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Provincial-Level Projection of the Current Mountain Pine Beetle Outbreak: An Overview of the Model (BCMPB v2) and Results of Year 2 of the Project

Marvin Eng, Andrew Fall, Josie Hughes,
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Mountain Pine Beetle Initiative
Working Paper 2005–20

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1.0 Executive Summary

The second version of BC Provincial-Level Mountain Pine Beetle Model (BCMPB v2) was developed as part of a two-year project to assess the impacts of mountain pine beetle (MPB), forest management, and interactions between these factors across the province. This report describes the model and the results of the second year of work. The results of the first year of work can be found at http://www.for.gov.bc.ca/hre/bcmpb/year1.htm. The MPB outbreak sub-model is driven by overview infestation maps from 1999 to 2004. The forest management sub-model uses inputs from the forest cover inventory and management information to simulate forestry activities within each timber supply area and tree farm license, including MPB management and salvage harvesting.

We project that the current outbreak will be at its worst in 2006. During that summer 90 million m^3 of merchantable pine on the timber harvesting landbase may be killed. Based on the behaviour of the outbreak to date we have no reason to expect that it will kill less than 80% of the pine volume. Nonetheless, there is uncertainty about when and how the infestation will end. We model the assumption that the infestation continues but kills less of each stand than we have observed. We also model the assumption that the infestation ends abruptly at a point earlier than we project as a worst case. Those assumptions have significantly different implications on forest management. The work required to determine which of the assumptions is most likely should be undertaken immediately.

There is significant uncertainty about the length of time that beetle killed wood will be useable for any given product (its "shelf-life"). We modeled differences in shelf-life and found dramatic effects on the amount of timber volume that we will be unable to harvest in a timely manner (non-recovered losses). By 2016 pessimistic assumptions about shelf-life result in 500 million m^3 of non-recovered losses whereas optimistic assumptions result in only 200 million m^3 of non-recovered losses. Work is currently underway to provide some better estimates of the biological and engineering/manufacturing aspects of shelf-life.

We examine the implications of various alternative harvest levels. Increasing harvest levels reduces non-recovered losses. However, the majority of the susceptible pine occurs in stands where it is mixed with non-pine species. Therefore, if we increase our salvage efforts we also increase our harvest of non-pine volume. For every cubic metre of non-recovered losses that are saved we also harvest 1.3 cubic metres of non-pine volume as an "incidental by-catch".

We observe that, if the volume harvested remains constant, the area harvested increases over the first 8 years of the projection and then decreases over the next 12 years. The reason is that volume per hectare harvested initially decreases as more of the dead pine becomes unusable, and then increases again as harvesting switches from salvage logging of dead pine to the harvesting of non-pine.

We will continue to refine the data and model over the coming year.

1.0 Résumé

La seconde version du modèle BCMPB (BC Provincial-Level Mountain Pine Beetle Model) a été mise au point dans le cadre d'un projet sur deux ans visant à évaluer les impacts de l'infestation du dendroctone du pin ponderosa (DPP), les mesures de gestion des forêts et les interactions entres ces deux facteurs dans l'ensemble de la province. Le présent rapport décrit le modèle et les résultats obtenus à l'issue de la deuxième année de travail. Les résultats de la première année sont présentés à http://www.for.gov.bc.ca/hre/bcmpb/year1.htm. Le sous-modèle de l'infestation de DPP est dicté par des cartes générales illustrant la progression de l'infestation de 1999 à 2004. Le sous-modèle sur la gestion des forêts part des données de l'inventaire du couvert forestier et des informations de gestion pour simuler les activités forestières dans chaque zone d'approvisionnement en bois et concession de ferme forestière, y compris l'exploitation dans les zones infestées et la coupe de récupération.

Nous prévoyons que l'attaque actuelle atteindra son apogée en 2006. Au cours de l'été de cette année-là, 90 millions de mètres cubes de pins marchandables pourraient être tués sur le territoire destiné à l'exploitation. Compte tenu de l'évolution de l'infestation à ce jour, rien ne permet d'espérer que la proportion d'arbres tués sera inférieure à 80 %. Il existe cependant des incertitudes quant au moment où s'arrêtera cette infestation et de quelle façon. Nous avons étudié deux hypothèses : la première voulant que l'infestation continue mais en tuant moins d'arbres que ce qui a été observé jusqu'à maintenant et la seconde, qui suppose une interruption abrupte de l'infestation avant une date fixée comme étant la limite la plus pessimiste. Ces deux scénarios ont des conséquences radicalement différentes pour ce qui est de la gestion de la forêt. Les travaux requis pour déterminer lequel de ces deux scénarios est le plus probable devraient être entrepris immédiatement.

Il existe des incertitudes importantes quant à la période pendant laquelle le bois provenant d'arbres tués par le scolyte pourra encore être utilisé pour la fabrication de produits – c'est-à-dire la durée de conservation du bois. Nous avons simulé différents scénarios mettant en jeu des durées de conservation différentes et les modèles ont montré que ce paramètre avait des conséquences énormes sur le volume de bois que nous ne pourrons pas récolter suffisamment tôt (pertes non récupérables). D'ici à 2016, les scénarios pessimistes concernant la durée de conservation indiquent que jusqu'à 500 millions de mètres cubes de bois pourraient être perdus, tandis que les scénarios optimistes prévoient seulement 200 millions de mètres cubes de pertes irrécupérables. Des travaux sont en cours pour estimer plus précisément les aspects biologiques et manufacturiers de la durée de conservation du bois.

Nous examinons les retombées de divers niveaux d'exploitation. L'augmentation des coupes réduit les pertes non récupérées. Par contre, la majorité des pins

susceptibles d'être attaqués se trouvent dans des peuplements mixtes. Si nous intensifions nos efforts de récupération, nous augmentons donc forcément le taux de coupe des essences autres que les pins. Pour chaque mètre cube supplémentaire de bois récupéré, nous récoltons « accidentellement » 1,3 mètre cube d'autres essences de bois.

Nous observons que si le volume de coupe reste constant, la surface récoltée augmente au cours des 8 premières années du scénario puis diminue au cours des 12 années suivantes. Ce phénomène s'explique par une diminution initiale du rendement volumique par hectare, en raison du nombre croissant de pins morts devenus inutilisables, qui est suivie d'une nouvelle augmentation lorsque les activités passent de la récupération des pins morts à la récolte des autres essences.

Les travaux de perfectionnement des données et du modèle vont se poursuivre au cours de l'année qui vient.

2.0 Introduction and Objectives

Mountain pine beetles (*Dendroctonus ponderosae* Hopkins) 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.

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

- consulting with potential users to develop and refine the scope and objectives;
- obtaining geographic, forest inventory, forest management and mountain pine beetle (MPB) infestation data for the study area;
- analyzing the data to understand as much as possible about the course of the outbreak over the past six 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. Our "reference scenario" does not include any infestation-stopping mechanisms such as severe winter weather events. We simply project the depletion of the mountain pine beetle's host (mature pine of all species). Therefore, the results of this project should be viewed as a worst-case scenario.

Our main goal this year was to examine the sensitivity of results about wood supply and non-recovered losses to various poorly defined model parameters. Last year our focus was on the efficacy of forest managers' aggressive attempts to slow the outbreak. We modeled their management strategy, known as "leading edge attack", given our current understanding of beetle biology and the observed behaviour of this outbreak. We found no evidence, virtually anywhere in the province, that the attempt to control the outbreak either slows its spread nor has any positive outcome with respect to the amount of live pine left on the landscape when the outbreak subsides. "Leading edge attack" may have had some success controlling previous outbreaks but the unprecedented size and aggressive nature of this outbreak appears to render it ineffective. However, there are hypotheses about beetle biology involving mechanisms that could slow or stop the outbreak, particularly at its periphery. If these hypotheses are correct, some efforts at beetle control at the periphery of the outbreak may be warranted. A detailed discussion of assumptions and conclusions about beetle management can be found in the report from the first year of the project (http://www.for.gov.bc.ca/hre/bcmpb/year1.htm).

This year our efforts were focused on answering the following questions that were raised in the first annual reporting out workshop (http://www.for.gov.bc.ca/hre/bcmpb/BCMPB_Workshop_Spring2004_Summary.pdf):

- How much beetle-killed wood, and of what quality will likely be harvested by the "sawlog" (dimensioned lumber) industry?
- What will be the amount of non-recovered losses and volumes available for various alternative industries under a set of "reasonable" assumptions?
- How sensitive are results to assumptions about:
  1. the duration of the outbreak,
  2. assumptions about the shelf-life of beetle killed timber for any particular purpose, and
  3. specification of what constitutes a valid salvage block (percentage of pine and volume of dead pine)?
- What are the implications of increasing harvest levels in affected management units?

It is important to note that our forest management model is designed to mimic the actions of the "traditional" forest industry in British Columbia's interior. Importantly, in this context, the model seeks wood useable for dimensional lumber (sawlogs) and "chips" (pulp) are considered a by-product. We do not attempt to model the actions of the anticipated "alternative" forest industry that will be using the dead pine primarily as "chips" for a variety of purposes such as oriented strand board (OSB), paper pulp and fuel. It is impossible to define the specifications of this alternative industry until it begins to emerge. Therefore, we only provide information about the amount, quality (time since death) and spatial distribution of timber volume that may be available for this industry.

The mountain pine beetle outbreak and our management response affect a wide range of forest values. We do not attempt to analyze the implications of these impacts, 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 descriptions of the management sub-model (including planning and harvesting) and the mountain pine beetle sub-model are provided by Eng et al. (2004) and Hughes et al. (2005) respectively. A detailed discussion of the input data is provided by Eng (2004b).

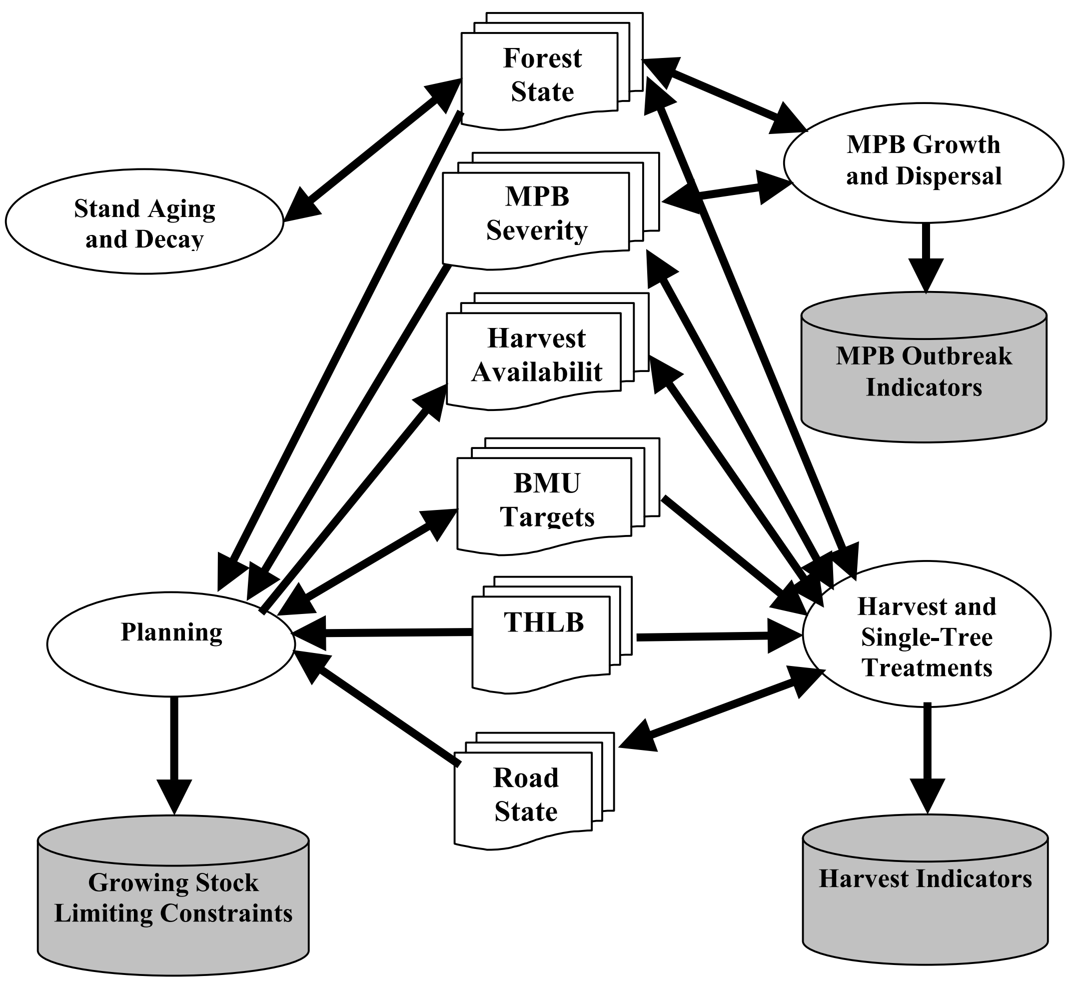

Figure 1. *Linkages between primary components of state (shown in the centre), model processes (shown in ovals) and output files (shown as grey drums).*

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 assumed to be 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(as reported in the inventory database).
(vii) Percent pine: Percentage of stand that is pine based on inventory (percentage of canopy, but also assumed to be percentage of volume).
(viii) Pine volume killed by beetles in each year since 1999, stored as a list in each cell to allow application of various decay functions (e.g., for sawlog and chip merchantability as described in the next section).
(ix) MPB Susceptibility: estimated according to the index developed by the Canadian Forest Service (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).
(xi) Cumulative percent of pine killed by beetles since 1999 using same classes as the above annual state.

