Application of the MPB/SELES Landscape-Scale Mountain Pine Beetle Model in the Lakes Timber Supply Area

Final Report
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Executive Summary
The Lakes Landscape Model (LLM) was developed to assess the impacts of mountain pine beetle management activities in Lakes Timber Supply Area and to analyze the potential spread of the current beetle outbreak across the TSA area. The model used the best current inputs available from inventory layers, weather data, and mountain pine beetle infestation maps. We calibrated the model by running experiments to assess model projections after estimating conditions 10 years ago at the start of the current outbreak.

A wide range of scenarios were run to assess the expected impacts of the current management regime and to test the sensitivity of the results to various management options and beetle growth rates. We assess three main types of effects:

(i) short term: area attacked and volume killed by beetles during current outbreak (our analysis was over 10 years).

(ii) medium term: volume salvaged and non-recovered loss expected during the outbreak, and the following decade after the outbreak is assumed to stop.

(iii) long term: timber supply impacts of the combination of the beetle outbreak and beetle management on sustainability of growing stock.
We considered two scenarios to form the base case: current beetle management using the AAC in the last determination (BM) and current beetle management using the current doubling of the AAC (BM_AAC200%). We then assessed how these scenarios compared with no beetle management and no management (no harvesting).

To assess sensitivity of results, we ran experiments varying the MPB growth rate, AAC level, forest cover constraints, detection of green attack, effect of fell and burn treatments, effect of including block size. These simulations were contrasted with the base case scenarios, no beetle management scenarios, and no harvesting scenarios.

In general, the model results predicted that beetle management in the Lakes TSA area will likely have a modest impact on the growth of the MPB outbreak over the next 10 years, and following timber losses, even with variations in the current management regime. The results only apply to the specific conditions (current forest inventory and beetle infestations) and management regimes run on the study area. Due to inherent uncertainties in all models, the results should be used to weigh the relative merits of the scenarios rather than as exact predictions. This document describes the objectives, methods and results of the LLM.
Introduction

The mountain pine beetle is the most destructive insect pest affecting the forest resource in British Columbia. Each year millions of mature pine trees are killed during epidemics of this insect. The magnitude of these losses creates havoc in the forest industry by disrupting the planning process. It forces the redirection of the allowable cut towards reducing the beetle population and salvaging beetle-killed timber.

Currently, a mountain pine beetle (MPB) epidemic is underway in the Lakes Forest District. Much of the effort of the district has been focused on dealing with this large outbreak, with emphasis on focussing resources towards having the most impact on the beetle while minimizing impacts on social and forest values. To provide information on expected projections of the outbreak using current best information on the landscape state and beetle and management behaviour, Forest Practices Branch determined that a model was required.

The core of the landscape model described in this document was developed largely with support from the B.C. Ministry of Forests for prior projects in Kamloops forest districts (Fall, et al. 2001), and has been applied and enhanced in a portion of the Lignum IFPA (Fall et. al. 2002). The mountain pine beetle models were derived with the expertise of Les Safranyik, Terry Shore and Bill Riel from Pacific Forestry Centre, Canadian Forest Service.

The general scope of the project involved inputting geographic, forest inventory, weather and mountain pine beetle infestation data for the study area into the system and projecting it forward using a landscape model to evaluate the course of the infestation, primarily in terms of area and volumes killed by the beetle. The beetle outbreak process proceeded with interactions between various management scenarios (e.g. no logging, no beetle management and approximations of the beetle management activities that are being conducted or considered). We cannot predict when the outbreak may end, but decided to artificially terminate it after 10 years to assess post-outbreak effects and long-term timber supply effects.

Through comparison of various scenarios, potential benefits of beetle management in terms of area infested and volume killed were identified. This information could be used to assess impacts directly, or could serve as input for further analysis of economic, social and/or ecological cost/benefits (e.g., by an economist or ecologist), although such analysis was not a direct part of this project.
Project Objectives

The main purpose of this study was to apply and refine a model methodology to evaluate the effectiveness of the district’s bark beetle management activities in reducing losses to the mountain pine beetle, and to analyze the potential spread of the beetle across the TSA.

Specifically, the goal of this project was to address three questions:

(i) What would be the likely range of impacts from the current beetle outbreak if no beetle management was undertaken (i.e. following assumptions in the recent timber supply review)?
(ii) What would be the likely range of impacts from the current beetle outbreak if the current beetle management activities continue, including the recent decision to temporarily increase the AAC?
(iii) What would be the likely range of impacts from the current beetle outbreak under a range of alternative beetle management regimes?

The goal was to start with the current conditions, and project likely outcomes under the various scenarios. The beetle outbreak terminates after 10 years, but the model may be run longer to assess the decay of killed merchantable wood over the following decade and long-term implications on growing stock and other timber supply indicators.

Methods

I. Overall Landscape Model Design

The following methodology describes the design for the Lakes TSA Landscape Model, which is a specific application of the SELES/MPBSim Mountain Pine Beetle Landscape Model. This covers a high level description of the model, including the state space and process sub-models.

The general design of LLM in terms of linkages between model state, landscape processes and output files is shown in Figure 1. For a description of the Spatial Timber Supply Model (STSM), which covers the main aspects of the harvesting, aging and inventory sub-models see (Fall 2002a).
Figure 1. Linkages between primary components of state (shown in the centre), model processes (shown in ovals) and output files (shown as grey drums).

Model State Space
All layers except where noted below, were derived using information from the current forest inventory on the Lakes TSA area.

