Integrating Landscape-Scale Mountain Pine Beetle Projection and Spatial Harvesting Models to Assess Management Strategies

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Abstract

A landscape-scale mountain pine beetle population model was developed to assess the impacts of mountain pine beetle outbreaks at spatial scales of over 1,000,000 ha. We integrated this model with spatial timber supply and strategic forest management models in the Lakes, Kamloops and Morice timber supply areas of British Columbia, Canada to analyze the potential spread of the current beetle outbreak under a range of potential management activities in various regions of the province. We analyzed a range of scenarios to contrast management alternatives and beetle conditions. Three main types of effects were assessed: area attacked and volume killed by beetles during the outbreak (over the next 10 years), volume salvaged and non-recovered loss expected during and post-outbreak, and cumulative timber supply impacts. The three study areas provide a gradient across the range of conditions within the overall outbreak area. In general, our analysis highlights the likely effects of applying different beetle management strategies under different conditions. Our results imply that an attack pressure threshold exists, below which fine-scale management can improve potential to control an outbreak, and above which management will likely have little effect on the outbreak.

Introduction

Mountain pine beetle (*Dendroctonus ponderosae* Hopk.) occurs across pine forests in western North America (Wood and Unger 1996). Over the past several years, a major outbreak of mountain pine beetle has been underway across a vast area of the central interior of British Columbia (BC), primarily in lodgepole pine (*Pinus contorta* var. *latifolia* Dougl.) stands (Safranyik et al. 1974; Wood and Unger 1996). The magnitude of this outbreak, and the losses faced by the timber industry, is creating havoc with long-term forest planning. It forces the redirection of the allowable cut towards reducing the beetle population and salvaging beetle-killed timber. The cumulative effects of the outbreak and management activities can impact maintenance of other forest values (e.g. caribou migration routes, ungulate winter range, visual quality, etc).

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*Mountain Pine Beetle Symposium: Challenges and Solutions. Octob*er 30-31, 2003, Kelowna, British Columbia. T.L. Shore, J.E. Brooks, and J.E. Stone (editors). Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Information Report BC-X-399, Victoria, BC. 298 p.

In timber supply areas (TSAs) affected by the current epidemic, resources have been focused towards maximizing 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, a series of projects to develop a landscape-scale mountain pine beetle and strategic management model that builds in prior work modelling mountain pine beetle dynamics and spatial timber supply was initiated. The main purpose of these studies was to address the question of what would be the likely range of impacts from the current beetle outbreak under a range of alternative beetle management regimes (Anon. 1995) including increased or decreased levels of effort. The core of the landscape model was developed largely with support from the BC Ministry of Forests for projects in Kamloops, Lakes and Morice Forest Districts (Fall et al. 2001; 2002; 2003a), and in a portion of Lignum Ltd.'s Innovative Forest Practices Agreement area near Williams Lake BC (Fall et al. 2003b). The mountain pine beetle model (SELES_MPB) was derived by the authors to scale results from a more detailed stand-level mountain pine beetle population model, MPBSIM developed at Pacific Forestry Centre (Riel et al. 2004).

Our approach was to start with the current conditions, and project likely outcomes and interactions between mountain pine beetles and management, under the various scenarios using spatially explicit stochastic simulation modelling. Input preparation involves assembly of geographic, forest inventory, weather and mountain pine beetle infestation data for each study area. We do not attempt to predict when the outbreak may end, but artificially terminate it after 10 years. We may extend the model time horizon to assess the decay of killed merchantable wood over the following decade and long-term implications on growing stock and other timber supply indicators. Through comparison of various scenarios, the influence of management actions in terms of area infested and volume killed were identified. This information can be used to assess impacts directly, or can serve as input for further analysis of economic, social or ecological costs and benefits. In this paper, we describe the conceptual basis for the management and mountain pine beetle models, and present some key results from the three study areas.

Methods

Overall Landscape Model Design

Our general approach is to integrate the SELES-MPB/MPBSIM Mountain Pine Beetle Landscape Model with the Spatial Timber Supply Model (STSM) (Fall 2002). The design 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, which covers details of the harvesting, aging and inventory sub-models see Fall 2002). The Lakes, Kamloops and Morice TSA Landscape Models (called LLM, KLM and MLM, respectively) are specific applications of this framework.

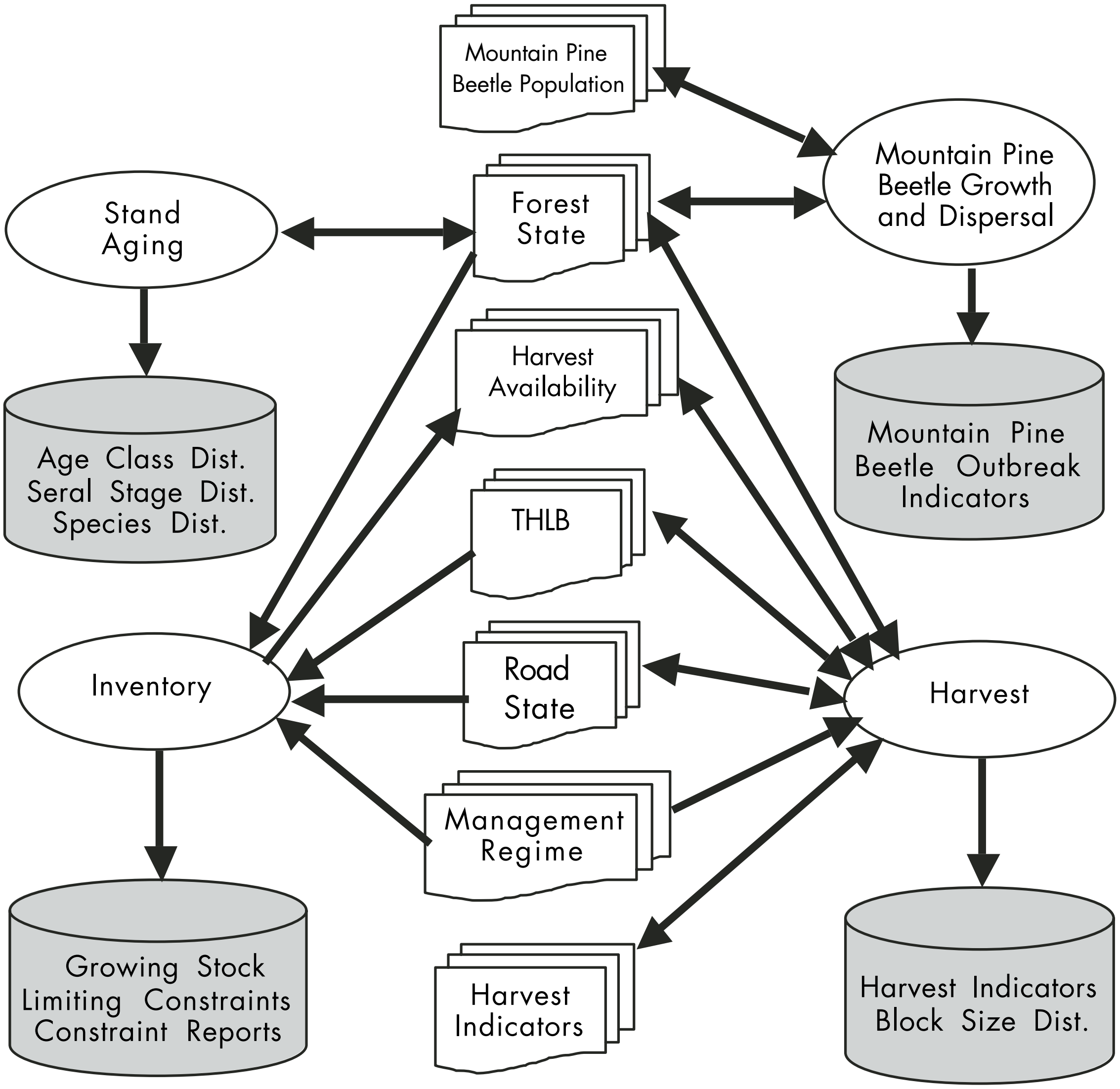

Figure 1. Linkages between primary components of state (shown in the centre), model processes (shown in ovals) and output files (shown as grey drums).

