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Alternative approaches for integrated area-wide management of the mountain pine beetle epidemic in Alberta.

Final report for fRI Research project 246.30

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Executive Summary

In 2013, we undertook a project to evaluate the efficacy of Mountain Beetle Management (MPB) management in Alberta. The primary objective was to determine the effectiveness of current direct control efforts at slowing the spread of MPB in comparison to alternative strategies, one of which included 'do nothing'. The work was conducted in two phases comprising three distinct activities. In Phase 1, (i) a model was developed to predict the productivity of MPB in relation to forest, climate and topographical conditions (*r*-model), and (ii) the efficacy of single tree removals (level 1 treatments) to reduce local MPB populations was directly assessed. In Phase 2, the *r*-model, control efficacy assessment, data regarding clear cutting to remove MPB (level 2 treatments), and forest inventory data, were combined, (iii) to develop a spread model (MPBSpread) to evaluate the relative impact of the current versus alternative control strategies at slowing the spread of MPB across a section of north-central Alberta.

This report is the result of a follow-up project initiated in 2017, utilizing MPBSpread and focusing on improving system resilience to the developing outbreak, broadening treatment options, and enhancing adaptive capacity, at a much broader scale. To that end, project objectives were: (a) predict whether the current reactive approach to MPB control can prevent the beetle's eastward spread across Alberta's pine forests. The principles and procedures developed in the earlier work were applied to only a very small landscape; this analysis is now expanded to the northern half of Alberta; (b) model the efficacy of proactive management strategies where the principal hypothesis is that a primary factor controlling the rate of MPB spread is landscape connectivity; and (c) develop a decision support tool (DST) to evaluate costs, tradeoffs, and outcomes.

The analysis is presented as a series of key questions (see below). These are integrated within the DST, which is currently available at https://bradseely99.wixsite.com/website. (Please note that the DST will be moved to http://fidel.forestry.ubc.ca and made available to the public pending approval by fRI Research). The key questions addressed in this project were:

1. **In the absence of control, will MPB spread across Alberta?**

Without ongoing controls, MPB is likely to colonize a substantial portion of Alberta's pine forests over the next several decades.

2. **Will climate change exacerbate spread?**

Under climate change, the probability of a colonization event over the next two decades is elevated in all regions of Alberta.

3. **When will MPB reach Saskatchewan?**

Model output indicates that, over the next 10 years, depending on climate conditions, much of Alberta's central region will be colonized by MPB, including the eastern border with

Saskatchewan. We derive an emigration index that strongly suggests that beetles will spread into Saskatchewan.

4. **Does the slow-the-spread (StS) strategy work?**

The control tactics employed by the Government of Alberta will significantly reduce additional pine mortality within Alberta, as well as the risk of extra-provincial spread, as compared to no control efforts.

5. **What effect will reducing StS have on spread?**

Area colonized by MPB by 2038 increased by 56% when level 1 controls were reduced to 35% of StS; however, this was still substantially below the 'no control' option. In terms of avoided volume losses, StS had the greatest impact (128 million m^3); at 70% and 35% of StS, avoided volume losses decreased by just 7% and 27%, respectively. Net present value of controls by 2038 decreased only marginally at 70% of StS but was markedly lower at 35% of StS.

6. **Would spread continue if StS was reduced before MPB collapse?**

If StS was reduced, the termination date is important in limiting beetle spread. If controls are terminated in 2020, area colonized increases rapidly while avoided volume losses reaches a plateau (at 74 million m^3). Delaying termination to 2025 lowers the increase in area colonized. Early abandonment thus risks a much greater spread of MPB.

7. **What if controls were implemented in the opposite direction to StS?**

Implementing the current 'leading-edge' (east to west) StS policy is more effective at limiting the spread of MPB than if controls had been implemented in the opposite direction (i.e. west to east, against "source" populations). Employing either control strategy offers considerable benefits over no control.

8. **Is there an end in sight - what does the future hold?**

Under the full StS strategy, the peak in area colonized is reached earlier (year 2025) and at a lower point than when StS is scaled back to 70% (year 2026), or 35% (year 2028). Regardless of which control strategy is employed, however, on average the MPB infestation in Alberta is expected to continue until at least year 2035.