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

(i) BEC: biogeoclimatic classification by variant.
(ii) Elevation: elevation in metres
Forest State: the forest is represented by the following layers:

(iii) AgeWith NSR: age in years with cells defined as not sufficiently restocked assigned appropriate negative ages representing time until regeneration.
(iv) ITG: inventory type group (leading and secondary species).
(v) Height and volume: derived from growth and yield tables.
(vi) Percent pine
(vii) Stand Density
(viii) SiteIndex: the site index (expected height in metres at 50 years). Since this is often provided with one decimal of accuracy, the STSM requires that the values in the SiteIndex layer are 10 times the actual site index.
(ix) AU: Analysis units represent sites with similar stand conditions, usually based at least on ITG, management history and SiteIndex.

MPB Population:

(x) MPB Population (beetles/cell): this includes an estimate of the initial beetles/cell derived from current infestation data.
(xi) Time since attack: years since last attack in cell.
(xii) MPB Susceptibility: computed according to the index developed by CFS (Shore, 1998)
(xiii) MPB Risk: computed by combining susceptibility with beetle locations (but using a different method than in Shore, 1998).

Harvest Availability:

(xiv) PotentialTreatmentType: The available forest is stratified into the type of treatment that would be applied if a harvest block were initiated at that cell. Valid treatments are discussed below.
(xv) SalvageableVolume: Amount of salvageable volume in various stages of post-disturbance (e.g. GreenAttack, RedAttack, 3rd year post-attack, etc.) to track standing dead volume that would either be salvaged or become non-recovered loss. There is no initial state for this information.

Timber harvesting landbase:

(xvi) THLB: the timber harvesting landbase is derived from the productive operable forests via a netdown process which removes forest for various reasons described in the recent timber supply review (B.C. Min. of Forests, 2001), but applied spatially. The majority of these remove entire cells (e.g. non-merchantable forest), but some may remove only portions of a cell (e.g. roads, riparian zones). Hence, the THLB is represented as a percentage of each cell that is in the THLB.
Management Zones: Some management zones are common to most analyses, while others are study-area specific. Each of these requires a legend file (in GRASS format). Zones used in the timber supply review for the Lakes TSA are:

(xvii) VQO: visual quality objective zones.
(xviii) Caribou: caribou management zones
(xix) IRM: integrated resource management zone
(xx) RMZ: resource management zones used to identify community watersheds
(xxi) BecBeo: overlay of biogeoclimatic zones and biodiversity emphasis options.
(xxii) LU: Landscape Units
(xxiii) ProductiveForest: each cell is classified as productive operable (2), productive inoperable (1) or non-productive/non-forested (0).

Management Parameters: A range of parameters and tables to set up the harvesting regime, including:

(xxiv) AAC: annual allowable cut
(xxv) BMUStrategies: beetle management unit strategies
(xxvi) minimum harvest age
(xxvii) management constraints
(xxviii) management preferences

Roads:

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

Stand Aging
This event increments stand age each time step, and updates the age class and seral stage information. This event is also responsible for changes to analysis units upon stand regeneration. The model does not model species shifts.

Inventory
This event performs an inventory analysis each time step. It tracks the amounts of forest above/below the thresholds specified for each constraint within the relevant zones, and determines which cells are available for harvest. For cells that are unavailable, it outputs information to determine which constraint(s) were responsible. For constraints for which recruitment is appropriate (e.g. min. old requirements), cells are recruited in order of age. Most harvest indicators do not influence model behaviour. One exception is the current block size distribution, which may influence the selection of block sizes.
Harvesting

This event performs forest harvesting in available cells. The basis of this model is the SELES spatial timber supply model (Fall 2002a), and is designed so that under conditions with no beetle outbreak, the model can be parameterized to match the results of the TSR analysis.

In general, this sub-model simulated the allocation of cutblocks (disturbance patches) as they initiate and spread across the landscape. Harvest rate (m$^3$/yr) along with volume per hectare (curves described volume for different types and ages of forest) were estimated from the recent Timber Supply Review analysis document (B.C. Min. of Forests, 2001). The annual allowable cut (AAC) and mean volume/ha determined the area logged and, in part, the number of cutblocks. The default cutblock size was up to 40-100ha, based on a spatial assessment of recent block sizes in the TSA. Cutblocks had to fall on eligible land (determined by the timber-harvesting land base, stand age, access, forest cover rules, and adjacency rules); location also reflected the economic and environmental differences (including distance to road, harvestable area in zone, and stand age) among eligible stands (table 2).

Table 2. Steps used to choose cutblocks in the logging sub-model.