Model State Space

All layers, except where noted, were derived using information from the current forest inventory on each timber supply area.

- Landscape structure: the landscape biogeographical context and the limits of the study area are defined with biogeoclimatic classification (Pojar et al. 1987), by variant (BEC) and elevation in metres.
- Forest state: represented by stand age in years, inventory type group (leading and secondary species), height and volume (derived from growth and yield tables), percent pine (percent of forest in each cell that is pine), stand density (estimate of number of stems per hectare), site index (expected height in metres at 50 years), and analysis unit (represents sites with similar growing conditions, usually based on species, management history and site index).

- Mountain pine beetle population: tracked using mountain pine beetle population (beetles/cell, initiated based on estimates of the initial beetles/cell derived from current infestation data), time since attack (years since last attack in cell), mountain pine beetle susceptibility [computed according to the index developed by Shore and Safranyik (1992)], and mountain pine beetle risk [computed by combining susceptibility with beetle locations but using a different method than in Shore and Safranyik (1992)]. Note that the risk and susceptibility estimated are only used to influence the management models, not the mountain pine beetle population model.
- Harvest availability: potential treatment type (available forest stratified into the type of treatment that would be applied if a block was initiated at that cell; treatments are discussed below), and salvageable volume. This latter variable tracks dead volume that would either be salvaged or become a non-recovered loss in various post-disturbance stages (e.g., green attack, red attack, third year post-attack, etc.). There is no initial state for this information.
- Timber harvesting landbase (THLB): derived from the productive operable forest via a net down process that removes forest for various reasons described in recent timber supply reviews (e.g., British Columbia Ministry of Forests, 2001a, b, c), 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 all analyses, while others are study-area specific. For example, zones used in the Morice TSA include visual quality objective zones, caribou management zones, integrated resource management zones, resource management zones used to identify community watersheds, landscape units, productive forest (cells classified as productive operable, productive inoperable or non-productive/non-forested), and identified blocks in current forest development plans.
- Management parameters: a range of parameters and tables to set up the harvesting regime, including annual allowable cut (AAC), beetle management unit (BMU) strategies (Maclauchlan and Brooks 1994), minimum harvest age, management constraints, and management preferences.
- Roads: distance to existing roads in metres.

Stand Aging

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

Inventory

This event performs an inventory analysis for each time step. It tracks the amount 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 constraints were responsible. For constraints for which recruitment is appropriate, cells are recruited in order of age.

Harvesting

This sub-model is designed so that under conditions with no beetle outbreak, it can be parameterized to match timber supply review (TSR) analysis results, enabled with spatial capability to simulate the allocation of cutblocks across the landscape. Harvest rate (m^3/yr) and volume yield curves for different types and ages of forest were based on recent Timber Supply Review analysis documents (e.g., British Columbia Ministry of Forests 2001a). The AAC and mean volume per hectare determine the area logged and, in part, the number of cutblocks. The following steps are applied to place blocks:

- Cutblocks must fall on eligible land, determined by the timber-harvesting land base, stand age (which must be older than minimum harvest age), access (within 2 km of an existing road), forest cover rules (age class structure in applicable zones allows harvesting), and adjacency rules.
- Eligible cells are classified into potential block types (see below), and cells are processed in this order. Without mountain pine beetle, all cells are classified as "green blocks."
- Within each type, relative preference is assigned to each map cell based on stand age (relative oldest first), potential block type (e.g., salvage opportunity in proportion to salvageable volume), and distance to road (linear decrease with distance). Block start points are selected probabilistically using these preferences to reflect economic and environmental differences among eligible stands.
- Once a harvest block is initiated, a target size is chosen from an input distribution. The default cutblock size was 40-100 ha based on spatial assessments of recent block sizes in the study areas. The cell is then harvested, and the block spreads to adjacent cells until the target size is reached or the adjacent eligible area is exhausted. As only clearcuts were modelled at the scale of the 1-ha cells, harvesting a cell involves setting stand age to zero and updating tracking variables (e.g., annual volume harvested).

Cutblocks were explicitly connected to the main road network by adding a link from the first cell harvested in the block to the nearest existing road. The model 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.

Beetle management was incorporated as strategies to target blocks during the stand selection based on detectable attacked stands, salvage opportunity, mountain pine beetle susceptibility and mountain pine beetle risk. At the start of each year each cell was classified probabilistically (based on detection uncertainty and planning rules) into one of the following cell types:

- Beetle cells: 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 > 1 km.
- Salvage cells: cells that had a sufficient level of salvageable timber (≥ 25 m^3/ha).
- Risk cells: cells that had a sufficiently high-risk index (default: 1% chance per unit of risk, which ranges from 0 to 100%).
- Susceptibility cells: cells that had a sufficiently high susceptibility index (default: 1% chance per unit of susceptibility, which ranges from 0 to 100%).
- Green-tree cells: all other cells.

When selected, a block takes on the type of the cell. In this way, *Beetle blocks* were applied in areas with significant detectable infested trees. *Salvage blocks* were applied in areas with significant detectable standing dead wood. *Risk blocks* were applied in areas with high risk of mountain pine beetle attack. *Susceptibility blocks* were applied in areas with high mountain pine beetle susceptibility. *Green-tree blocks* were placed outside the above areas, and blocks were cut using clear-cuts. Beetle, salvage, risk and susceptibility blocks cannot spread to green-tree cells.

The relative preferences used for cell classification, and the targeted order of harvest based on these types, was based on the beetle management activities carried out by each TSA. Generally, the treatments in a year were placed according to the order given above, but some scenarios placed higher emphasis on salvage or risk blocks. That is, first all beetle blocks were treated; if there was AAC remaining then salvage blocks were treated, etc. The model assumed 90% effectiveness for block treatments in terms of the percent of beetles removed.

Single-Tree Treatments

This sub-model simulated fell and burn and monosodium methanearsonate (MSMA) treatment methods, based on levels provided by each TSA. Fell and burn treatments are generally applied in inaccessible areas or areas with low beetle population levels. These treatments were applied to individual cells, and the volume was not recovered. The model assumed 95% effectiveness of beetles killed in a treated cell.