Harvest Availability:

(xii) 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 in a subsequent sub-section.

Timber harvesting landbase:

(xiii) 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 outside the THLB. Most reasons for removal apply to 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:

(xiv) MgmtUnit: management unit (timber supply area - TSA or tree farm licence - TFL)
(xv) LU: Landscape Units
(xvi) BMU: beetle management units and strategy type
(xvii) VQO: visual quality objective zones.

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

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

Roads:

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

3.1.2 Shelf-Life of Beetle Killed Wood

We developed a conceptual shelf-life model based on data presented by the Vanderhoof IFPA (Thrower 2003) and numerous communications with domain experts, primarily district level staff within the BC Forest Service. Details of the implementation of the shelf-life model can be found in Eng (2004c)**Error! Reference source not found.**.

We define shelf-life as "the length of time after death that a tree will be useable for a given product." Therefore, "shelf-life" is product specific and differs for sawlogs, OSB, pulp, bio-fuels, woodpecker habitat, etc. A corollary of this concept is that the actual volume of timber in a MPB killed stand may remain the same for some significant length of time but will change in character as time progresses.

A narrative version of our conceptual model of shelf-life is:

- There is a relationship between time since death and applicable products for (stands of) pine trees killed by MPB.
- Beetle killed logs will be useable as sawlogs (dimensional lumber) during the winter and summer harvesting seasons immediately following their death.
- For (X) subsequent years they loose their bark and begin to deteriorate in quality (with some minor checking) but essentially the entire volume will continue to be useable as sawlogs.
- From (X) to (N) years, the volume that can be used as sawlogs will decline in a linear fashion to the point where none of it is useable for dimensional lumber.
- From (X) to (M) some portion of the volume, in addition to that useable as sawlogs, will be useable for "alternative purposes", for example, chips, biofuel, etc. The decline in the amount of total usable wood (from X to M years) will occur in a linear fashion.
- (N) and (M) will vary depending on the biogeoclimatic subzone and will be shorter in wetter subzones than in drier subzones.

In order to implement this conceptual model we developed a process for grouping subzones into dry, moist and wet categories that would correspond to slow, moderate and fast degradation rates of timber quality. In general it is assumed that the rate at which standing fiber will degrade from sawlog to chips and then to unmerchantable bears some relationship to the moisture regime of the climate. Degradation is the result of two factors; checking and sap rot. Checking is assumed to be more severe and more rapid in moister climates because ring width is positively correlated with growing season moisture; narrow rings are denser and hence less susceptible to checking. In addition, it is believed that more checking may occur in moister climates because shrinkage may be more severe in wet wood, and because winter freeze-thaw cycles may be more pronounced. Sap rot is assumed to occur more rapidly in wetter climates (particularly growing season moisture) because moisture is an important determinant of the ability of those fungi to grow and reproduce.

The relationships described above are not well understood. For that reason we rely on a categorization of Biogeoclimatic Subzones into 3 groups; slow, moderate and rapid degradation rates. We use Biogeoclimatic Subzones rather than actual climatic maps because the Biogeoclimatic Subzones integrate a number of climatic variables and because forest practitioners are familiar with the zoning and can provide input and criticism based on local knowledge.

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 2004.

Locations 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 SELES-MPB model to estimate local 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 to existing outbreaks 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).

The primary effect of mountain pine beetle attack is to shift living pine volume to standing dead volume (potentially salvageable wood). By killing trees, mountain pine beetles 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 for each time step. It tracks the amounts of forest old enough to harvest (merchantable), and determines which cells are available for harvest subject to road access and visual constraints. 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.

Cells that may potentially be harvested as salvage are also identified. A cell may be classified as "salvage" if three criteria are met:

(i) There is sufficient pine in the cell (percent pine is $\geq$ 50%)
(ii) There is sufficient beetle mortality in the cell (percent of the pine that is killed is > 50%)
(iii) There is sufficient merchantable sawlog volume in the standing dead wood and residual live wood (sawlog yield is $\geq 100m^3$).

The first criterion ensures that the amount of non-pine "by-catch" is limited. The second ensures that the stand has sufficient cumulative attack to be classified as a salvage cell and to limit "by-catch" of live pine. The last criterion ensures that the stand is still economic to harvest. Note that, since a cell may experience multiple years of attack, it is possible for a cell to meet both the requirements for "green" harvest and for salvage. In this case, the logging sub-model will select the classification with the highest preference, which depends on the type of the BMU in which the cell resides. 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:

$$(\text{Area with endemic mountain pine beetle}) + (\text{Area with mountain pine beetle} > \text{endemic})^2$$

This index roughly places an emphasis on non-endemic levels, but otherwise corresponds to increasing levels of MPB activity. 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 remaining single-tree budget (after reductions for previously processed BMUs) plus remaining AAC for the management unit is capable of addressing at least 80% of the "treatable" attack (all endemic cells plus non-endemic in the THLB), then a BMU is assigned a *suppression* type. Otherwise, if the remaining AAC for the management unit is capable of addressing at least 50% of the non-endemic in the THLB, then the BMU is assigned a *holding action* type. Finally, unassigned BMUs are assigned a *salvage* type. Once a BMU reaches a "salvage" type, it will remain there. 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 annual allowable 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 for the reference scenario:

- 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 (> $50 m^3/ha$)
- 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 relative to estimated minimum harvest age. Both cases are influenced by road access. 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".

In some scenarios, the preference ordering above was modified. For example, to set up an "early switch to salvage" scenario, the preference for salvage blocks can be increased. As described in the previous section, if a cell is available for harvest according to both green criteria (i.e., min. harvest age, VQO) and salvage criteria (i.e., min. percent pine, min percent killed and min. volume yield), then the class with the highest preference will be applied. The default cutblock size was 16ha - 32ha (1-2 cells), based on an assessment of recent block sizes in different regions of the province, and on the bark beetle regulations. Note that smaller block sizes increases beetle management potential since harvest pattern can more closely track MPB attack pattern.

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. All merchantable salvage (i.e. sawlog and chip salvage) is assumed to contribute towards the AAC. 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 *suppression* BMUs. First the provincial budget is allocated among *suppression* BMUs proportional to the level of endemic mountain pine beetle state. This model component can also be described from the perspective of a single BMU, since all suppression BMUs are processed independently. 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 MPB", while low becomes endemic).

3.2 Model Outputs

3.2.1 Tracking timber volume

Management options involve tradeoffs between various forest values. To understand these tradeoffs, we have found it useful to consider what happens over time to all of the timber volume in the province. In general, timber volume can be:

- Logged or standing (live growing stock or dead)
- Non-pine or pine
- Green (i.e., growing stock not killed by beetles) or standing dead (i.e., killed by beetles and useful for sawlogs, chips, or not useful non-recoverable loss). Note that standing dead volume designations only apply to pine, because beetles do not kill non-pine species.

At any point in time, all timber volume falls into one of the following 10 categories:

- Standing non-pine growing stock
- Logged non-pine
- Standing green pine growing stock
- Standing dead sawlogs
- Standing dead chips
- Standing dead non-recovered loss
- Logged green pine
- Logged sawlogs
- Logged chips
- Logged non-recovered loss (i.e., non-merchantable dead wood in cutblocks).

In most cases, we focus on volume within the timber harvesting landbase. We consider results for the whole province, as well as for each management unit. We look at logged volumes on both an annual and cumulative (over the whole outbreak) basis.

3.2.2 Mountain Pine Beetle Outbreak Indicators

Specific mountain pine beetle indicators include:

- Area infested (cumulative or annual)
- Volume killed (cumulative or annual)
- Percentage of area infested (cumulative or annual)
- Percentage of volume infested (cumulative or annual)
- Number of hectares in each severity class.

3.2.3 Inventory Indicators

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 that 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.

This indicator is primarily for model verification.

3.2.4 Harvest Indicators

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.

3.2.5 Spatial output

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 kill*: percent of pine volume killed by mountain pine beetle since 1999 in each cell

(v) *Volume per hectare*: cubic metres/ha in each cell (live growing stock)

(vi) *Pine volume per hectare*: cubic metres/ha of pine in each cell (live pine growing stock)

(vii) *Salvageable merchantable volume per hectare*: cubic metres/ha of merchantable (sawlogs or chips) standing dead volume in each cell

(viii) *Salvageable sawlog volume per hectare*: cubic metres/ha of sawlog volume in each cell .

(ix) *Non-pine harvest volume*: cubic metres/ha of non-pine forest harvested in each cell

(x) *Green pine harvest volume*: cubic metres/ha of green (live) pine harvested in each cell

(xi) *Salvage harvest volume*: cubit metres/ha of salvage harvested in each cell

(xii) *Non-recovered loss volume per hectare*: cubic metres/ha of standing salvageable volume lost to economic decay in each cell.

3.3 Scenarios Evaluated

A range of scenarios were 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. 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 Hughes et al. (2005).

At the level of a single grid cell, the behaviour of BCMPB is highly stochastic. However, over the 982,000 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.

This year we focused on the amount of wood that would be available for harvesting and the non-recovered losses under a "Reference Scenario" that approximated current management. We also ran several sensitivity analyses to examine the impacts of uncertainty in key model parameters. We examined the implications of increasing harvest levels in affected management units defined as all Timber Supply Areas with more than 10% susceptible pine on the timber harvesting landbase. These scenarios are described below.

3.3.1 Reference Scenario

The reference scenario is meant to approximate current management and uses our "best guess" relative to the sensitivity analyses scenarios described below.

The reference scenario uses harvest levels based on the Annual Allowable Cut as of September 30, 2004. That is, the harvest level prior to expedited AAC determinations in Lakes, Prince George and Quesnel. We define this as the reference because the increases in harvest resulting from the expedited AAC determinations are intended for the alternative industry and we are not attempting to model the behaviour of that industry. We do examine the implications of the expedited level of harvest as described in Section 3.3.5

The reference scenario models current beetle management strategies. That is, Beetle Management Units are assigned to one of four categories based on the ability to address the outbreak:

- Suppression: address > 80% of the infestation
- Holding Action: address > 50% but <80% of the infestation
- Salvage: address <50% of the infestation
- Monitor: no infestation present.

Harvesting is then focused on leading edge attack where appropriate, and salvage or green tree harvest elsewhere. Single tree treatment levels are set at the 2003 amount.

The reference scenario represents the "mid range" of the sensitivity analyses described in Sections 3.3.2, 3.3.3 and 3.3.4.

3.3.2 Sensitivity to assumptions about the end of the infestation

There is considerable uncertainty about when the current outbreak will subside. The reference scenario assumes that the infestation will progress to a logical conclusion based on its observed behaviour over the past six years. The resulting projection is that more than 95% of the susceptible pine will be killed by 2024 and the infestation will simply continue after that, albeit at very low levels.

The reference scenario may over-estimate the amount of pine that will be killed for one of two reasons:

1. It may over estimate the level of kill within each stand. The reference scenario projects that many stands will see 100% of the merchantable pine killed. However, conventional wisdom indicates that during epidemics the mountain pine beetle inundates a stand, preferentially killing the largest diameter trees. Reproduction is proportional to the size of tree beetles breed in, and at a diameter at breast height (dbh) of < 20-25 cm there is a net loss of beetles. Beetles benefit by attacking the large diameter trees and then abandoning a stand, rather than working their way through every tree before moving on. Because of this, attack usually only goes on for 2-4 years in any given stand and some decent sized trees are missed not killed.
2. The infestation may simply collapse well before 2024. Historically, particularly in the Kootenays and the United States, there have been large infestations that have collapsed not because of winter cold weather or host depletion. There are several possible reasons. Weather can still be a factor if it is cool and wet during the flight season, which tends to stagger the flight and disrupt the synchrony of the population (for mass attack, etc). Another possibility is that beetles are less successful in mixed stands and mountainous areas where pine is more difficult to find. A third possibility is that as an epidemic grows an increasing proportion of beetles are left in already decimated stands, which results in a net loss of beetles.

