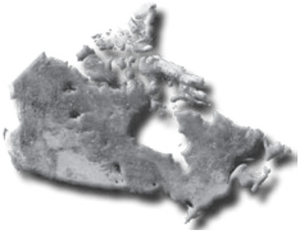

Provincial Level Projection of the Current Mountain Pine Beetle Outbreak:

An Overview of the Model (BCMPB) and Draft Results of Year 1 of the Project

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Supported by the
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April 2004

BCMPB: Draft Results of Year 1 of the Project

Table of Contents

List of Tables

List of Figures

Acknowledgments

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Funding for this project was provided by the Mountain Pine Beetle Initiative of the Canadian Forest Service of Natural Resources Canada. The BC Forest Service provided additional, in-kind, support.

1.0 Executive Summary

The BC Provincial Scale Mountain Pine Beetle Model (BCMPB) was developed as part of a two year project to assess the impacts of mountain pine beetle outbreak and management interactions across the entire province. This report describes the model and the results of the first year of work.

The model uses inputs from the forest cover inventory, management information, and mountain pine beetle provincial aerial overview maps. The main dynamics of the mountain pine beetle (*Dendroctonus ponderosae* MPB) outbreak sub-model were driven by the time series of overview infestation maps from 1999 to 2003, combined with information scaled up from the Canadian Forest Service stand model MPBSim (Safranyik et al. 1999) and the landscape scale model MPB-SELES (Fall et al. 2001). The management sub-model combines current and potential management activities across each timber supply area and tree farm licence, and is capable of processing a range of mountain pine beetle management activities such as leading-edge focus or salvage focus harvesting.

A range of scenarios was examined to assess the expected impacts of the outbreak under current and alternative management regimes. The main types of effects we assessed were mountain pine beetle impact indicators (volume and area affected or killed by mountain pine beetle), harvest indicators (volumes and areas harvested as green or salvage) and non-recovered loss indicators.

We considered one scenario as a *reference* that approximated current management at 2001/2002. We contrasted this with scenarios of alternative management (e.g. salvage focus, current management with no single-tree treatments, current uplifts in the allowable annual cut, etc.) and comparison scenarios (e.g. no harvesting, no beetle management).

The process of developing the model has highlighted some significant uncertainties in the "mountain pine beetle – forest management system". Primarily we are uncertain about:

- the levels of pine mortality that beetles may cause both at a stand and landscape level; and
- the rates of decay of dead pine as they relate to concerns about shelf life for various forest products.

The uncertainties in the system make it difficult to provide exact and unequivocal conclusions. Nonetheless we can conclude the following.

Previous research has shown that mountain pine beetle outbreaks are stopped by severe winter weather or depletion of the host. The vast spatial extent of the outbreak implies that a weather-stopping event is unlikely. The model projects that the current outbreak will continue to grow for three to four more years and then gradually decline over a period of 10 or more years. The model projects, as a worst case, that virtually all of the mature pine susceptible to mountain pine beetle

attack will be killed by 2020. Based on sensitivity analysis done to date we have no reason to expect that less than 80% of the pine will be affected.

Forest management, as modeled, does not alter the provincial scale spatial and temporal characteristics of the outbreak. In all scenarios the growing stock of pine in the province appears to be at substantial risk over the next two decades to significant decline due to the combined effect of mountain pine beetle attack and harvesting. Forest management has the potential to reduce the volumes killed by beetles by increasing the volume of green pine that is harvested. Focusing harvesting on salvage has the potential to reduce non-recovered losses.

Refinements on are ongoing to improve our confidence in the results. In the coming year we intend to thoroughly examine the sensitivity of various parameters in the beetle projection model and to make refinements and changes to that model as needed. We intend to engage a variety of domain experts in the field of forest management to help us specify and model various aspects of management with a focus on salvaging dead pine.

2.0 Introduction

Mountain pine beetles (*Dendroctonus ponderosae* MPB) are currently in the outbreak phase of the infestation cycle throughout much of their range in British Columbia. Adequate management of this provincial scale problem requires provincial scale knowledge. While we cannot hope to accurately predict the exact progression of the infestation, we can project a range of possibilities, given a variety of assumptions and uncertainties. Our hope is that these projections will help managers make more informed decisions about provincial and national level policies. Used appropriately, the results may also help guide actions at a management unit scale.

The landscape model described in this document was developed with support from the federal Mountain Pine Beetle Initiative, but we note that our work here builds upon the results of prior landscape modeling projects that were supported by a variety of sources. We would also like to acknowledge the contributions of Terry Shore, Les Safranyik and Bill Riel from Pacific Forestry Centre, Canadian Forest Service, upon whose expertise the mountain pine beetle models have been built.

This project can be described as a series of key steps:

- consulting with potential users to develop and refine the scope and objectives;
- obtaining geographic, forest inventory, forest management, weather and mountain pine beetle infestation data for the study area;
- analyzing the data to understand as much as possible about the course of the outbreak over the past five years;
- combining the results of our analysis with expert knowledge and results from more detailed fine-scale models to develop a provincial-scale projection model;
- projecting the outbreak forward given a range of management options and assumptions about beetles, and
- interpreting the projection results.

We investigated the course of the outbreak over a 20-year period, focusing mainly on the area affected and timber volumes killed by beetles, and the consequent effect on non-recovered losses and pine growing stock across the province. We did not include weather-stopping events, and so the results of this project are best viewed as a worst-case scenario.

We compared management scenarios to understand the benefits and impacts of various beetle management options. The mountain pine beetle outbreak and beetle management response affect a wide range of forest values. We did not attempt to analyze the implications of these impacts ourselves, as we believe that this is best done by topic experts (e.g. economists, caribou biologists). To this end, in collaboration with interested users we have designed indicator files that can serve as input for further analysis of economic, social and/or ecological cost/benefits by interested topic experts.

3.0 Methods

3.1 Overall Landscape Model Design

The general design of BCMPB in terms of linkages between model state, landscape processes and output files is shown in Figure 1. The following description summarizes the structure, operation and data requirements of the model. More detailed description of the management sub-model, including planning and harvesting, and the mountain pine beetle growth and dispersal sub-model are provided in Appendix 2 and Appendix 3 respectively. A detailed discussion of the input data is provided in Appendix 1.

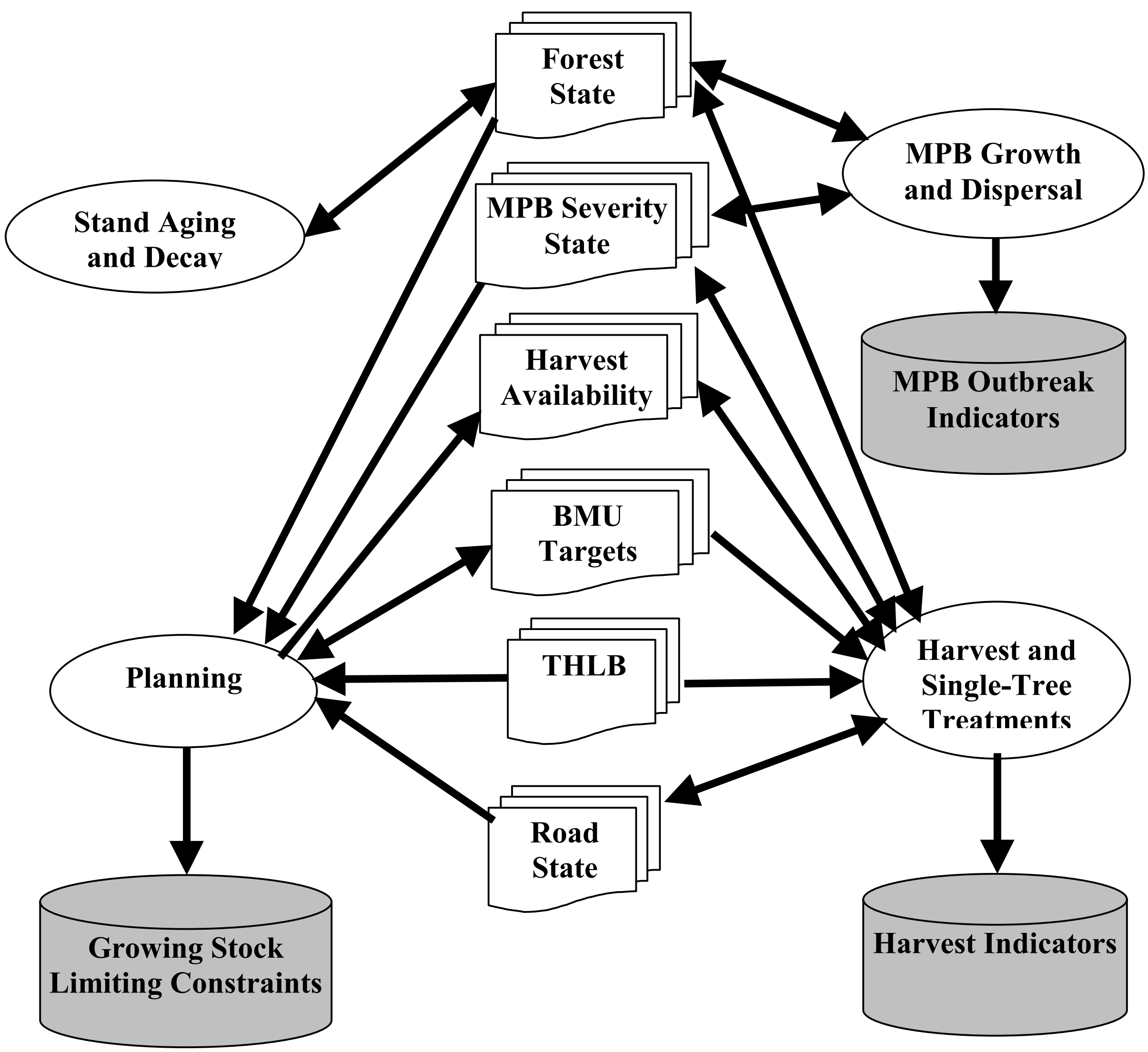

Figure 1. Linkages between primary components of state (shown in the centre), model processes (shown in ovals) and output files (shown as grey drums).

3.1.1 Model State Space

The following data layers comprise the model state space. Each spatial variable is represented by a grid of 16 hectare cells that are homogenous with respect to the layer attributes.

