to the total area salvaged per period and per each landscape class. For example, during the first four planning periods almost 100% of the salvage comes from the stands with the lowest cost (C21). If we consider the time while the shelf-life is active (i.e. until year 2021) the salvage activities are concentrated in the less expensive stands, old growth and mature, with medium-good site quality, stands with spruce as non-leading species, and in stands with a high composition of pine. After the shelf-life, Figure 4.11 shows that stands with high pine composition (P4) are not part of the salvage strategy and are being replaced by P2 stands and to a lesser extent, by P3 stands.

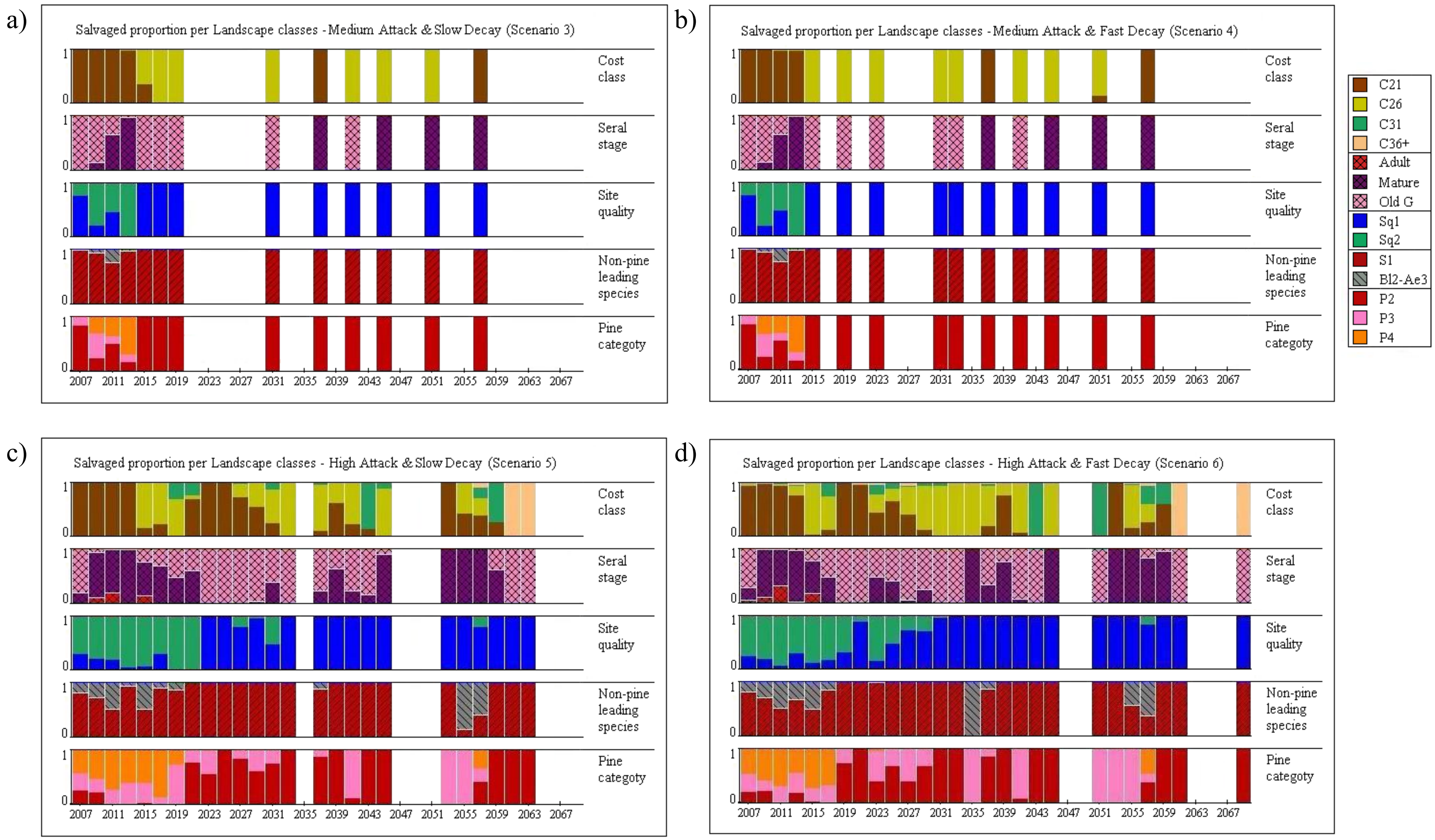



**Figure 4.11. Salvaged proportion by landscape class for Scenario 3 (a), Scenario 4 (b), Scenario 5 (c), and Scenario 6 (d).**

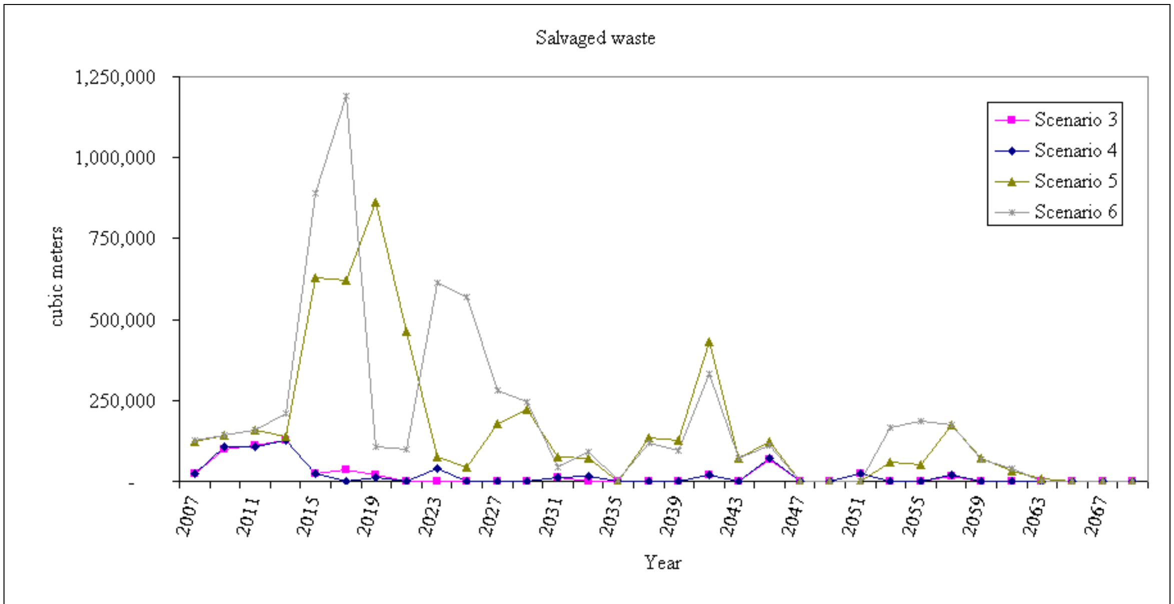
Figure 4.11 also illustrates that the stands with costs of 36 CAD\$/m$^3$ or higher are pushed to the end of the planning period. To illustrate the different responses to the intensity of attack, I will focus on the years between 2015 and 2027 of Scenarios 3 and 5. In Scenario 3 (Figure 4.11a), after salvaging the less expensive stands before 2015, the model moves to the cost range of 26 CAD\$/m$^3$ but this is composed of stands with a pine composition less than 25% (P2). For the same scenario there are no important salvage activities after 2019. Whereas in Scenario 5 (Figure 4.11c), we see the same shift to the 26 CAD\$/m$^3$ cost range, however, the stands are still mainly composed of pine (P3 and P4). After year 2019 new stands belonging to the lower cost range provide salvage supply and it is mainly composed of stands where pine is a secondary species (P2 and P3). These results show that the model delays the harvest of less expensive spruce species stands in order to salvage more pine stands during the active shelf-life, depending on the intensity of attack. This reinforces the results presented in Section 4.2 with respect to the gross profit. For Scenario 3, the fact the there are no salvage activities after year 2019 and the fact that it shifts right away to spruce-leading stands seems to demonstrate that the flow requirements are not as constraining as in a high attack. The same behaviour is apparent when comparing Scenarios 4 and 6.

### 4.6. Waste as a potential bioenergy source

The flow of waste volume is a potential bioenergy source. Figure 4.12 shows the amount of potential waste that might be produced for each salvage strategy. Waste does not include the amount of standing non-recoverable volume of the un-salvaged stands (considered as standing inventory waste) nor traditional losses due to harvest activities, because the yield curves contain only the net merchantable volume. Figure 4.12a shows that the greatest amount of waste harvested occurs during the earlier planning periods and that there is a close relationship with the salvage intensity. Approximately, 3,000,000 m$^3$ and 400,000 m$^3$ of waste are produced during the first 16 years of salvage for the high and medium intensities of attack, respectively. After this, the volume remains almost constant for the medium intensity of attack cases (Scenarios 3 and 4) because there is very little salvage occurring after the shelf-life. The accumulated volume of waste in each of these medium intensity scenarios reaches 600,000 m$^3$ at the end of the planning horizon. For Scenarios 5 and 6 the accumulated volume of waste at the end of the planning horizon is almost double than the amount at the end of the shelf-life and rises to more than 5 million $m^3$ (Figure 4.12b). Finally, to put into context the amount of waste and to complement the results already shown in Figure 4.12, Table 4.5 shows the proportions of waste related to the total volume salvaged and to the volume of recovered pine. Table 4.5 shows the species distribution of the salvaged volume grouped by two periods between years 2007 - 2022 and between years 2023 - 2070. The total amount of salvage is similar among both decay levels (e.g. Scenarios 3 & 4 and Scenarios 5 & 6). This is not the case with the intensity of attack. A total merchantable volume of 7 million $m^3$ was salvaged in Scenarios 3 and 4 and a total merchantable volume of 17 million $m^3$ was salvaged in Scenarios 5 and 6. It is also important to notice that sub-alpine fir is not a salvaged species in any of the scenarios. Table 4.5 also shows that the volume of waste is higher in the high intensity of attack scenarios but not proportional to that intensity. Indeed, the proportion of waste is more than double in all cases (i.e. per grouped period, pine, and total merchantable volume) for the high intensity of attack scenarios with respect to the medium intensity scenarios.