Given these possibilities we modeled four separate scenarios. In two of them we reduced the maximum level of kill to an average of 66% or 80% of the merchantable pine to simulate the first rationale described above. In these scenarios the infestation continues (past 2024) but the level of kill in each stand is less. In the other two scenarios we modeled the infestation as in the reference scenario but simply stopped it in 2011 and 2014 when approximately 66% and 80%, respectively, of the merchantable pine is projected to be killed.

3.3.3 Sensitivity to assumptions about shelf-life

Specification of the shelf-life of beetle killed pine for any given purpose or product is difficult because shelf-life is a complex concept composed of three inter-related variables:

1. the rate at which the wood will deteriorate given its characteristics and the characteristics of its location in the environment, particularly climate and soil moisture;

2. the capability of industry to utilize wood of various qualities given the state of engineering and the availability of machinery and processes; and
3. the demand for, and price of, the various products that can be made from beetle killed wood.

We have very little actual information about the first aspect of shelf-life. While there is a growing body of work on the engineering aspects of utilizing beetle killed wood, it is difficult or impossible to accurately project the demand for, and price of, those products. Therefore, we are unlikely to "know" the shelf-life. At best we can model shelf-life within reasonable bounds and examine the implications of that uncertainty.

We consider the estimates of biological rate of deterioration provided by Thrower (2003) to be "conservative" and we use them to represent the reference scenario. We model pessimistic and optimistic versions by subtracting and adding a constant amount of time, respectively, with one exception. The optimistic shelf-life in dry subzones is more different (optimistic) than the differences for the moist and wet subzones.

We model a reference[1], optimistic and pessimistic set of shelf-life assumptions, as follows:

Reference

All volume available for all products for **3 years** after death.

Subzones	Time to complete deterioration of sawlog volume	Time to complete deterioration of "alternative" volume
Dry	7	15
Moist	6	13
Wet	5	10

Note that this means that after 4 years in a moist subzone two thirds of the volume would be available for sawlogs.

Pessimistic

All volume available for all products for **2 years** after death.

Subzones	Time to complete deterioration of sawlog volume	Time to complete deterioration of "alternative" volume
Dry	5	10
Moist	4	8
Wet	3	5

Note that this means that after 3 years in a moist subzone one half of the volume would be available for sawlogs.

Optimistic

[1] based on information used in Thrower 2003

All volume available for all products for **4 years** after death.

Subzones	Time to complete deterioration of sawlog volume	Time to complete deterioration of "alternative" volume
Dry	15	25
Moist	8	18
Wet	7	15

Note that this means that after 6 years in a moist subzone one half of the volume would be available for sawlogs.

These relationships are shown graphically in Figure 1 where "alternative volumes" are labeled "chips".

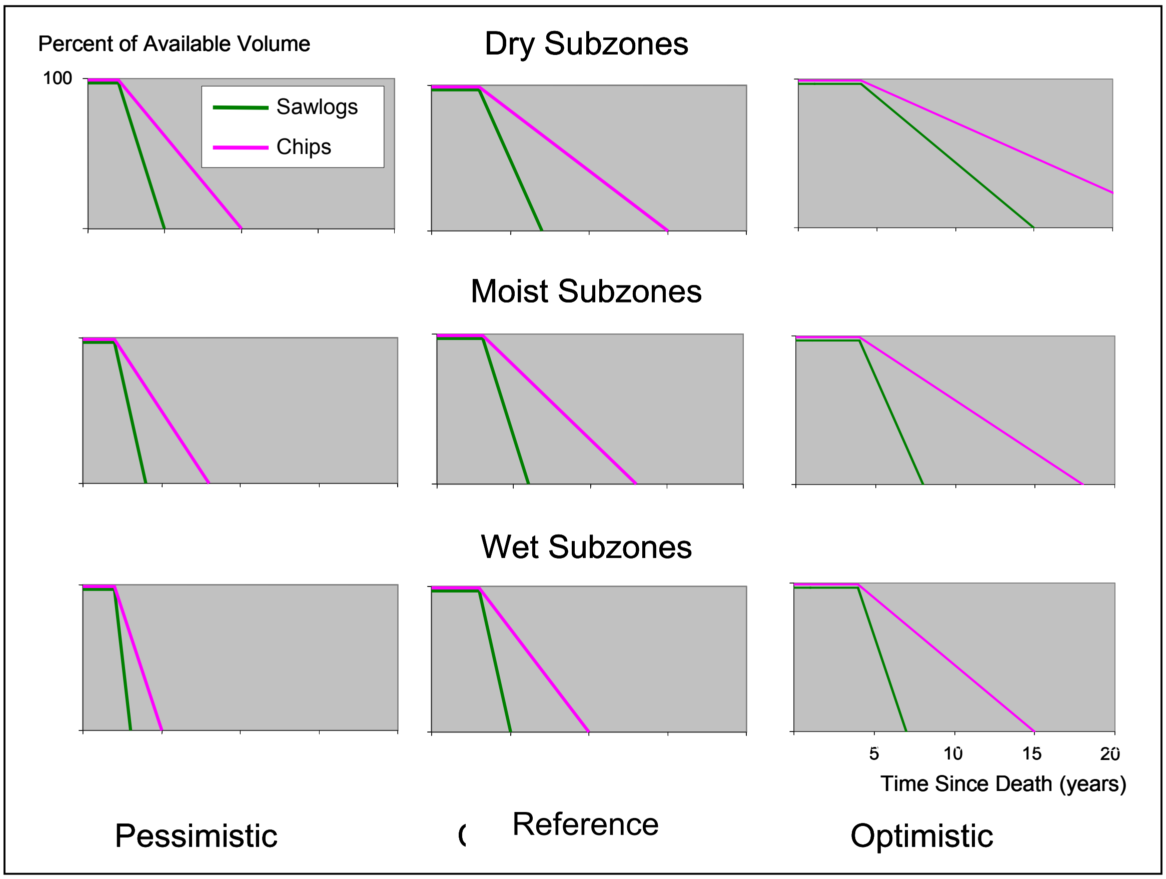

Figure 2. *Relationship between time since death and the amount of volume available for the sawlog and "alternative" (chip) industries in dry, moist and wet subzones under pessimistic, reference and optimistic assumptions.*

3.3.4 Sensitivity to assumptions about salvage priority

It is not completely clear how the forest industry will respond to the opportunity to salvage the beetle killed wood. Timber supply analyses model the salvage of dead wood using a harvest queue that sorts the stands starting with the highest percentage of pine (pure pine) and the highest percentage kill (100% kill). Stands are then "ordered" in decreasing percentage pine and percentage kill. It is assumed that the stand will be harvested in this order. However, achieving this harvest order given operational reality is not possible. Therefore, a minimum percentage pine and percentage kill that can be considered salvage is specified and the industry must operate "above" that minimum. It is conceivable that some licensees will, in fact, salvage the dead wood in the opposite order to that modeled in the timber supply review. That is, they will start with the stands with the minimum acceptable percentages of pine and dead wood.

We model three possible salvage priorities. In each case a stand can only be considered salvage if it has more than 50% pine and more than 50% of the pine has been killed. Stands must also have a minimum of 100 m^3 of live and dead wood suitable for dimensioned lumber production. The salvage priorities are:

1. Maximum dead volume. This is the priority used in the reference scenario and represents our attempt to model the assumptions used in timber supply analyses. The harvest model orders the acceptable salvage stands based on dead volume and starts with the highest dead volume stand, given other constraints such as the timber harvesting landbase and distance to roads.
2. Maximum live volume: This priority represents the "opposite" of the reference scenario. The model orders the acceptable salvage stands based on live volume in the stand and starts with the highest live volume stand.
3. Maximum total volume: This priority represents a "compromise" between the first two scenarios. The model orders the acceptable salvage stands based on the total volume, both live and dead, in the stand and starts with the highest total volume stand.

3.3.5 Implications of increasing harvest levels

One of the principal forest management tools available to the BC Ministry of Forests for dealing with the implications of the outbreak is the Allowable Annual Cut. In several management units harvest levels have been increased in an attempt to slow the progression of the outbreak. The harvest levels have also been increased in the Lakes, Prince George and Quesnel Timber Supply Areas to facilitate salvaging of the beetle killed wood. We model increases in harvest levels to examine the implications of doing so. The following harvest levels were examined:

- **Reference Scenario Harvest**. Based on AAC levels as of September 30, 2004. That is, levels prior to the expedited increases in the Lakes, Prince George and Quesnel Timber Supply Areas.
- **Expedited Harvest**: Based on AAC levels as of October 1, 2004. That is, levels including the expedited increases in the Lakes, Prince George and Quesnel Timber Supply Areas.
- **Up Now Harvest**: Expedited harvest levels plus increases in harvest levels in all other management units immediately. Increases in harvest level were based on the percentage of pine on the timber harvesting land base in the management unit plus a constant increase for all units:

  - New Harvest Level = Old Harvest Level + (Old Harvest Level (percent pine + 20%)
    This equation approximates uplifts considered for some management units, and results in a minimum increase of 32% in Robson Valley and a maximum increase of 74% in Williams Lake
- **Up Peak Harvest**: The increases in harvest were determined as in the previous case but, rather than increasing immediately, the increases were postponed until one year after the peak in annual kill in the management unit. This simulates postponing the increase until after there is no longer any attempt in the management unit to control the outbreak.
- **Up Peak Double Harvest**: The increases were timed as in the previous case but the amount that they were increased was doubled. That is a minimum increase of 64% in Robson Valley and a maximum increase of 158% in Williams Lake.

4.0 Results and Discussion

4.1 Forests at Risk to Mountain Pine Beetle

We estimate that in 1999, the "beginning" of the current outbreak, there were a total of 9.8 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)[2]. Of this, slightly less than one quarter was one of the five pine species found in the province (limber, lodgepole, western white, whitebark and Ponderosa pine; *Pinus flexilis, contorta, monticola, albicaulis*, or *ponderosa*, respectively). However, pine makes up 30% of the volume on the timber harvesting landbase, a much higher proportion than on the non-contributing landbase (18%) (Table 1).

Of the total pine volume in the province, approximately 1.8 billion m^3 is susceptible to mountain pine beetle attack (Table 2) by our definition (older than 60 years and in a 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 the current outbreak has not yet developed a significant coastal component. Of the 1.8 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	1.0	1.3	2.3
Other Species	4.3	3.3	7.5
Total	5.2	4.6	9.8

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	0.3	0.2	0.5
Yes	0.6	1.2	1.8
Total	1.0	1.3	2.3

The forested area of British Columbia is approximately 62 million hectares. Of that area 32 million hectares are in the Biogeoclimatic Zones that are climatically suitable for mountain pine beetles (see above). Forty six percent of the total

[2] Our volume and areas estimates are based on a combination of data sources, described in Eng (2004b).

forested area in the province contains some pine. In the susceptible BEC Zones 57% 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	Total
No Pine	8	6	14
With Pine	7	11	18
Total	15	17	32

The proportion of pine in forested stands varies significantly throughout the province (Table 4). Throughout the susceptible BEC Zones 36% of the pine is in forests with high percentages of pine (>=90%) but over 30% is in areas with less than 40% pine. These percentages are highly variable throughout the province (Table 4).