Mountain Pine Beetle Population Model

Stand-scale models for predicting mountain pine beetle spread and impact have been developed at the Canadian Forest Service (CFS) (Safranyik et al. 1999; Riel et al. 2004). We extended these to the landscape scale using the Spatially Explicit Landscape Event Simulator (SELES) modelling tool (Fall and Fall 2001). The CFS stand-level model MPBSIM projects expected development of a beetle outbreak in a stand of up to several hectares (Riel et al. 2004). Conceptually, our approach involves effectively running MPBSIM in each cell of the landscape with beetles. Since it is not feasible or desirable to do this via a direct link, we first run MPBSIM under a wide range of conditions to produce a table linking conditions to resultant consequences. Conditions include stand attributes (e.g., age, percentage of pine), outbreak status (e.g., number of attacking beetles), etc. (Riel et al. 2004). 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 uses this table to project mountain pine beetle dynamics in each 1-ha cell containing beetles. The stand table includes stochastic variation in number of emerging beetles, and we control this to capture synchronous annual variation and above-average weather conditions.

Dispersal between cells provides the spatial context for an outbreak, leading to an increased beetle population in cells within a current outbreak, or starting an outbreak in a currently uninfested cell, expanding a current beetle spot or starting a new spot. The flight period, including local and long-distance dispersal and pheromone production and diffusion, is modelled as a spatial process. Long-distance dispersal is largely governed by wind speed and direction used to select distance locations for mountain pine beetle spread, while local dispersal is influenced by wind, susceptibility, pheromones and distance. During attack, beetles kill pine trees, producing red trees (recently killed) and standing dead volume that may be salvaged by the logging sub-model. The 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 may degrade at a relatively fast rate (e.g., 20% starting 3 years after attack), depending on an input decay rate curve.

Model Outputs

Text output (aspatial annual time series) includes:

(i) age-class distribution of productive forest in 10-year age classes;
(ii) mountain pine beetle outbreak indicators (overall and stratified by beetle management unit), including volume killed, number of trees killed, area attacked and a range of verification indicators (e.g., number of long distance spots);
(iii) growing stock inventory in terms of cubic metres of live forest in various stratifications of the landbase;
(iv) harvest indicators such as annual volume and area harvested, mean age harvested, volume per hectare harvested, harvest species profile, volume of non-recovered loss, volume salvaged, amount of available salvageable wood and area harvested by the various treatment types (i.e., beetle blocks, salvage blocks, etc.); and
(v) amount of spur road constructed. We focus our results on the mountain pine beetle outbreak indicators.

Spatial output

Since multiple replicates of each scenario are run, creating spatial summaries across time and replicates is a challenge. The aspatial indicators summarize information across space and replicates, providing time-series information. We designed several spatial indicators that summarize information across time and replicates:

(i) *TimesAttacked* is the number of runs in which each 1-ha cell was attacked at least once, and can be roughly thought of as the probability that a cell will be attacked 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, and shows areas likely to have the highest time impacts;

(iii) *PercentPineKilled* is the cumulative percentage of pine killed, and shows areas likely to have the higher ecological impacts; and

(iv) *YearAttacked* is the first year attacked in the run, and shows how the main front of the beetle outbreak is expected to spread across the landscape.

Scenarios Evaluated

A wide range of scenarios was run in all study areas to verify the model prior to making the main "production" scenarios, and 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 relevant for management. We present selected scenarios from the three study areas to highlight key findings. There are a number of stochastic factors in the model, primarily affecting dispersal due to wind and cells selected by beetles. We ran 10 replicates of each scenario for 10 years (unless otherwise stated) so that we can report means and standard errors.

Calibration Scenarios (Lakes TSA)

Variation in the way historical outbreak information was collected makes it difficult to calibrate and parameterize the dispersal component of the model. Based on the approximate location where the present outbreak in the Lakes TSA was first detected in 1991, and an estimate of the landscape conditions at that time, we designed a set of scenarios to compare model projections with current infestation data. We only present 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 1,000-ha "origin" patch outside the TSA in Tweedsmuir Park on the north side of Eutsuk Lake, the purpose of which 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). We ran two scenarios, both for 10 years (1991-2001) and with no beetles in the TSA at the start. In the first (*Origin10)*, external dispersers from the origin patch continue for the entire horizon, and in the second (*Origin5)*, we stop immigration after five years.

Base Scenarios and Broad Management Sensitivity

The base scenarios are designed to address the primary questions regarding the expected impact of beetle management. These differed by study area, based on information obtained by workshops held at the forest district offices. Some common features include application of current forest management policy, operational constraints (e.g., in Morice, amount of pine that can be harvested is constrained by the need to address concurrent outbreaks of western balsam bark beetle (*Dryocoetes confusus*) and spruce beetle (*Dendroctonus rufipennis*)) and focus of effort on beetle areas. Differences included level of fine-scale treatments, harvest level, forest cover constraints, etc. To put the effect of beetle management (*BM* or *Base Run*) on the mountain pine beetle in a broad context, we compared the base scenarios with scenarios of no harvesting (*NoHarv* or *NoMgmt*), and no beetle management (*NoBM)*, and with current beetle management but with forest policy constraints disabled (*BMNoForPol)*.

We also assessed the effects of different levels of AAC with percentages relative to the base run, which applied the AAC level from the last determination (using an estimate for Kamloops TSA, as the study area is only a portion of a timber supply area). The levels assessed differed by study area, and are indicated by the suffix "AAC" followed by the increase over the base AAC (e.g., *AAC x 2* and *BMAAC200* both indicate the base scenario with two times the current AAC). In Morice TSA, we varied AAC from 50% to 500% of current levels.

In addition to the above, we assessed some scenarios specific to each area:

- Morice: The base runs for Morice also include an assessment of immigration from northern Tweedsmuir Provincial Park (indicated with an "*imm*" suffix). As the timber supply review analysis includes some effects of beetle management, we also applied this scenario (called *TSR*). As there is uncertainty regarding the over-winter weather conditions, we ran both "average" weather and "above-average" (*High* or *h* suffix in scenario name) weather.
- Lakes: To assess the effect of the current AAC increase set by the chief forester to deal with the outbreak ("AAC uplift"), we ran the base *BM* and *NoBM* scenarios at two times the current levels of harvest and the BM scenario at 10 times current levels. We also set up variations of the BM scenario with disabled fell and burn (*NoFell&Burn*), and ability to detect green attack (*DetGreenAttk*).
- Kamloops: We additionally assess halving and doubling the AAC (*BM/2* and *BM×2*, respectively), disabling fell and burn (*NoFell&Burn*) and allowing green attack detection (*DetGreenAttk*).

Salvage and Non-Recovered Loss (Lakes TSA)

We contrasted current management with a strategy of focusing on salvage rather than current attack, and assessing non-recovered losses. The difference between the *BM* and *Salvage* scenarios is that the former first targets beetle blocks, while the latter first targets areas with high amounts of salvageable timber.

Green Detection Sensitivity (Morice TSA)

To assess the relative impact of different levels of green attack detection, we varied green attack detection from 0%-100% in 20% increments for the *BM* and *BM + immigration* scenarios, and with average and above average weather. In the base runs, we assumed that only red attack could be detected (i.e,. 0% green detection).