Assuming the development of an energy industry during the next 16 years, a total a total of ~400,000 $m^3$ for Scenarios 3 and 4 and ~3 million $m^3$ for Scenario 5 and 6 will be available for energy production. Although it is not explicitly shown in Table 4.5, the bioenergy supply over the next 30 years will be ~500,000 $m^3$ for Scenarios 3 and 4, ~3.8 million $m^3$ for Scenario 5, and 4.8 million $m^3$ for Scenario 6.

a)




b)

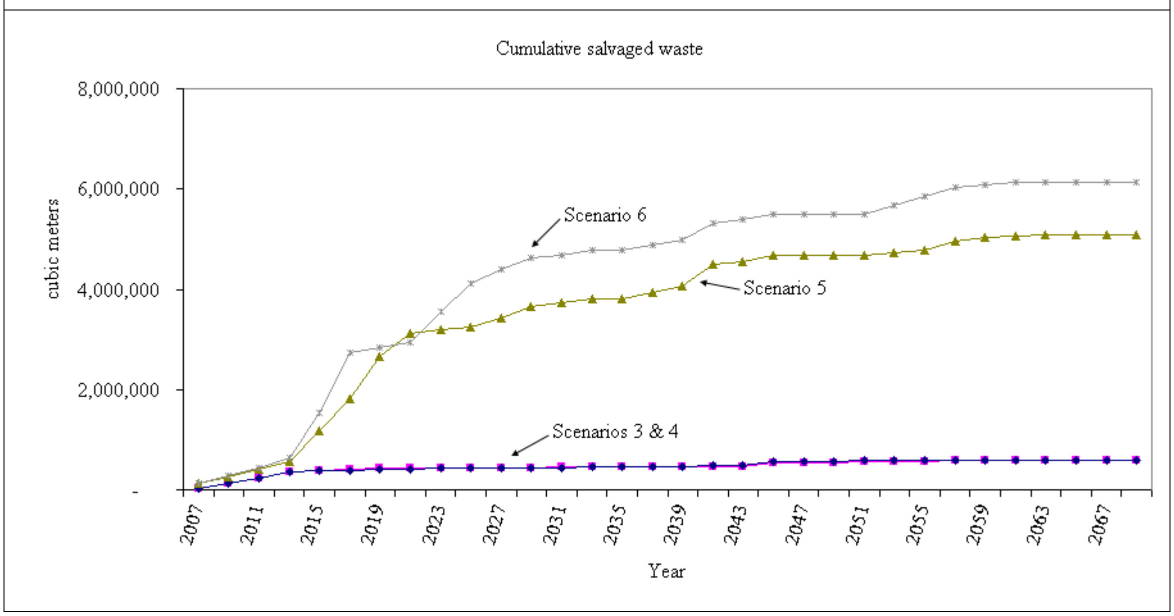



**Figure 4.12. Waste (non-recovered merchantable pine) harvested during the salvage activities by year (a) and cumulative (b).**

**Table 4.5. Salvage volume ($m^3$) by type of product or species. The division of the periods corresponds to after and before the end of the shelf-life related to the last attack.**

| Product or species | Period | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 |
|---|---|---|---|---|---|
| Total merchantable volume | 2007 - 2022 | 6,463,000 | 6,069,000 | 11,565,000 | 10,574,000 |
| | 2023 - 2070 | 614,000 | 891,000 | 5,750,000 | 6,717,000 |
| | Total | 7,077,000 | 6,960,000 | 17,315,000 | 17,291,000 |
| Spruce | 2007 - 2022 | 2,921,000 | 2,554,000 | 3,341,000 | 2,719,000 |
| | 2023 - 2070 | 614,000 | 891,000 | 5,602,000 | 6,561,000 |
| | Total | 3,535,000 | 3,445,000 | 8,943,000 | 9,280,000 |
| Aspen | 2007 - 2022 | 248,000 | 249,000 | 726,000 | 943,000 |
| | 2023 - 2070 | - | - | 148,000 | 156,000 |
| | Total | 248,000 | 249,000 | 874,000 | 1,099,000 |
| Pine * | ’07-’22=Tot | 3,294,000 | 3,266,000 | 7,498,000 | 6,912,000 |
| Waste | 2007 - 2022 | 438,000 | 396,000 | 3,130,000 | 2,927,000 |
| | 2023 - 2070 | 142,000 | 201,000 | 1,943,000 | 3,208,000 |
| | Total | 580,000 | 597,000 | 5,073,000 | 6,135,000 |
| % of waste with respect to pine | 2007 - 2022 | 13% | 12% | 42% | 42% |
| | Total | 18% | 18% | 68% | 89% |
| % of waste with respect to total merchantable vol. | 2007 - 2022 | 7% | 7% | 27% | 28% |
| | 2023 - 2070 | 23% | 23% | 34% | 48% |
| | Total | 8% | 9% | 29% | 35% |

* There is no pine recovery after year 2022 because of the assumed shelf-life (i.e. salvaged pine volume until 2022 is equal to the total salvaged during the planning horizon).

As seen in Figure 4.12a, the scenarios that represent a medium intensity attack resulted in waste being concentrated in the first 8 years. For the scenarios simulating a high intensity attack, the waste is concentrated between years 2013 and 2030, but it is still higher than the medium intensity during the earlier years. Figure 4.12a also demonstrates that the model does not include flow restrictions for the waste. Waste is considered as a by-product obtained from salvage activities that target green or dead recoverable pine. There are no activities in my model to collect only waste as target product. Unless there is a storage problem or a difference in the rate of decay for energy purposes between standing dead trees and stored dead logs, there does not seem to be any reason to include flow restrictions.

The average harvest cost of waste over the first 30 years was 24 CAD$/m$^3$ (almost 2 CAD$ higher than the cost for pine). This cost represents the lower range of analyzed costs. The average gross cost (including silviculture cost) was between 25 and 28 CAD$/m$^3$.

## 4.7. Age class distribution

a)

b)

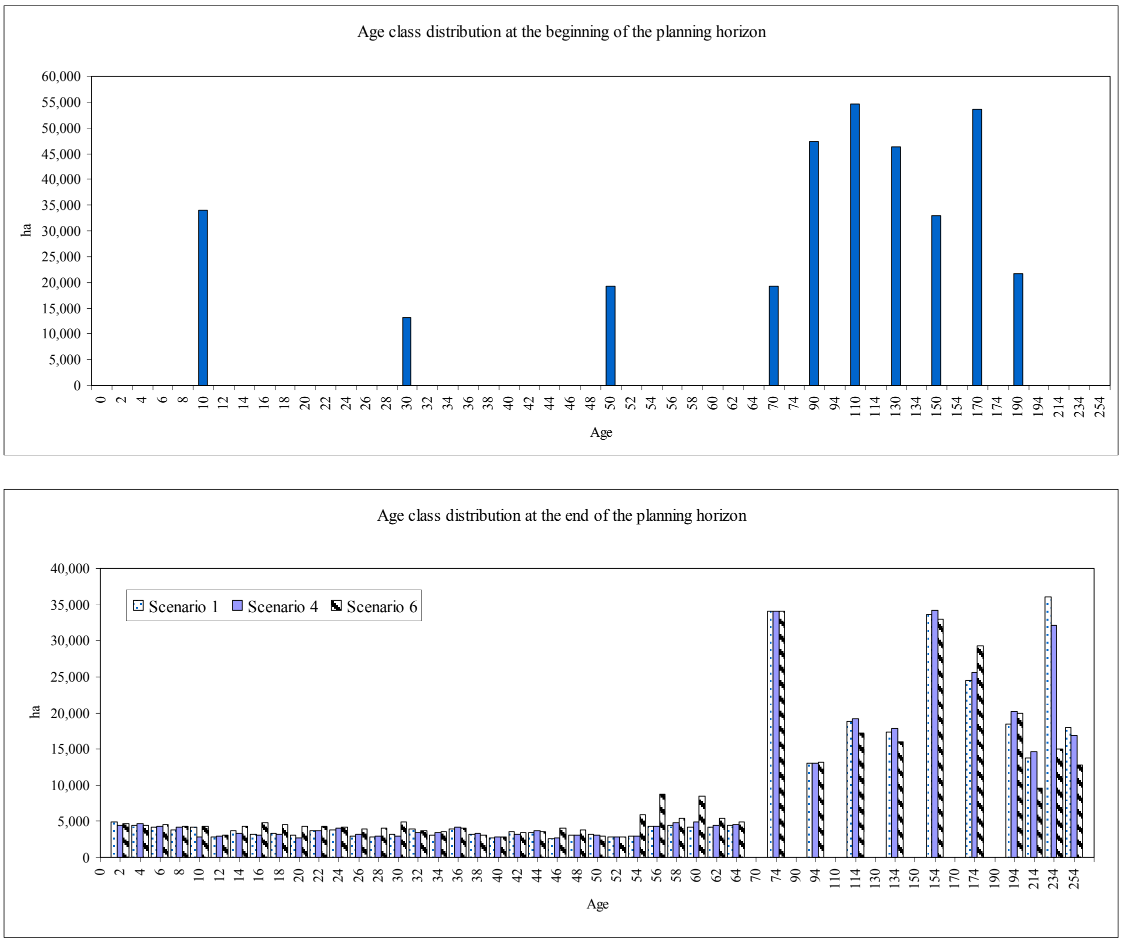



**Figure 4.13. Age class distribution for all scenarios at the beginning of the planning horizon (a) and age class distribution at the end of the planning horizon for Base-scenario 1 and for attacked-scenarios 4 and 6 (b).**

Figure 4.13a shows the initial age class distribution of the THLB and Figure 4.13b shows the ending age class distribution for three of the scenarios. The THLB has 61% of mature-old growth forest - older than 110 years - at the beginning of the planning horizon. For the base case Scenario 1 and the scenarios where the intensity of beetle attack is medium, the initial age distribution of mature-old forest decreased to 53%. In the scenarios with high intensity of attack mature-old growth dropped to 45%. Figure 4.14 shows the harvested percentage per age class and we can see that the scenarios 5 and 6 require close to 40% of the area to satisfy the harvest requirements. The other scenarios satisfied the demand using only 33% of the area. As expected, Scenario 2 was less demanding, requiring only a 30% of the area (represented in the total column of the graph). On average, 120,874 ha out of the 341,860 ha were required to obtain 40,320,000 $m^3$ over the planning horizon, with a minimum of 103,545 ha for scenario 2 and a maximum of 141,906 ha for scenario 6. Furthermore, in all scenarios the harvest was concentrated in the age classes 110 and 130 corresponding to stands with ages between 101 and 140 years, followed by the age classes 150 and 170. Scenarios 5 and 6 (high intensity attack) required a higher area that was satisfied mainly with the late seral stage classes compared to the other scenarios (Figure 4.14).