9. **How 'connected' is the pine landscape?**

Given what is known of MPB dispersal capabilities, a connectivity analysis indicated that a majority of the Alberta landscape likely constitutes a single, interconnected habitat patch. This suggests that if population growth continues unabated, MPB should have little difficulty in colonizing all areas of the province, and beyond.

10. **Can pine habitat 'connectivity' be impaired enough to disrupt the spread of MPB?**

Area colonized by MPB was always reduced after habitat was removed to reduce connectivity. The treatment **effect** was not substantial, however, and likely reflects the fact, as a proof-of-concept test, only a relatively small area was subtracted from the available pine cells.

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Introduction

Among the impacts of a warming environment are shifts in the distribution of mobile organisms (Parmesan 2006, Musolin 2007, Deutsch et al. 2008), both range expansions (Parmesan et al. 1999, Hickling et al. 2005, 2006) and contractions (Wilson et al. 2005). Range shifts by herbivorous insects capable of eruptive dynamics are of particular concern, especially in forest ecosystems with evolutionarily naïve host-tree populations or species. Widespread growth loss and/or mortality of host plants could threaten the resilience of these systems and fundamentally alter their structure and function (Raffa et al. 2008).

The mountain pine beetle (*Dendroctonus ponderosae* Hopkins, hereafter MPB) is a case in point. As an eruptive forest insect native to the pine forests of western North America, it is an aggressive bark beetle that feeds and reproduces within the phloem of its host trees. Successful colonization by MPB is conditional upon the death of the tree (Safranyik and Carroll 2006). Although it breeds successfully in most species of pine, lodgepole pine (*Pinus contorta* var. *latifolia*) is the beetle's main host through most of its range (Safranyik and Carroll 2006). Population outbreaks have been recorded during the past century in western North America (Taylor et al. 2006). The most recent outbreak, however, has exceeded previous episodes in size and severity by at least an order of magnitude. Since its beginning in the mid-1990s, MPB has caused the mortality of trees over approximately 20 million ha [ca. 16 million ha in Canada (Westfall and Ebata 2014), and 4 million ha in the US (USDA Forest Service 2014)].

This unprecedented outbreak is, in part, due to climate change-induced range expansion (Carroll et al. 2004; Safranyik et al. 2010; Sambaraju et al. 2012). MPB has historically been restricted to areas west of the Rocky Mountains and south of latitude 56° N (Safranyik and Carroll 2006). Lodgepole pine distribution, however, extends north into the Yukon and Northwest Territories and east across much of Alberta, where it hybridizes with jack pine (*Pinus banksiana*), another viable host for MPB (Figure 1; Cullingham et al. 2012). The ability of MPB to expand into these areas was limited by climate (Carroll et al. 2004; Safranyik et al. 2010). In recent decades, a warming climate has relaxed restrictions to MPB distribution (Carroll et al. 2004; Safranyik et al. 2010) and since 2002, populations have breached the northern Rocky Mountains and begun to spread across Alberta towards the boreal forest (Nealis and Cooke 2014).

Between 2006 and 2019, Alberta spent approximately $500 million on direct control efforts to slow the spread of MPB, and yet the efficacy of these efforts was unknown. It may be, for example, that control efforts are largely ineffectual and that resources may be better spent in mitigating the long-term impacts on the industry and the resource. Decision-makers need to understand the effectiveness of the management strategies and tactics implemented to date and their potential efficacy in the future.