Tweedsmuir Immigration Sensitivity (Morice TSA)

To clarify the debate regarding the role of the infestation in Tweedsmuir Provincial Park in Morice TSA, we ran scenarios with no immigration from Tweedsmuir and with immigration based on overview information. The forest cover information is outdated and of limited use for this analysis. We assumed instead that the areas with outbreak are quite susceptible. We estimated a range of potential immigration pressure based on overview information, and the number of long-distance dispersers likely to be dispersing from Tweedsmuir using the stand table. We varied the proportion of cells generating dispersers from 25% to 100% in 25% increments for the *BM*, *NoMgmt* and *NoBm* scenarios with both normal and above average weather. We used as a base "expected" case the mid-point of this estimated range, which effectively generates dispersers from 50% of the cells mapped as infested. The suffix "*Imm*" indicates that immigration from Tweedsmuir was included at the base 50% level of immigration.

Single-Tree Treatment Sensitivity (Morice TSA)

To assess the effects of different levels of single-tree treatments (fell and burn and tree injection with MSMA), we varied levels of single-tree treatments at 0%, 50% 100%, 150% and 200% of current levels, under the *BM* scenario (with average and above average weather). The base run applied 250 ha/year of fell and burn and 1000 ha/year of MSMA.

Results

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

Calibration Result (Lakes TSA)

Table 1 compares the estimated area of attack and mean volume killed of the calibration experiments with the first year of the main model runs (Initial2001). Although we cannot compare these values statistically, the area attacked seems to be a slight underestimation, but within reasonable limits. 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.

Figure 2 illustrates the spatial pattern of the projected outbreak after a decade for the *Origin10* scenario. The left image shows the probability of a cell being attacked (i.e., *TimesAttacked*), and the right one shows the mean proportion of pine killed. Both the area and 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 if it is attacked at least once in the 10 replicates, so the extent of grey in these images is somewhat larger than is projected by a single run.

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

Scenario	Cumulative Area (ha)	Cumulative Volume Killed (m^3)	Volume Killed (m^3) (final year)
Origin10	181,097	2,539,469	738,788
Origin5	152,687	1,462,039	486,901
Initial2001	192,001	1,070,039	1,070,039

Figure 2. Estimated probability of attack (left) and percent pine killed (right) during the decade 1991-2001 with beetles originating from outside Lakes 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 and Broad Management Sensitivity

Morice

The four base scenarios simulated current beetle management under average and above-average weather conditions for beetles, and with and without beetle immigration from Tweedsmuir (*BM, BMhigh, BMImm, BMImmh*). All of the base scenarios featuring *BM* resulted in reductions in both the volume killed and total area attacked and formed a cluster at the lower left of Figure 3. The scenarios that had no beetle management or no harvesting at all with average weather conditions formed an intermediate cluster and the same scenarios with above average beetle weather formed a cluster with the highest volume losses and largest area of attack (Fig. 3). These results suggest that the current beetle management employed in the Morice District can significantly reduce both the extent (area attacked) and the intensity (volume killed) of the beetle impact over the next decade even with uncertainties regarding weather and Tweedsmuir immigration. Weather had more of an effect than immigration.

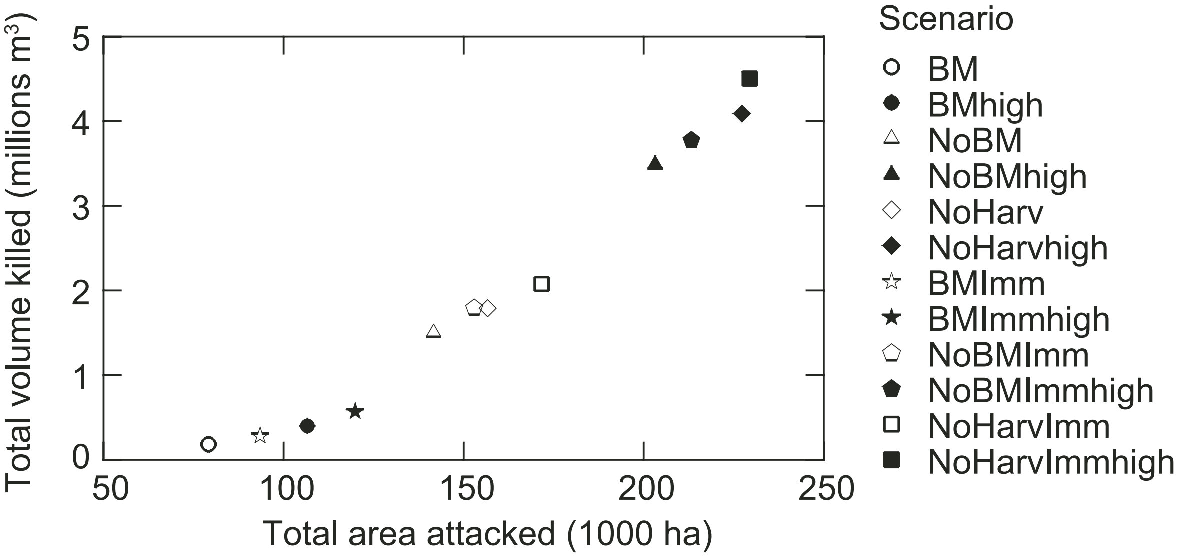

Figure 3. Total volume killed versus area attacked for the base beetle management (BM) scenarios and those with no BM and no harvesting in Morice study area (starting year: 2002).

Disabling forest policy constraints had virtually no impact on beetle damage indicating that these constraints are not limiting current beetle management efforts in the district (Fig. 4). Harvesting under *TSR* rules gave similar results to the *NoBM* scenario. The effect of any harvesting not directly targeted at beetles appeared to be minimal in this landscape with the present beetle population under average weather conditions. At above average beetle weather conditions, the *TSR* and *NoBM* scenarios were slightly more effective than no harvesting, but far less effective than the *BM* scenario (Fig. 4).

Varying the AAC to lower (50%) or to higher (200-500% in 100% increments) levels demonstrated that increases in AAC level above 50% more than the current level had almost no effect on volume losses under any of the four base *BM* scenarios, while reducing the AAC caused increased volume losses (Fig. 5). However, these increased losses need to be put in perspective. Even in the scenario with the highest beetle levels (immigrants and high beetle weather), the volume savings over a decade by increasing the AAC by 50%, are approximately 250,000 m^3. This would require an additional cut of approximately 12,000,000 m^3 to achieve this, so the return is only about 2%.