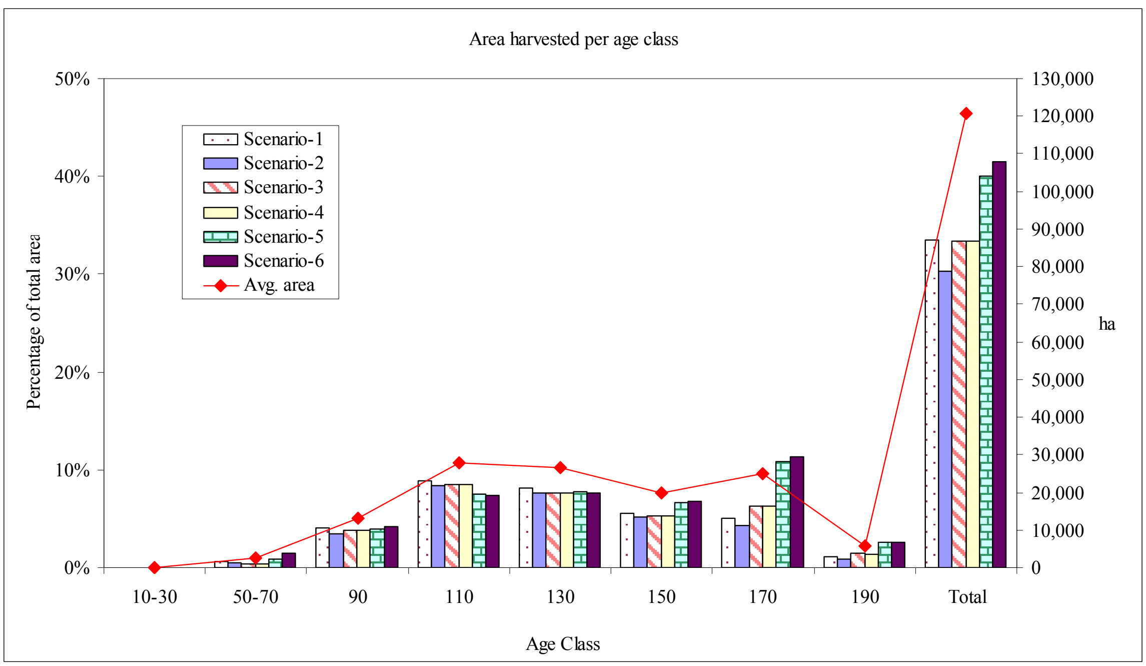



**Figure 4.14. Harvested area per age class. The column graph represents the percentage of the total harvested area on the left Y-axis and the line graph represents the average harvested area (hectares) on the right Y-axis.**

### 4.8. Sensitivity analysis for ending inventory and harvest flow

The shadow price for the high intensity and fast decay Scenario 6 ending inventory constraint is negative. This was expected since an NPV model with a positive discount rate tends to harvest as much as possible while being restricted by a minimum ending inventory and the minimum harvest age of the forest. The other expected result is that the harvest flow shadow prices during the uplift are positive. No sensitivity analysis was conducted for the uplift period because I expect that the model will rise as much as possible, trying to salvage most of the attacked volume. The un-expected result is that the shadow prices for the harvest flow are negative for coniferous volume and aspen volume after periods 9 and 12, respectively. Two runs were conducted to analyse the behaviour of the harvest flow. For the first run, a range of ± 300,000 $m^3$ for coniferous and ± 50,000 $m^3$ for deciduous was included for the harvest flow after the first decade (i.e. period 6 and later). For the second run, only a relaxation of the lower harvest level was allowed using the same amount for coniferous volume in period 9 and beyond and deciduous volume in period 12 and beyond, when the shadow prices were negative. Results from the first run show that the harvest flow reaches the upper bound for coniferous (periods 6 to 14) and aspen (periods 6 to 17), then declines to the lower bounds during the following periods. In the second case where only the lower bounds were relaxed, the model only reaches the lower bound after period 22 for both coniferous and aspen. These two runs achieved higher objective function values than was observed in the original Scenario 6. However, for both of the runs, the overall result was that the total harvest fell from roughly 40 million $m^3$ to less than 37 million $m^3$. Nonetheless, this lower harvest flow did not affect the total ending inventory, which was observed to be the lower bound of 49.25 million $m^3$ for all three cases. The gain in the net present value comes marginally from a higher valuation of the ending inventory but mainly from a re-distribution of the harvest schedule by shifting higher incomes closer to the present. In each case, the amount of salvage volume remained between 9 and 10 million $m^3$ during the shelf-life and between 14 and 17.5 million $m^3$ for the whole planning horizon. With respect to the negative shadow prices, the same behaviour was found when the model was run with a 1% discount rate. The changes that came about from using a lower discount rate were reflected in the decrease in the number of periods with negative shadow prices and with slightly less negative values in the remainder.

Scenario 6 resulted in a decrease of 31% of the total inventory at the end of the planning horizon. This scenario had an ending inventory of 49.25 million $m^3$ defined by the binding ending inventory constraint. The same scenario can reach an ending inventory of 52.5 million $m^3$ before becoming infeasible. This infeasibility demonstrates the conflict between keeping a high ending inventory and the assumed level of harvest when a high intensity MPB attack takes place. This increase of the ending inventory by 3.25 million $m^3$ means a cost of 60 million CAD$ as a decrease in the objective function (i.e. ~19 CAD$/$m^3$) (Table 4.6).

**Table 4.6. Sensitivity analysis for the ending inventory maintaining the same harvest flow constraints.**

| Scenario | Minimum Ending Inventory (million $m^3$) | Δ* (million $m^3$) | Percentage of Initial Standing Inventory | NPV (million CAD$) | Δ (million CAD$) | Average Opportunity Cost (CAD$/ $m^3$) |
|---|---|---|---|---|---|---|
| 6 | 49.25 | | 69% | 354.6 | | |
| | 52.5 | 3.25 | 73% | 293.7 | - 60.9 | - 18.7 |
| 4 | 54.8 | | 77% | 399.8 | | |
| | 63 | 8.2 | 88% | 329.4 | - 70.4 | - 8.6 |

* Δ represents the difference between both ending inventories and both objectives functions (NPV) per scenario (the original value and the value before the scenario became infeasible).

In order to reveal the different behaviour of the model, the analysis described above was repeated for the scenario with medium intensity attack and fast decay (Scenario 4). The ending inventory constraint was not binding at a level of 49.25 million $m^3$ for this scenario and the original run had an ending inventory of 54.8 million $m^3$ (Table 4.6). The ending inventory can be increased to 63 million $m^3$ before the problem becomes infeasible. The 8 million $m^3$ increase in the ending inventory resulted in a NPV decrease of 70 million CAD$ in the objective function (i.e. ~8.6 CAD$/$m^3$). The shadow prices for this scenario were positive for the harvest flow for the original problem but when the minimum ending inventory was pushed up to 63 million $m^3$, they became negative even for the uplift periods.

Finally, for both scenarios an increase in the minimum ending inventory constraint means an increase in the salvage level. Again, this has an effect on the species composition of the salvage activities. The increase of the salvaged volume for Scenario 6 has no significant increase during the shelf-life and an increase of more than 2 million $m^3$ for the whole planning horizon, composed mainly by spruce. Although there is no significant change to the volume salvaged during the shelf-life, a higher volume of pine is salvaged and a lower volume of spruce is salvaged compared to the original scenario. In the case of Scenario 4, the impact to the salvaged volume is higher as well as the gain to the ending inventory compared to Scenario 6 before both models become infeasible. Having said that, during the shelf-life there is an increase of 3.5 million $m^3$ of salvaged volume composed mainly of pine. After the shelf-life there is also an increase of about 2.3 million $m^3$ comprised almost totally of spruce.

### 4.9. Sensitivity analysis for discount rate

The absolute value of the objective function using a 1% and 4% discount rate is not comparable, but there is an important difference in the relative importance of its components. Table 4.7 shows a significant increase in the ending inventory valuation at a 1% discount rate. In other words, leaving stands as ending inventory becomes more important for the model at the lower discount rate; however, the absolute value of the scenarios at 1% shows little change.

The changes in the valuation of the ending inventory and the discount rate also drive other changes in the model. For example, sub-alpine fir becomes more important over the whole planning horizon for all scenarios at 1%, with an overall higher harvest volume and a distribution throughout the planning horizon (Figure 4.15).

**Table 4.7. Relative importance of the ending inventory value with respect to the total NPV under two discount rates.**

| Scenario | Description | Discount rate | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 4% | | | | 1% | | | |
| | | NPV* | Rel** | EI Val† | EI % NPV‡ | NPV | Rel | EI Val | EI % NPV |
| 1 | Base - SPMP#3 - w/Uplift – No Attack | 411.6 | 100% | 71.6 | 17% | 1,438.9 | 100% | 874.2 | 61% |
| 2 | Base - SFMP#3 - No Attack | 366.9 | 89% | 75.6 | 21% | 1,412.5 | 98% | 893.5 | 63% |
| 3 | Attack 60% - Medium Decay | 399.9 | 97% | 63.2 | 16% | 1,385.3 | 96% | 837.3 | 60% |
| 4 | Attack 60% - Fast Decay | 399.8 | 97% | 63.2 | 16% | 1,384.2 | 96% | 838.7 | 61% |
| 5 | Attack 100% - Medium Decay | 361.1 | 88% | 60.4 | 17% | 1,299.9 | 90% | 796.1 | 61% |
| 6 | Attack 100% - Fast Decay | 354.6 | 86% | 60 | 17% | 1,290.4 | 90% | 799.3 | 62% |

* NPV: Objective function value
** Rel: Percentage of the objective function with respect to Base scenario 1
† EI Val: Ending inventory valuation
‡ EI % NPV: Percentage of the ending inventory with respect to the objective function value

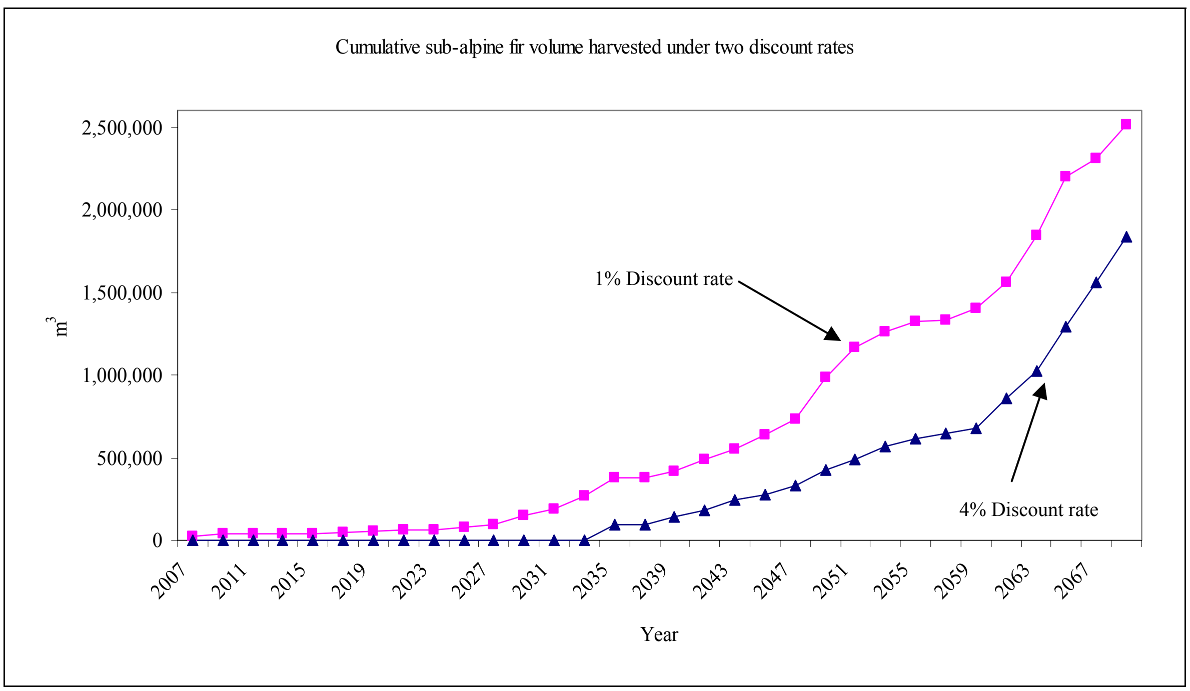



**Figure 4.15. Cumulative sub-alpine fir volume harvested on average for the four scenarios with attack, under two discount rates.**

a)

b)