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Limit harvesting disturbance to eligible land:</td>
</tr>
<tr>
<td></td>
<td>? the timber harvesting landbase;</td>
</tr>
<tr>
<td></td>
<td>? eligible zones (age class structure allows harvesting; status updated with each disturbance);</td>
</tr>
<tr>
<td></td>
<td>? areas within 2 km of an existing road;</td>
</tr>
<tr>
<td></td>
<td>? stands older than minimum harvest age;</td>
</tr>
<tr>
<td>2</td>
<td>Process cells in potential block type order described above.</td>
</tr>
<tr>
<td>3</td>
<td>Within each type, assign preference of new harvesting to each map cell based on</td>
</tr>
<tr>
<td></td>
<td>? stand age,</td>
</tr>
<tr>
<td></td>
<td>? potential block type (e.g. salvage opportunity for salvage cells, to increase probability of</td>
</tr>
<tr>
<td></td>
<td>selecting a cell in proportion to salvageable volume),</td>
</tr>
<tr>
<td></td>
<td>? distance to road (negative exponential distribution).</td>
</tr>
<tr>
<td>4</td>
<td>Select new cutblock location (first map cell to harvest) based on eligibility and probability:</td>
</tr>
<tr>
<td></td>
<td>? pick the size of the cutblock from a block size distribution;</td>
</tr>
<tr>
<td></td>
<td>? build a spur road from the cell to the nearest existing road cell.</td>
</tr>
<tr>
<td></td>
<td>? harvest the cell. Only clearcuts were modelled for all treatment types.</td>
</tr>
<tr>
<td></td>
<td>? update tracking variables (e.g. annual volume harvested and seral distribution for applicable</td>
</tr>
<tr>
<td></td>
<td>zones);</td>
</tr>
<tr>
<td></td>
<td>? reduce the area of THLB in the cell to account for new access roads and for within-block</td>
</tr>
<tr>
<td></td>
<td>development.</td>
</tr>
<tr>
<td></td>
<td>? Currently, the model assumes 90% effectiveness of killed beetles in a treated cell</td>
</tr>
<tr>
<td>5</td>
<td>Continue harvesting cutblock (spread to adjacent cells) based on eligibility until maximum</td>
</tr>
<tr>
<td></td>
<td>cutblock size is reached or until no more eligible, adjacent cells exist:</td>
</tr>
<tr>
<td></td>
<td>? update distance to road information</td>
</tr>
<tr>
<td></td>
<td>? harvest the cell (as above).</td>
</tr>
</tbody>
</table>
Beetle management was incorporated in the logging sub-model as a range of potential strategies for placing treatment blocks. Salvage opportunity, MPB susceptibility, MPB risk and detectable attacked stands may have formed part of the stand selection preference, capturing block level beetle management activities. The following general harvesting strategies were included in the model. Their relative importance was based on the beetle management activities carried out by Lakes TSA.

(i) *Beetle blocks* were applied in areas with significant detectable infested trees. A beetle block included adjacent high risk, high susceptibility and salvage areas.

(ii) *Salvage blocks* were applied in areas with significant detectable standing dead wood. A salvage block included adjacent high risk, high susceptibility and salvage areas.

(iii) *Risk blocks* were applied in areas with high risk of MPB attack. A risk block included adjacent high risk, high susceptibility and salvage areas.

(iv) *Susceptibility blocks* were applied in areas with high MPB susceptibility. A susceptibility block included adjacent high risk, high susceptibility and salvage areas.

(v) *Green-tree blocks* were placed outside the above areas, and blocks were cut using clear-cuts.

Generally, the treatments in a year were placed according to the order given above. That is, first all beetle blocks were treated; if there was AAC remaining then salvage blocks were treated, etc. Parameters could be varied to change this ordering. Success of treatments depended on area of application and tree characteristics, but model assumed 90% effectiveness for block treatments.

To apply the above order, at the start of each year every cell in the THLB was classified probabilistically (based on detection uncertainty and planning rules) into one of five potential block type categories based on the following:

(i) Beetle blocks: sufficient level of detectable green (year of attack) or red (one year after attack) trees (> 5 detectable trees). The default probability was 1% per detectable tree (i.e. 100% chance for ≥ 100 trees), but declined with distance from roads for distances > 1km.

(ii) Salvage block: cells that had a sufficient level of salvageable timber (≥ 25m³/ha).

(iii) Risk block: cells that had a sufficiently high-risk index (default: 1% chance per unit of risk, which ranges from 0 to 100%).

(iv) Susceptibility block: cells that had a sufficiently high susceptibility index (default: 1% chance per unit of susceptibility, which ranges from 0 to 100%).

(v) Green-tree block: all other cells.
Once a harvest block was initiated, it attempted to log adjacent cells until a chosen block size was reached or until the adjacent eligible area was exhausted (in which case, a smaller block was created).

The logging sub-model explicitly connected cutblocks to the main road network by adding a link from the first cell harvested in the block to the nearest existing road. It then updated a map that stored the distance from each cell to the nearest existing road. This feature permits estimation of the amount of road constructed under a given management regime.

**Fell and Burn Treatments**

These sub-models simulated fell and burn treatment methods (see technical specifications for details). These treatments are usually conducted by the Ministry of Forests, and were estimated to be a total of 250 ha per year. Fell and burn treatments are generally applied in inaccessible areas or areas with low beetle population sizes. These treatments were applied to individual cells, and the volume was not recovered (i.e. the volume was lost immediately as non-recoverable losses (NRL)). The model assumed 95% effectiveness of killed beetles in a treated cell.

**Mountain Pine Beetle Population Model**

The Bark Beetle Research Project at the Canadian Forest Service (CFS) research centre in Victoria has been developing models for predicting the spread and impact of mountain pine beetle infestations for a number of years. Over the past few years CFS bark beetle researchers have been collaborating with Dr. Andrew Fall to utilize the Spatially Explicit Landscape Event Simulator (SELES) landscape modelling tool to extend stand level CFS models to the landscape level.

The CFS stand level model projects expected development of a beetle outbreak in a stand of up to several hectares. Since the stand is not taken in the landscape context, there is no influence of incoming beetles from other stands. Methods were developed to scale from this model to the landscape. Conceptually, the landscape model runs the stand model in every cell of the landscape that has beetles. Since it is not feasible or desirable to do this through a direct link, the stand model is scaled by running it under a wide range of conditions, which produces a table where each row is of the form:

\[ \text{Condition} \rightarrow \text{Consequence} \]

Conditions refer to stand attributes (e.g. age, percentage of pine), outbreak status (e.g. number of attacking beetles), etc. Consequences refer to the effect of one year of attack under those conditions (e.g. number of dispersers and number of trees killed).
The landscape level model then applies this table in each cell of the landscape containing beetles. This approach provides the spatial context for an outbreak with dispersing beetles emigrating from source cells, and has the effect of increasing the beetle population in cells within a current outbreak, or starting an outbreak in a currently uninfested cell. The latter may result in expanding a current beetle spot, or starting a new spot.