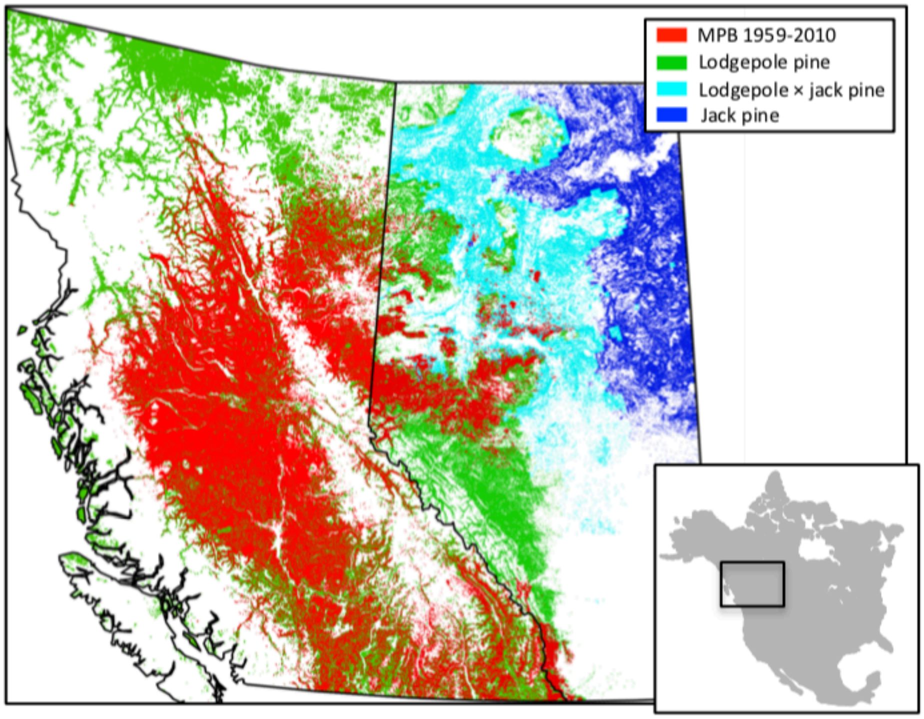

Figure 1. Pine species distributions in western Canada according to genetic markers (Cullingham et al., 2012), as well as the cumulative distribution of mountain pine beetle (MPB) infestations.

In 2013, we initiated a project to evaluate the efficacy of MPB management in Alberta. Our primary objective was to determine the effectiveness of current direct control efforts at slowing the spread ('StS') of MPB in comparison to alternative strategies, one of which included simply 'do nothing'. The work was conducted in two phases comprising three distinct activities. In Phase 1, (i) a model was developed to predict the productivity of MPB in relation to forest, climate and topographical conditions (*r*-model), and (ii) the efficacy of single tree removals (level 1 treatments) to reduce local MPB populations was directly assessed. Phase 2 combined the *r*-model, control efficacy assessment, data regarding clear cutting to remove MPB (level 2 treatments), and forest inventory data, to (iii) develop a spread model (MPBSpread) with which to evaluate the relative impact of the current versus alternative control strategies at slowing the spread of MPB across a portion of north-central Alberta[1].

[1] Carroll, A., Seely, B., Welham, C., Nelson, H. 2017. Assessing the effectiveness of Alberta's forest management program against the mountain pine beetle. Final report for fRI Research project 246.18 parts 1 and 2. (https://friresearch.ca/sites/default/files/MPBEP_2017_07_%20Control%20Efficacy%20report_0.pdf).

This report is the result of a follow-up project initiated in 2017, utilizing MPBSpread and focusing on improving system resilience to the developing outbreak, broadening treatment options, and enhancing adaptive capacity, at a scale encompassing the entire province. To that end, project objectives were: (A) Predict whether the current reactive approach to MPB control can prevent the beetle's eastward spread across Alberta's pine forests. The principles and procedures developed in the earlier work were applied to only a very small landscape; this analysis is now expanded to the entire northern half of Alberta. In addition, the StS strategy focuses on treating stands, beginning with the 'leading edge', and then moving in a westerly direction into the main region of beetle occupation. A majority of resources is therefore expended in eliminating new colonization events at the forefront of the infestation. A shortcoming of this policy is that a substantial buildup of the MPB population might occur behind the leading edge, thereby fuelling further spread as these beetles migrate eastward. The MPBSpread model was used to assess this idea by reversing the order of control efforts. In that regard, treatments were initiated at the western edge of the epidemic against potential "source" populations, and then in an easterly direction towards the leading edge. (B) Model the efficacy of proactive management strategies. The principal hypothesis is that a primary factor controlling the rate of MPB spread is landscape connectivity. Percolation theory provides a useful framework for quantifying connectivity in spatially structured systems (Stauffer and Aharony 1985), and much of its ecological application has been in understanding habitat loss and species conservation (With 2002, Oborny et al. 2007). Controlling the MPB epidemic, in contrast, is predicated on the successful *removal* of suitable breeding habitat, along with *increased fragmentation* (i.e., reduced connectivity). MPBSpread was used in conjunction with percolation metrics to ascertain where habitat might be removed prior to infestation to enhance resistance against beetle spread. (C) Develop a decision support tool (DST) to evaluate costs, tradeoffs, and outcomes.