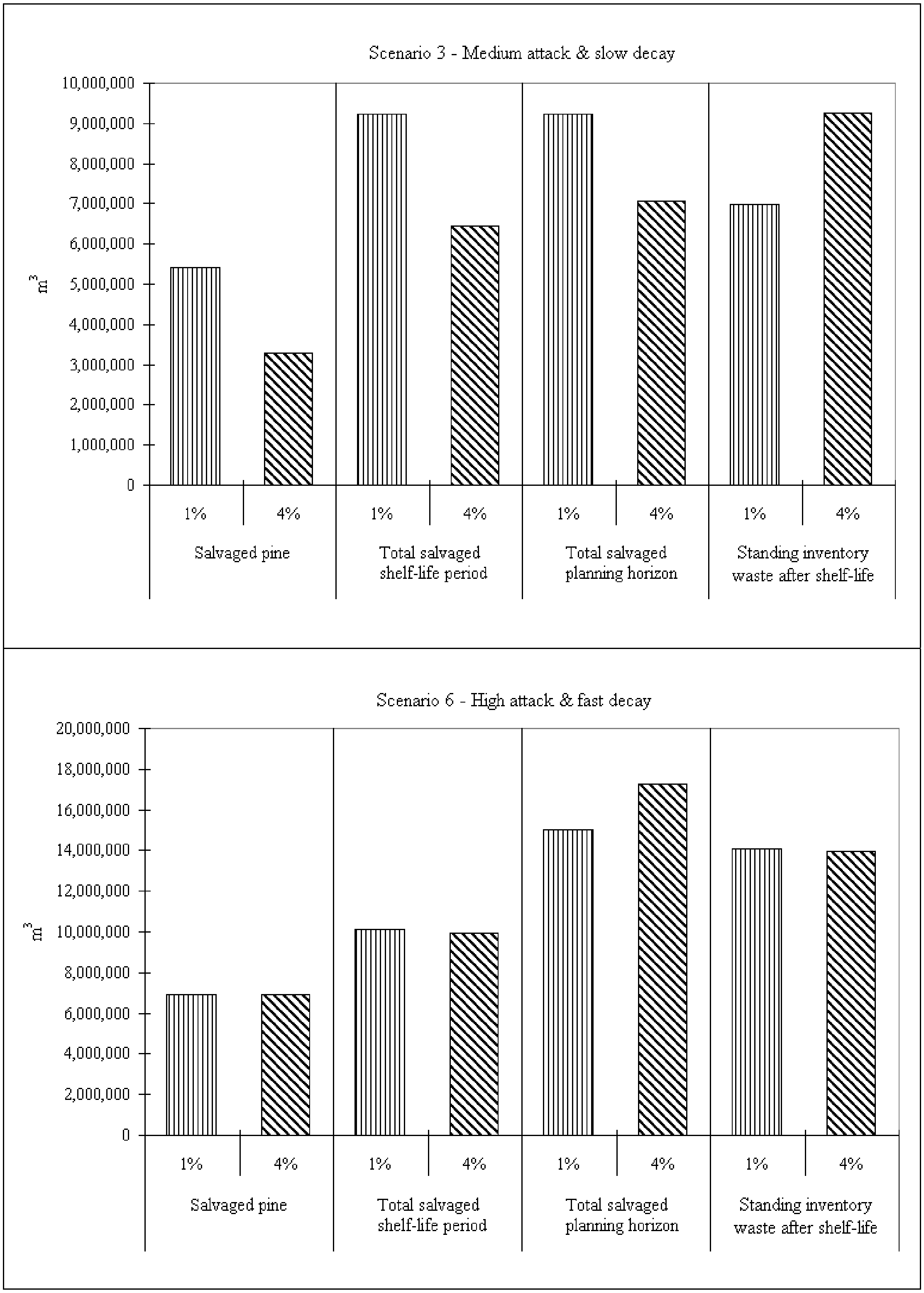



**Figure 4.16. Effect of the discount rate on the volume of salvaged pine, the total volume salvaged during the shelf-life, the total volume salvaged during the planning horizon, and the standing waste inventory after shelf-life for (a) Scenario 3 – with medium attack intensity and slow decay and for (b) Scenario 6 – with high attack and fast decay.**

Figure 4.16 shows the differences between Scenarios 3 and 6 with different discount rates. These differences are clearer in Scenario 3 (Figure 4.16a) because the model is not as constrained as Scenario 6. For Scenario 3, a 1% discount rate produces a better salvage strategy. In other words, a model using a 1% discount rate achieves a higher volume of salvaged pine and a higher overall salvaged volume that is mainly concentrated over the shelf-life of attacked pine trees. Thus, few stands are salvaged beyond the expected shelf-life. Furthermore, lower discount rates produce lower standing waste after the shelf-life is over and a higher ending inventory (by 7%). For scenario 6, both discount rates show similar trends, with the exception of the total volume salvaged over the planning horizon. The model with a 4% discount rate salvages more volume from stands where no pine is recovered, because the shelf-life is over.

There is also an effect of the discount rate on the area harvested and the proportion of the salvaged stands to non-attacked, harvested stands. First, a scenario with a high intensity attack requires more area than a medium intensity of attack to satisfy the same harvest flow. Second, the scenarios with a 1% discount rate require more area than the scenarios with a 4% discount rate, this being more obvious for the scenarios with a medium intensity attack (Table 4.8).

**Table 4.8. Total area harvested for scenarios with uplift under two discount rates (ha).**

| | Attack level | None | Medium Intensity | | High Intensity | |
|---|---|---|---|---|---|---|
| | Decay | None | Slow | Fast | Slow | Fast |
| | Scenario | 1 | 3 | 4 | 5 | 6 |
| Discount rate | 1% | 117,657 | 122,545 | 122,679 | 139,757 | 143,855 |
| | 4% | 114,343 | 114,287 | 114,302 | 136,860 | 141,905 |

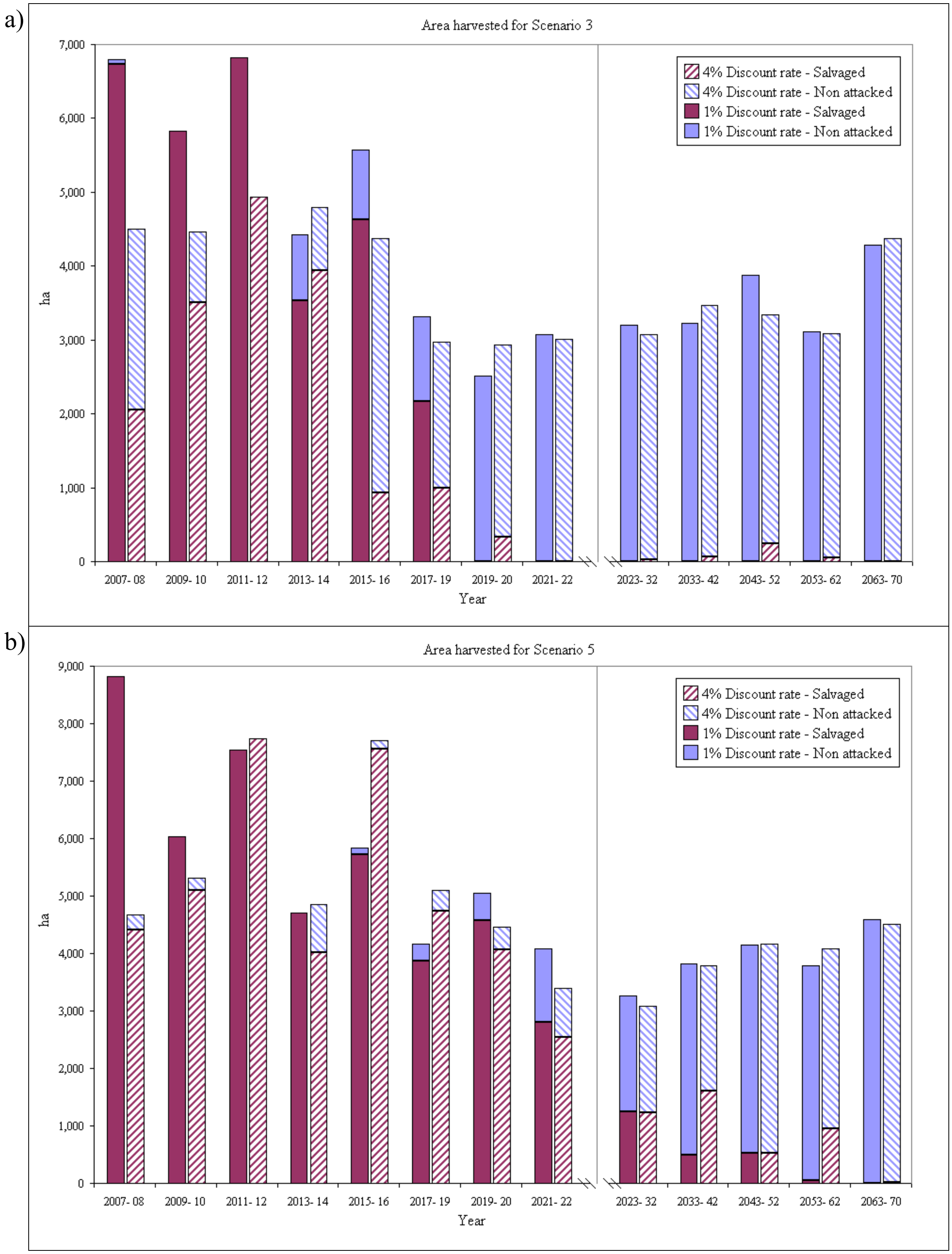



**Figure 4.17. Area harvested per period (2007 – 2022) and average area harvested per decade (2023 – 2070) for Scenario 3 (a) and Scenario 5 (b), with 1% and 4% discount rate and grouped by salvaged and non-salvaged areas.**

For both scenarios shown in Figure 4.17 there is a higher area harvested during the first six years of the planning horizon under a 1% discount rate. During the same period with a 1% discount rate, there is almost no area harvested from non-attacked stands. This pattern becomes clearer in the scenario with a medium intensity attack (Scenario 3, Figure 4.17a). Aside from the differences that are seen in the earlier years of the planning horizon, there is little difference in the harvest area between both discount rates over the remainder of the planning horizon. In brief, with a lower discount rate the salvaged activities became more relevant in magnitude and proportion, especially in the earlier years following a medium intensity beetle attack.

The last point to cover in the sensitivity analysis is in regard to the discount rate and the average profit per period. In general, Figure 4.18 shows that there is a lower profit in the earlier planning periods for all scenarios run with a 1% discount rate compared to the scenarios with a 4% discount rate. Although both discount rates show the same diminishing trend of profit over time, the scenarios run with a 1% discount rate are highly variable from one period to another (Figure 4.18).

