Comparing the impacts of mitigation and non-mitigation on mountain pine beetle populations

Sam B. Coggins*[1], Nicholas C. Coops[1], Michael A. Wulder[2], Christopher W. Bater[1], Stephanie M. Ortlepp[2]

1- Department of Forest Resources Management, University of British Columbia, Vancouver, Canada.

2- Canadian Forest Service (Pacific Forestry Centre), Natural Resources Canada, Victoria, British Columbia, Canada.

(*) corresponding author:

Sam B. Coggins

Phone: (604) 822 6452, Fax (604) 822-9106, *Email: scoggins@interchange.ubc.ca*

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Abstract

Mountain pine beetles, *Dendroctonus ponderosae* (Hopkins) attack and can ultimately kill individuals and groups of pine trees, specifically lodgepole pine (*Pinus contorta* Dougl. ex. Loud var. *latifolia* Engl.). In British Columbia, beetle attack has increased from 164 000 ha in 1999 to over 13 million ha in 2008. Mitigation efforts can play a key role in addressing the impact beetle infestations can have on the forested landscape. In this research, the impact of mitigation on a mountain pine beetle infestation is examined within a network of 28 research plots where sanitation harvesting was completed (10 mitigated plots) and not completed (18 unmitigated plots). Three forest stand level modelling scenarios which predict the number of attacked trees, based on current infestation within the plots, were utilized to compare the differences between mitigated and non-mitigated plots. In the first scenario in the non-mitigated plots, 125 trees were infested after 10 years, while in the mitigated plots no trees were infested in the same time period. The second scenario indicates the level of mitigation required to suppress beetle infestations where the proportion of mitigated trees was calculated for each plot by counting the residual attack and the number of mitigated trees. The average mitigation rate over all plots of 43% (range 0 – 100%) is not sufficient to provide control. In the non-mitigated plots, the average population expansion rate was 5 (range of 0 to 18) which requires a detection accuracy of 74% to reliably detect infestation. The third scenario estimated the length of time required for ongoing detection, monitoring, and mitigation to bring an infestation under control. If mitigation efforts were maintained at the current rate of 43%, the beetle population would not be adequately controlled. However, when aided by continued detection and monitoring of attacked trees, mitigation rates greater than 50% are sufficient to control infestations, especially with persistent implementation, aided by continued detection and monitoring of infested trees.

Keywords: mountain pine beetle; mitigation; population modelling; western Canada; lodgepole pine; field observations.

1. Introduction

1.1 The impact of mountain pine beetle infestations

The mountain pine beetle, *Dendroctonus ponderosae* (Hopkins) is a bark beetle that aggressively attacks and causes mortality of pine trees (*Pinus* spp.). The natural range of the insect extends from northern Mexico, through the western United States and into western Canada. Infestations are of particular concern in British Columbia, Canada, where in 1999 beetle damage was observed over an area of 164 000 ha of lodgepole pine (*Pinus contorta* Dougl. ex. Loud var. *latifolia* Engl.), which has now spread to 13 million ha in 2008 (Westfall and Ebata 2008). Mountain pine beetle infestations increase rapidly due to increasingly warm winters (Stahl et al. 2006; Macias Fauria and Johnson 2009) and the availability of susceptible host, those stands with a mean stem diameter larger than 15 cm, greater than 80 years of age, and with a stocking density between 750 and 1000 stems per ha are estimated to be the most susceptible (Shore and Safranyik 1992). Due to recent aggressive fire suppression in British Columbia, large areas of even-age mature lodgepole pine forests are present, which coupled with a warming climate provide a suitable environment for mountain pine beetle infestations initiate, expand, and cause extensive levels of tree mortality (Safranyik 1978; Taylor et al. 2006). Under regular climate conditions, larvae overwintering beneath bark experience mortality when temperatures drop below -40°C (Safranyik 1978; Wygant 1942) which diminishes the potential number of attacking beetles. Temperatures across western Canada have increased in the last century (1895 – 1995) by as much as 1.7 °C (Déry and Jackson 2005), resulting in higher survival rates and enabling a higher proportion of beetles to survive and attack susceptible host trees (Raffa et al. 2008). As a result of increasing temperatures, infestations occur at higher elevations and in areas that have no historical record of mountain pine beetle attack (Logan and Powell 2001). For instance, attack is thought to have expanded as small pockets of infestation in areas previously kept stable by cold weather (Macias Fauria 2006) and dispersing beetles are thought to have traversed the Rocky Mountains to impact the pine forests of western Alberta, and could potentially spread further eastwards and infest the Canadian boreal forest, an area where mountain pine beetle infestations have not been previously recorded (Carroll et al. 2004). The capacity for mountain pine beetle to thrive and subsequently spread in the boreal remains to be determined. Jack pine, the dominant pine species of the boreal, has been shown in some circumstances to support mountain pine beetles (Cerezke 1995). Further, the jack pine of the boreal is not as spatially contiguous as the pine forests of British Columbia and western Alberta also favoring a situation where spread will not be so rapid or upon such a high proportion of forests present. Although population development and subsequent spread has not been demonstrated in jack pine, mortality has been caused to lodgepole pine x jack pine hybrids near Grande Prairie, Alberta (Rice and Langor 2009). If infestation were to spread to jack pine it would be disastrous for the ecological, economical, and social values in the boreal (Ono 2004).