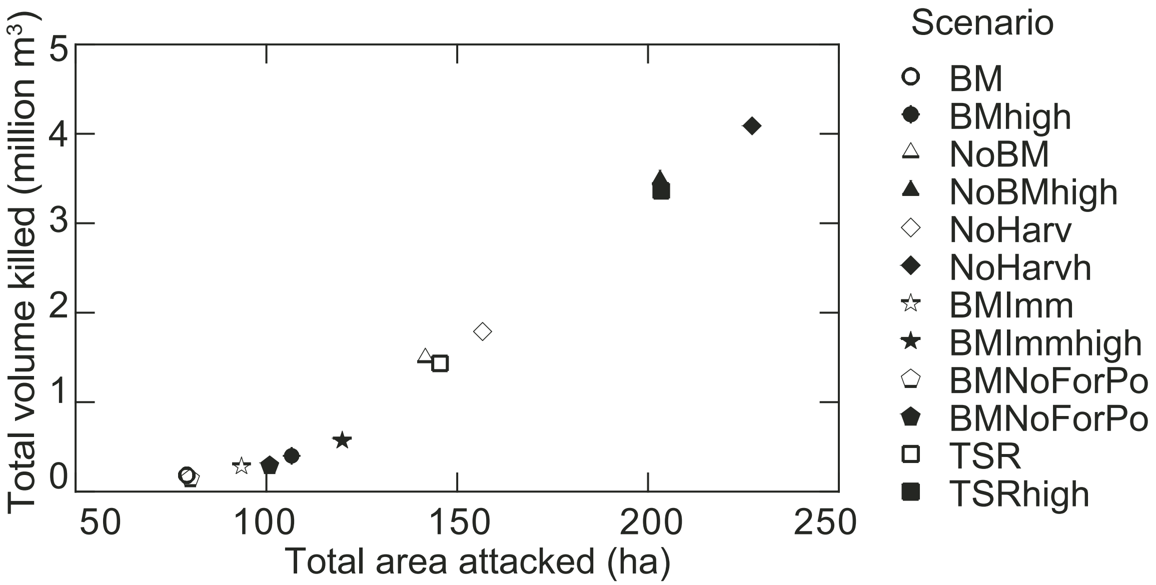

Figure 4. Total volume killed versus area attacked for additional management scenarios in Morice study area (starting year: 2002).

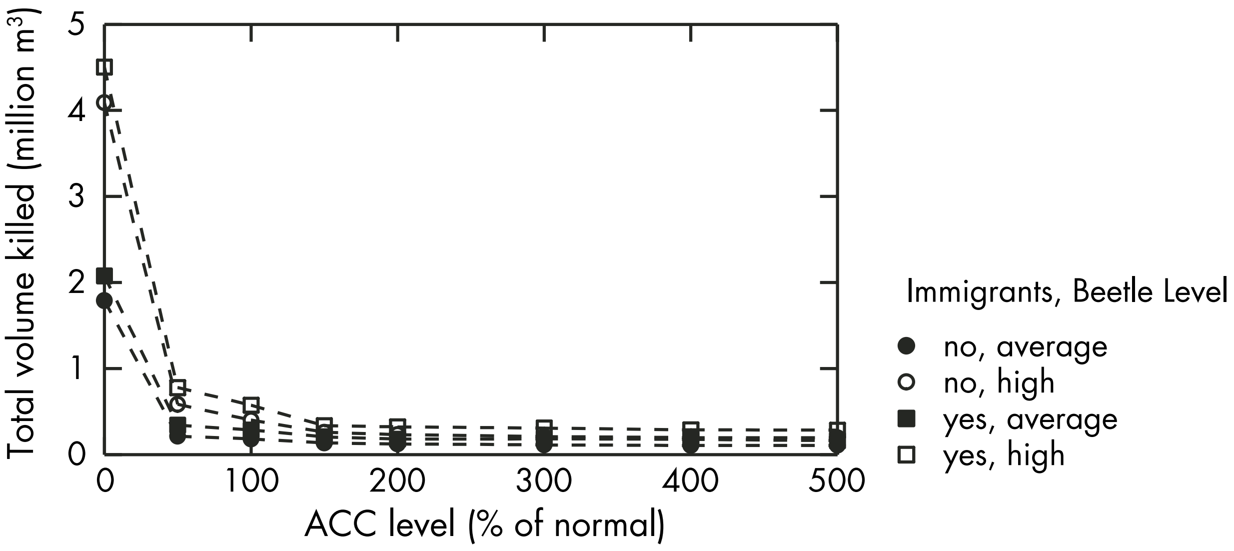

Figure 5. Relationship between volume losses and the AAC level in Morice study area (starting year: 2002).

Lakes

The base *BM* scenario reduced volume losses inside the THLB by approximately 1.5 million m^3 when compared with *NoBM* and about 3 million m^3 over *NoMgmt* during the 10-year simulation period (Fig. 6). Doubling the AAC (*BM_AAC200*) using beetle management treatments significantly reduced volume losses compared to the base BM run. However, the scenario with 10 times the current AAC (*BM_AAC1000*) did not significantly reduce volume losses compared with the *BM_AAC200* scenario. Doubling the AAC under *NoBM* rules resulted in virtually identical volume losses compared to the base *NoBM* scenario. This occurred because the *NoBM* scenarios log stands using the relative oldest first rules and ignore the presence of beetles. The additional cut from doubling the AAC with no beetle management were largely allocated to stands outside of the area of beetle attack and thus had no effect on volume killed.

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 simulation period when compared to the base run (Fig. 6). Indeed the only significant decrease in volume losses came from increasing the AAC (Fig. 6). Doubling the AAC decreased volume losses but had no effect on the extent of the outbreak. Only the 10 times AAC scenario significantly reduced both volume losses and the outbreak extent.

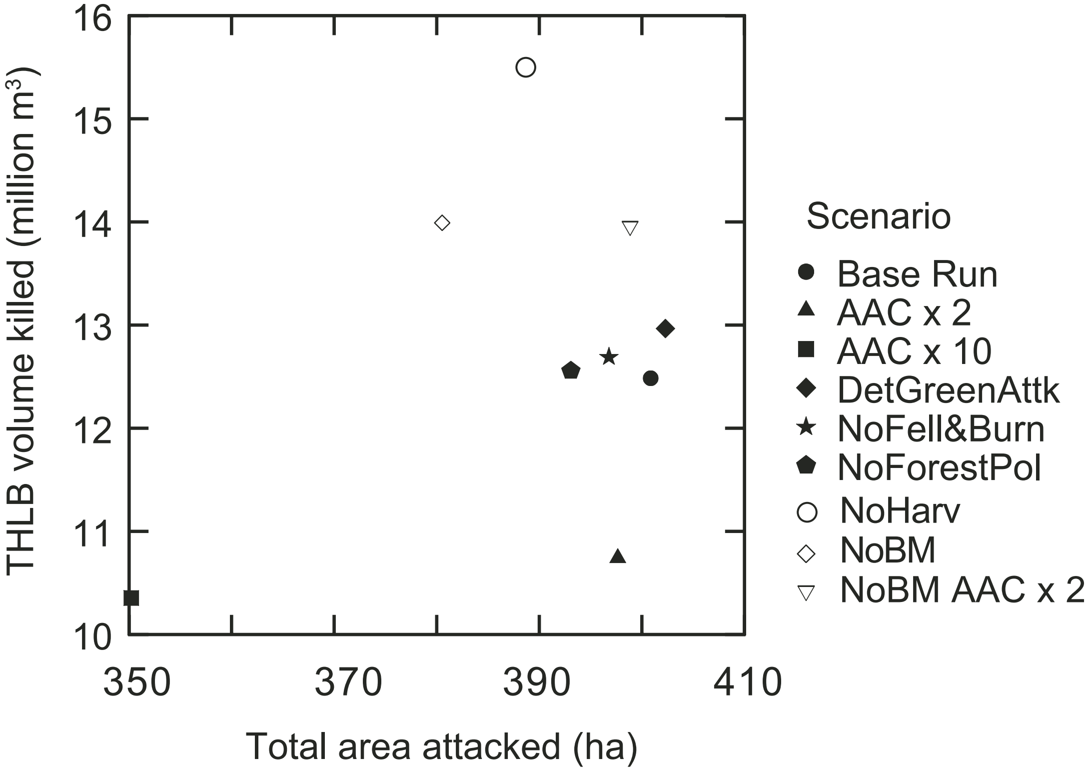

Figure 6. Projected volume losses in Lakes study area plotted against the cumulative area attacked under various management scenarios (starting year: 2001).