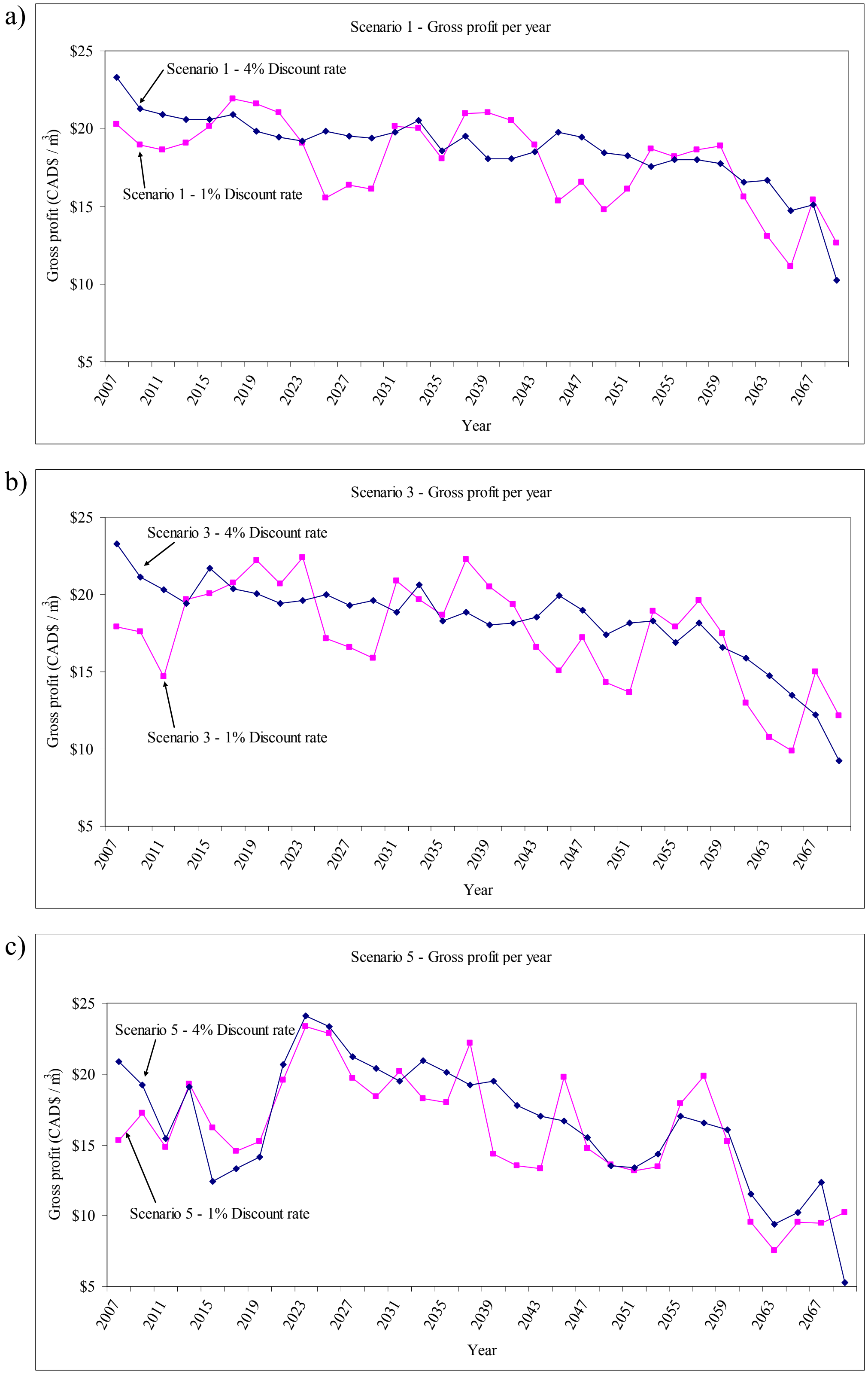



**Figure 4.18. Gross profit over time for the different scenarios with 1% and 4% of discount rate for Scenario 1 (a), for Scenario 3 (b), and for Scenario 5 (c).**

# 5. Discussion

This chapter is divided into five sections related to the objectives of my thesis. Objective #1 is covered under the Section "Impact on the harvest flow and inventory levels". The Section "Impact of the salvage strategy" addresses objective #2. The cost and supply of non-recovered volume is discussed under "Waste opportunities". The "Economic impact" Section gives a general overview of the problem and analyses potential differences between public and private salvage strategies. Finally, this chapter ends with the limitations of this study and future research opportunities.

## 5.1. Impact on the harvest flow and inventory levels

The results show that all scenarios are feasible for the proposed AAC and no fall-down is indicated in the mid-term supply. Although all scenarios were feasible, I present several factors that might impact the mid-term supply. If the salvage strategy includes objectives for decreasing the impact on cash flows, achieving a higher ending inventory level, avoiding the salvage of stands after shelf-life, and reducing impact on non-attack species, then the current harvest level will likely become infeasible and a mid-term supply fall-down will occur. Pousette and Hawkins (2006) made a similar analysis in one of the areas with the worst severity of attack and also suggest that the forest industry will face a mid-term supply fall-down.

The inventory levels of spruce (Figure 4.5a) and sub-alpine fir (Figure 4.5b) show the importance of these species in satisfying the timber supply. Specifically, we see that spruce becomes an important species under medium intensity attack scenarios, while both spruce and sub-alpine fir become important to the mid-term timber supply under high intensity attack scenarios. This result is important because it highlights the mid-term supply sensitivity of forest estates that only contain a high proportion of pine.

Scenarios with a high intensity attack show another aspect of the harvest flow that is related to the use of attacked stands following the shelf-life. Around 18% of the harvested area corresponds to attacked stands where there is no pine recovery. These stands might be targeted to meet flow requirements or because of the value of their non-pine species. If we assume that potential understory or regeneration will not be available as merchantable volume, this regeneration will be lost by harvesting these stands during this planning horizon. In other words, if stands that are not salvaged during the shelf-life are unavailable for harvest before the rotation age of the understory, the model will become very restricted, and thus unlikely to achieve the current harvest levels. The model does not consider any volume supply of understory or advanced regeneration because there was neither inventory information available at the time of the study nor any information on incremental growth of released trees. A model that includes the volume of the understory will provide a better estimate of re-stocking and a better overview of where to concentrate the salvage effort. However, if the stands are multi-aged some partial harvest system will have to be included and this will increase the size and complexity of the problem. The importance of the understory and its incremental growth following release was discussed by Griesbauer and Green (2006) and FPB (2007), respectively. Both authors noted that the understory will have important implications on future timber supply.

The final point regarding the harvest flow is related to the sensitivity analysis. The harvest flow shows negative shadow prices in the later planning periods and these decrease NPV. While there is typically an industry demand for a minimum timber supply, it would be interesting to consider a decrease in the future harvest level to achieve a higher NPV. I think that the harvest strategy will be different if a short-fall in the mid-term is allowed rather than trying to avoid it all together. A decrease of the mid-term harvest levels will decrease the pressure on attacked stands and will allow them to follow a natural re-stocking process.

## 5.2. Impact of the salvage strategy

The effectiveness of the salvage strategy can be assessed using indicators such as a) the area salvaged, b) the species composition of the harvest flow, c) the green-dead proportion, and d) the selection of stands for salvage and stands to be left as standing inventory. The salvage strategy following a high intensity attack scenario is more effective according to these indicators than under a medium attack. For example, a medium intensity scenario salvages ~20% of the attacked area compared to ~45% of the attacked area for a high attack scenario (Figure 4.8).

There is an important difference in the species composition of the harvest flow during the shelf-life. During the first eight periods of Scenarios 3 and 4, the proportion of the total harvested pine (dead and live) to other species is close to 1:1.5 compared to 1:0.66 for Scenarios 5 and 6 (Figure 4.7). High intensity attack scenarios produce a high concentration of the pine harvest in early periods and most of that volume corresponds to salvage activities. Again, the high intensity attack salvage strategy appears to be more effective by better targeting pine as the main species of the harvest.

The high intensity attack scenarios also produce a better salvage strategy by having a lower proportion of green species harvested as by-catch than a medium intensity attack. During the shelf-life, Scenarios 5 and 6 have a dead-green ratio close to 2:1 and Scenarios 3 and 4 have a dead-green ratio close to 1:1 (Figure 4.10 and Table 4.5). Pousette and Hawkins (2006) estimated that the pine-other species ratio for the Prince George TSA will be about 3:1 for the next 10 years. Parfitt (2007) used the BC's harvest billing system to determine a pine-other coniferous ratio of 2.3:1 for the period 2005-2007. This ratio is higher than the previous ratio reported for the period 2000-2005 (Parfitt 2007). Eng *et al.* (2005) differ with these findings and predict an overall harvest by-catch or dead-green ratio close to 1:1.3. All authors agree that an increase in the volume of salvage also means an increase in the volume of non-pine species. These different results might be due different scales of analysis, different shelf-life assumptions, the database used, and that 'pine' may also include the harvest of green pine volume. Even though the high intensity attack scenarios have the highest performance in terms of pine-recovery, further efforts are needed to reduce the dead-green ratio in all scenarios.

The last indicator is the type of stands that compose the salvage under a private strategy. Clearly, the harvest cost of the stands drive most of the salvage decisions (Table 4.4 and Figure 4.11). The next important factor is spruce as a non-leading species because of the higher price of spruce products relative to sub-alpine fir and aspen. The pine category also influences trends depending on the intensity of attack. For example, Scenario 3

(Table 4.4) has the highest proportion of salvage stands coming from stands with a pine composition under 25% (P2). Scenario 6 also salvages a high proportion of P2 stands but the highest proportion comes from stands with a 75% or higher pine composition (P4). The latter scenario seems to better represent the salvage strategy assumed by the public, as stated in the last AAC rationale for this TFL where "stands with at least 70 percent pine will be targeted over the next five years" (Benskin 2007).

The downside of a higher salvage linked to a high intensive attack is a higher volume of waste that comes out as a by-product, the salvage of attacked stands after the shelf-life to satisfy mid-term demand, and most likely, an increase in the harvest costs.

The assumed decay levels do not present significant differences compared to the importance of the intensity of attack. Fast and slow decays do not differ in the volume of pine salvaged for a medium intensity attack and there is a relatively small difference (~0.5 million $m^3$) for a high intensity attack (Table 4.5). The fact that medium intense attack scenarios do not salvage in the later periods of the shelf-life also reflects the minor influence of the decay level for this intensity of attack. This last argument leads to the conclusion that the importance of decay depends on the resource availability to satisfy harvest flow requirements. Another explanation for the relative low importance of the decay level might be the short four-year-difference between the fast and slow decay rates. If the amount of un-salvaged stands becomes a key issue, then the decay level will become more important.

### 5.3. Waste opportunities

The results show that waste is important as a by-product during and after the shelf-life. This waste is coming from stands with the lowest harvest cost, even though the periodic average harvest cost for waste is a bit higher than the periodic average cost for pine. This is an expected result because the most profitable stands are targeted first to recover merchantable pine volume.