In the landscape model, the flight period, including beetle dispersal and pheromone production and diffusion, is modelled as a spatial process. During attack, beetles kill pine trees, producing red trees (recently killed) and standing dead volume that may be salvaged by the logging sub-model. This model also tracks the loss of salvageable wood resulting from attack. Economic standing dead wood is a subset of ecological standing dead wood, since the latter contains non-merchantable snags. Hence salvageable wood “decays” at quite a fast rate (20% starting 3 years after attack), depending on the species.

II. Model Outputs

The primary model outputs relevant to this analysis are described below. In this analysis, we focus on the MPB outbreak, harvest report and growing stock indicators.

Forest State Indictors

**Age-Class Distribution**: Annual output of the number of hectares of productive forest in 10-year age classes (up to 400 years), stratified by the amount in the THLB and outside the THLB.

**Seral Stage Distribution**: Annual output of the number of hectares in various seral stages (young, mature, old) according to the biodiversity guidebook, stratified by BEC zone.

MPB Outbreak Indictors

**Summary**: Population size, volume killed (overall and in the THLB), number of trees killed, area attacked (annually and cumulative) and a range of verification indicators (e.g. number of long distance spots).

**Stratified by BMU**: Volume killed (overall and in the THLB) and area attacked (annually and cumulative).
Inventory Indictors

Growing Stock: Growing stock is the cubic metres of live forest in various stratifications of the landbase, and is a primary indicator of sustainability. The growing stock is output in the following classes:
- overall
- in the timber harvesting landbase (THLB)
- in cells older than the minimum harvest age in the THLB
- in cells available for harvesting according to the constraints

Limiting Constraints: Track the area of forest made unavailable for harvest according to the various constraints. This is output as net and gross values, where the net value is the incremental area constrained after preceding constraints have been accounted for, and the gross value is the total amount the would be constrained independent of the other constraints. The primary order of constraints applied is:
- minimum harvest age
- road access (if enabled)
- adjacency
- partial harvest reentry interval
- forest cover constraints (applied in order specified in input file)

Harvest Indictors

Harvest Report: A range of output values that track key aspects of the harvesting process. All are means across the period
- annual volume harvested
- area treated (which equals the area harvested plus the area retained)
- area harvested
- area retained
- mean age harvested
- percent of harvest target achieved
- volume per hectare harvested
- harvest profile in terms of the proportion of harvested stands by leading species in the inventory type groups
- area and volume accounted for as non-recovered loss
- volume salvaged
- estimated non-recovered loss of unsalvaged beetle-killed wood.
- amount of available salvageable wood.
- area harvested by the various treatment types (i.e. beetle blocks, salvage blocks, etc.)
- number of beetles removed by the various treatment types.
**Road Report:** Indicators tracking the amount of spur road created during harvest and the number of stream crossings, based on an estimate of stream classes derived from the elevation layer and a hydrological flow model.

**Spatial output**
The LLM is a spatial model, and any of the spatial dynamic layers could be output during a model run. However, since multiple replicates of each scenario are run, it would be difficult to process such information post-simulation. Additionally, we needed to consider how to deal with the temporal aspect. The aspatial indicators described above summarize information across space, providing time-series information (which we then average over replicates or sum up across time as well). We designed the model to track several cumulative spatial indicators that summarize information across time and replicate:

(i) *TimesAttacked:* is the number of runs in which each 1 ha cell was attacked at least once by beetles. If a cell was attacked in every simulation it received a value of 10. If a cell was attacked in only one simulation it received a value of 1, and so forth. These values can be roughly thought of as the probability that a cell will be attacked by beetles at some point in the 10-year horizon.

(ii) *THLBVolumeKilled:* is the total volume killed in the THLB over the time horizon of the run. This layer provides information on the areas of the landscape that are likely to have the highest impacts in terms of volume killed (timber impacts).

(iii) *PercentPineKilled:* is the percentage of pine killed summed over the time horizon of the run. This layer provides information on the areas of the landscape that are likely to have the higher ecological impacts.

(iv) *YearAttacked:* is the first year attacked in the run. This layer provides information on how the main front of the beetle outbreak will spread across the landscape.

**III. Scenarios Evaluated**
A wide range of scenarios were run to verify the model prior to making the main scenarios described below. These verification scenarios led to model improvements and refinements, as well as greater understanding of the model interactions and feedback. We don’t describe the results of the verification runs here, and instead focus on scenarios that produced information relevant for more operational MPB management at the district level and overall strategic planning at the provincial level.

There are a number of stochastic factors in the LLM, primarily affecting dispersal due to wind and cells selected by beetles. We ran all scenarios for 10 replicates so that we can report means and standard errors. In addition, we compared the results
of volume losses for the base scenarios using a Tukey’s HSD test at (α = 0.05) to determine significant differences in predictions.

**Calibration Scenarios**

Due to variations in the way historical outbreak information has been collected, it is difficult to apply infestation history information to calibrate and parameterize the beetle model. However, we do know the approximate location and year in which the present outbreak started. The purpose of these scenarios is to run the LLM from an estimate of the landscape conditions at the start of the outbreak to assess how the projections compare with current infestation data. We only present here the results of the final calibration scenarios.