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%)	33%	69%	14%
Moderate (40% - 89%)	32%	25%	27%
High (90% - 100%)	36%	6%	58%
Total	100%	100%	100%

4.2 Volume and area affected by mountain pine beetle in 2004

Based on the provincial aerial overview surveys we estimate that a total of 280 million m^3 of pine have been killed by mountain pine beetle as of 2004. This estimate is for the "observable" (red) dead pine and does not include estimates of "green attack". Of that, 170 million m^3 were in the timber harvesting landbase (14% of the total susceptible volume). The area affected by mountain pine beetle is difficult to summarize because of variability in proportion of the pine that is affected in any given place. We estimate that more than 1 million hectares of forest were in an "incipient" stage of infestation (> 0 and <1% of the pine killed) in 2004. Approximately 7 million hectares had experienced more than 1% of the pine killed by 2004. This represents 40% of the area of susceptible pine. This estimate is much higher than the 5 million hectares estimated by the provincial aerial overview data in 2003 (Westfall 2004) because that estimate only includes the current annual attack. We consider the cumulative attack over all years. We also estimate more attacked area 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 (though it has no effect on the volume of the attack). According to our grid-based data, the total area with any mountain pine beetle infestation (including trace amounts [<1%]) in 2004 is more than 8 million hectares whereas the total area estimated by the 2004 aerial overview survey is 7 million hectares (Westfall 2004). The majority of susceptible pine forest had experienced some level of mortality by 2004 (Table 5). However, the amount of pine killed is highly variable throughout the province (Table 5, Figure 3). The major concentration of kill by mountain pine beetle in 2004 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 2004	All Susceptible Pine	Arrow TSA	Quesnel TSA
No kill	43%	48%	0.5%
>0 and <1%	9%	13%	0.2%
1 - 10 %	17%	18%	5%
11 - 30 %	13%	14%	30%
31 – 50%	8%	4%	30%
51 - 70 %	5%	1%	20%
71 - 100 %	5%	1%	15%
Total	100%	100%	100%

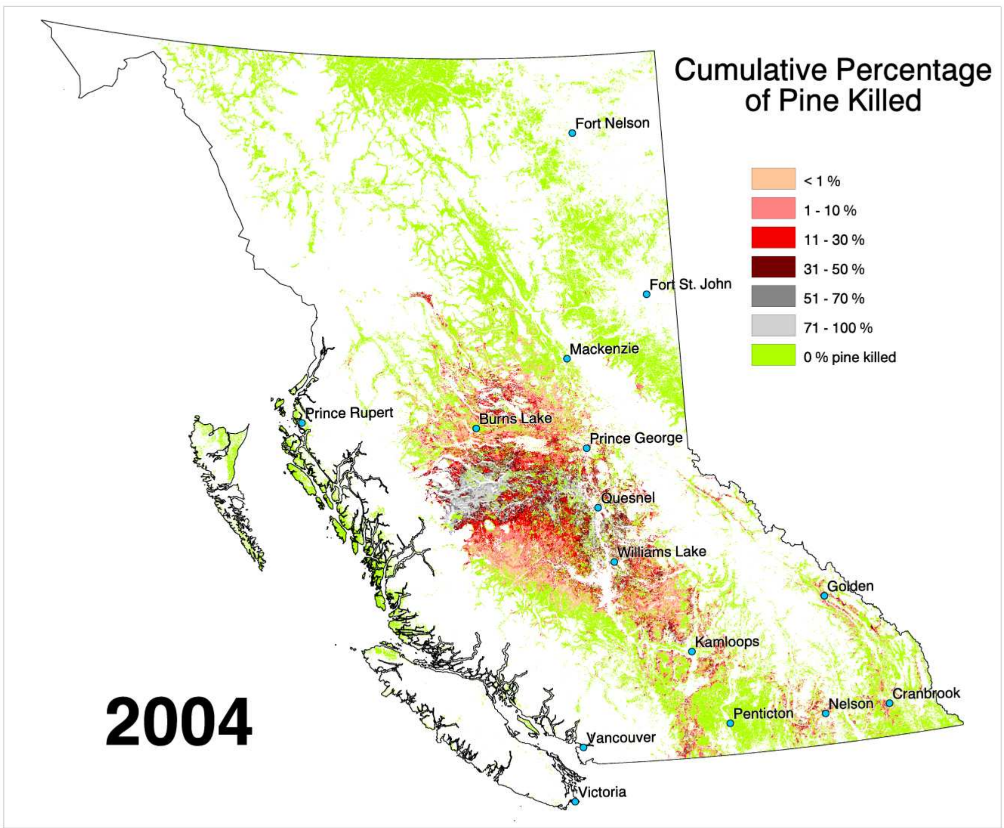

Figure 3. *Observed cumulative percentage of pine killed in 2004.*

(A high resolution (3 meg.) version of this figure is available at http://www.for.gov.bc.ca/hre/BCMPB/BCMPB_pctkill2004_Input.pdf)

4.3 Projection of the Reference Scenario.

We project that the annual volume of pine killed will peak during the 2006 flight at more than 90 million m^3 of merchantable pine in the timber harvesting landbase. The trees killed that summer will not be "observed" by the provincial aerial overview until the summer of 2007 (Figure 4). It is important to note that we also project that during 2006 we will harvest over 14 million m^3 of live pine as a "by-catch" of our efforts to control the outbreak and salvage dead timber. By the end of 2006 approximately 40% of the susceptible pine will have been killed or harvested. Over the next 6 or 7 years another 40% may be killed or harvested. We expect that 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).

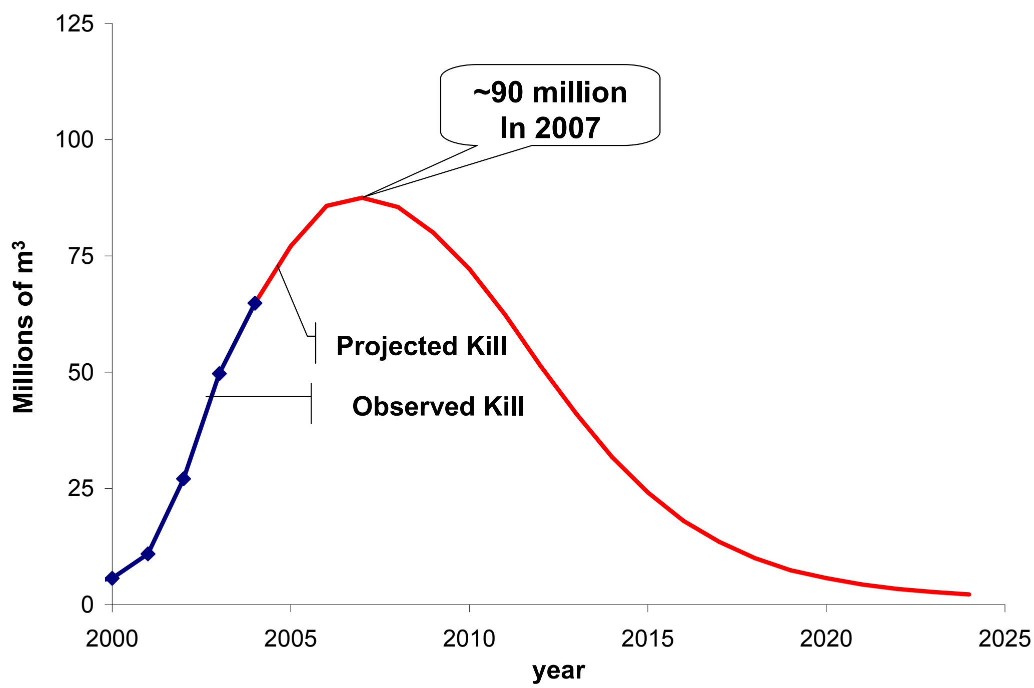

Figure 4. *Observed and Projected (for the Reference Scenario) Annual Volume of Pine Killed in the Timber Harvesting Landbase.*

We project substantial variability in the timing of the peak in annual kill in different areas of the province (Figure 5). Figure 5 shows the projected proportion of the pine that will be killed annually for each Timber Supply Area where more than 10% of the merchantable volume is susceptible pine. Note that the Prince George TSA is divided into its individual districts (Fort St. James, Prince George and Vanderhoof) because of the very large size of this TSA and the variability in amounts of kill throughout the area. The management units are listed on the right in descending order of the proportion of pine killed in 2004. Those units with the higher proportions of pine killed have an earlier peak in annual kill. Quesnel is already past the peak in annual kill (25% in 2003) but still has the highest proportion of pine killed in 2004 (15%). Vanderhoof is the only other unit that has passed the peak in annual kill. The Lakes TSA will experience 2 peaks in annual kill. One has already occurred in 2003 when a large proportion of the pine south of Ootsa Lake was killed. We project a second peak in annual kill in the Lakes TSA in 2006 when the areas of high volume pine in the west central portion of the TSA will be heavily infested.

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 occurrences 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.

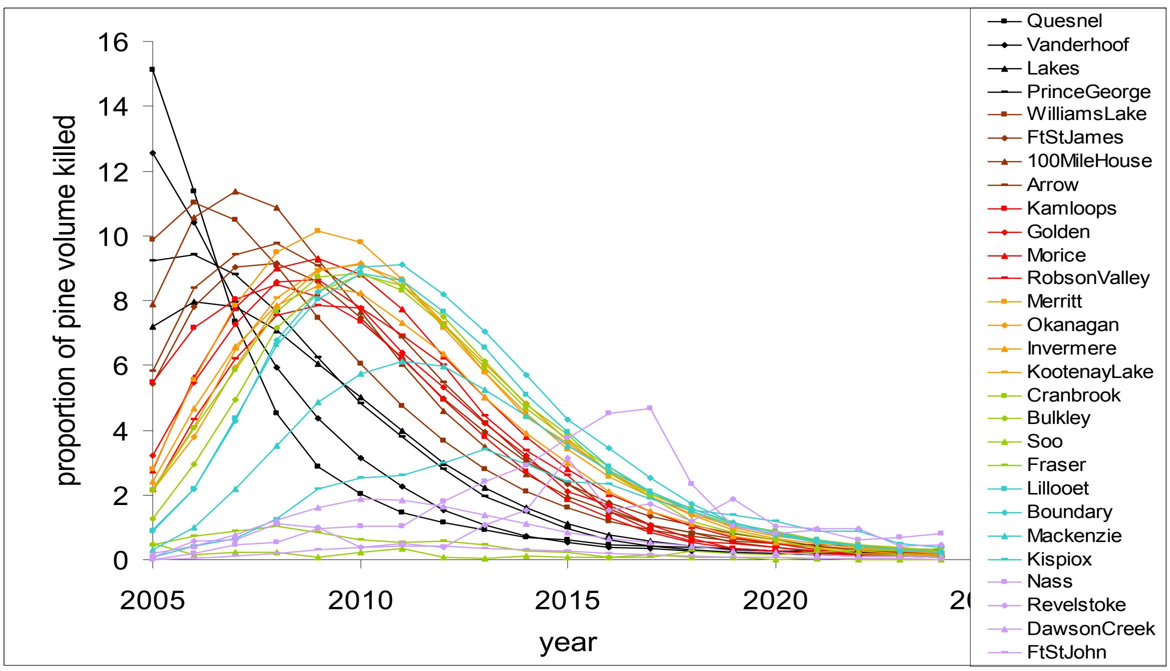

Figure 5. *Effect of initial proportion of volume killed on the progression of the outbreak.*

The Reference Scenario projects that over 95% of the susceptible pine on the timber harvesting landbase will be killed by 2024 (Figure 6). It should be noted that this is 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. We conducted sensitivity analyses to assess the implications of these two assumptions (described in Section 3.3.2 and reported in Section 4.5).

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. 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). Nonetheless, a brief survey of heavily infested stands near the center of the outbreak indicates that kill levels of 100% of the merchantable volume (>12.5 cm dbh) are not uncommon (Eng 2004d**Error! Reference source not found.**). Personal communications with BC Ministry of Forests district staff in Nadina, Quesnel and Vanderhoof districts corroborate these observations.

Despite the fact that all of the merchantable volume may be killed there are good biological reasons to expect that beetles will not kill all the 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 (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 more poorly 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 favourable for beetles. Whatever the explanation, it is reasonable to expect that stands thinned by previous beetle mortality are also less favourable for beetles.

By 2009, our model projects that 14 million ha of susceptible pine (92%) will have some level of infestation by mountain pine beetles and over 615 million m^3 of pine (~60%) on the timber harvesting landbase will have been killed (Figure 6).

That area will be distributed throughout the susceptible range with concentrations of current attack in the northern and southern portions (Figure 7).

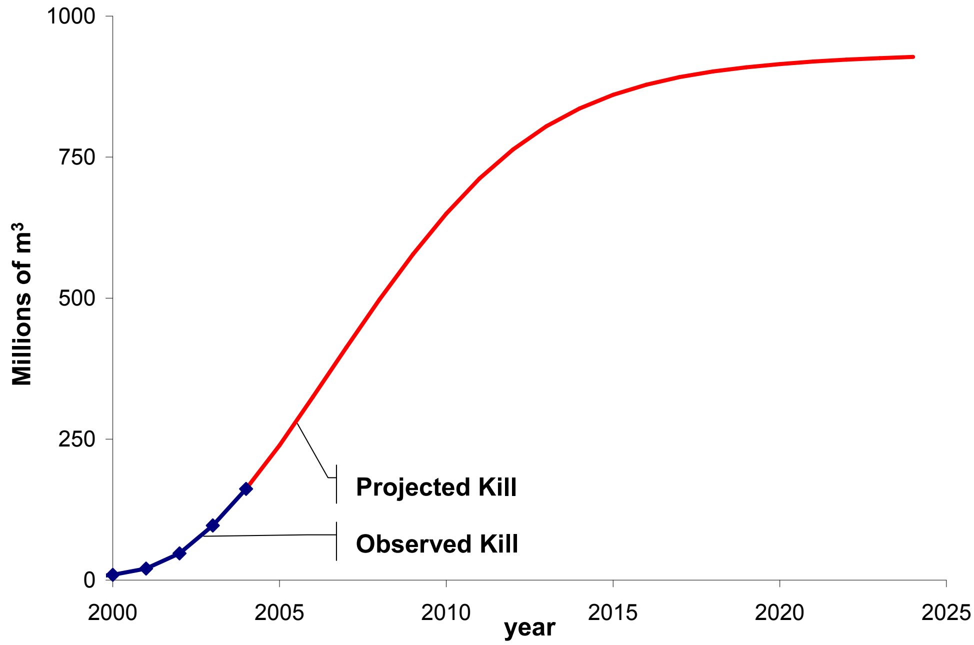

Figure 6. *Observed and projected (for the Reference Scenario) cumulative volume of pine killed in the timber harvesting landbase.*