Landscape structure: the landscape biogeographical context and the limits of the study area are defined with the following spatial variables:

(i) BEC: biogeoeclimatic classification by variant.
(ii) Elevation: elevation in metres

Forest State: the forest is represented by the following layers:

(iii) Age: age in years (projected to start year).
(iv) ITG: inventory type group (leading and secondary species).
(v) VolPerHa: standing volume/ha for trees greater than 12.5 cm dbh (as reported in the inventory database).
(vi) PineVolPerHa: standing volume/ha that is pine greater than 12.5 cm dbh.
(vii) Percent pine: PineVolPerHa divided by VolPerHa
(viii) SalvageableVolumePerHa: amount of salvageable volume in each cell.
(ix) MPB Susceptibility: estimated according to the index developed by CFS (Shore and Safranyik, 1992), but lacking stand density.

Mountain Pine Beetle Severity State:

(x) State of attack in each cell: represented using broad classes similar to those in the provincial aerial overview data: based on the percent of pine in each cell that has been attacked: no mountain pine beetle (0% attack), endemic (<1% attack), low (1-10% attack), medium (10-20% attack) and severe (> 20% attack).

Harvest Availability:

(xi) PotentialTreatmentType: the available forest is stratified into the type of treatment that would be applied if a harvest block were initiated at that cell. Valid treatments are discussed below.

Timber harvesting landbase:

(xii) THLB: the timber harvesting landbase is derived from the productive operable forests by using a netdown process that removes forest for various reasons, applied spatially. Individual cells are either completely within or without the THLB. The majority of these reasons for removal will generally remove entire cells (e.g. non-merchantable forest), but some may remove only portions of a cell (e.g. roads, riparian zones). In these latter cases, we chose whether to include or exclude a cell randomly using a probability equal to the proportion.

Management Zones:

(xiii) MgmtUnit: management unit (TSA or TFL)
(xiv) LU: Landscape Units
(xv) BMU: beetle management units
(xvi) VQO: visual quality objective zones.

Management Parameters: A range of parameters and tables represent the harvesting regime, including:

(xvii) AAC (annual allowable cut): the "target" for the area to be harvested per year for each management unit. For TSAs this was obtained directly from the most recent Timber Supply Analysis report. For TFLs the volume target was converted to an area based on average volumes per hectare.
(xviii) BMUStrategies: beetle management unit strategies described below.
(xix) Minimum harvest volume: generally 150 m^3 per ha except for salvage.
(xx) Management constraints: described below
(xxi) Management preferences: described below

Roads:

(xxii) DistanceToRoads: distance to existing roads in metres.

3.1.2 Stand Aging and Decay

This event increments stand age each time step (one year), and updates the susceptibility rating estimate. The model does not capture changes in tree species or the growth of trees through time. This event is also responsible for applying decay (currently combining ecological and economic decay) of salvageable wood. The next version of the model will separate these two factors. Economic decay depends on markets and target products, and hence in some cases ought to be interpreted post-simulation.

3.1.3 Mountain Pine Beetle Outbreak Model

The mountain pine beetle outbreak sub-model is a discrete state change model. In each year at each location the mountain pine beetle will be in one of five states. The states are based on percent of pine trees in 16-ha cells that are currently (current severity) or cumulatively (cumulative severity) attacked:

1. NoMPB: 0% attack
2. Endemic: 0-1% attack
3. Low: 1-10% attack
4. Moderate: 10-20% attack
5. High: 20-100% attack

These classes are similar to those used in the overview survey, except we have added an additional class (Endemic) for very low attack levels, and decreased the threshold between moderate and high from 30% to 20%.

In each year of a simulation, the current mountain pine beetle state in each cell may remain the same, or change to more or less severe states. The probability of a given beetle state arising depends on the previous year's state, the cumulative amount of kill by beetles, host conditions in the cell, external mountain pine beetle pressure, and management effects. The state-to-state transition matrix is parameterized using observed transition probabilities in the overview data from 1999 to 2003, supplemented by information from the landscape scale (MPB-SELES) and stand scale (MPBSim) models.

Previously un-attacked cells (NoMPB state) may be subject to local beetle dispersal pressure from nearby cells, long-distance pressure from cells many kilometers away, or no significant beetle pressure at all. There is some probability that infestations will arise "spontaneously" in areas not subject to significant dispersal pressure, presumably due to local increase in endemic beetle populations. We modify the beetle dispersal model from the landscape scale MPB-SELES model to estimate beetle dispersal pressure across the province. There is little information available on the long-distance dispersal behaviour of beetles, so that portion of the model is based on the observed ability of proximity of cells to existing outbreaks, relative to prevailing wind, to explain infestation starts in the past overview data (i.e. we do not presuppose the effect that dispersal pressure will have on the probability of infestations arising).

Currently attacked cells may increase or decrease their infestation severity depending on current infestation severity, depletion of hosts, and external beetle pressure. Owing to the relatively short time-depth of our data, and various other problems with applying the overview survey to this application, we rely mainly on the behaviour of the district scale model MPB-SELES to predict the progress of infestations once they have begun.

The primary effect of mountain pine beetle attack is to shift living pine volume to standing dead volume (salvageable wood). By killing trees, mountain pine beetle become indirectly visible to the management sub-model, thereby influencing the focus of harvest, single-tree treatments and BMU ratings.

3.1.4 Planning

This event performs an inventory analysis each time step. It tracks the amounts of forest old enough to harvest (merchantable), available subject to road access and visual constraints, and determines which cells are available for harvest. Note that the only forest cover constraint applied was for visual objectives (e.g. no rules for ungulate winter range, caribou, community watersheds, etc. were applied). For cells that are unavailable, this sub-model outputs information to determine which constraint(s) were responsible.

The second key task of this sub-model is to establish beetle management unit (BMU) types. The possible types, and general management policies are:

- *Monitor:* no beetles present; focus on green tree harvest
- *Suppression:* low to moderate mountain pine beetle; focus on reducing populations
- *Holding Action:* moderate to high mountain pine beetle; focus on reducing populations
- *Salvage:* high to very high mountain pine beetle, or post-outbreak collapse: focus on recovering standing dead volume.

For each BMU, an "outbreak level index" (*BMU rating)* was computed as follows:

Area with endemic mountain pine beetle state / area with mountain pine beetle > endemic

This index roughly corresponds to a spot:patch ratio. BMUs are processed sequentially in increasing order of this index. If there are no detectable mountain pine beetles, then a BMU is assigned a *monitor* type. If the single-tree budget (after reductions for previously processed BMUs) is capable of addressing at least 80% of the endemic cells, then a BMU is assigned a *suppression* type. Otherwise, if the BMU rating is < 0.2 (i.e. at most 80% of the attack is in higher mountain pine beetle attack states) and the total area attacked in the BMU is less than 5,000 ha, then the BMU is assigned a *holding action* type. Finally, unassigned BMUs are assigned a *salvage* type. See the following sub-models for details on how provincial single-tree budget, and management unit AAC is partitioned among BMUs, and how BMU types influence targeted harvesting.

3.1.5 Harvesting

This event performs forest harvesting simultaneously in each TSA/TFL in the province. Each management unit is processed independently, and so this sub-model can be described from the perspective of a single unit. In each unit, the target allowable annual cut (AAC), expressed using area, is harvested from the available cells.

Each year, the target area or volume AAC provides a "beetle management potential". How this is allocated across a unit depends on the BMU ratings, mountain pine beetle state, stand ages/volumes and salvage volumes, and is designed to capture the fundamentals of bark beetle management (MOF and BCE 1995). The available cells in the unit are stratified into groups based on BMU rating and mountain pine beetle outbreak state, and processed according to a priority order. Within each stratum, ordering is according to stand age or salvagable volume. The following describes the strata, from highest to lowest priority within a management unit:

- Low and moderate mountain pine beetle in suppression BMUs: focuses harvesting on leading edge attack.
- Endemic and severe mountain pine beetle in suppression BMUs: focuses harvesting on other mountain pine beetle attack in suppression BMUs.
- Low and moderate mountain pine beetle in holding action BMUs: focuses harvesting on leading edge attack
- Severe mountain pine beetle in holding action BMUs: focuses harvesting on high populations
- Salvage in salvage BMUs: areas with adequate salvage (> $50m^3$/ha)
- Moderate and severe mountain pine beetle in salvage BMUs: focuses harvesting on areas likely to result in substantial salvage
- Salvage in other BMUs, and low and endemic mountain pine beetle in salvage BMUs: remaining "mop-up" classes
- Green harvest (no mountain pine beetle) in any BMU: regular green harvest

In cases of salvage, prioritization within the stratum will be according to amount of salvageable wood, while in all other cases prioritization will be according to age. Hence in units with no mountain pine beetle (i.e. all BMU types will be *monitor*), all harvesting will be "green harvest", and hence according to "oldest-first, nearest to road". In management units with a mixture of BMU types, the actual allocation of harvesting will primarily focus on reducing populations, followed by salvage. In management units dominated by salvage BMU types, harvesting will be "highest salvage-volume first, nearest to road".

The default cutblock size was up to 16-32ha (1-2 cells), based on a spatial assessment of recent block sizes in different regions of the province, and on the bark beetle regulations.

Where blocks are placed, volume (green and salvage) is recuperated, harvest indicators are updated, mountain pine beetle state is reset to "no mountain pine beetle" (i.e. the model assumes close to 100% efficacy), stand age is reset to 0, and visual targets are updated. In addition, this sub-model explicitly connects cutblocks to the main road network by adding a link from the first cell harvested in a block to the nearest existing road. It then updates a map indicating the distance from each cell to the nearest existing road. This step permits estimation of the amount of road constructed under a given management regime, and to determine accessibility in future time steps.

3.1.6 Single-Tree Treatments

This sub-model simulates fell and burn and MSMA treatment methods in each *suppression* BMU of the province simultaneously. First the provincial budget is allocated among *suppression* BMUs proportional to the level of endemic mountain pine beetle state. As with the logging sub-model, the model description can be then cast from the perspective of a single BMU. Single-tree treatments are generally applied in inaccessible areas or areas with low (endemic and some low mountain pine beetle state) beetle populations. These treatments are applied to individual cells, and the volume is not recovered. The model assumes that the mountain pine beetle state is reduced by one level (i.e. endemic state becomes "no MBP", while low becomes endemic).

3.2 Model Outputs

The model outputs relevant to this analysis are described below. A description of the indicator files produced for each of the principal clients of the project is found in Appendix 4.

3.2.1 Mountain Pine Beetle Outbreak Indictors

MPB report: A range of output values that track key aspects of the mountain pine beetle outbreak for each management unit:

- Overall area attacked
- Number of hectares in each severity class
- Cumulative proportion of pine killed
- Volume killed
- Salvageable volume

3.2.2 Inventory Indictors

Growing Stock: Growing stock is the cubic metres of live forest in each management unit in various strata of the landbase (overall, pine, in the THLB, available, merchantable). Also output are salvageable volume and non-recovered losses.