Attack by mountain pine beetles on trees causes the crown foliage to fade from green (green attack) to red (red attack) over a period of approximately 12 months (Wulder et al. 2006). Approximately 12 months after attack 90% of trees will have red needles, which eventually fall from the tree. Approximately three years after attack trees are often completely defoliated (Wulder et al. 2006). Areas undergoing the early stages of infestation are characterized by the presence of red crowns and are likely associated with green attack trees (Wulder et al. 2009a), as when beetles emerge from previously attacked hosts they typically disperse less than 30 m (Safranyik et al. 1992) before attacking adjacent trees (Mitchell and Preisler 1991). Up to 0.2% of beetles disperse from the stand and travel on warm air thermals hundreds of metres, sometimes, hundreds of kilometres to infest stands (Safranyik et al. 1992). The association between green and red attacked trees is commonly expressed as a ratio or an expansion factor, for example, 2:1 (green:red) or an expansion factor of 2. Common expansion factors during the current outbreak reach 5 in southern British Columbia and 2 in northern British Columbia (British Columbia Ministry of Forests and Range 2002).

Historically, the area infested by mountain pine beetle has been halted by successive years of cold temperatures during winter. Mortality can also be expected during unseasonably cold weather, prior to the overwintering stage larvae that have not developed sufficient cold-hardiness can be killed during a cold snap. Similarly, mortality may also be experienced during spring, prior to emergence, should temperatures be unseasonably cold (Wygant 1942). To instigate effective control of mountain pine beetle infestations hazard and risk rating systems can be used to determine which stands are susceptible to attack (Fettig et al. 2007). Alternatively, in stands experiencing attack, mitigation tactics are implemented. Trees are best removed while beetle populations are low, and attack is infrequent and has not begun to rapidly expand. Areas where mitigation work has been completed should be monitored annually to ensure all attacked trees were removed (i.e. no red attack is visible) and infestations levels remain low.

1.2 Objectives

To better understand mountain pine beetle attack we examine the impact of infestations in a network of mitigated and non-mitigated plots in western Canada using field-based observations. The efficacy of mitigation is demonstrated using a suite of simple population models (described by Carroll et al. 2006) and mitigation is applied by removing a proportion of the infested trees. We first provide a summary of the types of mitigation available to forest managers. We then utilize the population models that use expansion factors to demonstrate how rapidly infestations expand, predict the number of trees affected, estimate the proportion of trees required to be treated to control infestations, and allow calculation of the length of time mitigation must persist to be effective. The models are used to demonstrate the differences in the spread of infestation under different mitigation scenarios using stand conditions derived from field data. In this paper we demonstrate three modelling scenarios, the first simulates the spread of infestation in mitigated and non-mitigated plots over time, the second demonstrates the mitigation levels required to control the current infestation in the non-mitigated plots, and the third examines the duration that mitigation must continue to ultimately halt the infestation. The effectiveness of current mitigation activates is also examined. Finally, we provide recommendations to improve the efficacy of future activities and examine the consequences of leaving infested trees in a given stand.

2. Summary of mitigation techniques

Mitigation techniques aim to remove either selected infested trees or all trees attacked an infestation (Carroll et al. 2006). Mitigation strategies can be either indirect or direct; the former is also known as preventive management (Whitehead et al. 2006) and consists of silvicultural techniques that create unfavourable conditions for beetle attack, or employ prescribed burns to reduce stand susceptibility to infestation (Shore et al. 2006). Direct control consists of removing green-attack trees to decrease the number of beetles that are available to infest trees in successive years, and is initiated after beetles have infested a given stand. For direct and indirect mitigation tactics to be effective timely detection, accurate susceptibility and risk assessment, and access to infestations are important considerations when selecting the appropriate mitigation tactic or combination of tactics (Coops et al. 2008; Shore et al. 2006). Six direct and indirect tactics are used to manage mountain pine beetle infestations (defined by Maclauchlan and Brooks 1998), tactics 1-3 are considered direct control and 4-6 are indirect. 1) Survey and assessment determines where infestations are in the landscape using fixed wing aircraft, aerial photography, and ground surveys to locate infestations and then provide an estimate of susceptibility to attack using a hazard and risk rating (Shore and Safranyik 1992); 2) Harvesting, which aims to reduce infestations by removing attacked trees (sanitation), provide revenue by logging dead trees (salvage), reduce attack hazard by removing high hazard host trees where pine trees older than 80 years with a stem diameter greater than 15 cm are most susceptible, and priority is assigned to harvest stands, where beetle attacked stands are most important; 3) single tree treatments remove individual trees or small groups (<2 hectares) where newly infested trees are treated with monosodium methane arsenate or can be removed using fall and burn where trees are felled and then burned, alternatively bark is removed from the trees to expose the life stages beneath the bark and cause mortality, insecticide can be used to prevent trees from being attacked, but is usually restricted to campsites, urban areas, and other specialized circumstances as it needs to be repeated annually and would be prohibitively expensive if applied to forest stands; 4) Baiting techniques, where pheromone baits are used to attract attacking beetles to trees which can then be removed or repel beetles from valuable stands. Baiting is often used in conjunction with single tree treatments, after baited trees are attacked they are felled to cause mortality to the beetles beneath the bark; 5) Beetle proofing (stand thinning), reduces susceptibility to attack by removing basal area or trees with thick phloem, which are thought to be selected preferentially so life stages may survive cold winters. This tactic also prevents beetles from attacking forest stands by spacing the trees to increase wind speed and temperature in the stand, and increasing tree vigour where vigorous trees are thought to be more resistant to attack (Whitehead et al. 2006). The minimum tree spacing recommended is 3.5 m with a maximum of 5 m, while optimal spacing is between 4 and 4.5 m; 6) Silvicultural treatments which include: species manipulation, where a mosaic of tree species is encouraged to grow to lessen the proportion of host tree in stands (Fettig et al. 2007), and; age class manipulation, by dividing the stands into age classes the long-term susceptibility of the forest will be decreased.