Kamloops

The base beetle management scenario (*BM*) reduced volume losses inside the THLB by over 300,000 m^3 compared with *NoBM* and no management scenarios (Fig. 7). The differences between *BM* and increased/decreased levels of beetle management are not nearly as much as the difference between beetle management and no beetle management. The cumulative area attacked over the 10-year period highlights the effect of increasing beetle management effort on reducing the area attacked.

Changing management policy had varying effects on projected volume losses (Fig. 7) compared to the base *BM* run. Disabling fell and burn led to a minor increase in volume killed, indicating that single-tree treatments may be important in this area. Increasing detection of green attack led to a large decrease in area attacked. This reduction is even higher than with a doubling of the AAC. These two scenarios indicate the importance of applying treatments as close as possible to beetle activity centres in this landscape. The scenarios that varied the AAC show the coarse-scale effect of "treatment budget" (total potential effort available in terms of area that can be treated). Decreasing the AAC has a larger relative effect than increasing it, with a 25% increase in volume killed at a 50% AAC reduction compared with 12% decrease for a 50% AAC increase, and 21% increase for a 100% AAC increase.

Figure 8 shows the projected severity of the attack spatially under the *BM* scenario. This image shows the areas that the KLM projects will receive higher levels of mortality during the outbreak. Bonaparte Plateau and Louis Creek seem to be areas of highest concern. Since we do not model incoming beetles from outside the TSA, we may be underestimating attack in some areas, particularly along the western and northern boundaries. Nonetheless, these images highlight some areas that at least warrant monitoring.

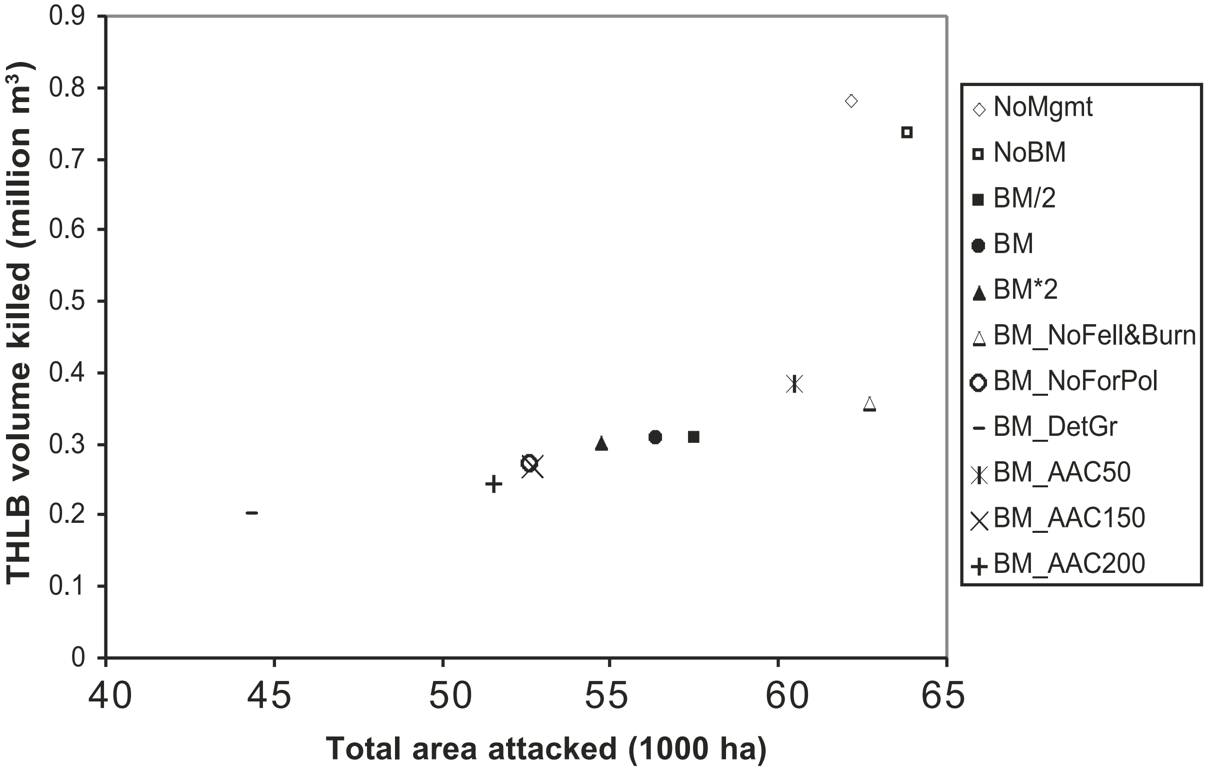

Figure 7. Projected volume losses in Kamloops study area plotted against the cumulative area attacked under various management scenarios (starting year: 1998).

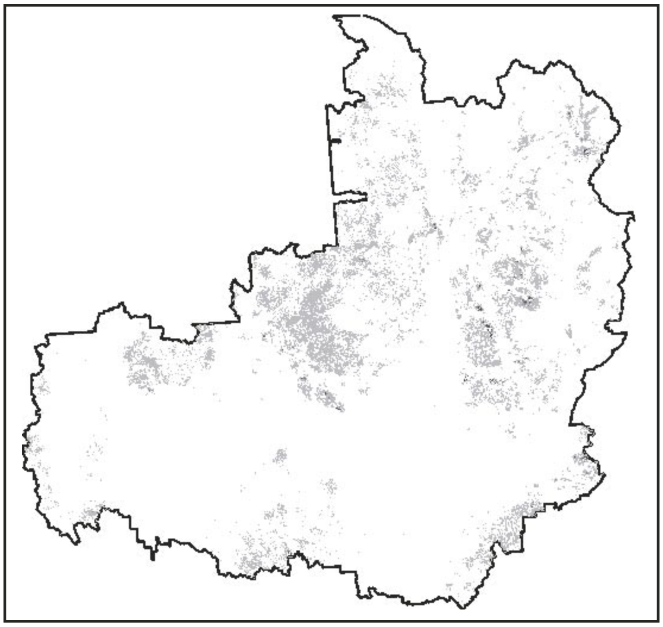

Figure 8. Estimated percent pine killed for the BM (current management) scenario in Kamloops study area. Darker areas indicate higher mortality, with black at or above 75% mortality (starting year: 1998).

Salvage and Non-Recovered Loss (Lakes)

The salvage scenarios resulted in slightly larger volume losses than the beetle management scenarios at current and double AAC levels (Fig. 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. Non-recoverable loss was reduced by both the beetle management and salvage scenarios compared with no management, with the salvage scenario slightly out-competing *BM* (Fig. 10). Hence, although the salvage scenarios tend to result in more volume impacts, they also recover more salvage volume than the beetle management scenarios at both AAC levels.