Limiting Constraints: Track the area of forest made unavailable in each management unit for harvest according to the various constraints. This is output as net and gross values, where the net value is the incremental area constrained after preceding constraints have been accounted for, and the gross value is the total amount the would be constrained independent of the other constraints. The primary order of constraints applied is:

- minimum harvest age
- road access (if enabled)
- adjacency (if enabled)
- VQO constraints
- Available after all constraints have been applied

3.2.3 Harvest Indictors

Harvest Report: A range of output values that track key aspects of the harvesting process overall, for each management unit and for each landscape unit:

- annual volume harvested
- annual area harvested
- mean volume per hectare harvested
- percent of harvest target achieved
- mean age harvested
- kilometers of roads built
- area harvested by mountain pine beetle severity state and salvage
- area processed with single tree treatments

BMU report: Values that track key aspects of BMU management:

- BMU type (strategy applied)
- Number of hectares treatable with single tree
- Single tree budget applied in BMU
- Proportion of provincial single tree budget
- Number of hectares actually treated with single tree

3.2.4 Spatial output

The client specific indicator files are described in detail in Appendix 4. These files are generated in a post-simulation step using spatial time series of layers output from BCMPB during a run. This is done to keep the underlying dynamics in BCMPB as simple and clear as possible, to improve efficiency, and to allow changes in indicator strata without requiring that we re-run the main model. The following layers are output annually during each simulation:

(i) *Stand age*: age of forest in each cell
(ii) *BMU type*: type of each BMU as assigned during the planning sub-model.
(iii) *mountain pine beetle severity*: current mountain pine beetle severity class of each cell
(iv) *mountain pine beetle cumulative severity*: cumulative mountain pine beetle severity class of each cell
(v) *Time since attack*: number of years since cell was last attacked
(vi) *Volume per hectare*: cubic metres/ha in each cell (live growing stock)
(vii) *Pine volume per hectare*: cubic metres/ha of pine in each cell (live growing stock)
(viii) *Salvageable volume per hectare*: cubic metres/ha of merchanable standing dead volume in each cell.
(ix) *Green harvest volume*: cubic metres/ha of green (live) forest harvested in each cell
(x) *Salvage harvest volume*: cubit metres/ha of salvage harvested in each cell
(xi) *Non-recovered loss volume per hectare*: cubic metres/ha of salvageable volume lost to economic decay in each cell

3.3 Scenarios Evaluated

A range of scenarios was run to verify the model prior to running the main scenarios described below. These verification scenarios led to model improvements and refinements, as well as greater understanding of the model interactions and feedback. We don't describe the results of the verification runs here, and instead focus on scenarios that produced information relevant for project objectives. Some details of the verification of the model can be found in Appendix 5.

At the level of a single grid cell, the behaviour of BCMPB is highly stochastic. However, over the 982 thousand susceptible forest cells in British Columbia this stochasticity averages out, so the main indicators are largely stable between runs at the provincial scale. We ran each scenario for one replicate, but expect to assess how variation in multi-replicate runs affects our results in the upcoming year.

The key scenarios used to assess management alternatives are as follows

Scenario Name	**Description**
BM_Reference	2001/2002 AAC (i.e. no uplifts), plus current levels of single tree treatments. Focus on leading edge attack where possible, and salvage elsewhere
BM_Uplift	Same as reference scenario, but increase AAC in specific management units with uplifts as determined by the chief forester
BM_NoSST	Same as reference scenario, except apply no single tree treatments
Salvage_HighestVol	Focus on salvage. Same harvest levels as reference scenario. Effectively, treat each BMU as if it was assigned a *salvage* type. Salvage is only allowed where there is more than 50 m^3 per hectare of dead pine
Salvage_HighestProp	Same as salvage scenario, except focus harvest on stands with highest proportion of salvage:green vs. highest amount of salvageable wood.

Several other scenarios were run, not as plausible management options, but rather to provide a context for comparing the main scenarios.

Scenario Name	**Description**
NoMgmt	Apply no harvesting nor single-tree treatments
NoBM	Harvesting using general management rules, but ignoring mountain pine beetle and salvage
BM_DoubleCut	Double annual harvest rates in all management units in the province. Otherwise same as reference scenario.
SalvageExt	Extreme salvage. Same as the Salvage_HighestVol scenario, but allow salvage harvest of any stand with at least 1m3/ha of salvageable wood

4.0 Results and Discussion

4.1 Forests at Risk to Mountain Pine Beetle

We estimate that there are a total of 9.9 billion m^3 of timber with a diameter at breast height greater than 12.5 cm (the "primary utilization level") in the province of British Columbia (Table 1)[1]. Of this slightly less than one quarter is one of the 5 pine species found in the province (Limber, Lodgepole, Western White, Whitebark or Ponderosa Pine; *Pinus flexilis, contorta, monticola, albicaulis*, or *ponderosa*, respectively). However, the proportion of pine on the timber harvesting landbase (30%) is much higher than on the non-contributing landbase (18%) (Table 1).

Of the total pine volume in the province approximately 1.9 billion m^3 is susceptible to mountain pine beetle attack (Table 2), by our definition (older than 60 years and in climatically suitable Biogeoclimatic zone – i.e. not AT, BWBS, CDF, CWH, SWB). Although mountain pine beetle has caused significant damage to coastal pine in the past (Collis and Alexander 1966) we find it convenient to exclude these areas for the purpose of this analysis primarily because there the current outbreak has not yet developed a significant coastal component. Of the 1.9 billion m^3 of susceptible pine 1.2 billion m^3 is in the timber harvesting landbase. This represents the timber volume "at risk" of loss.

Table 1. Billions of cubic metres of timber volume in British Columbia prior to the outbreak

	timber harvesting landbase		
	No	Yes	Total
Pine	0.97	1.36	2.33
Other Species	4.33	3.22	7.55
Total	5.30	4.58	9.88

Table 2. Billions of cubic metres of pine volume in British Columbia prior to the outbreak

	timber harvesting landbase		
Susceptible to mountain pine beetle	No	Yes	Total
No	0.33	0.14	0.47
Yes	0.64	1.21	1.85
Total	0.97	1.35	2.32

The forested area of British Columbia is approximately 61.6 million hectares. Of that area 33.1 million hectares are in the Biogeoclimatic Zones that are

1 Our estimates of volumes and areas are based on a combination of data sources as described in Appendix 1.

climatically suitable for mountain pine beetles (see above). Forty six percent of the total forested area in the province contains some pine. In the susceptible BEC Zones 60% of the forest stands contain some pine component (Table 3).

Table 3. Forested area with and without pine in the susceptible Biogeoclimatic Zones (millions of hectares).

	timber harvesting landbase		
Tree Species	No	Yes	Totall
No Pine	7.6	5.6	13.2
With Pine	8.1	11.8	19.9
Total	15.7	17.4	33.1

The proportion of pine in forested stands varies significantly throughout the province (Table 4). Throughout the susceptible BEC Zones 39% of the pine is in forests with a high (>=90%) pine but almost 30% is in areas with less than 40% pine. Again, these percentages are highly variable throughout the province.

Table 4. Percentage of pine in stands in the susceptible BEC Zones and selected TSAs

Percent Pine	Entire Susceptible Area	Arrow TSA	Quesnel TSA
Low (<40%)	29%	59%	13%
Moderate (40 - 89%)	32%	31%	26%
High (90 - 100%)	39%	10%	61%
Total	100%	100%	100%

4.2 Volume and Areas affected by mountain pine beetle in 2003

Based on the provincial aerial overview surveys we estimate that a total of 164 million m^3 of pine have been killed by mountain pine beetle as of 2003. This estimate is for the “observable” (red) dead pine and does not include estimates of “green attack”. Of that, 106 m^3 were in the timber harvesting landbase (9% of the total susceptible volume). The area affected by mountain pine beetle is difficult to easily summarize because of the variability in proportion of the pine that is affected in any given place. We estimate that approximately 1.2 million hectares of forest were in an “incipient” stage of infestation (> 0 and <1% of the pine killed) in 2003. Approximately 5.5 million hectares had experienced more than 1% of the pine killed by 2003. This represents 40% of the area of susceptible pine. This estimate is much higher than the 4 million hectares estimated by the provincial aerial overview data in 2003 (Anon 2003) because that estimate only includes the current annual attack, rather than the cumulative attack over all years, and because the method we use to convert the polygon based aerial overview data to a grid based map tends to increase the apparent area of the attack even though it has no effect on the overall volume of the attack. According to our grid-based data, the area infested by beetles in 2003 is approximately 4.3 million hectares, so converting polygon to raster data increases the apparent infested area by 8%. The majority of susceptible pine forest had experienced little or no mortality by 2003 (Table 5). However, the amount of pine killed is highly variable throughout the province (Table 5, Figure 2). The major concentration of kill by mountain pine beetle in 2003 was centered on the Quesnel, southeastern Nadina and Vanderhoof Forest Districts

Table 5. Proportion of area with pine by class of cumulative kill for all susceptible pine and selected management units

Cumulative Kill at 2003	All Susceptible Pine	Arrow TSA	Quesnel TSA
No kill	65%	79%	25%
>0 and <1%	7%	8%	2%
1 - 20 %	17%	10%	36%
21 -50 %	7%	3%	27%
51 - 75 %	3%	0%	7%
76 - 100 %	1%	1%	3%
Total	100%	100%	100%