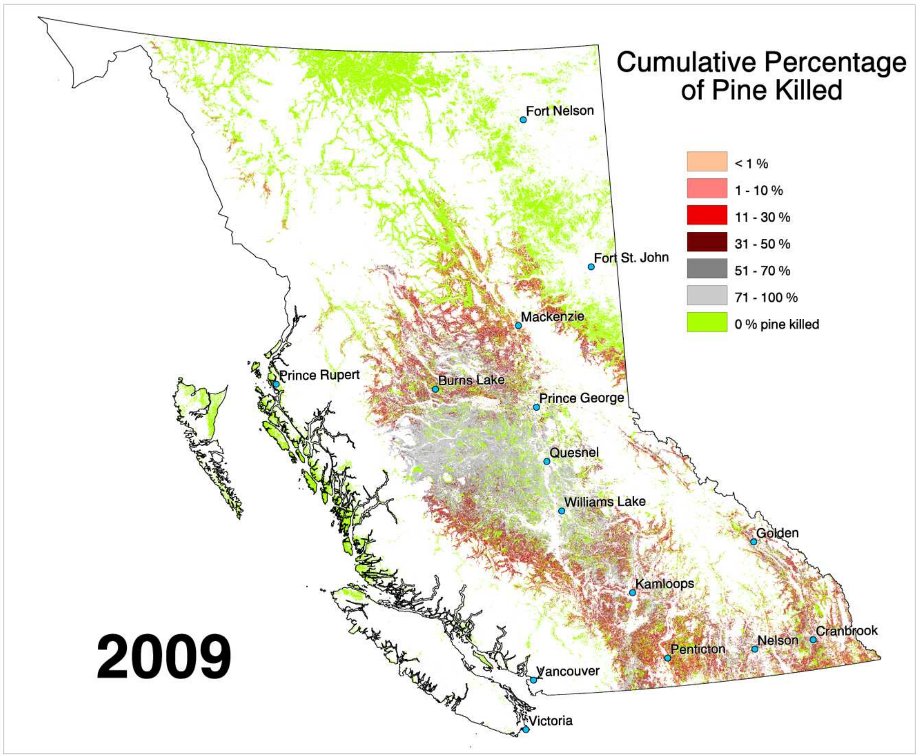

Figure 7. *Projected cumulative percentage of pine killed in 2009 under the Reference Scenario.*

(A high resolution (3 meg.) version of Figure 7 is available http://www.for.gov.bc.ca/hre/BCMPB/BCMPB_pctkill2009_Output.pdf)

4.4 Volume of Pine Harvested, Available and Lost under the Reference Scenario.

Figure 8 illustrates the effect of the mountain pine beetle outbreak and associated management activities on pine volume within the timber harvesting landbase for the 21 Timber Supply Areas where more than 10% of the volume on the timber harvesting landbase is susceptible pine (100 Mile House, Arrow, Boundary, Bulkley, Cranberry, Cranbrook, Dawson Creek, Golden, Invermere, Kamloops, Kootenay Lake, Lakes, Lillooet, Mackenzie, Merritt, Morice, Okanagan, Prince George, Quesnel, RobsonValley, Williams Lake).

As described in Section 3.1.2, we report on four categories of pine:

- Live pine: merchantable and susceptible pine that has not been killed by mountain pine beetles.
- Sawlogs: dead pine that has been killed recently enough that it is suitable for the manufacture of dimensioned lumber products.

- Chips: pine that has been dead long enough that it is no longer suitable for dimensioned lumber products but is still useable for "alternative" products such as pulp, oriented strand board or bio-fuel.
- NRL: Non-recovered loss. Pine that has been dead for so long that it is no longer useable even for alternative products.

In Figure 8 we present the volumes that are projected to be in each of these four categories through time, further subdivided into volumes that have been harvested and volumes that are still standing. Note that the "Logged NRL" category represents the volume of "residue" that will occur in harvested blocks. This is volume that will not be useable but must be logged because it will be intermixed with sawlog and chip volume. Note also that the Logged Chips are, effectively, a by-product of harvesting. As stated previously, we are modeling the traditional dimensioned lumber industry. The model is "looking for" sawlogs. The chips that it harvests are, again, intermixed with the sawlogs and live pine that are harvested. We do assume that the harvested chips will contribute to the target harvest level.

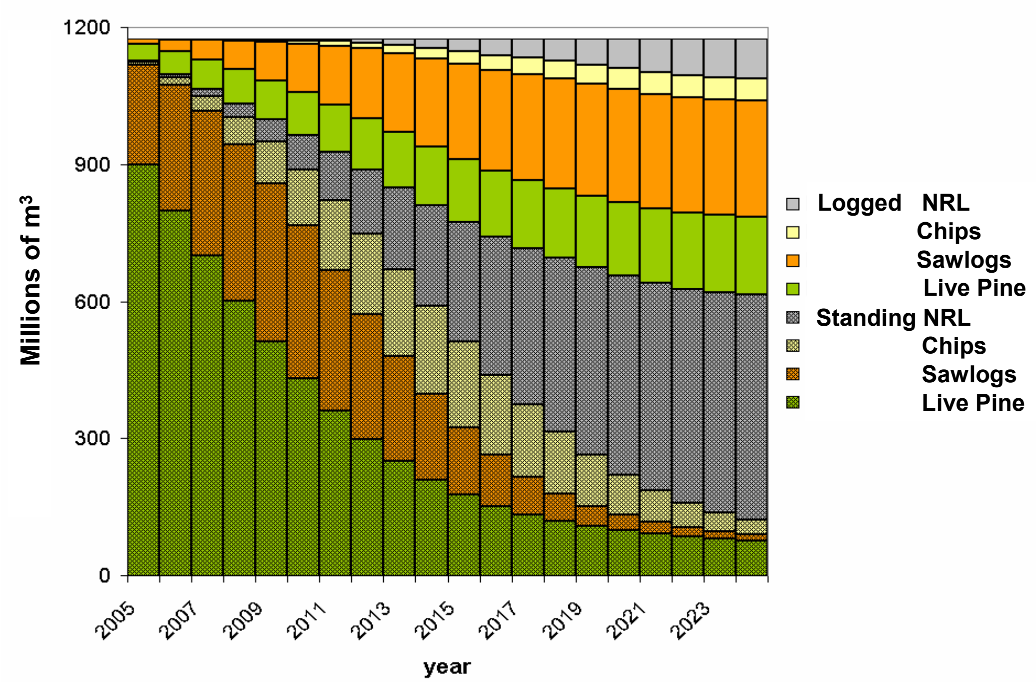

Figure 8. *Projected proportion of susceptible and merchantable pine volume on the timber harvesting landbase in various categories under the Reference Scenario.*

In 2005 we project that there will be 900 million m^3 of live pine and 230 million m^3 of standing dead pine of which 220 million m^3 will still be useable as sawlogs. By the end of the projection we estimate that there will be 80 million m^3 of live pine in the 21 TSAs and the combined standing and logged non-recovered losses will amount to 580 million m^3. The volume of available dead sawlogs will peak in 2009 at 350 million m^3 and will not fall below 100 million m^3 until 2017. The volume of available chip quality pine will not peak until 2104 at 190 million m^3 and will not drop below 100 million m^3 until 2020.

Over the next 20 years we estimate that the harvest in the 21 TSAs will consist of (in millions of m^3):

- Non pine: 490
- Live pine: 170
- Sawlog quality dead pine: 250
- Chip quality dead pine 50
- Dead pine residue (NRL) 90

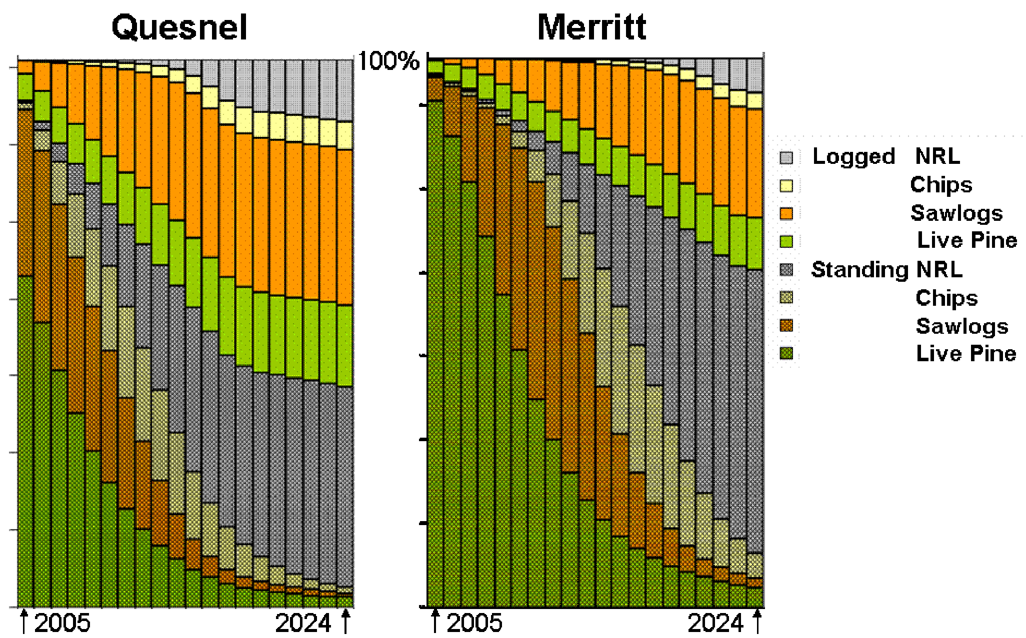

Figure 9 *Projected proportion of susceptible and merchantable pine volume on the timber harvesting landbase in various categories under the Reference Scenario in the Quesnel and Merritt TSAs.*

The general trend remains consistent throughout the province but the specifics vary substantially depending on the management unit examined (Figure 9). In Quesnel, because of the already advanced state of the outbreak, the peak in standing dead sawlogs occurs in 2006. This does not occur in Merritt, where the infestation is beginning, until 2011. In Quesnel we project that 70% of the pine volume would be lost under the pre-expedited harvest level and 60% will be lost under the expedited increase. In Merritt, under current harvest levels 60% of the pine volume will be non-recovered losses by 2024.

4.5 Sensitivity to assumptions about the end of the infestation

We made four sets of assumptions about the end of the infestation in addition to the reference scenario assumption (described in Section 3.3.2). These assumptions result in infestation trajectories shown in Figure 10.

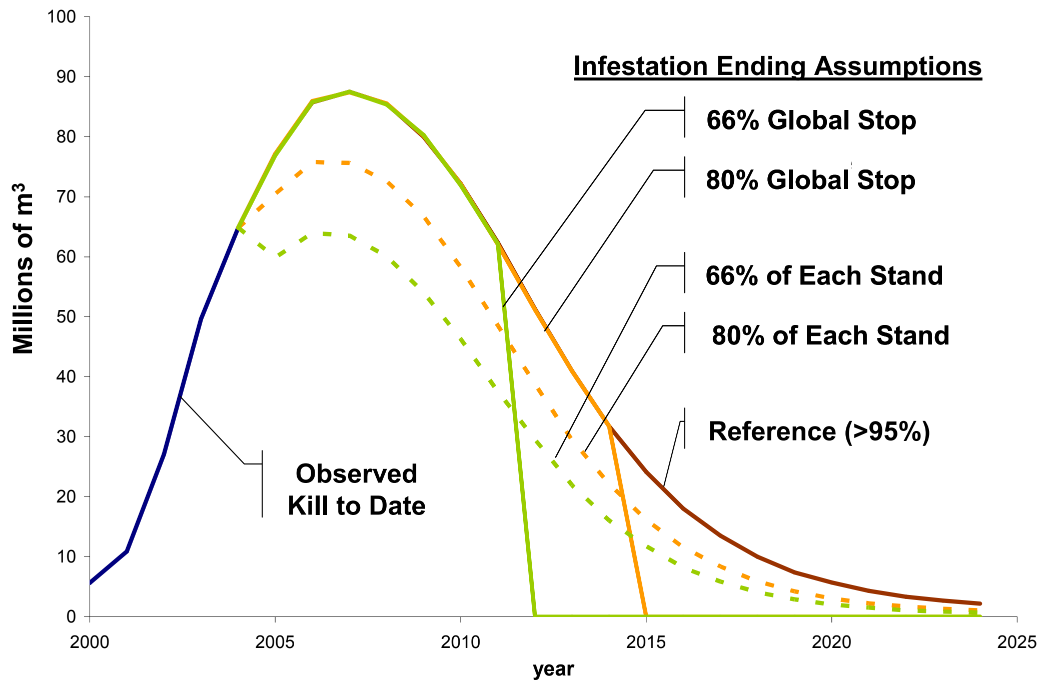

Figure 10. *Annual volume killed on the timber harvesting landbase under different assumptions about the end of the infestation.*

The results are simply an explicit consequence of the assumptions that were made. As discussed in some detail in Section 4.3, we have no way of actually knowing when the infestation will end or which of the five assumptions is most reasonable. We note that if we assume that, on average, only 66% of the pine volume in each stand will be killed, the result is that the infestation has to "slow down" in 2005 before increasing in intensity again. This is unreasonable behaviour and, therefore, the only other possibility that would make this assumption reasonable is that we have significantly over-estimated the observed kill to date, particularly in heavily infested areas. We have no indication that is so, and believe we can reject this assumption about the end of the infestation at a provincial scale. However, it is still possible that beetles will kill less at the periphery of the infestation. The "global stop" assumptions are modeled in a way that is too extreme. That is, we would not expect the infestation to completely end in one year. However, given the uncertainty about these assumptions modeling a more realistic global stop seems unwarranted, particularly given that it would have little or no impact on management conclusions.