There are no specific activities planned to get only waste as a targeted product. Unless there is a storage problem for energy purposes or a difference in the decay rate between standing dead trees and stored dead logs, there is no reason to consider any flow restrictions on waste. There is an important difference in the feedstock supply for bioenergy between both intensities of attack. Since the objective of the study was to account for waste volume without actually including it in the decision process (i.e. priced as an output or under flow restrictions), the amount of waste was variable.

A higher intensity of salvage also produces higher waste production. Scenarios with a medium intensity attack concentrate the waste in the first decade (~40,000 $m^3$/year). Scenarios with high intensity attack have a higher waste production (~150,000 $m^3$/year) during the first decade but with a peak in the second decade (~250,000 $m^3$/year) (Figure 4.12a). The sensitive analysis done with higher ending inventory levels, achieves a higher salvage volume but the waste increased to ~216,000 $m^3$/year for the first decade of the medium intensity attack and up to ~720,000 $m^3$/year for the second decade of a high intensity attack.

Hall (2002) estimated that a 30-MW power station – which is enough to supply electricity for 30,000 homes – needs approximately 285,000 $m^3$/year. Mani *et al.* (2006) considered a pellet plant that would require 110,000 $m^3$/year (45,000 t). Therefore, a medium intensity attack might not be sufficient to provide enough feedstock for such a power station or such a pellet plant, but a high intensity attack would.

Despite the fact that the volume might be available, waste is a by-product on the forest and not a by-product of wood processing (e.g. bark, sawdust) and therefore, the harvest cost has to be fully included in the feedstock production cost. If we consider a minimum of 24 CAD$/$m^3$ for harvest and silviculture costs plus 7 CAD$/$m^3$ for chipping (MacDonald 2006), a total of 31 CAD$/$m^3$ is needed to supply this product to a production plant in the same location as the mill. This cost is similar to the 27 CAD$/$m^3$ (65.88 CAD$/BDT)[d] found by Stennes and McBeath (2006) for the Prince George Region and higher than the 19-23 CAD$/$m^3$ (45-54 CAD$/ODt)[e] chipped and hauled to the plant found by MacDonald (2006). Although, Many *et al.* (2006) estimated a lower

[d] 1 BDT (Bone Dry Tonne) = 2.44 $m^3$. Source: Stennes and McBeath 2006.
[e] ODT (Oven Dry Tonne). Conversion rate of 0.42 ODt/m3 or 1 ODt ≈ 2.38 $m^3$. Source: MacDonald 2006.

cost of 10 CAD$/$m^3$ (19.73 CAD$/t)[f] for pellet production using wet sawdust, they concluded that raw material is one of the major cost factors of biomass pellets and that it cannot compete with fossil fuel sources. If the energy market can cover these costs, then other low value green species could be also considered as energy feedstock. This will also affect the pulpwood industry supply as Bolkesjo *et al.* (2006) and Lundmark (2006) reported for Scandinavian countries. For BC, this might not be a problem in the short-term since pulp mills are dealing with some levels of oversupply (Watson 2006). However, if there is a potential market for energy feedstock in the same location as a pulpmill, this market will compete with the pulpwood market.

The inclusion of any harvest flow constraint for bioenergy purposes or any valuation of bioenergy at a lower price than the unit harvest cost will decrease the NPV. Low quality products are dependent on low transportation costs to be profitable. A closer destination to the source for bioenergy supply might make this economic analysis more attractive. An integration of bioenergy supply, even at a very low unit marginal profit, will increase the overall performance of the business by decreasing general costs such as silviculture and overhead. Further research in beetle attacked volume for bioenergy should focus more on the production costs rather than in the supply.

### 5.4. Economic impact

The results of this research confirm that the mountain pine beetle outbreak represents a large economic impact and has significant implications for the timber supply over the short-, mid-, and long-term. The magnitude of the impact depends largely on the intensity of attack and less on the decay rate. The majority of BC's productive forests are on public land where the two main stakeholders are the owner (Crown) and the tenure holder (forest companies). As such, involvement from both stakeholders will be required to develop strategies and coordinate interests that satisfy their different objectives. This part of the discussion is centered on the costs and benefits of a MPB salvage strategy for both stakeholders.

[f] 1 wet tonne of sawdust with 40% (wb) moisture content $\approx 2$ $m^3$. Assumed by the author based on the conversion factor of 1 oven dry tonne wood chip = 2.60 $m^3$ (Source: Manitoba Conservation, Forestry Branch. http://nofc.cfs.nrcan.gc.ca/mbprimary/en/appendix2_e.php#selected. Visited: 17/03/2008)

Following MPB attack, there is a direct loss due to un-recovered merchantable volume and an opportunity cost of salvaging attacked stands with less value. The loss of un-recoverable merchantable volume affects both public and private stakeholders, but it is mainly an impact on the public, as the owner of the forest. The expected losses of standing pine for TFL48 through waste and salvaged pine waste are between 9.7 million $m^3$ for a medium intensity attack with a slow decay to 16.7 million of $m^3$ for a high intensity attack with a fast decay.

The overall NPV increases when the AAC is uplifted. Even under a medium intensity attack, a private salvage strategy ends up with a higher NPV than the base scenario without uplift and without attack (Table 4.1). However, this solution might not represent the best strategy to minimize the un-recovered merchantable losses, maximize re-stocking, or produce the desired ending inventory for future requirements.

The determination of the uplift was not part of my analysis and was considered as an input. The uplift and the salvage reflect a benefit for the private sector by achieving a higher NPV and a benefit for the public by achieving a higher salvage rate. The model assumed constant prices over the planning horizon. This assumption may not be real if this massive salvage strategy affects the equilibrium market price of wood products by causing a depressing effect (Wagner *et al.* 2006). The price depressing tends to benefit consumers and the salvage tends to benefit the owners of damaged timber but tends to harm owners of undamaged timber. If public efforts to maximize the salvage are effective, these will accentuate these transfers (Holmes 1991, Prestemon and Holmes 2004).

The magnitude of the economic impact is also dependent upon different intensities of attack and desired levels of ending inventory. When the aim is to reach a higher rate of recovery or to maintain a higher level of ending inventory, there is a decrease in the NPV. This result shows that there is also an opportunity cost that should be addressed in the salvage strategy. For example, in Scenario 6, the worst case scenario, efforts to gain 3.25 million $m^3$ as ending inventory represents an opportunity cost of 19 CAD$/m^3$. This opportunity cost is even higher than the average profit of pine (17 CAD$/m^3$). In contrast, Scenario 4 reaches a higher ending inventory than Scenario 6 with a lower opportunity cost (9 CAD$/m$^3$) before becoming infeasible.

The discount rate analysis also reflects discrepancies that exist between a public and a private salvage strategy. These results clearly show that from a public point of view (lower discount rate) the future forest has a higher value, reflected in the relative importance of the ending inventory valuation (Table 4.7). An ending inventory valuation at roughly 60% of the NPV is observed when using a 1% discount rate, compared to 16% when using a 4% discount rate. This higher valuation of the ending inventory leads to higher efficiency of the salvage strategy. A 1% discount rate leads to a higher amount of pine salvaged, higher amount of total volume salvaged, and a lower standing waste inventory than a 4% discount rate. The impact of the discount rate in the salvage strategy is more evident in a medium intensity attack scenario (Figure 4.17). These results also show that under a high intensity attack, the harvest schedule solution is less resilient to changes and easily becomes infeasible.

The cash flow, reflected in profit per period, is one of the most important variables in a private salvage strategy and is largely dependent upon the intensity of attack. As I pointed out in my results, the intensity of attack and the discount rate affect the cash flow by shifting some of the most profitable stands to the future in order to salvage other stands during the shelf-life. This shift can be up to 20 years with a high intensity attack and has differences in profit up to 10 CAD$/m$^3$. In all scenarios, there is a decrease in profit during the first decade when a lower discount rate is used. This shows how sensitive the model is to 'sacrificing' initial profit to satisfy mid-term flow requirements. The impact on the cash flow over the forest tenure is considerable and helps explain public concerns about the amount of salvage and the amount of green species within the salvage (Burton 2006, Eng *et al.* 2005, Parfitt 2007). In general, regardless of the intensity of attack, as the salvage intensifies, the costs increase.

Since more area is cut during salvage operations (less volume/ha relative to green stands) silviculture costs will rise. These results agree with the findings of BCMOF (2001) and Byrne *et al.* (2006) about the incremental costs of salvage operations. Incremental costs can be expected for administration, increased road building, and moving of harvest machinery.

Because my model does not include all costs, it overestimates profitability. The administration cost is estimated at 9 CAD$/m$^3$ (MacDonald 2006). Including this cost in the model without any other change will decrease the periodic profit and NPV. If we were to add the administration cost as a lower bound for the periodic profit, the later planning periods will not be able to satisfy this constraint. The inclusion of a lower bound for the periodic profit will produce a lower NPV or an infeasible solution, unless the later harvest levels are reduced. The NPV reduction is caused by rescheduling stands to increase the average profit of the later periods or by harvesting uneconomic stands to strictly satisfy harvest flow constraints.

Under a relaxed harvest flow constraint companies will likely decrease their production (or even shut-down) to avoid sub-marginal stands. This was partly demonstrated in the sensitivity analysis for the later periods of the planning horizon. The increase of sub-marginal stands means that volume might be available, but not at a competitive cost. Although the traditional private strategies that maximize NPV tend to harvest as much volume as possible and as early as possible, there is some evidence that shows that tenures are not achieving their current AACs (BCMOF 2007a). I can speculate why this might be happening. First, firms are not able to adjust their current cost structure to the current market conditions, like poor markets in the USA. Second, they may have limited milling capacity to process the current uplifts. Finally, it is likely that the marginal costs of the MPB epidemic are sufficient to make the commodity based industry less competitive. The BC forest industry is basically a commodity industry that focuses on the production of standard products at the lowest possible cost. With the current global competitiveness there is no slack to relax this cost leadership strategy. This extremely tight cost structure can help to explain why companies likely follow a short-term strategy that maximizes the profit and favours a salvage strategy closer to a medium intensity scenario.

Prestemon and Holmes (2004) highlight “the importance of developing a plan for salvage that prioritizes stands based at least in part on the net value of materials that could be obtained from each potential site”. My study shows that under a MPB attack, as opposed to a hurricane or a wildfire where every product is proportionally damaged, the ‘net value of materials’ comes from the un-attacked species and that the net value of each site depends mainly on the products but also on the harvest costs. Therefore, a strict focus on short-term profit will target mainly green species instead of maximizing the salvage of dead pine.

Salvage has higher harvest costs than non-attacked stands and attacked logs have higher processing costs than green logs. So, what is the real incentive for a forest company to salvage? The public, as owner of the forest, has to find ways to support the salvage with economic incentives or by regulation to achieve higher salvage rates. For example, stumpage reduction is one of the incentives but it could be also masked by the higher harvest and processing cost of the attacked stands.