In British Columbia, in order to implement control and to measure the efficacy of mitigation, forest health surveys are conducted to assess the severity and extent of infestations. Typically, infestations are detected and monitored using a top-down hierarchy consisting of aerial and ground surveys. In British Columbia, annual province-wide aerial overview surveys are used to assess the severity and extent of infestations, and are intended to provide a broad overview of forest health conditions and aid in wide-area strategic decision making. Areas of interest identified during aerial overview surveys can later be targeted by helicopter surveys to record the location and number of red-attack trees. Lastly, in areas deemed at highest risk, ground crews may be dispatched to locate, fell, and burn newly attacked trees (Maclauchlan and Brooks 1998). Given the nature of newly infested trees close to those that were previously attacked, it is possible that trees missed by aerial surveys will be detected on the ground, reducing the potential for future infestation expansion (Carroll et al. 2006; Coggins et al. 2008).

Mitigation of attacked trees is often not fully effective as infested trees can be difficult to detect, necessitating ongoing annual monitoring to track the severity and extent of infestations (Coops et al. 2008). If a low proportion of trees are mitigated (i.e., less than 50%) infestations continue to expand to cause mortality to trees (Carroll et al. 2006). Mitigation of infested trees should remove a proportion that is equal to, or higher than, the rate of infestation to cause a beetle population to decline or remain stable. If mitigation consistently causes a decline in population numbers, populations could be extirpated and attack could eventually be halted (Carroll et al. 2006). For mitigation to be fully effective it should be rapid and continuous (Carroll et al. 2006; Coggins et al. 2008). Trees remaining after mitigation that contain viable populations of beetles support infestation development and spread. If mitigation is effective, attack from within the stand should not occur because the attacking population is removed when the trees are felled and burned.

The most important step when beginning a mitigation program is to detect all the infested trees and provide the locations of these trees to ground crews who can remove attacked trees and reduce the insect population (Carroll et al. 2006). Mitigation carried out with ground surveys must be completed at the appropriate time of year, after beetles have dispersed, and should be completed as the larvae overwinter beneath the bark (Maclauchlan and Brooks 1998). Flight times are influenced by temperature as beetles rely on heat accumulation to develop (Safranyik 1978) and the approximate flight time can be estimated in day degrees calculated from weather data collected on site and this should be accounted for when planning mitigation surveys (Macias Fauria and Johnson 2009).

2. Methods

2.1 Study area

This research was conducted using a network of plots in forests situated on the border of British Columbia and Alberta, which represents the edge of the current infestation (Figure 1). This location is representative of economically valuable forest stands in this area. The topography within the study area consists of high-elevation (1800 m) mountainous regions, mid-elevation forests (1200 m), and some low-elevation prairie land (900 m). The forested areas are dominated by mature lodgepole pine occasionally mixed with black spruce [*Picea mariana* (Mill.) BSP] which grow on valley sides. Subalpine fir [*Abies lasiocarpa* (Hook.) Nutt], western larch (*Larix occidentalis* Nutt.), and a large proportion of black spruce grow in flat areas, around swamps and on river banks.

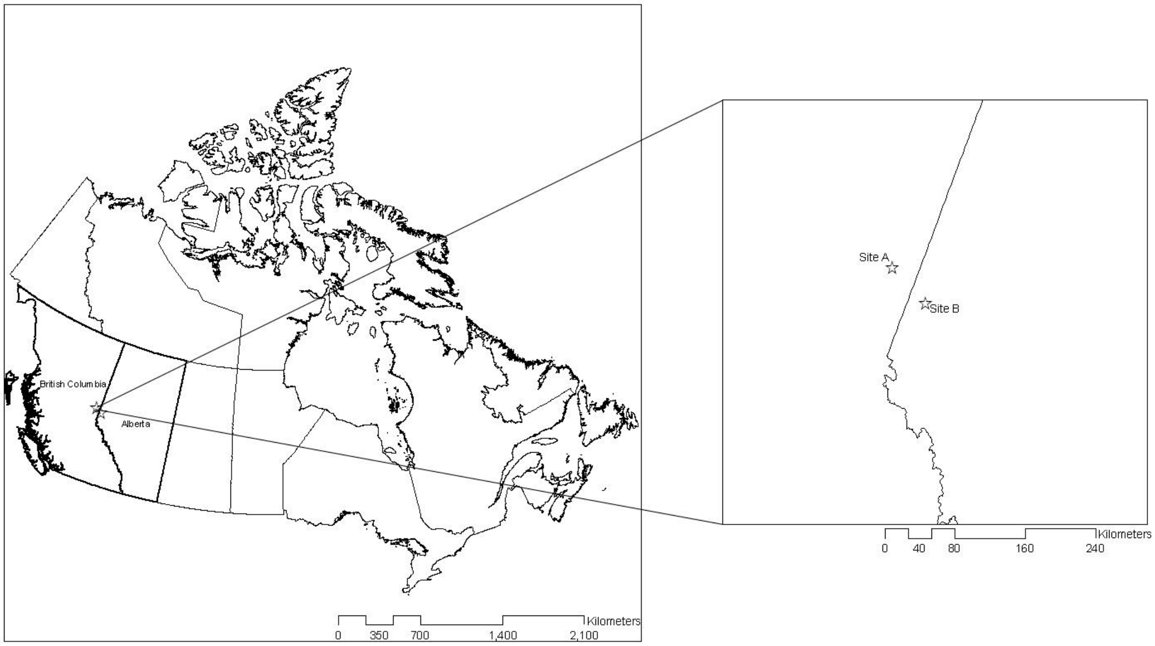

Figure 1. Study plot location, Site A indicates where the centre of each of the non-mitigated plots, Site B indicates the location of the mitigated plots.

Lodgepole pine naturally regenerated following fires in the early part of the 20th Century, which resulted in even-aged, pine dominated stands that grow to uniform dimensions (Moir 1965) as is typical of many lodgepole pine forests. The lodgepole pine present in the area was considered to be susceptible to mountain pine beetles due its proximity to the infestation spreading north and east across British Columbia, and because the majority of trees are larger than 15 cm in diameter. When combined with elevation and stand age, these conditions were favourable to the continued spread of the mountain pine beetle infestation (Shore and Safranyik 1992; Shore et al. 2000).