The five different infestation assumptions have a dramatic impact on the levels of non-recovered losses anticipated to occur by 2024 (Figure 11). Total non-recovered losses differ by 200 million m^3 between the most optimistic and most pessimistic assumptions. However, if we reject the "66% of each stand" assumption as being unreasonable because of the behaviour it requires for the outbreak then the difference between the most optimistic and most pessimistic assumptions is only 100 million m^3. These conclusions are based on an examination of the state of the system at 2024. There is very little difference between the Reference scenario (>95% kill) and the "80% Global Stop" assumption at this time. However, non-recovered losses for both assumptions will continue to increase after 2024 and the difference between these two assumptions will also increase. There is very little difference in non-recovered losses among the different assumptions for at least ten years because under all assumptions substantial volumes continue to be killed for at least 7 more years and the reference scenario assumptions about shelf-life result in no losses of useable volume for 3 years after death.

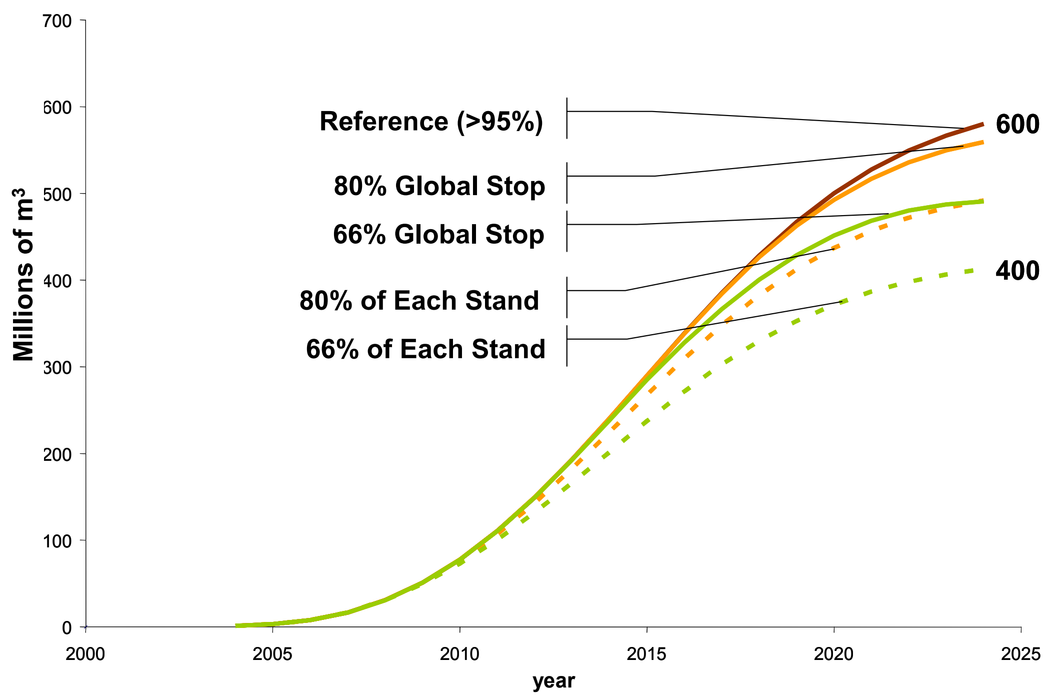

Figure 11. *Cumulative non-recovered losses under five different assumptions about the end of the infestation.*

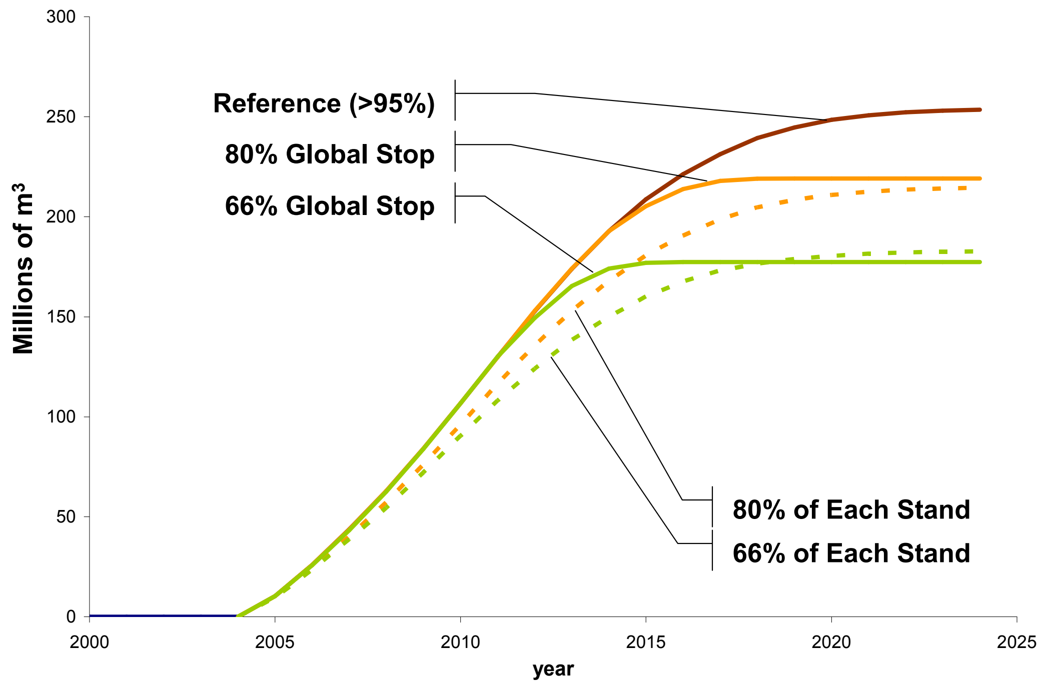

Figure 12. *Cumulative volume of dead sawlog quality pine harvested under different assumptions about the end of the infestation.*

If one assumes that the infestation will completely stop at some point (globally after 66% or 80% of the pine is killed) then the harvest of dead sawlog quality pine stops shortly after the infestation ends (Figure 12); no new dead sawlogs are being created and the existing ones have a relatively short shelf-life. However, if one assumes that the infestation continues but kills only a portion of each stand (66%, 80% or more than 95%) then the volume of dead sawlog quality pine that is harvested continues to increase, albeit slowly, near the end of the projection because new sawlog quality dead pine continues to be created.

A somewhat unexpected corollary is demonstrated by Figure 13. If the infestation stops abruptly, the amount of logged non-recovered loss (residue) is much lower than if the infestation continues to kill some amount of pine in each stand. The reason is that if the infestation stops abruptly then harvesting focuses entirely on salvage for some period, resulting in an increase in harvested non-recoverable losses (NRL) over the reference scenario. Harvesting then switches fairly rapidly from salvage to the harvest of live pine and non-pine stands as the dead pine deteriorates beyond usability as sawlogs. Once harvesting is concentrated on live pine and non-pine, the amount of logged non-recovered loss begins to level off although it does not end completely because there is still some dead pine mixed in with the live wood that must be dealt with. In contrast, if the infestation continues to kill pine at some level then opportunities for salvage continue to be generated. This results in a concomitant requirement to log non-recovered loss at relatively high levels because it is mixed in with the salvageable pine. Unexpectedly, the amount of logged non-recovered loss is higher if we assume that the infestation will kill on average 80% of pine in each stand rather than more than 95% of the pine. The reason is that if the infestation kills a lower proportion of the pine in a mixed stand then that stand is more likely to remain a viable harvesting opportunity once the model switches from salvaging to harvesting live volume. However, because there is a substantial harvest of mixed pine stands that have been affected there is a concomitant requirement to deal with the dead wood in those stands. If all, or almost all, of the pine in mixed stands is killed then those stands are more likely to be undesirable when the model switches to harvesting live wood. As a result, the non-recovered loss is simply left in the woods, at least in the short term (before 2024). On the other hand, if a maximum of 66% of each stand is killed, then even more mixed stands remain viable when the model switches from salvaging to harvesting live volume. However, such stands on average have lower levels of mortality and so not only is the proportion of non-recovered loss in each stand lower, but fewer stands need to be harvested to meet the harvest target.

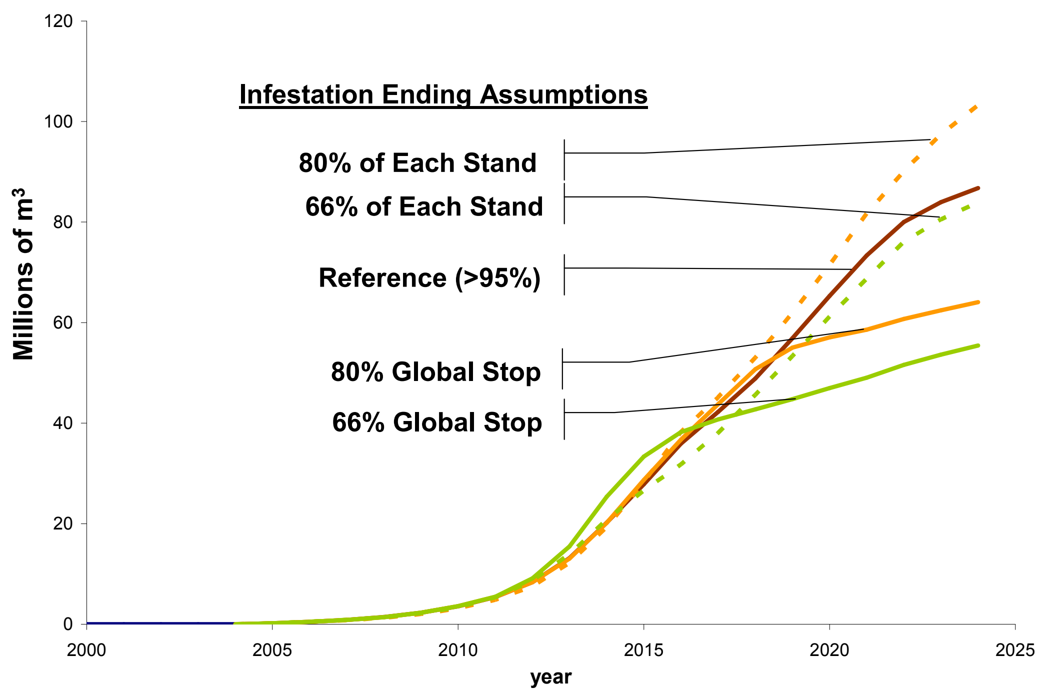

Figure 13. *Cumulative volume of logged non-recovered loss (residue) under different assumptions about the end of the infestation.*

4.6 Sensitivity to assumptions about shelf-life

As described in Section 3.3.3 we used the Thrower (2003) information to develop a “conservative” estimate of shelf-life for the reference scenario that is most applicable to the plateau ecosystems in central British Columbia where there is the highest volume of pine and where the outbreak is most intense. Given the significant uncertainty about shelf-life we also developed "pessimistic" and "optimistic" versions of the parameters derived from Thrower (2003).

The effect of shelf-life on cumulative non-recovered losses is shown in Figure 14. This sensitivity differs from the sensitivity to assumptions about the end of the infestation (Section 4.5) in that the different scenarios about shelf-life begin to diverge immediately. In 2005 there are already approximately 280 million m^3 of standing dead pine that is suitable for sawlogs. Much of that wood has been standing dead for long enough that it will begin to rapidly deteriorate in quality given pessimistic shelf life assumptions.