We estimated the landscape conditions in 1991 by “standing up” cells currently less than 10 years old (by assigning the age and stand density of the nearest unharvested neighbour at the patch boundary). We then created a 1,000ha “origin” patch outside the TSA in Tweedsmuir Park on the north side of Eutsuk Lake. We don’t have inventory information for Tweedsmuir, and the only purpose of this origin patch was to provide a source of long-distance dispersers during flight period (at a rate of 10,000 dispersers per ha in the origin patch per year). There are no beetles in the TSA at initiation.

We ran two scenarios, both for 10 years (1991-2001). In the first, external dispersers from the origin patch continue for the entire horizon, and in the second, we stop the external dispersers after five years.

<table>
<thead>
<tr>
<th>Scenario Name</th>
<th>Management Type</th>
<th>Time period for external dispersers from origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Origin10</td>
<td>No Harvesting</td>
<td>10 years</td>
</tr>
<tr>
<td>Origin5</td>
<td>No Harvesting</td>
<td>5 years</td>
</tr>
</tbody>
</table>

**Base Scenarios**

The base scenarios are designed to address the primary questions of this analysis regarding the expected impact of beetle management. We consider there to be two “current management” regimes: both applying current beetle management but one with the AAC level from the last determination and the second using the raised AAC level. We compare these two scenarios with a no harvesting scenario and two no beetle management scenarios (i.e. applying only the rules from the timber supply review analysis, with the exception that we don’t apply the Chelaslie partition which is a coarse form of beetle management).

We call the NoMgmt, BM and TSR scenarios the “base” scenarios.
<table>
<thead>
<tr>
<th>Scenario Name</th>
<th>Management Type</th>
<th>AAC (as a percent of TSR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NoMgmt</td>
<td>No Harvesting</td>
<td>N/A</td>
</tr>
<tr>
<td>BM</td>
<td>Beetle Management</td>
<td>100%</td>
</tr>
<tr>
<td>BM_AAC200</td>
<td>Beetle Management</td>
<td>200%</td>
</tr>
<tr>
<td>TSR</td>
<td>No Beetle Management</td>
<td>100%</td>
</tr>
<tr>
<td>TSR_AAC200</td>
<td>No Beetle Management</td>
<td>200%</td>
</tr>
</tbody>
</table>

**Beetle Growth Rate Sensitivity**

There is substantial uncertainty regarding the appropriate growth rate of the beetle population. The calibration scenario allowed us to objectively determine beetle growth and dispersal parameters consistent with the growth of the outbreak over the last decade. These scenarios, however, are designed to assess the sensitivity of the model results if the MPB growth rate was higher or lower than the expected level.

<table>
<thead>
<tr>
<th>Scenario Name</th>
<th>Base Scenario</th>
<th>MPB Growth Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>NoMgmt_Low</td>
<td>NoMgmt</td>
<td>Low</td>
</tr>
<tr>
<td>NoMgmt_High</td>
<td>NoMgmt</td>
<td>High</td>
</tr>
<tr>
<td>BM_Low</td>
<td>BM</td>
<td>Low</td>
</tr>
<tr>
<td>BM_High</td>
<td>BM</td>
<td>High</td>
</tr>
<tr>
<td>BM_AAC200Low</td>
<td>BM_AAC200</td>
<td>Low</td>
</tr>
<tr>
<td>BM_AAC200High</td>
<td>BM_AAC200</td>
<td>High</td>
</tr>
</tbody>
</table>

**AAC Level Sensitivity**

One of the main tools for beetle management is the AAC, since it determines the potential extent of management actions in terms of area treated. The base case scenarios already assess the effect of doubling the AAC from the level from the last AAC determination (i.e. the currently applied level). This scenario assesses the impact of increasing the AAC by a factor of 10 to explore how much harvesting might be required to control the outbreak.

<table>
<thead>
<tr>
<th>Scenario Name</th>
<th>Base Scenario</th>
<th>AAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM_AAC1000</td>
<td>BM</td>
<td>1000% (10 times TSR level)</td>
</tr>
</tbody>
</table>

**Management Option Sensitivity**

These scenarios were designed to assess the relative impact of various options for beetle management. Some, but not all, were applied at both AAC levels from the base scenarios. Generally, the model assumes the ability to detect red attack (i.e. one year post-attack). Enabling green attack detection permits the harvesting sub-model to detect trees killed in the current year.
The salvage only scenarios focus management on salvage operations, with no
direct preference for beetle spots (beetle blocks or high risk stands). The risk
focus scenarios change the preference ordering for selecting stands for harvesting
to place a higher priority on high risk cells than salvage cells.

The no Fell and Burn scenario disabled fell and burn treatments to assess the
contribution of fell and burn treatments to the management impacts on the
outbreak. The no forest policy scenario disables forest cover constraints (e.g. old
growth requirements, visual quality objectives, etc.) to assess the degree to which
forest policy limits the ability for management to address the outbreak. The no
BMU scenarios assess the effect of turning off the beetle management unit
strategies. The single cell scenarios assess the effect of applying small treatments
instead of 40-100 ha blocks used in the base scenarios.