2.2 Study plots

A network of 28 study plots were established in the study area, and were centered in areas known to contain mountain pine beetle attack (n = 18; located at 120° 34' 54") or where mitigation of infested trees had been completed (n = 10; located at 119° 42' 54"). Each plot had a 30 m radius, which corresponds to the expected distance beetles have been observed to disperse (Safranyik et al. 1992). Plots were chosen that share similar attributes, similar slope, aspect, stem diameter, stocking density, and proportion of host trees (Table 1). In the plots subject to mitigation activity, trees undergoing attack have been removed since 2005 using the fall and burn strategy, where green attacked trees are felled and burned on site. Field work for all plots was undertaken in August 2008, and at each plot the total number of trees was counted and the mountain pine beetle attack status recorded according to foliage colour (healthy, green attack, and red attack). In all plots, infestation expansion factors were calculated for 2008 using the attack status of trees. In the mitigated plots, the health status of attacked trees and the number of trees within each attack class was recorded along with the number of tree stumps, which indicated the number that were felled and burned. The total infestation (red attack plus stumps) was calculated for each plot to determine the number of infested trees prior to mitigation. The number of stumps was divided by the total number of trees infested to generate the proportion of trees mitigated. For this research we assumed that the inverse indicates the proportion of infested trees remaining undetected during mitigation in each plot or trees that had been attacked after mitigation took place. The average mitigation was calculated for all plots to determine the efficacy of mitigation.

Table 1. Stand characteristics and measurements within the study sites.

	Site A	Site B
Aspect	South East	North East
Mean slope (degrees)	8.2	7.5
Mean stocking density (trees per plot)	213	245
Mean stem diameter (cm)	25.3	20.8
Proportion of pine within stands	76%	86%
Proportion of other species within stands	23%	14%

2.3 Modelling

The models applied in this study build upon the work in Coggins et al. (2008), who examined the impact of mountain pine beetle infestations across a range of forest stands under differing infestation intensities using three population modelling scenarios with hypothetical expansion factors. The population-scale modelling scenarios adapted from Carroll et al. (2006) were again utilized in this research to assess the impacts of mountain pine beetle infestations on forest stands with expansion factors generated from field observations. These models are stand level and therefore, we assume migration is from the trees infested within the stands only and do not account for long-range dispersal by beetles into these stands. Further, long range dispersal is highly stochastic and not appropriately added to models such as this at this time. A non-zero infestation level can likely be assumed for any susceptible pine stand known to be in an eligible catchment for long-range dispersal. The first investigated the potential spread of infestation in the mitigated and non-mitigated plots. Infestation expansion factors were calculated for each of the mitigated and non-mitigated plots by calculating the ratio of green attack to red attack trees observed during the 2008 field campaign. The number of green attack and red-attack trees were established in each plot and the number of red attacked trees was backcast to become the number of green attacks in the previous year (2006), following Wulder et al. (2009b). The attacked trees in 2007 were then forward cast to 2008, whereby the red attacks became grey attacked and the green attacks became red attack. The expansion factor for each plot in each year was then calculated by dividing the number of green attacked trees by the number of red attacked trees averaged for the mitigated and non-mitigated plots. To model the potential infestation, the number of green attacked trees in 2006 was projected forwards annually using the average infestation expansion factors estimated from the field data. In 2009 and thereafter, an expansion factor of 2 was utilized because this has been determined to represent the common rate of infestation expansion experienced in the study area (British Columbia Ministry of Forests, 2002; Carroll et al. 2006; Wulder et al. 2009b).

In the second scenario, we utilized the average mitigation efficacy from field data to determine whether removing attacked trees in a single time step will impact a population of attacking beetles in the long term. The proportion (*P*) of trees requiring mitigation according to the rate of population increase is defined as (Carroll et al. 2006):

$$P = 1-1/R \qquad (1)$$

where *R* is the rate of infestation expansion. In this scenario, the average mitigation accuracy was calculated from the mitigated field plots where the number of infested trees removed compared to those remaining defined mitigation accuracy in each plot, and was then used to determine whether suppression of the beetle population was possible at the current rate of mitigation. If all attacked trees are removed, the forest stand should experience no further infestation in subsequent years, with the exception of immigration from long-range dispersal. If however, attacked trees remain in the stand, the infestation may continue and should infestation expansion rates increase, attack will become more severe. Conversely, the level of detection required can also be determined if the expansion factor is known. The required detection levels for the mitigated and non-mitigated plots are derived based on average infestation expansion levels in 2007.

The final scenario calculates the length of time required for ongoing detection, monitoring, and mitigation to bring an infestation under control. In the long-term persistent mitigation may be required to reduce infestations, low-level attack may be controlled in a single time step, larger infestations are more difficult to control even when doubling (R = 2), and are dependent on persistent removal of a proportion of the attacked trees. For example, Carroll et al. (2006) describe an infestation covering 300 000 ha with R = 2, where 150 000 ha of trees must be removed each year to ensure the infestation remains stable. To remove such a large proportion of trees would be impossible if attempted in a single mitigation event (Carroll et al. 2006). The number of trees infested in a given year can be estimated using:

$$N = N_0[R(1-P)]^t \qquad (2)$$

where the number of trees initially infested (N_0), the yearly rate of increase (R), the proportion of trees treated each year (P), and the number of years (t). Estimates of R and P can determine the number of years for persistent direct mitigation as defined in Equation 1 (Carroll et al. 2006). The concept is explored to determine the time required to suppress the infested trees within the field plots. The total number of attacked trees remaining in the mitigated and non-mitigated plots were used as a baseline. The number of years required to bring the infestation under control is then estimated using the current mitigation efficacy.