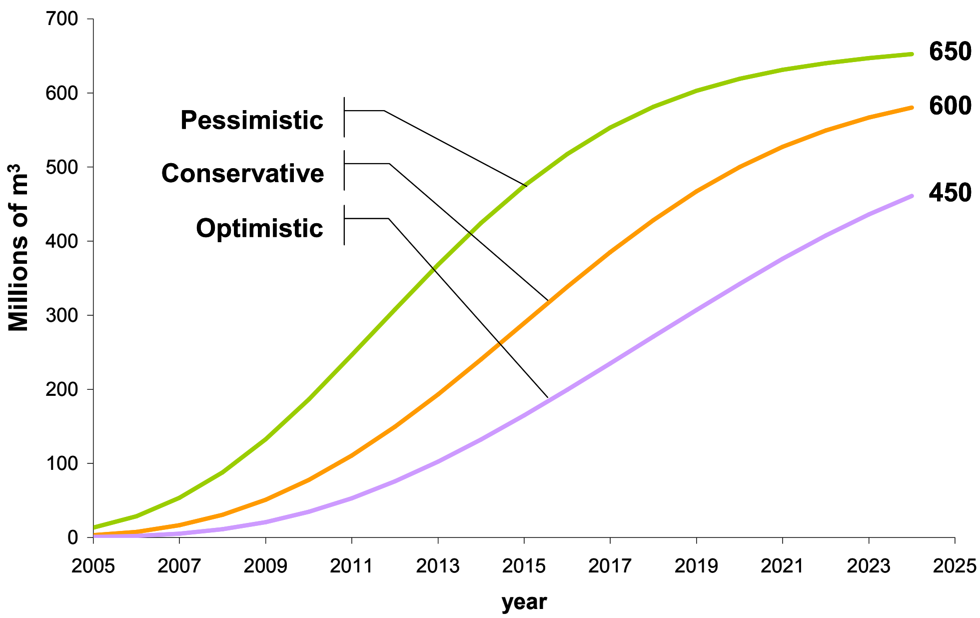

Figure 14. *Cumulative non-recovered losses under three sets of assumptions about the shelf-life of beetle killed pine.*

The differences between the pessimistic and optimistic assumptions about shelf-life are not symmetrical around the reference scenario (conservative assumptions). This is due solely to the optimistic assumptions about shelf-life in dry ecosystems. In those ecosystems we optimistically assume that the some wood will remain useable as sawlogs for up to 15 years. Note that the non-recovered losses under optimistic assumptions are continuing to rise at the end of the projection because there is still a substantial quantity of dead wood that has some value but is not being harvested rapidly enough. In the pessimistic scenario virtually all of the dead wood has completely deteriorated by 2024 and as a result non-recovered losses have begun to level off. The maximum difference between the two sets of assumptions is approximately 320 million m^3 and occurs in 2016 when large volumes of dead wood are still deteriorating under pessimistic shelf-life assumptions.

4.7 Sensitivity to assumptions about salvage priority

It is not entirely clear how the forest industry will respond to the opportunity to salvage beetle-killed wood. As described in Section 3.3.4, we model three different assumptions. In the reference scenario we assume that the industry will concentrate salvage activities in areas with the maximum dead volume. It is possible that some licensees will preferentially salvage in areas that meet the minimum criteria for salvage blocks (set here at 50% pine and 50% kill), thus maximizing the live volume harvested during salvage. A "compromise" scenario is one in which the industry maximizes the total volume (both live and dead) that is harvested. At a provincial scale the difference among these scenarios is relatively minor, amounting to only 50 million m^3 in non-recovered losses by 2024 (Figure 15). A similar impact on the amount of non-pine volume harvested occurs, rising from 500 million m^3 to 550 million m^3 (10%) provincially by 2024. However, this varies substantially throughout the province. In management units near the beginning of the infestation with many mixed pine stands there can be a much more dramatic impact on the amount of non-pine harvested. The Merritt TSA provides an instructive example (Figure 16).

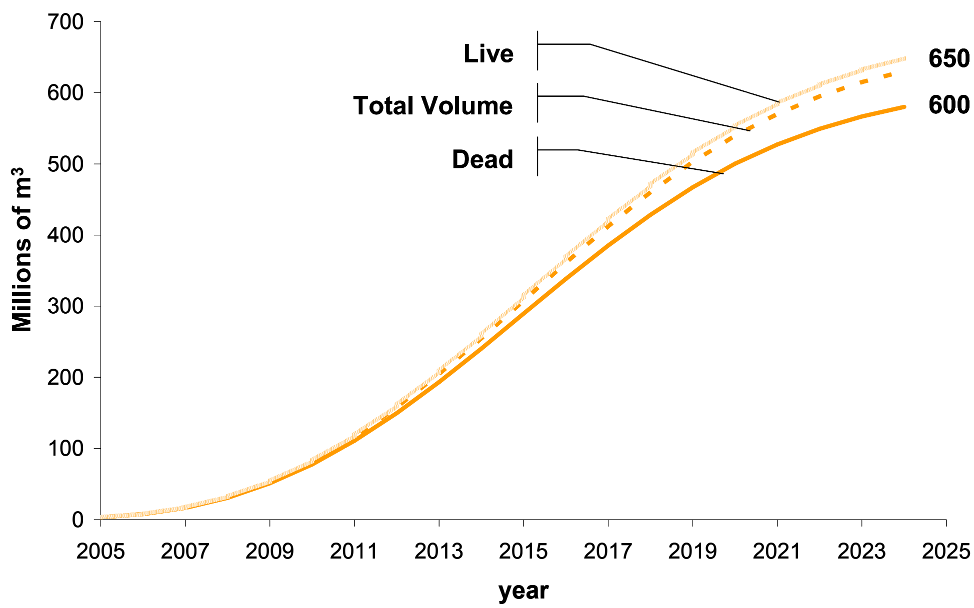

Figure 15. *Cumulative non-recovered losses under three different assumptions about salvage priority employed when harvesting.*

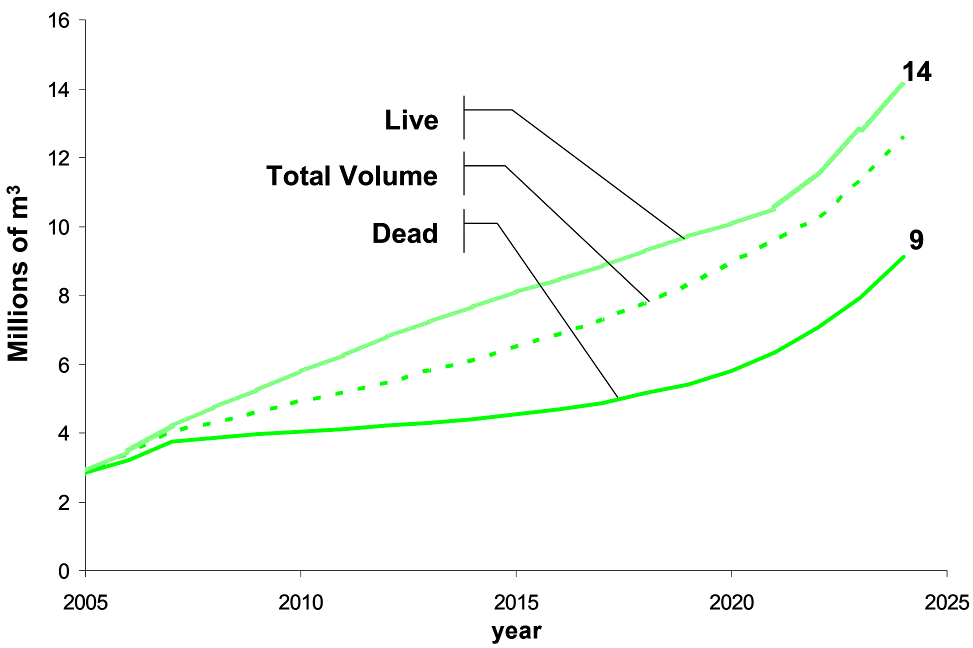

Figure 16. *Cumulative volume of non-pine species harvested in the Merritt TSA under three different assumptions about salvage priority employed when harvesting.*

4.8 Implications of alternative harvest levels

We examine the implications of various alternative harvest levels, as described in Section 3.3.5 in an attempt to illustrate the implications on a variety of indicators. It is important to understand that we are not recommending any of the alternative harvest levels nor do we have any expectation that any of the specific alternatives will come to pass.

Figure 17 shows the implications of increasing harvest levels on cumulative non-recovered losses. This figure shows several important implications other than the simple fact that increasing the harvest level decreases the non-recovered losses (by as much as 150 million m^3 given the alternatives we examined). The reference scenario has noticeably higher non-recovered losses than the harvest level that includes the expedited increases in AAC for the Lakes, Prince George and Quesnel TSAs. Note also that an immediate increase in the harvest level has the same effect on non-recovered losses as doubling the increase at the peak kill in each unit. The reason is that by increasing the harvest level now we harvest more live pine, primarily in an attempt to control the outbreak. If we wait until after the peak in annual kill in each unit then much of that pine that would have been killed will begin to deteriorate. In effect, we get behind in our salvaging efforts and we can't catch up because of the deterioration rate.

An important implication of increasing harvest levels is illustrated by a comparison of Figure 18 and Figure 17. For every 0.75 m^3 of non-recovered losses that are saved by increasing harvest levels we lose 1.0 m^3 of non-pine volume as an "incidental by-catch" of our attempt to ameliorate the non-recovered loss. The reason is that the majority of the susceptible pine occurs in stands where it is mixed with non-pine species (Table 4). By increasing our salvage efforts we also increase our harvest of non-pine volume.

Figure 18 also illustrates that around 2017 the harvest of non-pine species begins to increase dramatically under all harvest levels. Around this time most of the impact of the infestation has been felt for several years. Recall that 80% of the susceptible volume will be killed by 2013 or 2014. By 2017 most of that volume will no longer be useable as sawlogs. Harvesting will switch from salvage to the remaining non-pine volume.

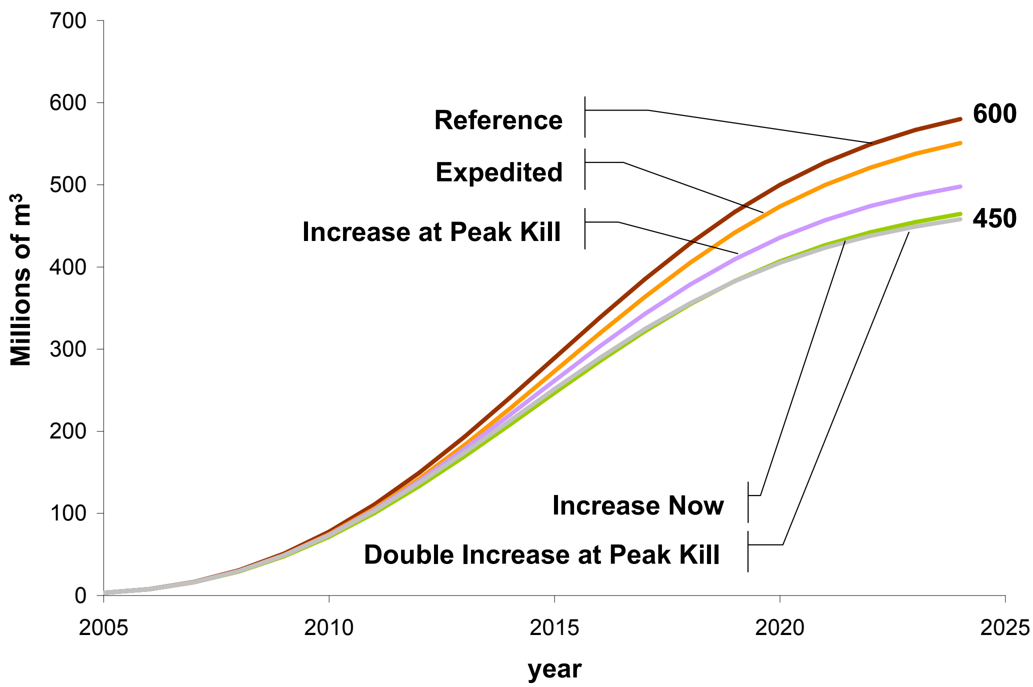

Figure 17. *Cumulative non-recovered losses under various alternative harvest levels.*