My work demonstrates that the current uplift allows a higher salvage rate but it does not necessarily maximize the salvage of pine. Policies that prioritize the salvage of more severely attack stands with high pine composition have been widely recommended (e.g. Benskin 2007, BCMOF 2003). However, it is unclear who is assuming the cost of such policies, whether it is the private sector or the public. If the objective is to maximize the salvage or to secure mid-term supply, new policies have to be implemented that include the opportunity cost of maximizing the salvage instead of maximizing the NPV. The uplift and the stumpage may have to be reinforced by other policies that guide the salvage. These salvage policies should be focused at the stand level and promote salvaging of pine-leading stands, decreasing the dead-green proportion, and alternative management options on non-salvaged stands.

The BC forest industry is in a difficult competitive position and the health of its wood supply is uncertain. Zhang (2001) demonstrated that private strategies become more focused on the short-term under uncertainty and this is another reason for the government to implement the appropriate policies that ensure reasonable protection of the future forest.

### 5.5. Decision model

The model considers clear-cutting as the only harvest method. Selection or other harvest methods might be better if the objective is to salvage pine, but with less impact on the regeneration and without harvesting by-catch green species. These harvest methods were not included because they are not used in current salvage alternatives and because they tend to be more expensive (e.g. Han and Renzie 2005) and are usually used with high value species, not dead and decaying ones.

One of the limitations of the model is that the attack allocation is part of the optimization process. Thus, the model finds the best stands to attack to satisfy constraints. This is reflected in the medium attacked scenarios because the lowest proportion of area attacked was for management units with spruce as a secondary species, with the lowest harvest and silviculture cost, the best site quality, and the highest pine composition. The 'attack distribution' constraints were important to control this limitation. The attack allocation could be approached in other way, for example by running a simulation of the attack distribution as an input for the LP or by completely changing the approach by running a simulation or a heuristic model.

Another need for further research is the length of the shelf-life and decay levels of the different types of products. The model considered the same proportion of decay for all products and only degrading to waste. Changes in the intensity of attack, the decay rate, incremental growth due to release, or understory re-stocking (included only in terms of an increase of volume), could be added to the current model formulation without much difficulty.

## 6. Conclusions

This thesis explored the economic impact of a MPB attack under different intensities of attack, different lengths of shelf-life and how this drives different salvage strategies. The objectives of this thesis were to quantify different scenarios of attack and decay, to identify different salvage strategies and their potential effect on the medium term timber supply, to assess how a public strategy might differ from a private strategy, and to analyse the supply of non-recovered volume for possible bioenergy uses. These objectives were achieved by first developing a forest-level optimization model to determine a strategic harvest schedule for each scenario and second, applying the model to a large landscape in northeastern BC under two intensities of MPB attack and two decay rates. The model maximized NPV and sensitivity analysis of the minimum ending inventory and the discount rate was used to determine differences in objectives of the public and the private salvage strategies.

The current MPB outbreak will cause significant reductions to the forest resources of BC and there is broad concern about the limited capacity to salvage and recover all dead pine. When resources become scarce, strategies become less flexible and it becomes more difficult to satisfy all objectives at once. Although pine accounts for less than half of the total inventory for this case study, a high intensity attack produces a great economic impact and reduces resource availability. The shelf-life has a secondary impact – compared to the intensity of attack– and this depends on other factors such as the salvage effort. The non-attack species play and important role in the salvage activities and also to mitigate the impact on the harvest flow. Waste comes as a by-product during the salvage activities but its bioenergy opportunities will depend more on the supply cost than on its availability. Finally, although all harvest flows were feasible, there are factors that suggests that it will be difficult to achieve these harvest flows in the mid-term. These factors are: concerns about damaging advanced regeneration during salvage, adequate regeneration in un-salvaged stands, and declining profitability over time.

The government will have to develop economic incentives to deal with the MPB attack during and after the pine shelf-life, if the goal is to support higher levels of salvage or to support more expensive management alternatives to reduce the impact on future timber resources. Otherwise, the higher harvest costs or the lower value of the forest will likely move forest companies away from the attacked stands. The other choice will be to leave attacked stands as standing inventory and wait for a natural re-stocking. The complex forest dynamics of a post-attack stand will also create management challenges. Either way, the forest industry in BC will have to deal with limited resources in the mid-term.

The modelling of natural disturbances has always been a challenge and there are always research opportunities to achieve a better understanding of these events. Insect and diseases, as different from severe wind damage and wildfire, affect only a specific part of the forest composition, and therefore modelling approaches might not be the same. Finally, we cannot forget that although the MPB attack resulted in a 'catastrophic' event, with huge economic and social impacts, it is still a natural disturbance and we are never going to be able to totally avoid them.

Opportunities for further research for this MPB topic are mainly related to the type of the data used as input for the model. These include a better understanding of the forest dynamics after an attack and which management alternatives best meet the reestablishment of a healthy stand. On the industry side, there are some branches of research related to the length of the shelf-life, the lumber recovery factor for dead wood, the relative commercial value of the different species, and the opportunity to include the bioenergy supply as an integrated part of the harvest and thus maximize the value of the salvaged stands. If there is a market price for bioenergy, waste should be explicitly valued as a bioenergy product in the objective function. On the modelling side, the inclusion of new management alternatives and their respective costs may help the government to develop mid-term strategies and to define current investment effort by assessing its effect in the future. These types of models can increase the scope of analysis by including the complete cost structure (e.g. overhead and road building). A complete cost structure will highlight the issue of sub-marginal stands, the decrease of profit, and the limitations of rigid harvest flow policies. Finally, such models can help the government explore the relative influence of stumpage rates as an incentive tool.

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**Appendix 1 - Summary of the difficulties in processing beetle-killed pine at British Columbia Interior sawmill operations.***

| Problem area | Description |
|---|---|
| Log handling | • Higher log breakage and damage in log yard<br>• Barkers adjusted for green logs will tend to remove excess wood and increase downgrade |
| Cutting tools | • Minor effects, except for the increased occurrence of dirt and stones in splits and bark-free areas that cause damage to saws<br>• Dry wood dulls cutting tools more quickly than green wood<br>• Dry wood causes saws to heat up and lose stability when set up to cut frozen wood in winter |
| Pulp chips | • Dry wood results in more chip fines<br>• Chip volumes increase significantly when processing a high proportion of infected pine |
| Lumber recovery | • A reduction in lumber recovery factor that accelerates with years since attack<br>• Spiral checking is a major factor contributing to reduced recovery |
| Grade yields | • A higher % of low grade dimension lumber is produced and lower % of #2 and better. |
| Markets | • Blue stain and worm holes reduce lumber value and marketability, although blue stain has only a visual effect<br>• Oversupply/low demand result in greater customer sensitivity to quality<br>• Oversupply produces a decrease in prices |
| Drying | • Uneven final moisture content distribution due to mix of green and partly dry stock |
| Planing | • More breakage and jam-ups at planer; over dried wood reduces planer productivity<br>• Increased trim loss at planer |
| Small-log salvage | • Higher than normal proportion of small logs results in lower lumber-recovery factor, lower mill productivity and higher unit costs |

* Source: Giles (1986).

**Appendix 2 - Mathematical LP formulation of the three traditional harvest scheduling models.**

1. Model type I (Johnson and Scheurman 1977):

Objective Function

$$MAX \quad \sum_{l=1}^{U} \sum_{q=1}^{R_l} D_{lq} \; X_{lq}$$

Subject to

Area Constraints: (a) $\sum_{q=1}^{R_l} x_{lq} = A_l \qquad l = 1,\ldots,U$

Where

$x_{lq}$ = hectares of management unit *l* assigned to regeneration harvest sequence *q*

$A_l$ = number of hectares in management unit *l*

$U$ = number of management units—number of age classes which contain hectares in period one

$R_l$ = Number of possible regeneration harvest sequences over the planning horizon for management unit *l*

$D_{lq}$ = discounted net revenue per hectare of management unit *l* over the planning horizon, if assigned to regeneration harvest sequence *q*.

2. Model type II (Johnson and Scheurman 1977):

Objective Function

$$MAX \quad \sum_{j=1}^{N} \sum_{i=-M}^{j-Z} D_{ij} X_{ij} + \sum_{i=-M}^{N} E_{iN} w_{iN}$$

Subject to

Area Constraints: (a) $\sum_{j=1}^{N} x_{ij} + w_{iN} = A_i \qquad i = -M,\ldots,0$

(b) $\sum_{k=j+Z}^{N} x_{jk} + w_{jN} = \sum_{i=-M}^{j-Z} x_{ij} \qquad j = 1,\ldots,N$

Where

$x_{ij}(x_{jk})$ = hectares regenerated in period *i* (period *j*) and regeneration harvested in period *j* (period *k*)

$w_{iN}(w_{jN})$ = hectares regenerated in period *i* (period *j*) and left as part of the ending inventory in period *N*

$A_i$ = number of hectares present in period one that were regenerated in period *i*, *i* = -*M*, . . . , 0, with each $A_i$ being a constant at the beginning of the planning horizon (period 1). As an example, $A_{-5}$ represents hectares regenerated six periods before period one

$M$ = number of periods before period zero in which the oldest age class present in period one was regenerated

$Z$ = minimum number of periods between regeneration harvests

$D_{ij}$ = discounted net revenue per hectare from hectares regenerated in period *i* and regeneration harvested in period *j*.

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

$P_{ikj}$ = unit price of volume harvested in period *k* on hectares regenerated in period *i* and regeneration harvested in period *j*.

$V_{ikj}$ = volume per hectare harvested in period *k* on hectares regenerated in period *i* and regeneration harvested in period *j*.

$C_{ikj}$ = cultural treatments costs per hectare in period $k$ on hectares regenerated in period $i$ and regeneration harvested in period $j$.

$\gamma^k$ = discount rate for period $k$.