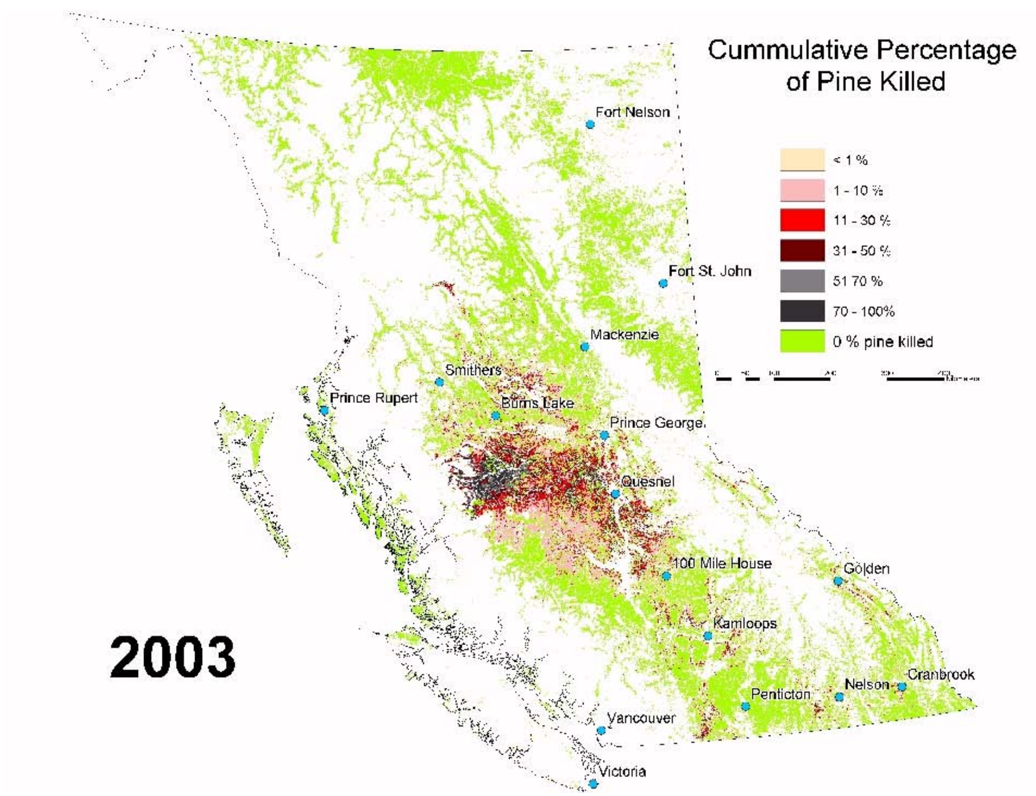

Figure 2. Observed cumulative percentage of pine killed in 2003

(A high resolution (3 meg.) version of this figure is available http://www.for.gov.bc.ca/hre/BCMPB/BCMPB_pctkill2003_Input.pdf)

4.3 Projection of the Reference Scenario.

We project that the annual volume of pine killed will peak during 2007 or 2008 at more than 70 million m^3 of pine in the timber harvesting landbase (Figure 3). Significant volumes of pine will continue to be killed at least until 2015 and we project that the volume killed will not decrease to pre-outbreak levels until after 2020. In general the outbreak initially expands rapidly for several years because it currently is centered on very high quality beetle habitat (large areas of continuous mature pine). The outbreak subsides as that habitat is depleted and the beetles move into less desirable habitat (smaller areas of more dispersed pine). Our projections are based on the understanding that the provincial aerial overview data over estimates the volumes killed in severely infested areas (Ebata, pers. comm.). As a result our projection of the annual kill does not "follow" the apparent trend in the overview data (Figure 3). Both our representation of the overview data and the model projections include this understanding.

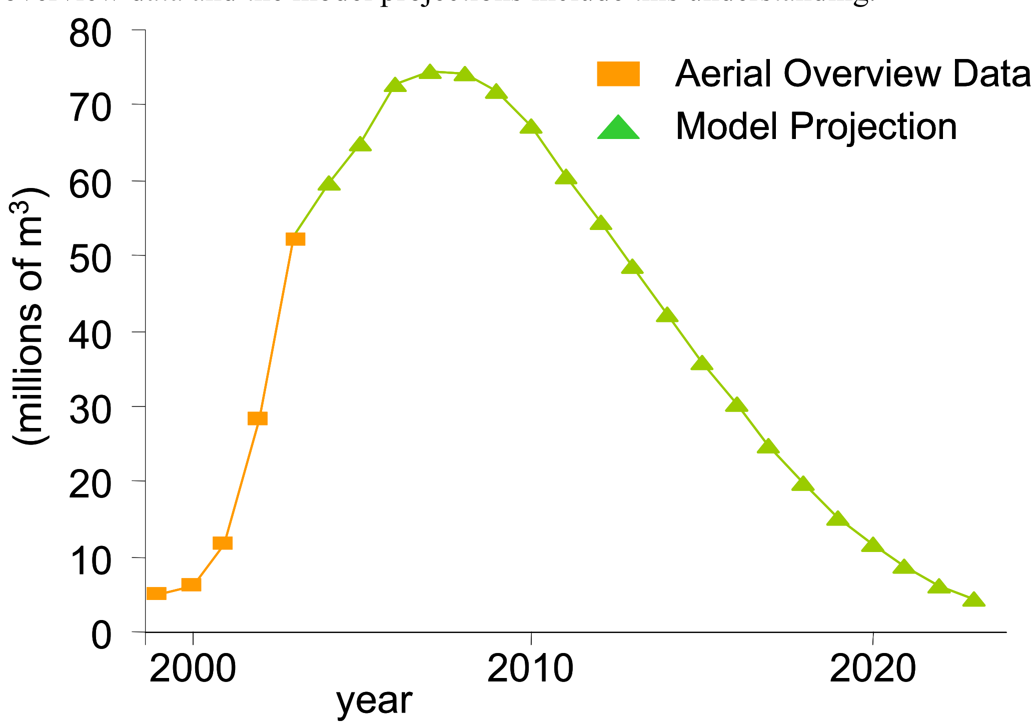

Figure 3. Observed and Projected (for the Reference Scenario) Annual Volume of Pine Killed in the Timber Harvesting Landbase.

We project substantial variability in the timing of the peak in annual kill in different areas of the province (Figure 4). Figure 4 shows the annual kill for each Timber Supply Area. The management units are listed on the right in descending order of the proportion of pine killed in 2003. Those units with the higher proportions of pine killed have an earlier peak in annual kill. Quesnel has the highest proportion of pine killed in 2003 (25%) and is the only management unit that has already passed the peak in annual kill. Units with lower proportions of pine killed are generally further from the center of the outbreak and thus take longer to experience the peak in annual kill. In general, the later the occurrence of the peak in annual kill the lower the percentage of pine that is killed at the peak. We attribute this to the fact that those units that peak late tend to have relatively poor, discontinuous beetle habitat.

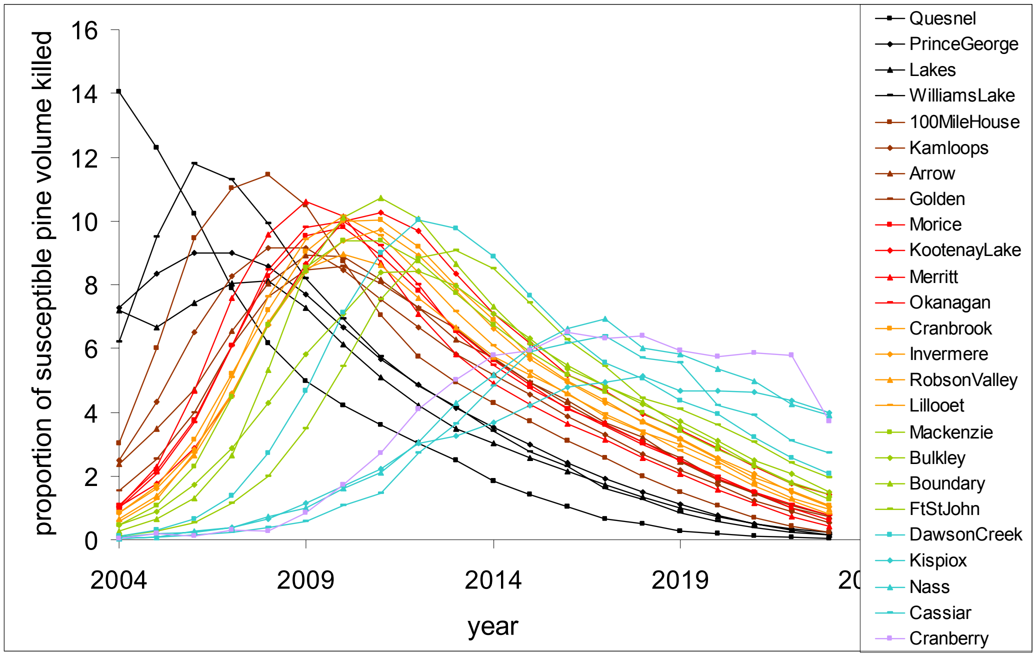

Figure 4. Effect of initial proportion of volume killed on the progression of the outbreak.

The Reference Scenario projects that well over 90% of the susceptible pine on the timber harvesting landbase will be killed by 2020 (Figure 5). It should be noted that this effectively represents a "worst case" scenario. The projection indicates how long it would take to get as bad as it could possibly get. Past outbreaks of mountain pine beetle have been "stopped" by very cold winters (Wood and Unger 1996). It is not inconceivable that cold winters may slow or stop the progression of this outbreak. However, it is very unlikely that the entire outbreak area will experience sufficiently cold weather to affect a significant proportion of the beetle population. Our projection may also represent an over estimate because we project that virtually all the volume within all stands will eventually be killed by mountain pine beetle. Appendix 5 describes sensitivity tests in which this assumption is relaxed by not allowing the infestation to "re-start" in cells where it had subsided completely even if there remained susceptible pine. This modification to the model results in projections of approximately 80% of the susceptible volume being killed by 2020.

We are not aware of any systematic survey of kill rates that could definitively tell us what proportion of trees might be killed by beetles in a typical outbreak, but the suggestion from beetle researchers is that beetles rarely kill more than 90% of the volume in a stand. From their collective experience, researchers from the

Canadian Forest Service suggest that, in pure pine stands subject to heavy beetle pressure, 70% of the stems and 90% of the standing volume might be killed by beetles. Over the whole landscape, they suggest the average is probably closer to 50-60% of the stems and 60-70% of the volume (T. Shore, pers. comm.). An incomplete survey of the literature corroborates these opinions: 32-92% of merchantable basal area killed in 10 study areas in Wyoming and Idaho (Amman and Baker 1972); 50 – 75% of stems killed in 40 stands in Northern Utah (Stone and Wolfe 1996); and 41- 67% of stems killed in 10 stands in southwestern Yellowstone (Romme et al 1986).