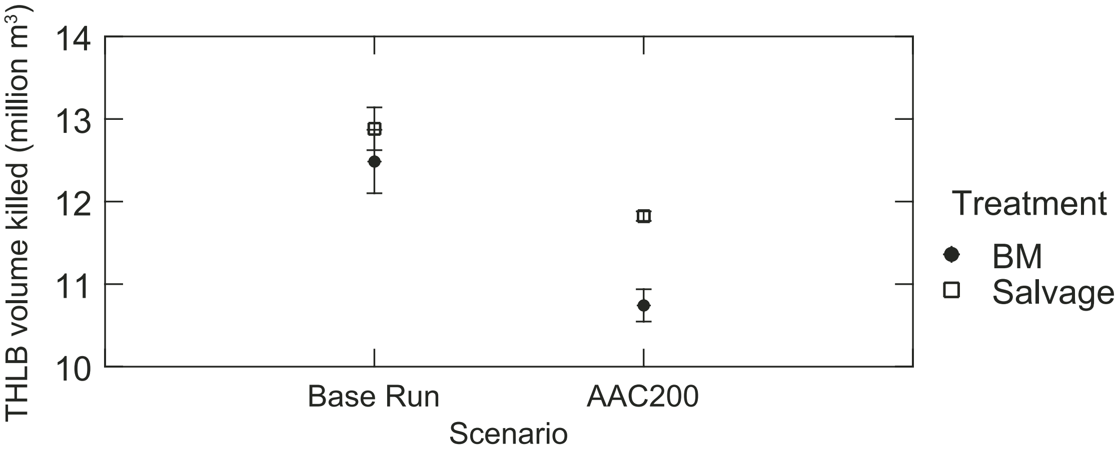

Figure 9. Comparison of predicted volume losses in the THLB using the standard beetle management scenario and a salvage only scenario at two levels of AAC in Lakes study area (starting year: 2001).

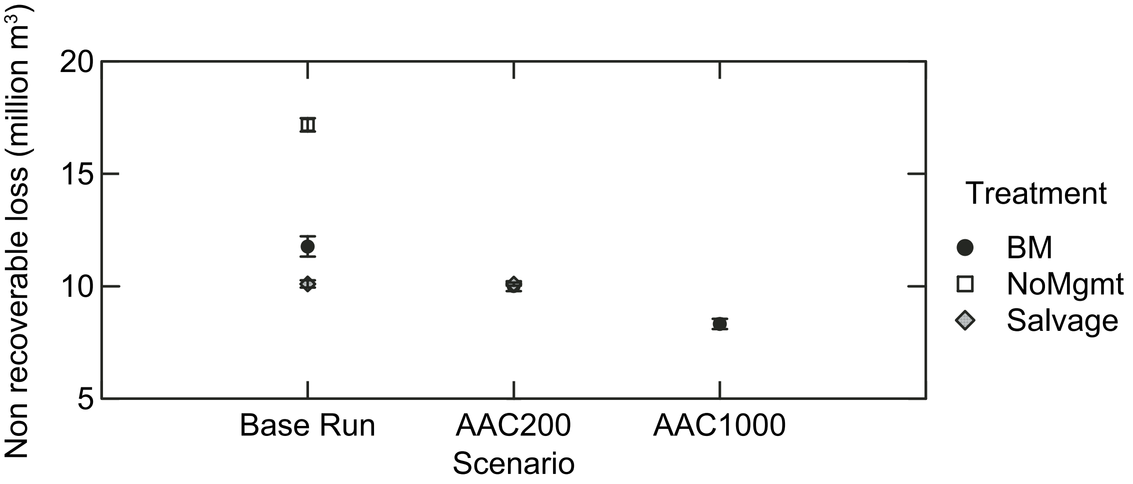

Figure 10. Cumulative predicted non-recoverable loss under no management, beetle management, and salvage preference scenarios at three levels of AAC in Lakes study area (starting year: 2001).

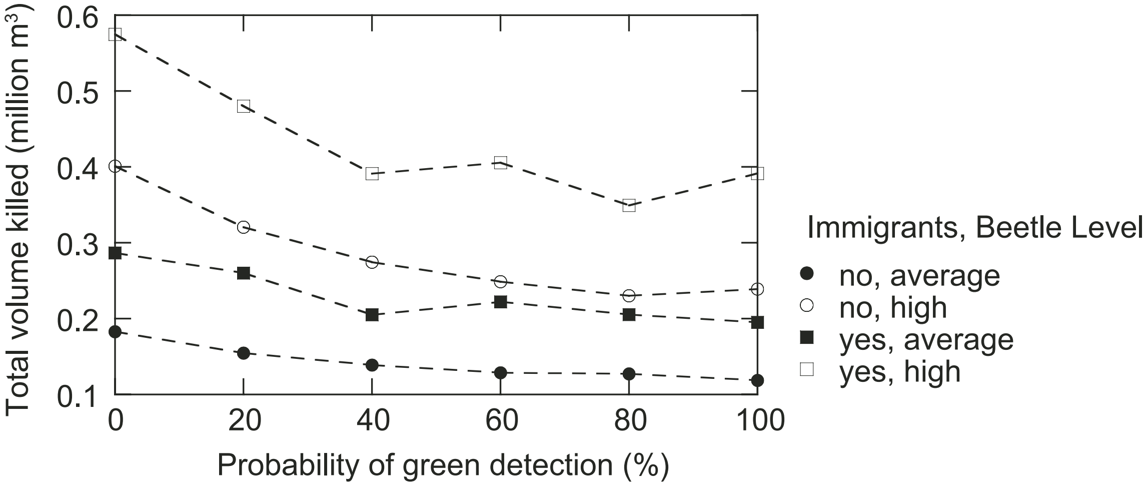

Figure 11. Effect of increasing probability of green attack detection on total volume killed under the BM scenario with and without immigrant beetles under average and above average beetle weather conditions in Morice study area (starting year: 2002).

Green Detection Sensitivity (Morice TSA)

Figure 11 shows that increasing green detection capacity in Morice TSA can improve management somewhat, in particular under increased beetle pressure, and for improved detection at the lower end of the scale. Above 40%, improved detection has less effect.

Tweedsmuir Immigration Sensitivity (Morice TSA)

Increasing the percentage of external long distance immigration pressure caused a slight increase in the volume killed due to a larger beetle population, although the increase was very small (Fig. 12). The *BM* runs used a value of 50%. Volume losses were far more sensitive to weather conditions and management (*BM* vs. *NoBM* and no harvesting; Fig. 3).

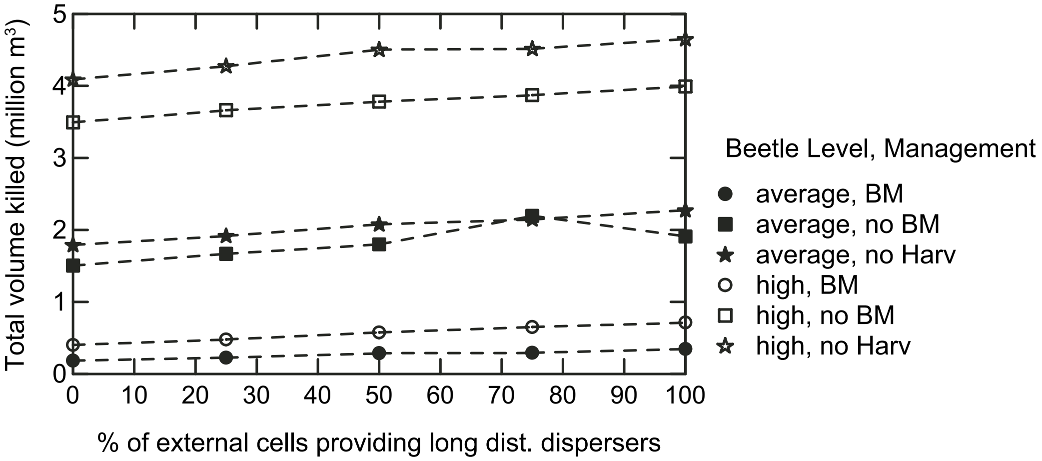

Figure 12. The relationship between volume losses and the percentage of external cells (in Tweedsmuir) that provide long distance dispersers in Morice study area (starting year: 2002).