<table>
<thead>
<tr>
<th>Scenario Name</th>
<th>Base Scenario</th>
<th>Management Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMGreenAttack</td>
<td>BM</td>
<td>Enable detection of green attack trees</td>
</tr>
<tr>
<td>BMGreenAttack_AAC200</td>
<td>BM_AAC200</td>
<td>Enable detection of green attack trees</td>
</tr>
<tr>
<td>BMSalvage</td>
<td>BM</td>
<td>Focus on salvage only</td>
</tr>
<tr>
<td>BMSalvage_AAC200</td>
<td>BM_AAC200</td>
<td>Focus on salvage only</td>
</tr>
<tr>
<td>BM_Risk</td>
<td>BM</td>
<td>Focus on risk before salvage</td>
</tr>
<tr>
<td>BM_Risk_AAC200</td>
<td>BM_AAC200</td>
<td>Focus on risk before salvage</td>
</tr>
<tr>
<td>BM_NoForPol</td>
<td>BM</td>
<td>Disable fell and burn treatments</td>
</tr>
<tr>
<td>BM_NoBMUs</td>
<td>BM</td>
<td>Disable forest policy (cover constraints)</td>
</tr>
<tr>
<td>BM_SingleCell</td>
<td>BM</td>
<td>Don’t apply beetle management unit strategies</td>
</tr>
<tr>
<td>BM_AAC200SingleCell</td>
<td>BM_AAC200</td>
<td>Apply harvesting as single hectare blocks</td>
</tr>
</tbody>
</table>

No Beetle Scenarios

To understand the timber supply implications of the model projections we first
need to assess conditions without beetles. In (Fall 2002c) we calibrated the LLM
to match the timber supply review analysis results, and we analyzed the effect of
applying spatial effects (i.e. spatial blocks; road access constraints) and an annual
vs. decadal time step. We ran the following scenarios that model the suite of
effects in the TSR and BM scenarios, but with no outbreak.

<table>
<thead>
<tr>
<th>Scenario Name</th>
<th>Base Scenario</th>
<th>AAC (as a percent of TSR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMnoMPB</td>
<td>BM</td>
<td>100%</td>
</tr>
<tr>
<td>BMnoMPB_AAC200</td>
<td>BM</td>
<td>200%</td>
</tr>
<tr>
<td>TSRnoMPB</td>
<td>TSR</td>
<td>100%</td>
</tr>
<tr>
<td>TSRnoMPB_AAC200</td>
<td>TSR</td>
<td>200%</td>
</tr>
</tbody>
</table>
Results and Discussion

All results reported graphically are the mean and standard error of 10 replicate simulations of each scenario.

Calibration Result

The following table summarizes the results of the origin experiments in comparison with the estimated area of attack and mean volume killed in the first year of the main model runs (initial2001). Although we cannot compare these values statistically, the area attacked seems reasonable (with a slight underestimation).

Table 1. Comparison of cumulative area and volume killed, and volume killed in final year of run in the two origin experiments in comparison with the estimates for current area and volume killed used for initial conditions in main model runs.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Cumulative Area</th>
<th>Cumulative Volume Killed</th>
<th>Volume Killed (final year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Origin10</td>
<td>181,097.2</td>
<td>2,539,469</td>
<td>738,788.7</td>
</tr>
<tr>
<td>Origin5</td>
<td>152,687.3</td>
<td>1,462,039</td>
<td>486,901.3</td>
</tr>
<tr>
<td>Initial2001</td>
<td>192,001.2</td>
<td>1,070,039</td>
<td>1,070,039</td>
</tr>
</tbody>
</table>

The mean growth rate, after two years, for the beetle population in the Origin10 experiment was 1.75, which is close to an expected growth rate for this area of the province (L. Safranyik, personal communication).

The left image Figure 2 shows the probability of a cell being attacked by the model during the calibration experiment, measured as the proportion of runs in which the cell was attacked at least once. The right image in Figure 2 shows the mean proportion of pine killed during the experiment. These images illustrate the spatial pattern of the projected outbreak after a decade. Both the area attacked and the relative severity of attack correspond reasonably well with the current infestation data used to initialize the main model runs. Attack is concentrated in the southern portion of the Chelaslie landscape unit and Entiako protected area, with moderately high levels of attack in the central area of the landscape unit and some areas of attack across Ootsa Lake. Note that a cell will show as grey it is attacked at least once in the 10 replicates, so the extents shown in grey in these images are somewhat larger that is projected by a single run.
Figure 2. Estimated probability of attack (left) and percent pine killed (right) during the decade 1991-2001 with beetles originating from outside the TSA on the lower left of the study area. Brighter areas indicate higher probability and mortality, with white at or above 50% probability and 80% mortality, respectively.

**Base Scenarios**

The base beetle management scenario (BM) reduced volume losses inside the THLB by approximately 1.5 million m$^3$ when compared with the TSR scenario and about 3 million m$^3$ over no management during the 10-year simulation period (Figure 3). All three treatments differed significantly ($\alpha=0.05$) at the base AAC. Doubling the AAC (AAC200) using beetle management treatments significantly reduced volume losses when compared to the base BM run. However, the scenario featuring 10 times the current AAC (BM_AAC1000) did not significantly reduce volume losses when compared with the BM_AAC200 scenario. Doubling the AAC under TSR rules resulted in virtually identical volume losses compared to the standard TSR scenario. This occurred because the TSR scenarios log stands using the relative oldest first rules and ignore the presence of beetles. The additional cut from doubling the AAC under TSR rules were largely allocated to stands outside of the area of beetle attack and thus had no effect on volume killed by beetles.
Figure 3. Base scenarios showing the effect of beetle management and increasing the AAC under the beetle management, no management and TSR scenarios on predicted volume losses inside the THLB during a 10-year simulation.