In addition to the opinion of CFS researchers and a few corroborating studies, there are good biological reasons to expect that beetles will not kill all trees. Even within uniform-aged pure pine stands there is variation in tree diameter and vigour. Smaller trees tend to have thinner phloem, which provides beetles with less food, and also protects them less well from drying out (Safranyik et al 1999). Beetles tend to attack large trees first (Geiszler et al. 1980; Mitchell and Preisler 1991), where they can reproduce successfully. Once they have exhausted the quality food supply, they turn to smaller trees, but will survive less well in these trees, causing populations to decline before all the small trees can be killed. Beetles might also tend to do poorer in stands with fewer live pine trees. It has been established that thinning lodgepole pine stands reduces forest susceptibility to beetles (Amman et al. 1988; Mitchell et al. 1983; Preisler and Mitchell 1993; Waring and Pitman 1985). This might be because the vigour of trees increases in less crowded stands, because it is more difficult for beetles to switch between trees that are further away from one another, or because the microclimate in more open stands is less good for beetles. Whatever the reason, it is reasonable to expect that stands thinned by previous beetle mortality are also less good for beetles.

We are currently working on refinements to the mountain pine beetle projection sub-model to reflect the variability in estimates of percentage kill within stands.

By 2008, at the projected peak in annual kill, our model estimates that 10.2 million ha of susceptible pine (72%) will be infested by mountain pine beetles and over 400 million m^3 of pine on the timber harvesting landbase will have been killed (Figure 5). That area will be distributed throughout the susceptible range with concentrations of current attack in the northern and southern portions (Figure 6)

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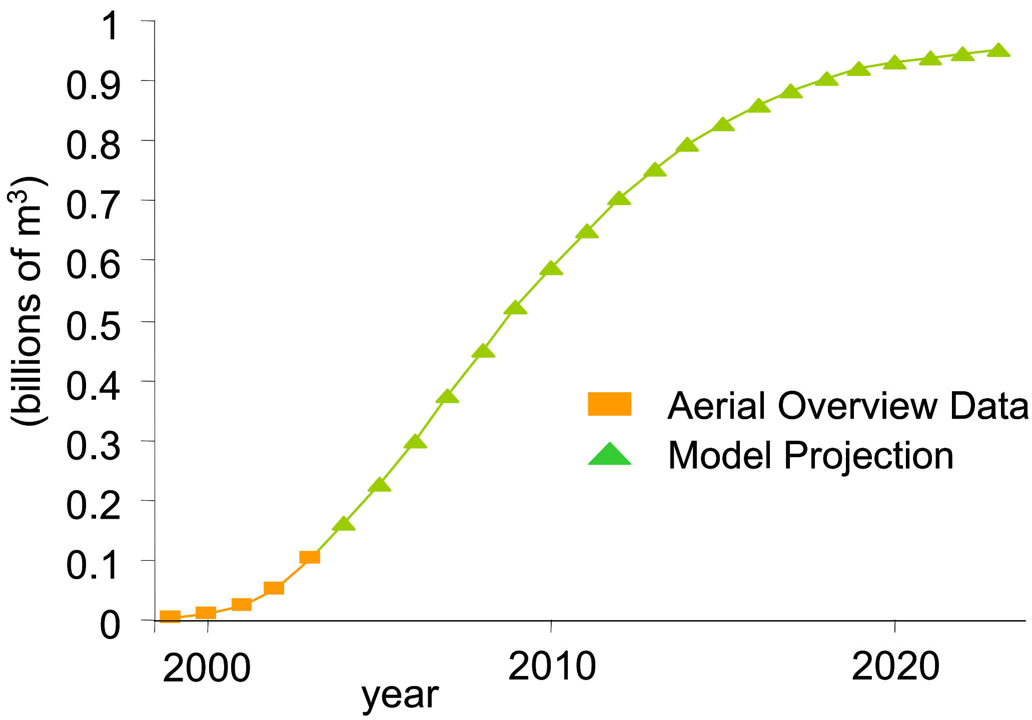

Figure 5. Observed and Projected (for the Reference Scenario) Cumulative Volume of Pine Killed in the timber harvesting landbase

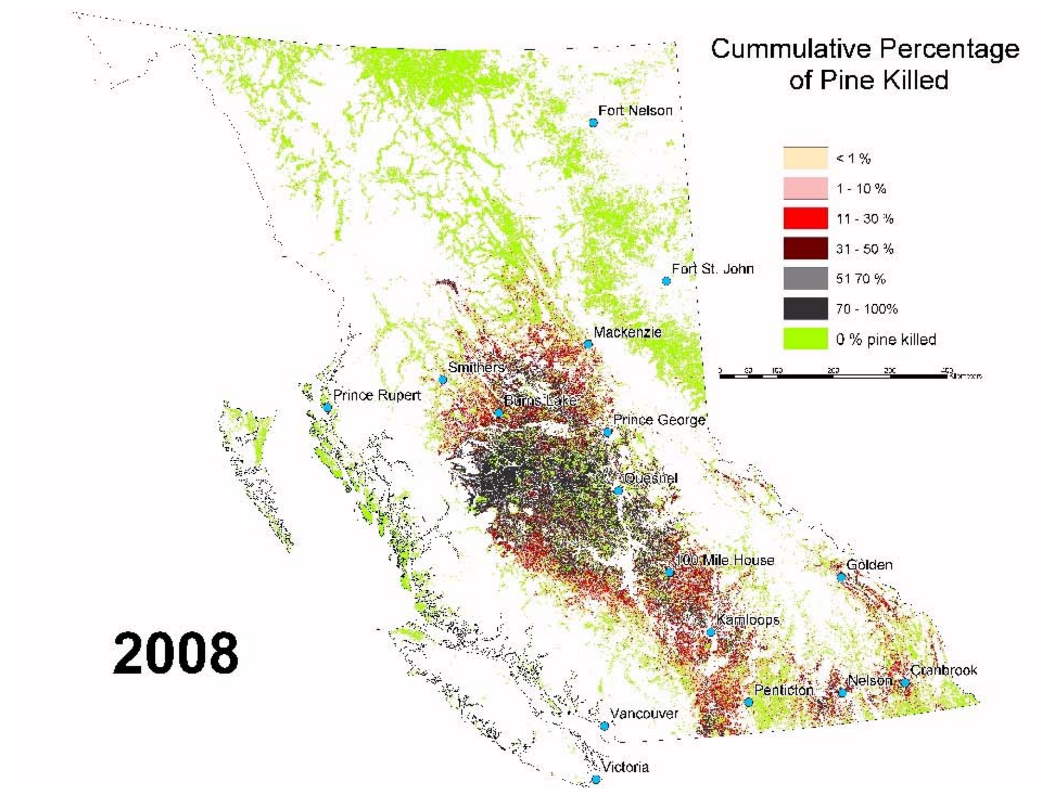

Figure 6. Projected cumulative percentage of pine killed in 2008 under the reference scenario

(A high resolution (3 meg.) version of Figure 6 is available http://www.for.gov.bc.ca/hre/BCMPB/BCMPB_pctkill2008_Input.pdf)

Figure 7 illustrates the effect of the mountain pine beetle outbreak and associated management activities on pine volume within the timber harvesting landbase . As a worst case scenario, we project that less than 20% of the total pine volume in the province will remain living after 20 years. That is, only the non-susceptible pine will remain living. A significant proportion of the remainder will be harvested, either as green volume or as salvage, but almost half the volume will become "non-recovered" losses.

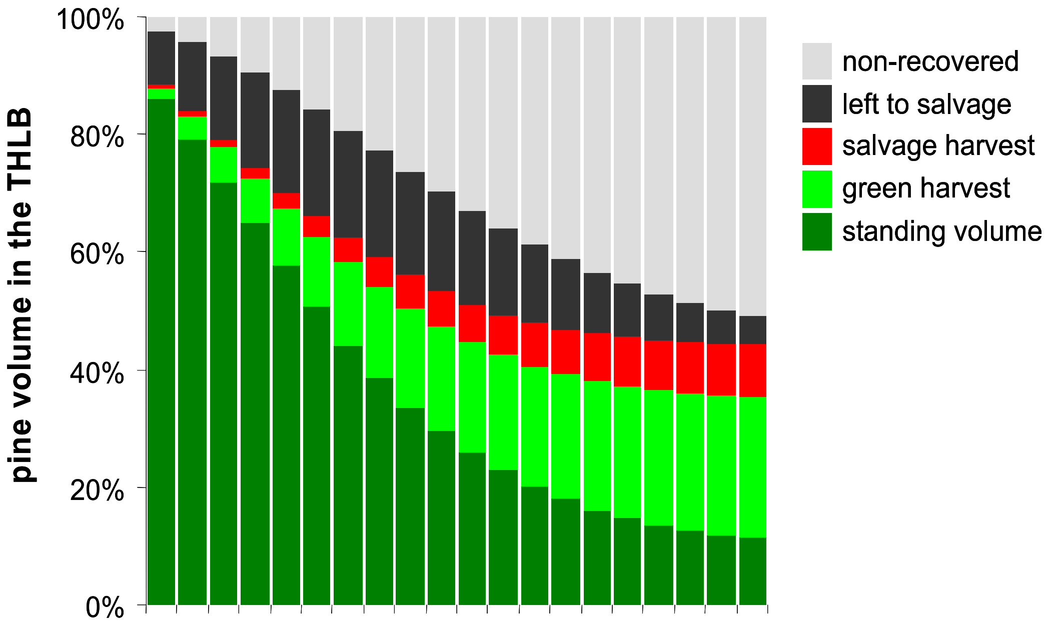

Figure 7. Projected proportion of pine volume on the timber harvesting landbase in various categories under the Reference Scenario

4.4 Comparison of Beetle Management Scenarios

We constructed and projected four beetle management scenarios as described in Section 3.3:

1. BM_Reference: the reference scenario with the application of beetle management strategies and the AAC as of 2001/2002
2. BM_Uplift: the reference scenarios with uplifts in the AAC as of January 2004
3. BM_NoSTT: the reference scenario with no single tree treatments.

We include three more scenarios for comparison purposes only. These are not meant to be plausible alternatives but rather are meant to place "bounds" on the problem:

1. NoMgmt: No forest harvesting – just the beetle outbreak

2. NoBM: Forest harvesting based on oldest first harvesting rules rather than any applying any beetle management or salvage strategies.
3. BM_DoubleCut: the reference scenario with twice the AAC in all management units.

The difference in the projected annual kill among scenarios is presented in Figure 8. We would expect that if beetle management strategies were slowing the outbreak then the peak in annual kill would occur at later times in scenarios with more aggressive beetle management. Note that, with the exception of BM_DoubleCut the peak in annual kill occurs at the same time for all the scenarios – at 2008. This indicates that beetle management, as modeled, does not slow the outbreak at a provincial scale. In fact the most aggressive beetle management scenario, BM_DoubleCut, moves the peak forward two years, while decreasing its amplitude. This is because the substantial increase in harvest level serves to more quickly reduce susceptible hosts. Note also that, as expected, the height of the peak in annual kill is depressed as more aggressive beetle management is imposed. Single tree treatments do have an effect on the height of the peak in annual kill but have no effect on the amount of kill as the infestation subsides.