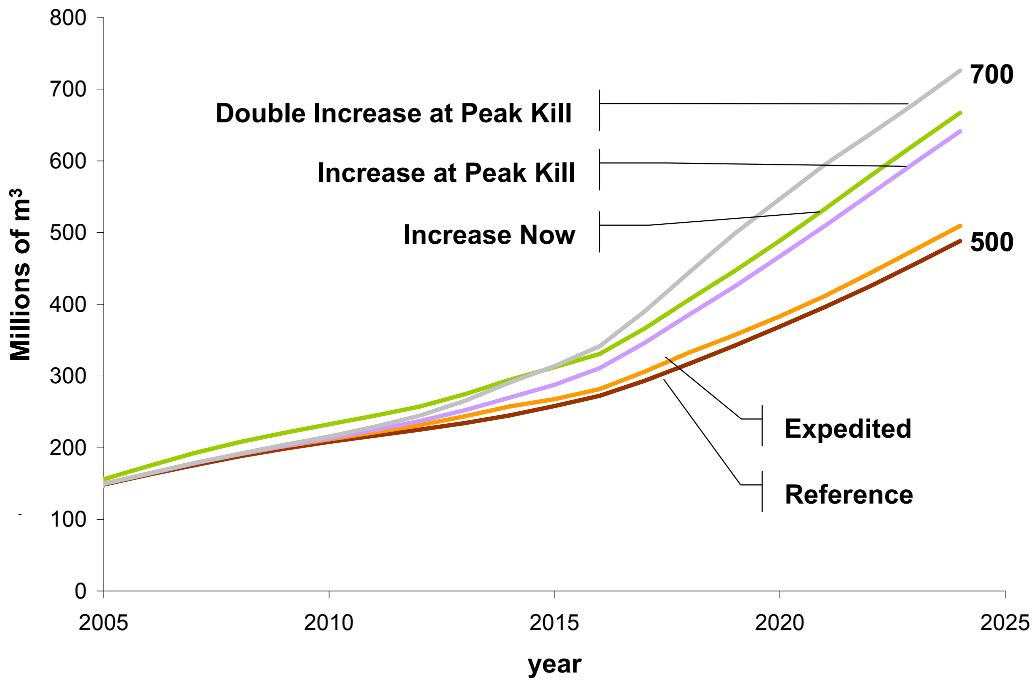

Figure 18. *Cumulative harvest of non-pine volume under various alternative harvest levels.*

4.9 Best and worst case scenarios

We modeled best and worst case scenarios with respect to non-recovered losses based on uncertainty about when the infestation will end, what the shelf-life of beetle killed wood will be and how the industry will respond to the opportunity to salvage the beetle killed wood. The specifications for these scenarios and the reference scenario are provided in Table 6. The results, with respect to non-recovered losses, are illustrated in Figure 19. Non-recovered losses differ by 400 million m^3 between the best and worst case scenarios. This difference is very asymmetrical with respect to the reference scenario. The best case projects that losses will be half the amount projected by the reference scenario whereas the worst case projects that losses will only be 100 million m^3 higher than the reference scenario. The reason for this asymmetry is partly a result of asymmetry in the shelf-life assumptions (as discussed in Section 4.6) and because the assumption about the infestation end in the best case scenario results in lower losses whereas the assumption about the infestation end in the worst is the same as in the reference scenario.

Table 6. *Specification of best and worst case scenarios for non-recovered losses.*

	Best-Case	Reference	Worst-Case
Shelf-Life	Optimistic	Conservative	Pessimistic
Salvage Priority	Dead Volume	Dead Volume	Live Volume
Infestation End	Stand Level 66% kill	>95% kill	>95% kill

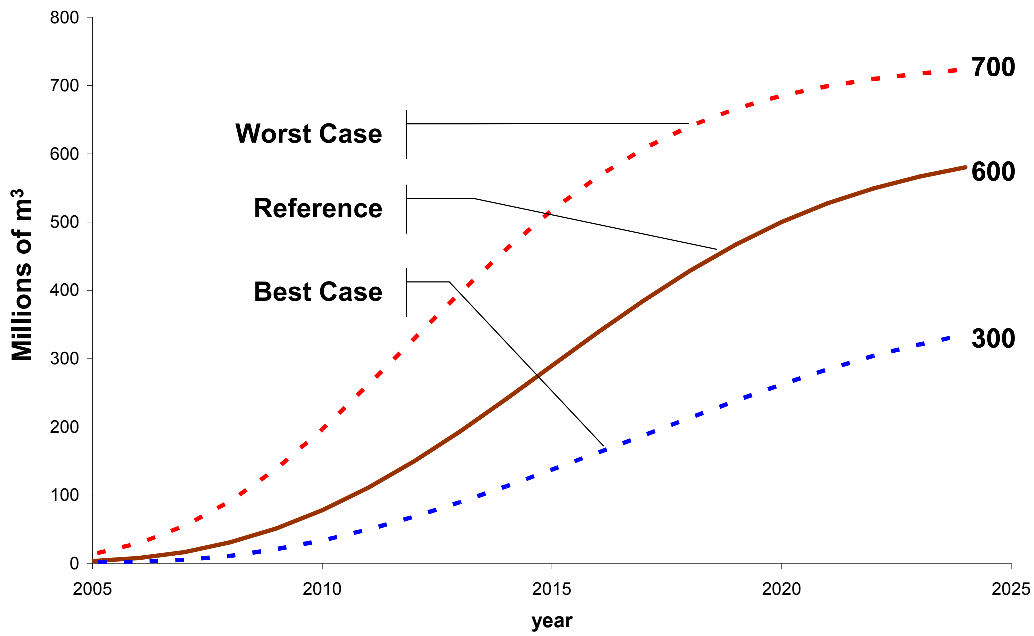

Figure 19. *Cumulative non-recovered losses under best-case, reference and worst-case scenarios.*

4.10 Implications for area harvested

Virtually all of the preceding discussion has been about indicators relevant to timber values (wood volume). Most other values (e.g., water quality, wildlife habitat, non-timber forest products) are more closely linked to the area harvested than the volume harvested. In general, as the area harvested increases there is a more significant negative impact on non-timber values.

Our model uses a more-or-less constant target for volume harvested over the projection period for all scenarios except those where the harvest target is explicitly increased (those scenarios discussed in Section 4.8). We modeled 17 separate scenarios where there was no explicit increase in the volume harvest target. On average, the area harvested by those scenarios in 2005 was 150 000 hectares. By 2013 the average area harvested had increased to 200 000 hectares (Figure 20). After 2013 the area harvested begins to decrease and by 2024 less than 150 000 hectares per year are being harvested. Area harvested changes over time because the volume per hectare harvested changes. During the first eight years of the projection the volume per hectare harvested is decreasing because there is an increasing amount of residue (logged non-recovered loss) in the stands. In order to meet the volume harvest target the model has to log additional area. After 2013 the harvesting begins to switch from salvage logging to logging non-pine volume. These areas generally have higher volumes per hectare than the areas with pine so the total harvested area begins to decrease. This effect on area harvested is not intended but it is rather a consequence of the constant volume harvest target and changes in the nature of the forest that is being harvested through time.

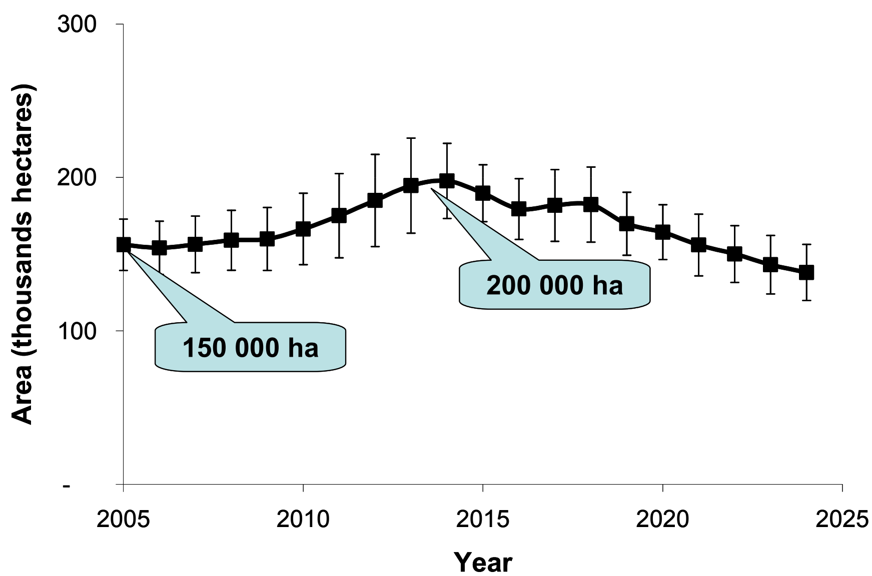

Figure 20. *Mean and standard deviation of annual area harvested in the 21 'pine' TSAs under 17 scenarios not involving explicit increases in harvest levels.*

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 known outbreak. 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 has been 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 spatial extent 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 analyses in Kamloops, Williams Lake, Morice and Lakes (Fall et al. 2001; 2002; 2003a; 2003b).

The model projects that the peak of the outbreak will occur in 2006 (detected by the provincial aerial overview in 2007) and the annual kill of pine volume, at that time, will be more than 90 million m^3 per year. We project that significant volumes (>25 million m^3 per year) 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 mortality within stands may not be as high as we project. We modeled various alternate scenarios about when the infestation might end. In addition to the obvious conclusions about the amount of dead pine that will be left on the landscape, the alternate scenarios have different implications with respect to forest management. If the infestation ends abruptly at some point in the future it will be much easier to deal with the consequences than if the infestation kills a lower proportion of the pine in each stand but continues to kill pine for the foreseeable future. We note significant differences in the amount of residue (logged non-recovered losses) that the forest industry will have to deal with under these two different possibilities. We should begin now to systematically assess the levels of mortality being caused by the outbreak in an attempt to distinguish between these two possibilities.

We modeled what appeared to be relatively small differences in the shelf-life of beetle killed wood. These differences had dramatic effects on the level of non-recovered losses. At the peak in difference between the optimistic and pessimistic assumptions about shelf-life (in 2016) the non-recovered losses differed by 150% (200 million m^3 with optimistic assumptions versus 500 million m^3 with pessimistic assumptions). Work is currently being funded by the Mountain Pine Beetle Initiative of the Canadian Forest Service to provide some better estimates of the biological and engineering/manufacturing aspects of shelf-life. That work may resolve some of this uncertainty. However, given that economic factors substantially contribute to the "realized" shelf-life, it is entirely conceivable that we will not "know" the shelf-life until after the infestation has subsided and the dead wood has been recovered.

Overall there is such significant uncertainty that estimates of provincial scale non-recovered losses by 2024 vary from 300 million m^3 in the best case to 700 million m^3 in the worst case. The amount of dead wood that will be available for harvest varies significantly in space and time. Decisions about forest management made at the management unit level can ameliorate non-recovered losses.

We observe that there is an unintended consequence of maintaining a constant volume based harvest target during the infestation. That is, if the volume harvested remains constant, the area harvested increases from 150 000 to 200 000 hectares per year over the first 8 years of the projection and then decreases again during the last 12 years of the projection to less than 150 000 hectares per year. Harvested area changes because the volume per hectare harvested first decreases as more of the dead pine becomes unusable (residue or non-recovered loss) and then increases as harvesting switches from salvage logging to the harvesting of non-pine volume.

During the next fiscal year (2005-2006) we intend to improve the model and continue to provide decision support at a provincial scale and management unit scales as appropriate. Improvements to the model will include incorporation of the results of research funded by the Mountain Pine Beetle Initiative of the Canadian Forest Service. At a minimum we hope to do the following:

- Incorporate the work that Dr. Allan Carroll has done under his project titled "Impacts of Climate Change on Range Expansion by the Mountain Pine Beetle". Significant collaboration between one of us (Bill Riel) and Dr. Carroll has allowed us to specifically design BCMPB to enable the incorporation of the spatially explicit climatic suitability surfaces being developed. This will begin in 2005-06 and be finalized in 2006-07.
- Improve some of the parameters related to the large-scale spatial dynamics of the outbreak using the work being conducted by Dr. Allan Carroll ancillary to his project investigating "MPB Outbreak Development: the Endemic-Incipient Transition". We will work closely with Dr. Carroll during 2005-06 to ensure that the work is appropriately incorporated.
- Improve some of the parameters related to macro-scale and meso-scale dispersal using the results of Dr. Peter Jackson's work under the project titled "Modeling of MPB Transport and Dispersion using Atmospheric Models". We have already incorporated the basic synoptic climatology work conducted by Dr. Jackson. Starting in 2005-06 and continuing through 2006-07 we intend to refine the synoptic climatology using a higher resolution re-analysis dataset. We also intend to incorporate parameters related to a process-oriented model describing interactions between wind and weather, local topography and the initiation of MPB outbreaks resulting from meso-scale dispersal.
- To the extent possible we will refine the parameters used in our shelf-life model by acquiring any available field data. We anticipate that one of the most important sources will be the shelf-life field work funded by the MPBI and the subsequent analysis of the data by Dr. Kathy Lewis under

the project titled “Investigating the Relationship between Timber Recovery, Quality and Time-since-death for Beetle-killed Stands”.

We also intend to significantly improve our base model data and the forest management model. We will:

- Obtain a new set of spatial data layers from the Land and Resource Data Warehouse. Our current data will be 3 years out of date this spring.
- Obtain a refined timber harvesting landbase for the province.
- Obtain data required to provide a more complete set of forest cover constraints for the management model. At a minimum we intend to include ungulate winter ranges as a constraint.
- Improve the harvest targets used in the model by modifying those targets based on more realistic assumptions about the changes in harvest targets that may occur over the projection period.
- Incorporate forest stewardship recommendations included in Eng (2004a) into the modeling environment. Importantly these recommendations include large cutblocks with high levels of retention.
- Attempt to realistically model the “alternative forest industry” that will emerge as a result of the issuing of forest licenses specifically targeted at salvage logging.

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