3. Results

In both 2007 and 2008 the non-mitigated plots experienced higher levels of tree mortality attributed to mountain pine beetle attack than the mitigated plots, and infestations expanded more rapidly. The first scenario was run for a period of ten years, starting in 2006 with green attack trees, to provide a realistic demonstration of the progression of an infestation when mitigation is utilized versus when no control is applied to a stand. The expansion factors calculated from the 2007 and 2008 field observations were used to estimate the amount of new infestation in each of those years. In 2007 infestation expanded at a rate of 5.09 in the non-mitigated plots, and 1.35 in the mitigated plots. Attack decreased in 2008, with average expansion rates of 0.29 and 0.12 in the non-mitigated and mitigated plots, respectively (Table 2). Some plots listed as mitigated had no evidence of mitigation activities indicating they were either of low priority and had not been completed or had been assessed and were not seen as a threat to surrounding forest because there had been no expansion from these plots or because expansion was so small they were not worth mitigating at this time.

An expansion factor of 2 was used to determine the rate of infestation spread, which is similar to rates found in other studies conducted within the study area (Wulder et al. 2009b), and which was recommended by Carroll et al. (2006) and the British Columbia

Ministry of Forests and Range (2002) in northern British Columbia. After 10 years, the non-mitigated plots had an average of 125 infested trees, ranging in number from 0 to 768 (Figure 2). If infestation levels increased, more trees would be attacked over the time period, and to examine these effects the proportional increase from the average amount of infestation to the maximum in each year was calculated and used to provide a range between which infestation might fluctuate. If infestation increased there would be 146 attacked trees; however, if infestation decreased by the same proportion there would be 105 infested trees to mitigate after a period of 10 years. The mitigated plots all had 0 infested trees after 10 years because the rate of infestation after 2008 did not produce sufficient numbers of infested trees within the stand to continue attack.

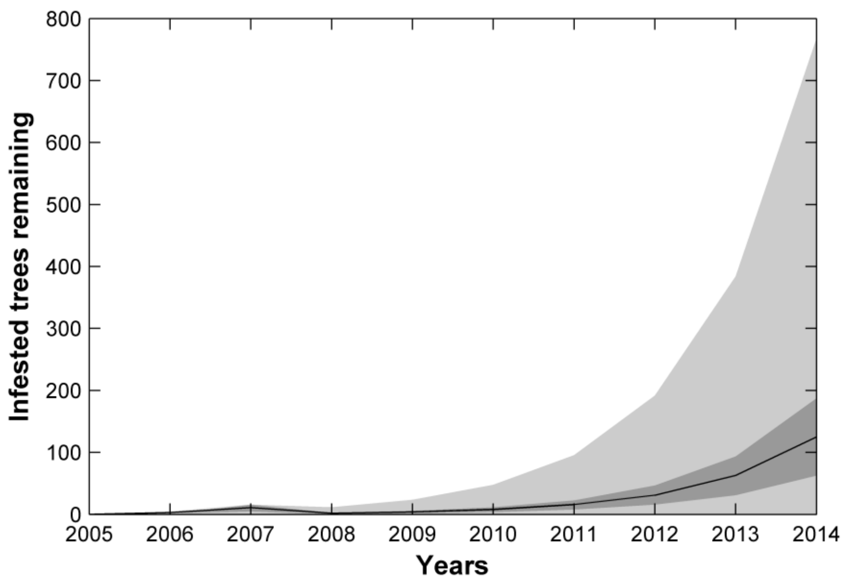

Figure 2. The number of infested trees expected to be present without mitigation using the number of infested trees in the non-mitigated plots to initiate the model and using expansion factors derived from field-based observations in 2007 and 2008, with an expansion factor of 2 used in 2009 onwards. The average infestation per year is shown by the thick black line, with the range of infestation that could be expected in each year in dark grey, and the minimum and maximum amount of infestation shown in light grey (after Carroll et al. 2006).

Table 2. Estimated expansion factors in 2007 and 2008 for each non-mitigated (top) and mitigated plot (bottom), where GA = green attack, RA = red attack, and GR = grey attack.

	2008				2007				2006	
GA	RA	GR	Expansion	GA	RA	GR	Expansion	GA	RA	GR
0	53	22	0.00	53	22	0	2.41	22	0	0
6	14	7	0.43	14	7	0	2.00	7	0	0
12	16	1	0.75	16	1	0	16.00	1	0	0
1	3	2	0.33	3	2	0	1.50	2	0	0
2	2	1	1.00	2	1	0	2.00	1	0	0
0	1	0	0.00	1	0	0	1.00	0	0	0
0	2	1	0.00	2	1	0	2.00	1	0	0
0	14	14	0.00	14	14	0	1.00	14	0	0
3	21	8	0.14	21	8	0	2.63	8	0	0
3	15	3	0.20	15	3	0	5.00	3	0	0
1	17	3	0.06	17	3	0	5.67	3	0	0
0	25	5	0.00	25	5	0	5.00	5	0	0
11	18	0	0.61	18	0	0	18.00			
6	11	4	0.55	11	4	0	2.75	4	0	0
5	19	2	0.26	19	2	0	9.50	2	0	0
4	21	3	0.19	21	3	0	7.00	3	0	0
1	3	0	0.33	3	0	0	3.00	0	0	0
			0.29				**5.09**			

	2008				2007				2006	
GA	RA	GR	Expansion	GA	RA	GR	Expansion	GA	RA	GR
0	8	3	0.00	8	3	0	2.67	3	0	0
0	0	4	0.00	0	4	0	0.00	4	0	0
0	5	4	0.00	5	4	0	1.25	4	0	0
1	0	4	1.00	0	4	0	0.00	4	0	0
1	3	0	0.33	3	0	0	3.00	0	0	0
0	8	4	0.00	8	4	0	2.00	4	0	0
0	1	3	0.00	1	3	0	0.33	3	0	0
0	4	2	0.00	4	2	0	2.00	2	0	0
0	4	5	0.00	4	5	0	0.80	5	0	0
0	4	5	0.00	4	5	0	0.80	5	0	0
0	4	2	0.00	4	2	0	2.00	2	0	0
			0.12				**1.35**			

In the second scenario, the average mitigation accuracy was used to determine how effective the current level of mitigation will be (Table 3) with an average efficacy of 43% determined (Figure 3). The average infestation expansion factor in the non-mitigated plots in 2007 was 5.1, requiring an 80% detection accuracy to maintain a static population (Figure 3). However, the uppermost range of infestation expansion in the plots was 18, which requires a detection rate of 94% (Figure 3). The average infestation expansion factor in 2007 in the mitigated plots was 1.1, which requires a minimum detection rate of less than 10% (Figure 3), with a range between 0 and 2.67.