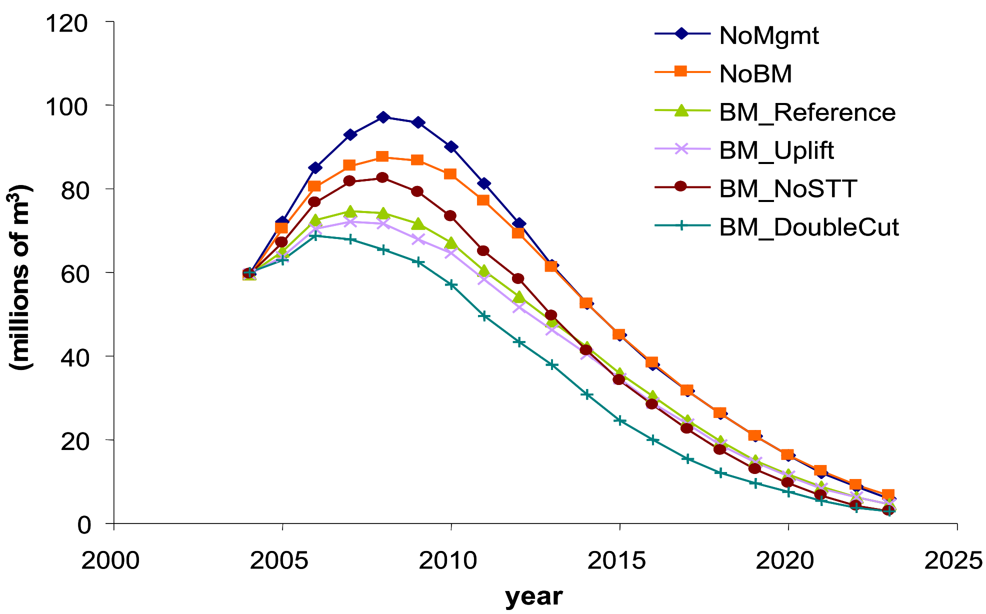

Figure 8. Comparison of projections in annual volume of pine killed on the THLB among beetle management scenarios.

There is some variability throughout the province in the impact that beetle management has on the outbreak. In areas near the center of the province, the provincial scale conclusions hold (see for example100 Mile House in Figure 9). However, at the periphery of the outbreak (see for example Cranbrook in Figure 9) beetle management does appear to have the desired effect. That is, the peak in annual kill occurs later as beetle management is implemented and single tree treatments depress the amount of kill throughout the outbreak. This is consistent with the findings of modeling work done at district scales in the Lakes District, near the center of the outbreak (Fall et al. 2002) and Kamloops and Morice Districts, at the periphery of the outbreak when the modeling was done (Fall et al. 2001; 2003a).

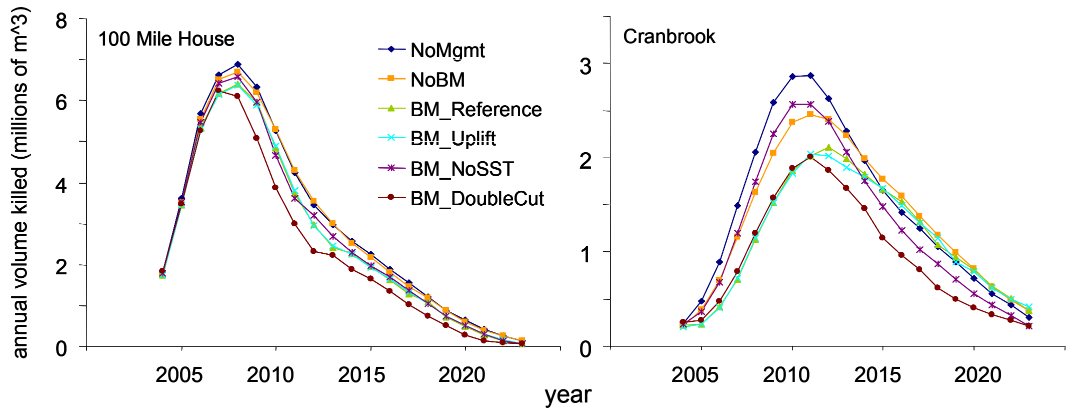

Figure 9. Comparison of projections in annual volume of pine killed on the THLB in the 100 Mile House and Cranbrook TSAs among beetle management scenarios.

Figure 10, Figure 11 and Figure 12 illustrate the projected cumulative effect of the mountain pine beetle outbreak and the beetle management activities on the volume of standing pine on the timber harvesting landbase. Figure 10 shows a comparison of the cumulative volume of pine killed on the THLB among scenarios. As expected, the no management (no harvesting) and no beetle management scenarios have the highest cumulative kills. By concentrating harvest on pine, as is done in the other four scenarios, we appear to have a positive impact on the volume of pine killed. As an aside, note that, over the course of the infestation, single tree treatments have little impact on the total volume killed. Examining Figure 11 shows that in order to have the "desired" effects on beetles we must harvest pine. That is, achieving lower cumulative kill by beetles is only accomplished by a concomitant increase in the harvest level of green pine. The result is that, regardless of the effort expended on beetle management, the combined impact on the standing volume of pine is virtually the same (Figure 12). This result indicates that, at a provincial scale and given the extent and severity of the outbreak, beetle management appears to have little effect on the overall impact of the outbreak with respect to future timber supply considerations.

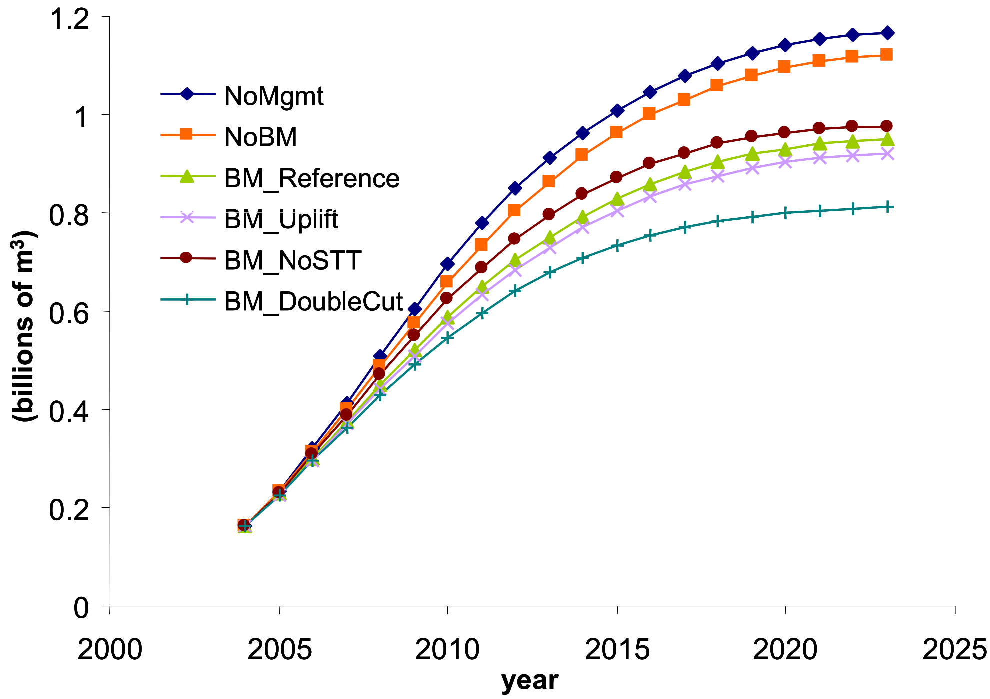

Figure 10. Comparison of projections in cumulative volume of pine killed on the THLB among beetle management scenarios.

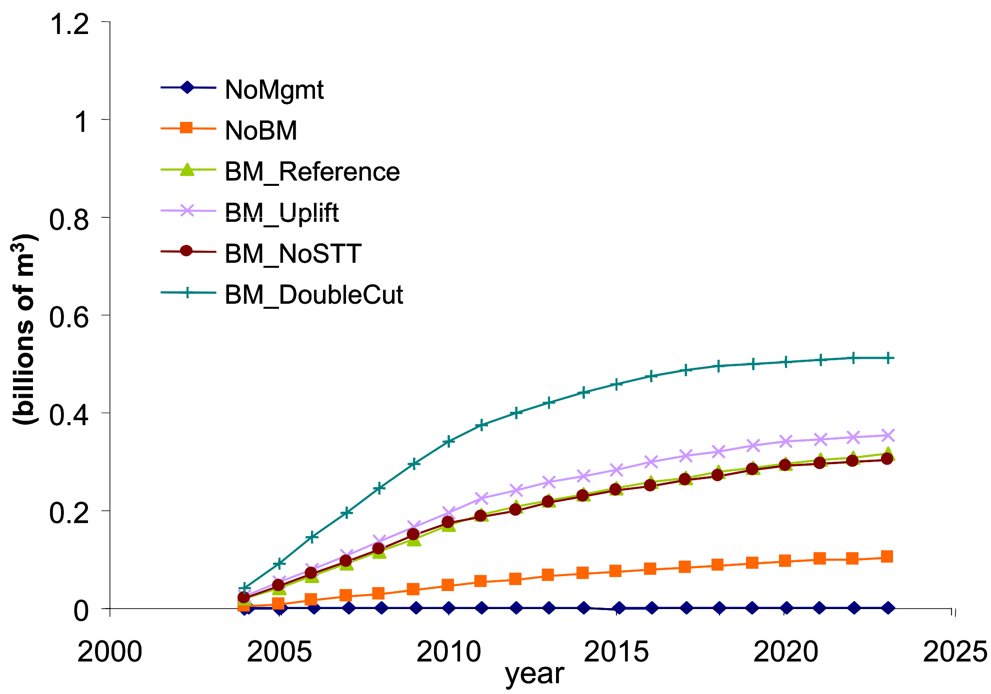

Figure 11. Comparison of projections of volume of green pine harvested among beetle management scenarios.