$E_{iN}$ = discounted net revenue per hectare during the planning horizon from hectares regenerated in period $i$ and left as ending inventory in period $N$ plus discounted net value per hectare of leaving these hectares as ending inventory

3. Model type III based on Gunn and Rai (1987) and Reed and Errico (1989):

Objective Function

$$MAX \quad \sum_{j=1}^{J}\sum_{t=1}^{N}\frac{P_{jt}V_{jt}h_{jt}}{\gamma^t}+\sum_{j=1}^{J}\frac{P_{j(N+1)}V_{j(N+1)}X_{j(N+1)}}{\gamma^{N+1}}$$

Subject to

Area Constraints: (a) $X_{j1} = A_j \qquad \forall\ j = 1,\ldots,J$

(b) $X_{1t} = \sum_{j=1}^{J} h_{j(t-1)} \qquad \forall\ t = 1,\ldots,N$

(c) $X_{jt} = X_{(j-1)(t-1)} - h_{(j-1)(t-1)} \qquad \forall\ t = 1,\ldots,N+1 \wedge j = 2,\ldots,J-1$

(d) $X_{Jt} = X_{(J-1)(t-1)} - h_{(J-1)(t-1)} + X_{J(t-1)} - h_{J(t-1)} \qquad \forall\ t = 1,\ldots,N+1$

(e) $X_{jt} \geq h_{jt} \qquad \forall\ t = 1,\ldots,N \wedge j = 1,\ldots,J$

Where

$P_{jt} \wedge V_{jt}$ = price and volume, respectively, for the hectares of age class $j$ harvested in period $t$

$\gamma^{t}$ = discount rate for period $t$

$h_{jt}$ = hectares of age class $j$ harvested in period $t$

$X_{jt}$ = State variable that denotes the area of forest with even-age stands in age-class $j$ at the beginning of the period $t$

$X_{Jt}$ = state variable that denotes the area of forest with even-age stands in age-class $J$, which includes all stands of age $J$ and older

$A_j$ = number of hectares present at the beginning of the planning horizon (period one) of age class $j$

$X_{j(N+1)}$ = hectares remaining in period $N+1$, that can represent the value of the ending inventory

## Appendix 3 - Summary of the yield curves used for the model.*

| Crv_Id | Description | Type | C_Suc | S_Atk |
|---|---|---|---|---|
| 12110 | Spruce-pine low - ESSF - SI 11 - St/ha1600 - Sx(65%) Pl(35%) | Nat | 321100 | Yes |
| 12120 | Spruce-pine med/good - SBS - SI 17-St/ha2000 - Sx(65%) Pl(35%) | Nat | 321200 | Yes |
| 12210 | Subalpine fir-pine - ESSF - SI 8 - St/ha1600 - Bl(65%) Pl(35%) | Nat | 322100 | Yes |
| 12310 | Dec-pine - SBS - SI 14 - St/ha2500 - At(70%) Pl(30%) | Nat | 323100 | Yes |
| 13110 | Med Pine-spruce low -ESSF -SI 11 -St/ha2000 -Pl (65%) Se (35%) | Nat | 331100 | Yes |
| 13120 | Med Pine-spruce med/good - SBS - SI 17 - St/ha2000 - Pl(65%) Sx(35%) | Nat | 331200 | Yes |
| 13210 | Med Pine-subalpine fir - ESSF - SI 11 - St/ha2500 - Pl(60%) Bl(40%) | Nat | 332100 | Yes |
| 13310 | Med Pine-Dec low - SBS - SI 12 - St/ha2500 - Pl(60%) At(40%) | Nat | 333100 | Yes |
| 13320 | Med Pine-Dec med/good - SBS - SI 17 - St/ha2500 - Pl(60%) At(40%) | Nat | 333200 | Yes |
| 14110 | High Pine-spruce low - ESSF - SI 11 - St/ha2500 - Pl(85%) Se(15%) | Nat | 341100 | Yes |
| 14120 | High Pine-spruce med/good - SBS - SI 17 - St/ha2500 - Pl(85%) Sx(15%) | Nat | 341200 | Yes |
| 14210 | High Pine-subalpine fir - ESSF - SI 11 - St/ha3000 - Pl(85%) Bl(15%) | Nat | 342100 | Yes |
| 14310 | High Pine-Dec low - SBS - SI 12 - St/ha3000 – Pl(85%) At(15%) | Nat | 343100 | Yes |
| 14320 | High Pine-Dec med/good - SBS - SI 17 - St/ha3000 - Pl(85%) At(15%) | Nat | 343200 | Yes |
| 11110 | Spruce low - ESSF - SI 9 - St/ha1500 - Se(75%) Bl(25%) | Nat | 311100 | No |
| 11120 | Spruce med/good - SBS - SI 17 - St/ha2000 - Sx(70%) Pl/At(30%) | Nat | 311200 | No |
| 11210 | Subalpine fir - ESSF - SI 8 - St/ha1600 - Bl(75%) Se(25%) | Nat | 312100 | No |
| 11310 | Deciduous - BWBS - SI 16 - St/ha3000 - At(90%) Sx(10%) | Nat | 313100 | No |
| 11510 | Dec - Mixed wood - BWBS - SI 15 - St/ha2500 - At(65%) Sx(35%) | Nat | 315100 | No |
| 11610 | Con - Mixed wood - BWBS - SI 15 - St/ha2000 - Sx(65%) At(35%) | Nat | 316100 | No |
| 311100 | Spruce low | Man | 311100 | No |
| 311200 | Spruce med/good | Man | 311200 | No |
| 312100 | Subalpine fir | Man | 312100 | No |
| 313100 | Deciduous | Man | 313100 | No |
| 315100 | Dec - mixed wood | Man | 315100 | No |
| 316100 | Con - mixed wood | Man | 316100 | No |
| 321100 | Spruce - pine low | Man | 321100 | No |
| 321200 | Spruce - pine med/good | Man | 321200 | No |
| 321202 | Spruce - pine med/good | Man | 321202 | No |
| 322100 | Subalpine fir - pine | Man | 322100 | No |
| 323100 | Dec - pine | Man | 323100 | No |
| 331100 | Med Pine - spruce low | Man | 331100 | No |
| 331200 | Med Pine - spruce med/good | Man | 331200 | No |
| 331202 | Med Pine - spruce med/good | Man | 331202 | No |
| 332100 | Med Pine -subalpine fir | Man | 332100 | No |
| 333100 | Med Pine Dec low | Man | 333100 | No |
| 333200 | Med Pine Dec med/good | Man | 333200 | No |

| Crv_Id | Description | Type | C_Suc | S_Atk |
|---|---|---|---|---|
| 333202 | Med Pine Dec med/good | Man | 333202 | No |
| 341100 | High Pine - Spruce low | Man | 341100 | No |
| 341200 | High Pine - Spruce med/good | Man | 341200 | No |
| 341202 | High Pine - Spruce med/good | Man | 341202 | No |
| 342100 | High Pine - subapline fir | Man | 342100 | No |
| 343100 | High Pine - dec low | Man | 343100 | No |
| 343200 | High Pine - dec med/good | Man | 343200 | No |
| 343202 | High Pine - dec med/good | Man | 343202 | No |
| 3 | BWBS dry-(1)-(CON)-(Pl)-M | Nat | 84 | No |
| 6 | BWBS mesic-(2,3)-(CON)-(Pl)-P | Nat | 85 | No |
| 9 | BWBS mesic-(2,3)-(CON)-(Pl)-M | Nat | 86 | No |
| 18 | BWBS mesic-(2,1,3)-(MXC)-(Pl)-M | Nat | 95 | No |
| 19 | BWBS mesic-(2,1,3)-(MXC)-(Pl)-G | Nat | 96 | No |
| 21 | BWBS mesic-(2,1,3)-(MXD)-(At,Ac,Ep,Act)-M | Nat | 101 | No |
| 43 | SBS mesic-(7,6,8)-(DEC)-(At,Ac,Ep,Act,W)-M | Nat | 112 | No |
| 49 | SBS mesic-(7,6,8)-(MXC)-(Pl)-M | Nat | 115 | No |
| 50 | SBS mesic-(7,6,8)-(MXC)-(Pl)-G | Nat | 116 | No |
| 52 | SBS mesic-(7,6,8)-(MXD)-(At,Ac,Ep,Act)-M | Nat | 118 | No |
| 62 | ESSFm mesic-(12)-(CON,MXC)-(Pl)-P | Nat | 121 | No |
| 65 | ESSFm mesic-(12,11)-(CON,MXC)-(Pl)-M | Nat | 122 | No |
| 68 | ESSFm mesic, ESSFw mesic-(12,11,17,16)-(CON,MXC)-(Pl)-G | Nat | 123 | No |
| 82 | ESSFw mesic-(17,16)-(CON,MXC)-(Bl,Pl,B)-M | Nat | 134 | No |
| 84 | BWBS dry-(1,2,3)-(CON,MXC)-(Pl)-M | Man | 84 | No |
| 85 | BWBS mesic-(2,1)-(CON)-(Se,Sw,Sx,Sb,S,Ss,B,Bl,Sxw)-P | Man | 85 | No |
| 86 | BWBS mesic-(2,1)-(CON)-(Se,Sw,Sx,Sb,S,Ss,B,Bl,Sxw)-M | Man | 86 | No |
| 89 | BWBS wet-(3,4)-(CON)-(Se,Sw,Sx,Sb,S,Ss,B,Bl,Sxw)-M | Man | 89 | No |
| 95 | BWBS mesic-(2,1)-(MXC)-(Se,Sw,Sx,Sb,S,Ss)-M | Man | 95 | No |
| 96 | BWBS mesic-(2,1)-(MXC)-(Se,Sw,Sx,Sb,S,Ss)-G | Man | 96 | No |
| 101 | BWBS mesic-(2,1,3)-(MXD)-(ALL)-M | Man | 101 | No |
| 104 | SBS dry-(6,16,17,9,18,11,12,7,8,10,15,19,20)-(CON,MXC)-(Pl)-M | Man | 104 | No |
| 106 | SBS mesic-(7,6,5)-(CON)-(Se,Sw,Sx,Sb,S,Ss,B,Bl,Sxw)-M | Man | 106 | No |
| 109 | SBS wet-(8,9,10)-(CON)-(Se,Sw,Sx,Sb,S,Ss,Sxw)-M | Man | 109 | No |
| 112 | SBS mesic-(7,6,8,9,10,11,12,13,14,15,16,17,18,19,20)-(DEC)-(ALL)-M | Man | 112 | No |
| 115 | SBS mesic-(7,6,8,9,10,11,14)-(MXC)-(Se,Sw,Sx,Sb,S,Ss,Sxw)-M | Man | 115 | No |
| 116 | SBS mesic-(7,6,8,9,10,11,14)-(MXC)-(Se,Sw,Sx,Sb,S,Ss,Sxw)-G | Man | 116 | No |
| 118 | SBS mesic-(7,6,8,9,10,11,12,13,14,15,16,17,18,19,20)-(MXD)-(ALL)-M | Man | 118 | No |
| 121 | ESSFm mesic-(12,15,20,11,14)-(CON)-(Se,Sw,Sx,Sb,S,Ss,B,Bl,Sxw)-P | Man | 121 | No |
| 122 | ESSFm mesic-(12,11,15,20,14)-(CON)-(Se,Sw,Sx,Sb,S,Ss,B,Bl,Sxw)-M | Man | 122 | No |

| Crv_Id | Description | Type | C_Suc | S_Atk |
|---|---|---|---|---|
| 123 | ESSFm mesic, ESSFw mesic-(12,17,11,15,20)-(CON)-(Se,Sw,Sx,Sb,S,Ss,B | Man | 123 | No |
| 125 | ESSFm wet, ESSFw wet-(13,18,16,20)-(CON,MXC)-(Se,Sw,Sx,Sb,S,Ss,Sxw) | Man | 125 | No |
| 133 | ESSFw mesic-(17,19)-(CON,MXC)-(Se,Sw,Sx,Sb,S,Ss,Sxw)-M | Man | 133 | No |
| 134 | ESSFw mesic-(17,19,7,8,9,10,15)-(CON,MXC)-(Bl,B)-M | Man | 134 | No |

Crv_Id: Curve Id; Type: Nat = Natural stands and Man = Managed stands; C_Suc: Succession curve; S_Atk: Curves susceptible to attack
* Source: Seely *et al.* (2007)