Single-Tree Treatment Sensitivity (Morice TSA)

Reducing the number of hectares treated annually with single-tree treatments caused an increase in volume losses in above-average beetle weather conditions (Fig. 13). There was almost no effect under average beetle weather except when single-tree treatments were eliminated. Increasing single-tree efforts above current levels had no effect in this landscape under either weather condition. There were no scenarios run at single-tree levels between 0 and 50% of current levels; therefore, it is unknown whether the response between these points is linear. However, the experiment suggests that the modelled levels of treatment are having a significant impact on the outbreak.

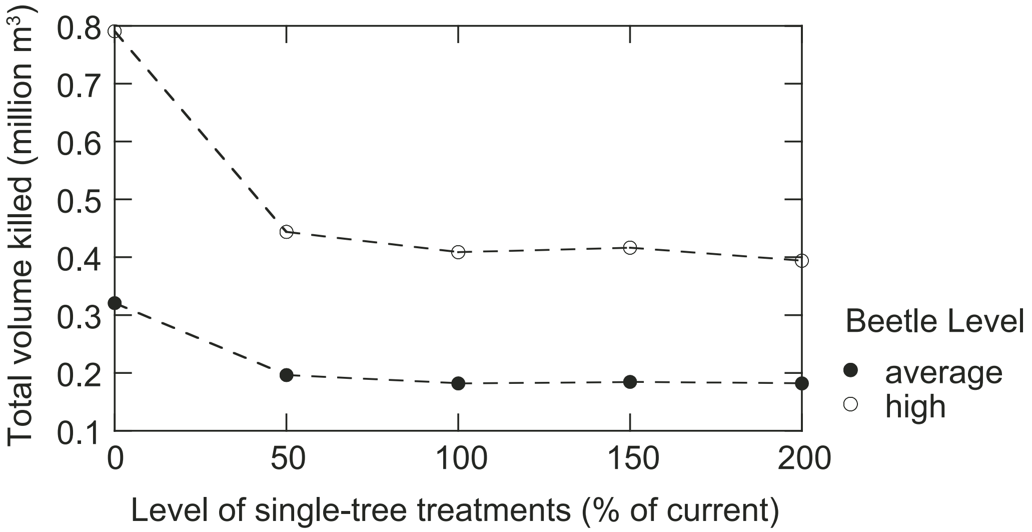

Figure 13. Effect of the level of single-tree treatments on volume killed at average and above-average beetle weather conditions in Morice study area (starting year: 2002).

Discussion

Our analysis of the current mountain pine beetle outbreak in the Morice and Kamloops TSAs, as well as another study in Williams Lake (Fall et al. 2003b), suggest that these outbreaks are of a moderate scale and management efforts can have a significant impact in reducing losses. That is, applying fine-scale beetle management, including small-scale blocks and single-tree treatments, and accurate treatment of spot loci are important in areas with small to medium scale outbreaks, but are less important in situations with many beetles.

Conversely, our analysis in Lakes TSA 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 it 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 m^3). 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 non-recovered losses (approx. 20%).

Uncertainty in model predictions arises from several sources. First, inventory and mountain pine beetle overview input data are not 100% accurate. Some layers such as the percentage of pine and total stand density per hectare were derived from the inventory data and regression (for unmapped areas). A second level of uncertainty involved the structure of the model itself. Like any model, the one we described is simply an approximation of reality and ongoing refinement and improvement will continue through sensitivity analysis and examination of the model projections. However, the results we presented 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.

Conclusions

These three study areas provided insight into the potential effects of various management strategies in a cross-section of outbreak conditions. The overall message is that there is a threshold of attack, below which fine scale treatments (intensive detection, fell and burn, small blocks, etc.) are warranted and above which overall focus on mitigating impacts may be better. That isn't to say that fine scale management should be completely abandoned, but rather that such management should be targeted at specific areas (e.g., woodlots). We can draw some general conclusions from the analyses we have performed:

- Beetle management can be effective to manage an outbreak provided the outbreak is below a critical threshold (e.g., Kamloops and Morice). Above this threshold (e.g., Lakes), the potential for the outbreak to expand exceeds resource capacity.
- Treatment efficacy is critical for single-tree treatments, but less so for mid-to-large clearcut blocks. Although we didn't assess partial harvesting, we expect that the underlying process is largely related to distance of residual beetles to potential hosts, and the dilution effect of increasing distance (i.e., area increases with the square of distance). Hence, the closer susceptible hosts are to a treatment, the more important it is to have a high degree of treatment efficacy.
- Increased detection capacity is only helpful in cases where detection is a limiting factor. For example, where the number of infested trees far exceeds the resources available, increased detection capacity is not helpful.
- External sources of immigration (e.g., immigration from Tweedsmuir to Lakes and Morice TSAs) are only a major factor in the early stages of an outbreak. Once established, weather factors and dynamics within management units dominate.
- Early attack (as is applied in fire suppression management) is a key approach in reducing the risk of an outbreak growing beyond containment resources.

- AAC uplift is not in itself effective at reducing mountain pine beetle populations, but can be effective at reducing non-recovered losses. That is, at relatively low outbreak levels, finer scale management (focused blocks, single-tree treatments, increased detection) is more effective. At relatively high outbreak levels, management has little potential to stop an outbreak regardless of AAC level.
- Salvage-focused management is a key tool to reduce non-recovered losses, especially in areas with relatively high outbreak levels. In such situations, management is unlikely to be able to stop an outbreak, but may have more opportunities to reduce losses.
- Forest policy (e.g., forest practices code policies) does not appear to hinder the overall efficacy of mountain pine beetle management activities.
- High quality overview mapping surveys are crucial to applying spatial modelling as a decision-support tool. The ability to project with any degree of certainty rests largely on inventory mapping and outbreak mapping.
- Weather and climate are key drivers in outbreak growth rates. In these analyses, we only assessed historic mean *vs.* above average (more current) weather conditions. Further work is ongoing to link mountain pine beetle outbreak assessments with climate change research as part of the CFS Mountain Pine Beetle Initiative.
- Applying and extending these results to other areas can be done in three ways. The simplest is to assess if an area is similar to one of the study areas presented and consider the general recommendations and trends. The most complex would be to adapt and refine this modelling methodology to a new study area. A third option is part of two other CFS Mountain Pine Beetle Initiative projects. At a finer landscape unit scale, we are developing methods to assess likely impacts and interactions of mountain pine beetle and management under a range of potential host and outbreak conditions. This will produce a key that can be accessed using a given landscape unit. At a broader scale, work is currently being done to make a projection of the current outbreak at the scale of the entire province.

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