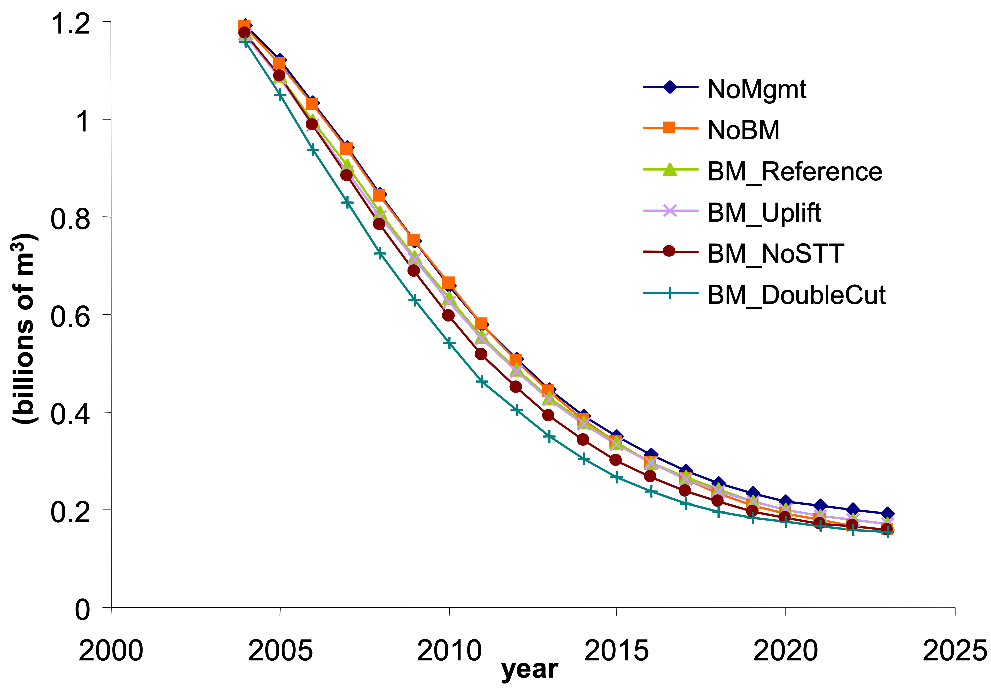

Figure 12. Comparison of projections of standing volume of pine on the THLB among beetle management scenarios.

4.5 Comparison of Salvage Focus Scenarios

As might be expected given the results reported in the previous section, focusing harvest on dead pine reduces non-recovered losses over the losses experienced in the reference scenario (Figure 13) where harvesting is focused on live pine at the leading edge of the outbreak. Focusing salvage on the highest volume of salvage available reduces losses more than focusing on the stands with the highest proportion of salvage (Figure 13). The reason is that stands with a high proportion of salvage do not necessarily contain a high volume of salvage. Focusing on any salvageable volume, rather than only stands with more than 50 m^3 of salvage, only makes a difference at the end of the simulation period when the remaining salvage is distributed throughout the landscape in relatively low volumes because of decay.

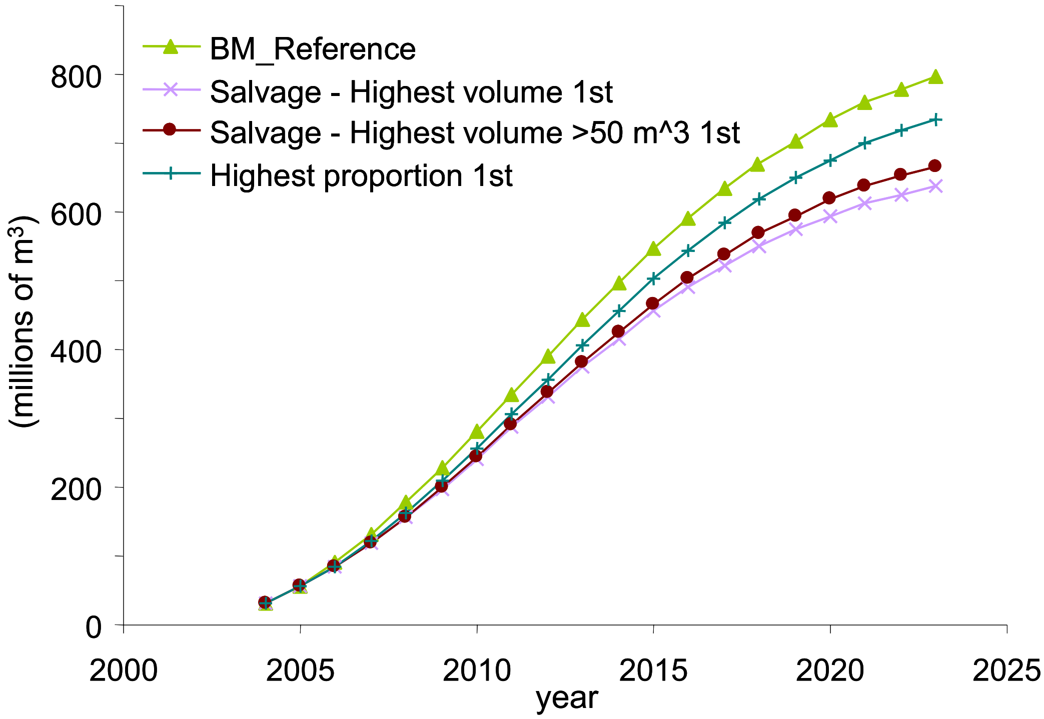

Figure 13. Comparison of cumulative non-recovered losses among salvage scenarios.

The reduction in non-recovered losses resulting from focusing harvest on salvage is not as great as one might expect or hope. In fact, losses are reduced by less than 25% from the reference scenario by the end of the simulation in the most optimistic salvage scenario (Figure 13). There are two reasons. First, there is a vast volume of dead pine to be harvested – on average throughout the projection period we estimate that there will be an average of approximately 200 million m^3 of dead pine volume on the landbase that could be salvaged. Given that the allowable annual cut for the interior of the province is 56 million m^3 (http://www.for.gov.bc.ca/hts/aac.htm) very high losses are to be expected regardless of the effort expended on salvage harvesting. Secondly, a large portion of the dead pine will be intermixed with green wood of other species (Table 4). As a result any harvesting targeted at salvage will also harvest green wood, thus reducing the efficiency of salvage at reducing non-recovered losses (unless harvesting techniques were applied to selectively harvest only standing dead pine).

As in the scenarios focusing on beetle management, the effect of salvage on non-recovered losses depends on the location in the province. For example, Figure 14 shows that, in Quesnel, focusing on the highest proportion of salvage results in more non-recovered losses than the reference scenario. The reason is that the forest in Quesnel is dominated by stands with a high proportion of pine (Table 4) and a relatively high proportion of that is already killed at the beginning of the simulation (25%). As a result the strategy forces some of the harvesting into stands with high proportions killed, but low overall volumes (e.g. younger ages) whereas the reference scenario and the other salvage scenarios focus on stands with higher volumes of dead wood, regardless of the actual level of kill, which in this case forces harvesting in stands that tend to be older and with higher proportions killed. Note that in Quesnel none of the strategies result in much difference in non-recovered losses simply because of the very large quantity of dead and decaying pine that is present.

The result for Bulkley TSA (Figure 14) shows that, in the case of a management unit with relatively low levels beetle kill at the beginning of the simulation and relatively low amount of pine overall, focusing on salvage can have a much more significant effect on non-recovered losses over that experienced over the entire province.

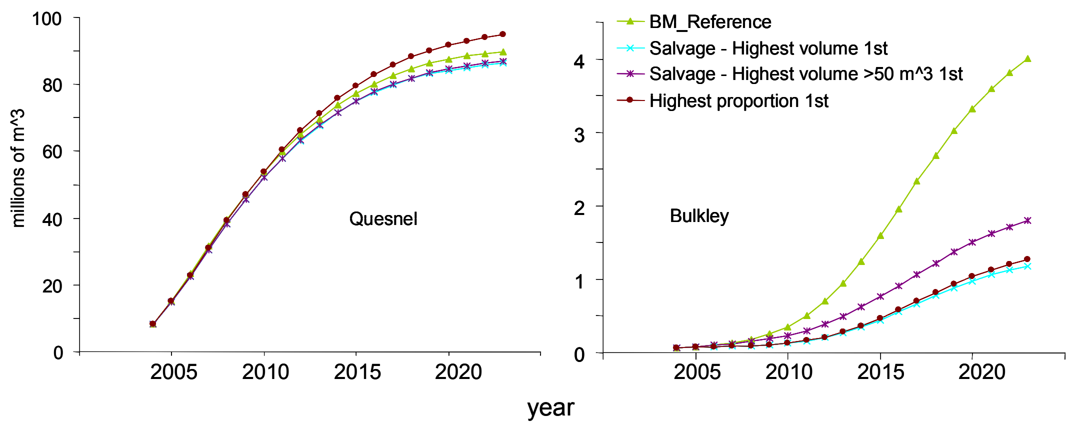

Figure 14. Comparison of cumulative non-recovered losses among salvage scenarios for the Quesnel and Bulkley TSAs

Figure 15 illustrates an unexpected result of the modeling of the salvage focus scenarios. That is, the salvage focus scenarios result in <u>lower</u> levels of kill by beetles than does the reference scenario in which “beetle management” is the focus. The reason is that the reference scenario focuses on newly attacked stands at the leading edge of the outbreak, regardless of the capacity of these stands to contribute to the outbreak. By focusing on salvage, stands with high levels of attack are targeted, often several years after the outbreak has grown in these stands when they are at the height of their capacity to produce beetles. That is, targeting the leading-edge attempts to reduce the *extent* of an outbreak. However, targeting high-attack stands behind the leading edge may correspond to an approach to reduce the *intensity* of an outbreak. We will adjust the behaviour of the beetle management scenarios during the next year’s work to assess the importance of this finding.