The analysis is presented as a series of key questions. These are integrated within the DST, which is currently available at https://bradseely99.wixsite.com/website. (Please note that the DST will be moved to http://fidel.forestry.ubc.ca and made available to the public pending approval by fRI Research). The key questions are:

1. In the absence of control, will MPB spread across Alberta?
2. Will climate change exacerbate spread?
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7. What if controls were implemented in the direction opposite to StS?
8. Is there an end in sight - what does the future hold?
9. How 'connected' is the pine landscape?
10. Can pine habitat 'connectivity' be impaired and disrupt the spread of MPB?

Methods

Dataset development

Alberta vegetation inventory (AVI) data and Digital Elevation Maps were obtained for the province from government sources[2] and through data sharing agreements with industrial forestry partners. The AVI data were overlain on the Canadian Forest Service National Forest Inventory dataset[3], and forest stand attribute data extracted from the combined dataset using standard techniques. These stand attributes were the percentage of susceptible pine basal area, and stand age and density; important factors in MPB colonization (Shore and Safranyik 1992; Shore et al. 2000). They form the basis for calculation of a stand susceptibility index (SSI; Shore and Safranyik 1992) that has seen wide application in support of management decisions. The SSI contains a "location factor" to account for variation in MPB reproduction in relation to elevation, latitude and longitude. A modified version of this element of the SSI is included in the MPBSpread model (see below).

A combination of aerial and point survey data are collected annually by Alberta Agriculture and Forestry (AAF) to document the current status of the MPB infestation, and for management planning and control. This information was used to calibrate the MPBSpread model by inputting the locations of red-attack trees within a cell and the amount of associated green-attack trees, for the year 2008, the starting year of the simulations. Model simulations (see below) were restricted to an area of the province, north of 51°31'18"N latitude. This region has an abundance of pine, with a continuous distribution encompassing the northern, western, and eastern provincial boundaries. It also represents the most likely pathway by which MPB could spread extra-provincially.

A daily climate data time series from Jan. 1, 2006 through Aug. 31, 2016 was assembled using data from the Edson climate station (Lat: 53°34'49.007" N; Long: 116°27'12.007" W; Elevation: 927m). This station was selected because it is located within the core of the MPB epidemic and contains a complete daily climate record.

Model simulations

A brief description of the MPBSpread model is provided below (a more detailed description and validation is referenced in Footnote 1).

Model structure

MPBSpread uses a spatially explicit cellular automata approach (*sensu* Wolfram 1986) to simulate MPB spread. This involves the application of a series of rules describing MPB behavior in relation to host characteristics. These rules are used to calculate from one year to the next,

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[2] https://www.alberta.ca/forest-and-vegetation-inventories-data.aspx

[3] https://nfi.nfis.org/en/

the probability of colonization from an occupied cell to suitable but unoccupied 'recipient' cells (see Molofsky and Bever 2004). Actual colonization events are then triggered as binary events (colonized, or not) by a randomization process.

Core elements

The model is used to calculate $P_{i,t}$, the probability of successful MPB colonization of a given unoccupied cell, *i*, in year, *t*, as:

$$P_{i,t} = HQ_i \sum_{j=1}^{n} (BEF_{j,t} \cdot G_{j,t} \cdot W_{i,j}) \quad (1)$$

where HQ_i is the habitat quality of an unoccupied cell. Collectively, the terms inside the summation represent the probability of beetles from an occupied cell, *j*, infesting an unoccupied cell within a given year. $BEF_{j,t}$ is a MPB export factor, an index of annual dispersal from an occupied cell that accounts for host depletion; $G_{j,t}$ a directional scalar accounting for wind direction; and $W_{i,j}$ a distance weighting factor between an occupied cell and a given unoccupied cell. All terms are scaled between 0 and 1. The architecture of the model is similar to that developed by Prasad et al. (2010), to predict risk of spread in emerald ash borer (*Agrilus planipennis*).