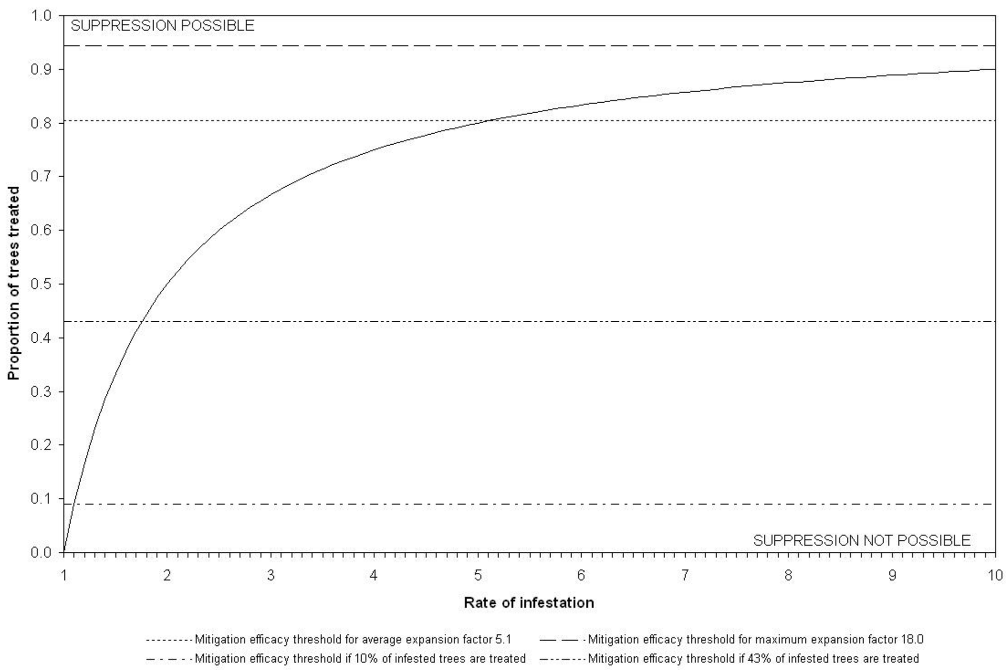

Figure 3. The minimum proportion of infested trees requiring treatment during mitigation can be calculated for the average, minimum, and maximum expansion factors in the non-mitigated plots, and for the average mitigation efficacy in the mitigated plots. The minimum proportion of infested trees requiring treatment to control an infestation expansion of 5.1 (the average expansion factor calculated) is approximately 80%. The maximum expansion rate was 18 which required a minimum of 93% of the infested trees to be treated to provide control. Infestation in the mitigated plots requires a minimum of 10% of infested trees to be treated to control current levels of infestation. The average mitigation efficacy of 43% is ineffective at controlling a doubling population (after Carroll et al. 2006).

Table 3. Mitigation efficacy determined from field observations in the mitigated plots, where GA = green attack and RA = red attack.

Plot	GA	RA	STUMP	Total RA	% mitigated	% missed
1	0	4	6	10	60%	40%
2	1	0	0	0	0%	100%
3	0	4	8	12	67%	33%
4	0	1	0	1	0%	100%
5	0	0	1	1	100%	0%
6	0	5	4	9	44%	56%
7	0	4	4	8	50%	50%
8	1	3	0	3	0%	100%
9	0	8	3	11	27%	73%
10	0	4	14	18	78%	22%

The final scenario estimated the length of time that is required to conduct ongoing detection, monitoring, and mitigation activities. The average number of red attack trees remaining in the non-mitigated stands after 10 years was 273 (approximately 15% of the total number of trees measured during the field work). The minimum and maximum numbers of attacked trees found in the plots were 64 and 768, respectively. These numbers were used as a baseline to determine the number of years required to provide control to forest stands. If the average mitigation efficacy of 43% calculated for scenario 2 is utilized, none of the infestation in the plots will be controlled effectively. If the average number of red attack trees remaining after the plots were mitigated were used as a baseline, with a 70% detection accuracy mitigation will take 11 years, at 80% mitigation will take 6 years, and at 90% mitigation will take 3 years. If the number of red attack trees started at the maximum number of red attacks found in a plot (768 trees), mitigation will take 13 years with a detection accuracy of 70%, 7 years with 80%, and 4 years with 90%. Finally, with the lowest number of infested trees found in a plot mitigation with a 70% detection accuracy will take 8 years, 5 years with 80%, and 3 years with 90% (Figure 4 and Table 4).