Figure 4. Estimated percent pine killed (left) and volume killed in the THLB (right) for the BM_AAC200 (current management with doubling of AAC) scenario. Brighter areas indicate higher mortality, with white at or above 80% mortality or 100m$^3$, respectively.
Figure 4 shows the projected severity of the attack under the BM_AAC200 scenario. The BM scenario is similar, with slightly higher severity. These images show the areas that the LLM projects will receive higher levels of mortality and more volume killed during the outbreak. The trend towards the northeast is partly due to prevailing winds and sources of beetles within the study area. Since we do not model incoming beetles from outside the TSA, we may be underestimating attack in some areas, particularly along the western boundary. Nonetheless, these images highlight some areas that may at least warrant monitoring.

Figure 5. Estimated progression of the outbreak front: (i) mean extent of outbreak after 3 years; (ii) mean extent after 5 years; and (iii) mean extent after 10 years. Brightness indicates year when a cell was first attacked, with later years shown brighter.

The main portion of the outbreak in this TSA is expanding somewhat analogously to a fire front. Figure 5 illustrates how the outbreak front grows in the model under the BM scenario. The leftmost image shows those areas that are attacked on average within 3 years. The center image shows that within the subsequent two years, the model projects a significant expansion, but with scattered coverage. The rightmost image shows the infilling of this expanded front. Note that since these are averages across 10 replicates, the images do not show the wide range of possible front advances. In particular, the first image seems to imply a fairly
compact front, but in fact each model run projects lots of scattered spots ahead of the main front. It isn't until these spots grow that the different runs start to coincide, as seems to happen after 5 years (centre image).

**Beetle Growth Rate Sensitivity**

As expected, a higher growth rate resulted in increased volume losses and the lower growth rate scenarios predicted smaller volume losses. However, the relative effect of beetle management compared to no management was almost identical under all three growth rate assumptions (Figure 6). This gives confidence that the relative ranking of various management options is reasonably robust given uncertainty surrounding the future beetle growth rate. All other model runs were made with the moderate MPB growth rate.

![Graph showing effect of changing assumptions about the growth rate of MPB populations on predicted volume losses inside the THLB during a 10-year simulation.](image)

Figure 6. Effect of changing assumptions about the growth rate of MPB populations on predicted volume losses inside the THLB during a 10-year simulation.

**Management Option Sensitivity**

The scenarios that individually removed various forest policy constraints, turned off fell and burn treatments, ignored BMUs, and increased the probability of green attack detection had no significant effect on predicted volume losses over the 10-year simulation period (Figure 7) when compared to the base run. Indeed the only significant decrease in volume losses came from increasing the AAC (Figure 3). Plotting volume losses against the cumulative area of attack shows that the beetle management scenarios form a cluster because there is little difference in their effects on either volume losses or the area of the outbreak (Figure 8). Doubling the AAC decreased volume losses but had no effect on the
extent of the outbreak. Only the 10 x AAC scenario significantly reduced both volume losses and the outbreak extent.

The salvage scenarios resulted in slightly larger volume losses than the beetle management scenarios at current and double AAC levels (Figure 9). This is not surprising given that beetle management scenarios primarily cut beetle blocks which are targeted at infested stands as soon as they can be detected, and salvage blocks target stands after they are attacked and a significant amount of salvageable volume is available for logging. The salvage blocks do manage to suppress the beetle population and result in lower volume losses when compared with the no management scenario (Figure 3). This is because, in the salvage scenario, if there was a lack of salvageable wood, any additional AAC was allocated to log susceptible stands. Thus, although salvage of stands with very high mortality levels will not affect MPB growth, supplementary harvest of susceptible stands may remove hosts.

![Graph showing THLB volume killed (million m^3) for different scenarios](image)

Figure 7. Effect of various changes to the base beetle management scenario on predicted volume losses inside the THLB during a 10-year simulation. See text for description of scenarios.

**Non-Recovered Loss Estimate**

Non-recoverable loss was reduced by both the beetle management and salvage scenarios compared with no management. Increasing the AAC level had relatively little effect on non-recoverable loss (Figure 10). The salvage scenarios do recover more salvage volume than the beetle management scenarios at both AAC levels (Figure 11), but also tend to result in more volume impacts. Both scenarios harvest approximately 1.5 million m^3 annually at base levels of AAC, but a higher percentage of this is directed salvage in the salvage scenario.
Figure 8. Predicted volume losses plotted against the cumulative area attacked under various management scenarios.

Figure 9. Comparison of predicted volume losses in the THLB using the standard beetle management scenario and a salvage only scenario at two levels of AAC.
Figure 10. Cumulative predicted non-recoverable loss under no management, beetle management, and salvage preference scenarios at three levels of AAC.

Figure 11. Cumulative volume salvaged under the beetle management and salvage preference scenarios at two levels of AAC.

**Timber Supply Implications**

We focus on growing stock as the main indicator of timber supply in this analysis, and present results for total growing stock on the timber harvesting landbase and merchantable growing stock (older than min. harvest age).
Figure 12. Total growing stock in the THLB under the base scenarios without beetles in comparison with the TSR analysis results.

Figure 13. Merchantable growing stock in the THLB under the base scenarios without beetles in comparison with the TSR analysis results.
Figure 12 and Figure 13 show the growing stock projections in the absence of beetle in comparison with the results from the TSR analysis. Consistent with our alignment (Fall 2002c), growing stock for the TSR scenario tracks the analysis results fairly closely until after decade 15 when it declines. We found that this was primarily due to applying spatial blocks. In a timber supply analysis, one goal is to ensure a stable (flat) growing stock over the long-term. Our goal here, however, is to assess how the MPB outbreak and beetle management together influence growing stock.