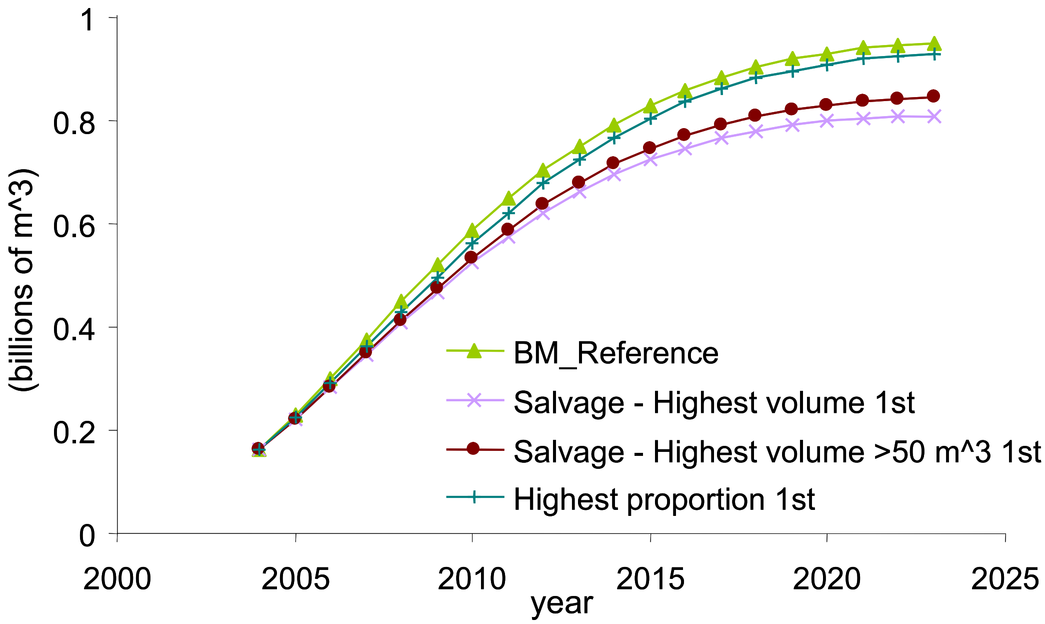

Figure 15. Comparison of cumulative volume killed by beetles among salvage scenarios

Our overall conclusion about the expected level of non-recovered losses is extremely sensitive to the annual rate of decay of useable dead pine volume (Figure 16). Losses a low as 10% per year have been reported for some areas on the Chilcotin Plateau with cold, dry climates (Taylor, pers. comm.). Feedback at a recent workshop on the modeling approach described here indicated that we should adopt a concept of “shelf life” for a given product (e.g. sawlogs, pulp, bio-fuels, etc.) rather than use a decay rate. It was suggested that “shelf life” is a step function in which there is no little or no loss of “utility” for some period of time and after that there is no “utility”. It has been suggested that the shelf life for sawlogs may be a little as 2 years and a great as 10 years depending on climatic conditions. In the coming year we will endeavour to obtain the best possible shelf life estimates for modeling purposes

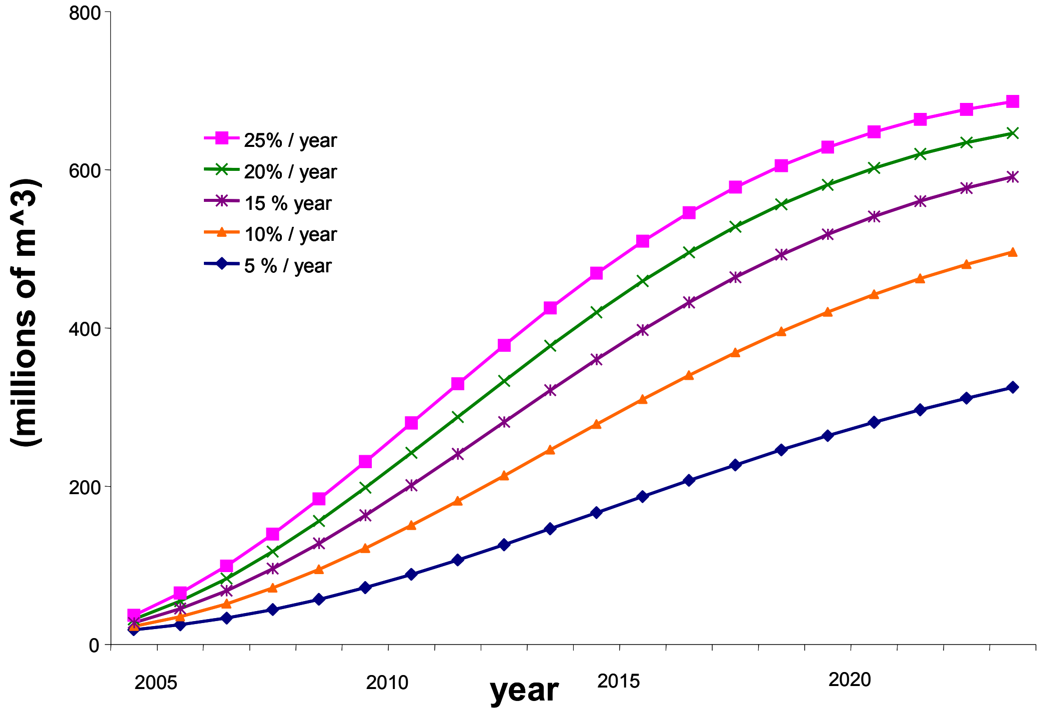

Figure 16. Sensitivity of projections of cumulative non-recovered losses to assumptions about annual rate of decay.

5.0 Conclusions and Next Steps

Our analysis of the current mountain pine beetle outbreak suggests that this outbreak is an order of magnitude larger, both in area infested and volume killed than any previous out break. The largest previous outbreak described by Wood and Unger (1996) was 650 000 hectares in size and occurred on the Chilcotin Plateau between 1930 and 1936. Our analysis indicates that it is most likely that the current outbreak will continue largely unabated until the majority of susceptible host stands in the province are affected. The model might be criticized because we do not include events such as unseasonably cold winter weather that might stop or slow the outbreak. It is true that by excluding the effect of unfavourable weather patterns, we are essentially projecting a worst-case scenario. However, we note that this outbreak is by now so widely distributed that there is not a high probability that the province will experience a severe cold weather event of sufficient to affect a significant proportion of the population (Spittlehouse pers. comm.). While there is a wide range of factors that affect mountain pine beetle population dynamics, the general understanding seems to be that once an outbreak has developed, it tends to proceed either until very cold weather causes massive beetle mortality, or until the supply of suitable hosts is depleted (Berryman et al. 1984; Samman and Logan 2000; Wood and Unger 1996). The only possible exception to this pattern appears to be the outbreak in the Flathead in 1977 to 1981 although observations about the collapse of this outbreak are equivocal (Young 1988). The results of this analysis are broadly consistent with conclusions from previous landscape scale-scale analyses in Kamloops, Williams Lake, Morice and Lakes (Fall et al. 2001; 2002; 2003a; 2003b).

The model results project that the peak of the outbreak will occur in 2007 or 2008 and the annual kill of pine volume, at that time, will be more than 70 million m^3 per year. We project that significant volumes (>30 million m^3) will continue to be killed until at least 2015. Further we project that pine mortality will not decrease to pre-outbreak levels until after 2020. We stress that these projections represent the worst possible case. It is conceivable that some unforeseen population stopping/slowing event may occur and/or that level of mortality within stands may not be as high as we project.

Our analysis indicates that single tree treatments, at currently funded levels, reduce the peak in annual kill but have little effect on total cumulative kill. We stress that this is a provincial scale conclusion. There is good evidence from both the provincial scale model and the district scale modeling done in Kamloops (Fall *et al.* 2001) that single tree treatments can be effective in protecting specific forest values under outbreak conditions that are less severe than those being experienced near the centre of current the infestation.

We examined scenarios that modeled a range of green tree harvesting directed at beetle management. Our fundamental conclusion is that, regardless of the "effort" expended on beetle management, the standing volume of green pine at the end of the outbreak is approximately the same. The reason for this is that in order to manage beetles we harvest green pine. Increasing our efforts on beetle management results in a concomitant increase in the harvest of green pine. Further we found that focusing harvest on green-infested trees does not delay the timing of the peak in annual mortality of pine due to beetles. This demonstrates that, as modeled, beetle management does not slow the outbreak at a provincial scale. This result may not be applicable for any given management unit, particularly those at the periphery of the outbreak.

Our results indicate that focusing harvesting on salvage focus is not as effective at reducing non-recovered losses as we might hope or expect. Salvage strategies are only partially effective for two reasons: there will be a very large amount of decaying pine and it will be intermixed with live pine. Again we note that while this conclusion holds broadly over the whole province, there are some areas where salvage strategies seem much more effective. Where salvage operations are undertaken near the beginning of the outbreak and there is a relatively low volume of susceptible pine, our projections show that salvage focus management can have a very significant impact on mitigating non-recovered losses. There is some indication that focusing harvesting on salvage can be as effective, if not more effective, at managing the beetle outbreak than focusing harvesting on "green attack" is.

There are two major sources of uncertainty in our current results:

- We are uncertain about mountain pine beetle stopping conditions within a given stand. That is, although we are confident that our projection of timing and pattern are justified based on the overview data, we have some reservations regarding the actual final volumes killed within each stand. This is partially due to the lack of empirical experience with declining epidemics. We suspect that our estimates of volume killed within any given stand may be too high (but not likely by more than 20%). We also have some uncertainty about the rates at which the infestation begins in areas outside the currently infested area (i.e. more mountainous and fragmented habitat than is seen on the interior plateau).
- We are uncertain about ecological and economic decay rates. We applied a rate of 20%/year. Clearly this would vary across diverse site and climatic conditions in the province. We expect that the rate applied may be on the high side, both in terms of the magnitude (which may be high for drier areas of the province) and because no delay was considered (i.e. volume may not begin to degrade for several years post-mortality). Economic decay also depends on the target products, which we did not consider (e.g. trees targeted as sawlogs may experience more rapid economic decay than trees targeted as pulp).

Hence, the first issue suggests that total volumes killed may be somewhat less than reported here, while the second issue suggests that volume recovered may be somewhat higher (and NRL somewhat lower) that reported.

Both of these issues will form a central focus for refinement and exploration in the upcoming year. Our other tasks will be to refine how BMU types are established, understand some odd behavior in specific management units, and improve the indicator file format. We will also assess some other management scenarios, such as using a volume-based AAC (vs. the area-based AAC reported herein) and improving salvage-focus harvesting and how policies for uplifts may differ from the base AAC.

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Appendix 1

Spatial Metadata
http://www.for.gov.bc.ca/hre/bcmpb/BCMPB_Appendix1_SpatialMetadata.pdf

Appendix 2

Management Sub-model Details
http://www.for.gov.bc.ca/hre/bcmpb/BCMPB_Appendix2_ManagementModel.pd
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Appendix 3

MPB Sub-model Details
http://www.for.gov.bc.ca/hre/bcmpb/BCMPB_Appendix3_MPBProjectionModel.
pdf

Appendix 4

Indicator Files
http://www.for.gov.bc.ca/hre/bcmpb/BCMPB_Appendix4_IndicatorFileDescripti
ons.pdf

Appendix 5

Verification and Sensitivity of the Beetle Projection Sub-Model
http://www.for.gov.bc.ca/hre/bcmpb/BCMPB_Appendix5_BeetleModelVerificati
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