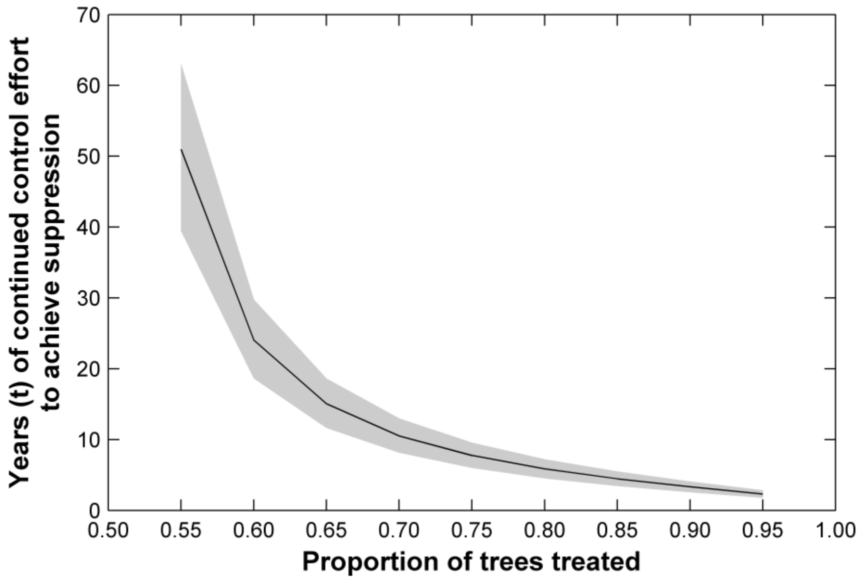

Figure 4. Number of years required to suppress infestations of mountain pine beetle using the number of red attack trees was derived from those remaining after mitigation and the expected infestation after 10 years in the non-mitigated plots. The average number of years required to complete mitigation is shown by the thick black line, with the range of infestation that could be expected in each year in dark grey, and the minimum and maximum amount of infestation shown in light grey (after Carroll et al. 2006).

Table 4. The number of years (t) required to suppress infested stands of mountain pine beetle using a range of initial infestation (N_0) and a range of detection accuracies where the number of red attack trees was derived from those remaining after mitigation and the expected infestation after 10 years in the non-mitigated plots.

	Detection accuracy		
Number of red attack	70%	80%	90%
Average	11	6	3
768 (High)	13	7	4
64 (Low)	8	5	3

4. Discussion

In British Columbia and Alberta, it is difficult to halt mountain pine beetle infestations because beetles have infested over 13 million hectares of forest. However, with persistent detection, monitoring, and mitigation, forest managers can reduce attacking beetle populations at the infestations edge and strive for control. Infestations can be halted by removing all infested trees; although, attacked trees that remain after mitigation is completed will extend the duration of the local infestation. Therefore, continued monitoring in subsequent years can detect and reduce the impact of mountain pine beetles by removing infested trees.

The three modelling scenarios employed utilise field data to demonstrate how infestations could behave if mitigation is not completed, whether mitigation is possible with current detection capabilities, and how long mitigation will be required to be completed. The first scenario suggests that where mitigation was conducted, the infestation appears to have been controlled, considering no infestation exists in 2014. However, compared to the infestation expansion in 2007, the 2008 attack appears to be minimal, which may be the result of environmental conditions. Extreme cold in the winter, as is common in the study area, may have caused extensive beetle mortality and decreased attack in subsequent years. Differences in temperature as well as the amount of infestation already present near plots influenced the levels of infestation. The maximum number of infested trees after the 10 year modelling period was 768 and an average over all the non-mitigated plots was 125 infested trees. This range demonstrates the influence by external factors such as climate, stand and tree characteristics, and beetle pressure on stands should the average number of infested trees increase or decrease by 50%. If beetle pressure is high and winter temperatures are suitable for insect development, infestation could be expected to be above average, whereas if the opposite external influences were experienced infestation levels may be expected to be lower than the average.

If a proportion of trees are felled and burned, trees are removed that contain beetles that may otherwise cause infestation. In the second scenario, the mitigated plots require a minimum of less than 10% of trees to be removed to control infestations. If more than 10% of trees are removed mitigation will be more effective at controlling attack and will lead to a shorter infestation period and consequently, over the long term, fewer healthy trees will be attacked. This scenario relies on expansion factors estimated from previous studies and does not allow for increases or decreases in population survival and lacks the ability to incorporate immigration. It is important to continue monitoring these plots to ensure mitigation has been successful and to monitor for future attacks.

The third scenario suggests that by using the average mitigation efficacy beetle infestations will not be controlled. However, if a detection accuracy of approximately 70% is achieved, infestations at all levels of severity are controlled within 15 years (Table 3). Shorter periods of time are required to control infestations if less attack is present and if the detection accuracy achieved is higher. Such information can be used to guide the need to monitor areas, although expansion factors should be taken into account, as these can fluctuate widely from year to year resulting in vastly different detection rates being required to control attack. Infestations are likely to increase rapidly if monitoring is not completed, especially if temperatures during the winter allow beetle populations to increase.

In scenarios 1 and 3, the expected variation around the average amount of infestation is given to demonstrate how infestations may change over an area. Variation may exist in some areas within a region because they will experience differences in climate or biophysical characteristics of the forest stand and trees, which influences beetles as they develop, with colder climates causing greater mortality of a brood as they overwinter beneath the bark of trees (Macias Fauria and Johnson 2009). Other areas may be closer to infested trees and the pressure from attacking beetles causes great infestation than in areas further away. There are also the physical properties of forests stands to consider, such as the presence of suitable host trees to support attacking beetles, and the proportion of host trees within the stand (Fettig et al. 2007). If forest stands contain a small proportion of pine trees compared to other species and are of small diameter they are less likely to be attacked than stands of large diameter pure pine. Whitehead et al. (2004) reviewed a number of manipulation studies describing the effects on forest stands by thinning trees. Beetle attack was significantly less if trees were spaced, than if they remained at the same stocking density because both wind speed and within-stand temperatures were increased. These effects are debated, Waring and Pitman (1985) posit that as stands are thinned, tree vigour increases and are able to more effectively resist beetle attack. Both sets of effects are outcomes of thinning and contribute towards reducing stand susceptibility and mortality due to mountain pine beetle attack (Coops et al. 2009).