HQ_i has similarities to the stand susceptibility index (SSI) derived by Shore and Safranyik (1992; see also Shore et al. 2000). The SSI is calculated using four variables, percentage of susceptible pine, stand age, diameter at breast height (DBH), and a location factor. There does not appear to be a strong relationship between SSI and brood production, however (Bjorklund et al. 2009), and so we modified HQ_i to more directly link host availability to MPB reproductive potential. HQ_i is calculated as (percent pine in an unoccupied cell * r_{DBH}), where r_{DBH} indexes MPB reproductive output to pine DBH (as per equation 5; see also Bjorklund and Lindgren 2009). With the exception of DBH, all variables were obtained directly from the Alberta inventory data. DBH (cm) was estimated for cells > 10 m average height, as follows; shorter trees were assumed to have a DBH = 0 (and thus were excluded):

$$DBH = a + b \cdot Height + c \cdot Age \quad (2)$$

where *a*, *b*, and *c* are parameters (Table 1).

The beetle export factor, $BEF_{j,t}$, is calculated annually for every infested cell:

$$BEF_{j,t} = r_t \cdot M_{at} \cdot E_t \cdot Pine_{adj,t} \quad (3)$$

where, r_t is MPB reproductive output (the number of offspring per female) in year, t, M_{at} is annual beetle-induced pine mortality (%), E_t (%) an annual beetle emigration factor, and $Pine_{adj,t}$, the amount (%) of susceptible pine within a cell in a given year after accounting for any previous MPB-induced mortality.

Reproductive output (the number of offspring per female) in the initial infestation year, r_1, is first calculated (see below), after which r_t is simply decremented annually by 20% of the preceding year's value. The latter represents the impact of accumulating mortality on the quality of remaining pine in terms of host suitability (see, for example, Bjorklund and Lindgren 2009).

$$r_1 = r_{DBH} \cdot r_{clim} \cdot r_{temp} \quad (4)$$

where r_{DBH} indexes MPB reproductive output to the initial pine DBH (equation 5; Bjorklund and Lindgren 2009), r_{clim} is the effect of the minimum temperature during incubation on reproductive output (equation 6), and r_{temp} is a location-based temperature index (see below; see also Shore and Safranyik 1992).

$$r_{DBH} = a \cdot \text{Cell mean DBH} - b \quad (5)$$

where *a* and *b* are parameters (Table 1). Note that if $r_{DBH} \leq 0$ cm, then $r_{DBH} = 0$.

$$r_{clim} = \frac{a}{(1+b\ e^{c\,T_{min}})} \quad (6)$$

where *a*, *b* and *c*, are parameters (Table 1), and T_{min} is the minimum daily winter temperature.

r_{temp} is calculated as the product of two terms, an elevation temperature (T_{Elev}) and a location temperature (T_{locale}), and the result scaled between 0 and 1.

$$T_{Elev} = (\text{Elevation} - 1000)/100 \quad (7)$$

At elevations $\leq$ 1000 m, $T_{Elev} = 0$.

$$T_{locale} = (\text{Latitude} - 49.6) \cdot 0.7 \quad (8)$$

At latitudes $\leq$ 49.6 ° N, $T_{locale} = 0$.

Annual pine mortality in a colonized cell, M_a, is first calculated for the initial infestation year, M_{a1}, using the following modified logistic equation:

$$M_{a1} = \frac{a}{(1+b\ e^{c\,P_{i,t}})} \quad (9)$$

where a, b, and c are parameters (see Table 1), and $P_{i,t}$ the probability of an unoccupied cell being colonized, as per equation (1)

Table 1. Parameters and their values.