In the absence of beetles, the BM scenario differs from TSR by focusing on high susceptibility stands. The two graphs show that this has no effect on growing stock. Doubling the AAC for the first decade has the effect of drawing down mature growing stock in the short to medium term. This recovers over the long term (by around decade 12). This recovery of stock is primarily due to assumed increases in site index (growth rate) in harvested stands. Hence, doubling the AAC has the combined effect of reducing stock earlier on in the horizon, but also more rapidly creating stands with assumed improved growth rates.

Figure 14 and Figure 15 show the effect on timber supply of incorporating the MPB outbreak in the timber supply projection. We compare the results of the base scenarios with the BMnoMPB scenario. One main effect is that the short-term loss of mature growing stock in the first decade due to beetle never seems to fully recover over the entire horizon. Otherwise, the BM scenario follows the same trends with and without beetles. Doubling the AAC draws down growing stock slightly more early in the horizon, but has virtually no long-term impacts. The short-term draw down of mature stock appears less with beetles than without in relation to the BM scenario because the BM_AAC200 scenario applies a significant portion of the AAC increase to salvage of MPB-killed wood, which has already been removed from the growing stock in the figures (since by definition, growing stock refers to living trees). Increasing the AAC 10-fold for the first decade, however, causes an additional draw-down of mature stock early in the horizon, which never recovers. In fact, towards the end of the horizon, the BM_AAC1000 curve appears to be declining more rapidly than the BM of BM_AAC200 curves.

The two TSR scenarios are distinctly different from the BM scenarios. Recall that the TSR scenarios tended to permit a loss of 1.5 to 4 million cubic metres more than the BM scenarios. However, Figure 14 shows that by decade 5, the TSR scenario has approximately 10 million cubic metres less growing stock than BM, more than 10%. Doubling the AAC in the first decade exacerbates this difference. However, over the time horizon this difference declines and disappears by decade 22. Once again, the reason lies in the assumed improved growth conditions on harvested sites. Since the TSR scenario does not salvage, beetle-killed sites regenerate on unmanaged (lower site index) yield curves. However, once these start being harvested, they receive the site index adjustment and the higher yields close the gap between the BM and TSR scenarios.
However, given the magnitude of the difference between BM and TSR scenario in the mid-term, it appears that the BM efforts are well justified in terms of reducing risk both to timber supply and to non-timber values.

Figure 14. Total growing stock in the THLB under the base scenarios with beetles in comparison with the BM, no MPB results.

Figure 15. Merchantable growing stock in the THLB under the base scenarios without beetles in comparison with the BM, no MPB results.
Conclusions

Our analysis of the current MPB outbreak in the Lakes district suggests that this outbreak is of such a large scale that management efforts can only expect to slow down, but not stop its progression. Nonetheless, by slowing its spread, management can buy some time to reduce the non-recovered losses caused by the outbreak until the outbreak terminates, either due to extreme weather or by population collapse after hosts are no longer available.

Doubling the AAC had the effect of reducing volume killed by approximately 15% (2 million cubic metres). Although this is significant, it represents a saving of approximately 15% of the total increase in harvesting over the 10 years. However, increasing the AAC had a somewhat larger relative effect in reducing NRL (approx. 20%). We explored the sensitivity of these results to a range of management options and beetle growth assumptions. And found our main results to be quite robust.

Our analysis of long-term effects of the current outbreak and beetle management efforts on timber supply indicated a minor effect compared to projections without beetles. This is primarily due to significant site index (growth rate) adjustments made after harvesting stands. In effect, although the outbreak and increased AAC both draw down the current mature growing stock, post-harvest regenerating stands are assumed to grow significantly faster than natural stands and hence after several decades post-outbreak the growing stock returns to levels close to those in the TSR. However, in the mid-term, our analysis showed that beetle management reduces the amount of draw-down of mature growing stock.

It is important to understand the uncertainty in the model predictions, which arises from several sources. First, it must be recognized that inventory data is an extrapolation from sample plot data and aerial photography and is therefore not 100% accurate. Important layers such as the percentage of pine and total stand density in each hectare were derived from the inventory data and regression (for unmapped areas). Another source of information was a map of beetle outbreak provided by MOF (Jim Richards). This map provided fairly general information on the level of attack, but not details down to the cell level. As a consequence, the model likely over-estimates the beetle population within the infestation polygons, but underestimates it in small unmapped spots.

A second level of uncertainty involved the structure of the model itself. To our knowledge, there hasn’t been any other attempt to combine spatially explicit models of harvesting, beetle management treatments and mountain pine beetle dynamics. Like any model, the one designed for this project is simply an approximation of reality and ongoing refinement and improvement will continue through sensitivity analysis and thorough examination of the model projections. However, the results presented in this report are based on the best available current information and models. These results are best used to weigh the relative
merits of management scenarios and are not intended as predictions of exact harvest results or beetle patterns.

This project was successful at adapting and applying methodology for landscape-scale modelling of MPB outbreaks, and for refining methods of capturing MPB management strategies for strategic level planning and assessment of beetle management at broad spatial scales. The spatially explicit beetle and harvesting models were modified to reflect conditions and practices in the Lakes TSA area based on the best currently available information. Although there is uncertainty in the beetle and management models, the results suggest that the current beetle management efforts of the district are likely having a modest effect on the beetle outbreak. The model is a work in progress and this project has helped to identify further areas that can be improved upon. For the Lakes Forest District, further explorations of various management options may help to refine projections. At the provincial level, continued application and refinement of this method in other jurisdictions may serve to extend our understanding of beetle outbreaks at the landscape scale in various ecological and management situations.

References