The infestation expansion rates in the field plots are highly variable, suggesting that at some locations mitigation was successful and all infested trees were removed. In others mitigation was partially complete or had not been completed, which left a proportion or all previously infested trees in the plots. In some areas it may not be feasible to deploy crews until the infestation has reached a certain size, and only possible when the benefit of removing the trees is commensurate with the cost of removal. In some plots it is possible mitigation was prioritised, with higher priority given to developing infestations, once infested trees are removed mitigation is completed in areas thought to be less susceptible to attack. The biophysical characteristics of trees within the stands could also explain the variability of expansion factors. Sites with desirable features for mountain pine beetle attack (as listed by Shore and Safranyik 1992), large stem diameter, optimal stocking, greater than 80 years old, on north facing versus south facing slopes all influence the development of beetles beneath bark. Forest stands with preferred characteristics will increase the probability that beetles survive the winters and will provide a higher population of attacking beetles than other sites with less suitable host (Shore and Safranyik 1992). A second influence on the amount of expansion is temperature, some years stands experience higher temperatures than others, as a result less mortality is caused to beetle populations beneath the bark and after beetles disperse more previously unattacked trees are colonised, and infestation increases at a greater rate than in colder years. Temperature fluctuations over the year can explain some of the temporal variability found in our study sites; where beetles emerge and disperse late in the year in these areas due to colder weather which slows development. In previous years, winter temperatures had not become cold enough to cause mortality and supported the development of life stages, allowing infestations to increase once adult beetles emerged, dispersed, and colonised. However, it appears that recently most life stages did not become cold hardy to winter temperatures and were killed beneath the bark due to a colder winter which caused a decrease in the level of infestation. If subsequent years experience warmer winter weather infestations are expected to increase, but will decrease if winters continue to be cold.

Mitigation should concentrate on areas with higher infestation severity in forest stands where healthy trees have susceptible characteristics, such as stands older than 80 years with large diameters. The average mitigation efficacy is currently too low to provide control of doubling infestations, and will not control population expansions experienced in the non-mitigated field plots with a single treatment. We found a range of infestation expansion factors. At the uppermost expansion factor of 18, over 90% of trees currently infested by mountain pine beetle need to be removed to bring a population under control. Detection accuracy to this extent is not likely; however, expansion factors of this level appear to be extreme, with factors of near 3 being more common and more easily controlled. Once beetle pressure builds in an area, mitigation intensity will have to increase to ensure the attacking population is controlled effectively and economically. In other areas outside the study area, expansion factors may be greater and will give greater chance for the infestations to expand because beetle pressure will be higher.

Persistent monitoring and detection is required to provide continued management to mountain pine beetle infestations, unless mitigation is 100% effective (Carroll et al. 2006; Coggins et al. 2008). Even so, dispersing beetles from nearby (or distant) infestations may attack trees within the stand and cause further damage. Furthermore, if susceptible trees remain within the stand (pine trees, with a stem diameter greater than 15 cm and older than 80 years) a higher likelihood of being attacked exists than for stands that do not share these known susceptibility characteristics. Mitigation is required not only on Crown land in British Columbia, but also on private land, in parks, and remote areas where infestations may flare up unnoticed or may be left uncontrolled. The aerial overview surveys performed each year monitor the amount of infestation over the province (Wulder et al. 2009c), however mitigation activities are subject to certain constraints. The first being the financial constraint to private land owners, locating and removing trees before infestations become too large to control can be costly; secondly, access to infestations within parks has been restricted until recently allowing infestations to build and populations to increase unabated and provide a source of beetles to stands outside the park where land owners are attempting to control beetles; lastly, in infestations are not easily detected in remote areas where infestations due to sheer size of land to be covered and further research is required to provide accurate geographic locations of small infestations before they become larger. Infestations in each of these areas provide a viable source of beetles which given adequate climatic conditions and suitable host will disperse and expand infestations. Therefore, it is necessary to monitor these areas also, to determine how much infestation is present and to ascertain the risk to surrounding forest from dispersing beetles.

5. Conclusion

Mitigation is a vital strategy to control infestations of mountain pine beetle in western Canada. Using field observations to initiate modelling scenarios, we demonstrated a current level of mitigation achieved may not be sufficient to control mountain pine beetle. As such, we recommend that detection rates of 50% or greater are used to control doubling populations of mountain pine beetle. The average infestation expansion rate estimated in this study area was 3.8 in non-mitigated plots, requiring a detection accuracy of 73%. In mitigated plots, expansion rates were 1.1, requiring a minimum detection accuracy of approximately 10% to begin to decrease infestation spread. Considering infestations can expand at a rate of 18, mitigation rates should be effective to control very high rates of spread. When determining an appropriate detection accuracy, it should be considered the uppermost range in the expansion factors in this study was a population expanding at 18 newly infested trees for each previously attacked tree. The consequences of not completing mitigation at the edge of the infestation would be that stands experiencing the early stages of attack will increase to the point where mitigation becomes uneconomical to be completed and therefore, persistent detection, monitoring, and mitigation should be completed to ensure infestations do not spread. The models could be expanded to include a variable for climate change, increasing temperatures would allow a more beetles to survive winters and would cause increased expansion factors. At present the models used are based on current expansion factors, we hope the range of expansion factor provided demonstrate the scale infestations may increase to if left uncontrolled. At present these models only account for dispersal from within the stands, an adjustment for long range dispersal by beetles could also be added. Either of these variables require the expansion factors to increase to account for higher number of beetles attacking the stands.

Further research is needed to provide detection and monitoring over remote areas, private forest, and other inaccessible land. Remote sensing applications could be used to detect and monitor infestations and can also provide estimates on other variables such as forest composition, stand age, stocking density which together can be used to calculate susceptibility. Another advantage of using remotely sensed data would be to improve the model by adding a spatial component to produce realistic, spatially exhaustive, results of infestation expansion and severity.

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