	Parameter values		
Equation	**a**	**b**	**c**
DBH	14.8	0.7	0.02
r_{DBH}	0.25	2.71	
r_{clim}	1.0	4.85E-11	0.604
M_{a1}, M_{ai}	0.550	2.694	-1.600
M_{max1}	1.154	7.350	-4.268
M_{max2}	0.992	123.2	-1.815
E_t	0.19	0.08	
$W_{i,j}$	1.7		

In subsequent years, M_a is calculated as:

$$M_{ai} = \frac{a}{(1+b\ e^{c\ r_t})M_{max1}} \tag{10}$$

where a, b, and c are parameters (see Table 1), and r_t is defined in equation 4. M_{max1} is defined in equation 12 and used as a scaling factor to account for the pine content of an infested stand.

Cumulative mortality occurs until stand maximum mortality (M_{max}) is reached:

$$M_{max} = M_{max1} \cdot M_{Max2} \tag{11}$$

$$M_{max1} = \frac{a}{(1+b\ e^{c\ Pine_{adj}})} \tag{12}$$

where, a, b, and c are parameters (Table 1) and $Pine_{adj}$ is as defined above (equation 3).

$$M_{max2} = \frac{a}{(1+b\ e^{c\ r_{DBH1}})} \tag{13}$$

where, a, b, and c are parameters (Table 1) and r_{DBH1} refers to MPB reproductive output in the first year of an infestation (see equation 4).

Emigration (E_t; %), the proportion of beetles leaving the infested cell in a given year, and is represented as a simple linear function:

$$E_t = a \cdot Y_{infest} - b \tag{14}$$

where a and b are parameters (Table 1), and Y_{infest} the year of infestation.

$G_{j,t}$, a directional scalar accounting for wind direction (as per eq. 1), is derived by summarizing daily wind data from climate stations located within the area of interest during the main MPB dispersal period (August 1 to September 15), and time of day (1200 – 1800 h) (Carroll and

Safranyik 2004). For each day, hourly wind direction is classified into one of 8 cardinal directions. These data are then summarized into frequency distributions for each cardinal direction and converted to probabilities. The latter are used in equation 1 as the probability of MPB dispersal in the direction from an occupied cell to any given unoccupied cell.

In the final term of equation 1, $W_{i,j}$ weights the distance between an occupied and an unoccupied cell, beginning with the following equation:

$$W_{i,j} = e^{-D_{i,j}/a} \tag{15}$$

where *a* is a shape parameter (Table 1), and *D* the distance between an occupied and an unoccupied cell (*i*, and *j*, respectively; km). Given the structure of equation 15, unoccupied cells located in close proximity to occupied cells will always receive a higher weighting than distant cells. The potential for long-distance dispersal is therefore introduced in the form of a fat-tailed distribution (FTD). The FTD generates a higher probability of extreme values than would be derived simply from the application of equation 15. Hence, short-distance dispersal is described by the negative exponential function until it reaches a threshold probability after which the probability remains constant and thus is distance invariant (see Clark 1998; Schwartz et al. 2001). This combination of simple diffusion and the FTD is referred to as 'stratified dispersal' (Shigesada et al. 1995). $W_{i,j}$ was converted to a fat-tailed distribution by constraining its threshold value at 0.00005. This latter value was derived qualitatively from a series of simulations conducted using MPBSpread and comparing the predicted distance distribution against that observed in a British Columbia epidemic (see below).

Calculating Pi,t and annual colonization

Pi,t values were calculated each and every year. For every uninfested cell, the product of *BEF*, *G*, and *W* was calculated for all infested cells and summed (see equation 1). This value was then multiplied by the *HQ* index of the uninfested cell to generate its $P_{i,t}$ value. An uninfested cell very close to numerous infested cells could, in principle, receive an infestation probability $\geq$ 1.0. In this case, the cell was given a 100% probability of being infested in that year. For cells with summed probability of infestation < 1, a random number < 1.0 was chosen from a cumulative normal distribution (CND). All cells with $P_{i,t}$ values that exceeded the random number were infested in that model step (Figure 2). This element of stochasticity is designed to account for interannual variability in climate conditions and other factors not accounted for within the model. Evidence suggests the relative susceptibility of pine to MPB attack depends on their evolutionary history. The lodgepole pine stands in BC, for example, have a long history of coexistence with MPB whereas the lodgepole and jack pine stands in Alberta are novel hosts. BC pine therefore have well-developed mechanisms for resisting attack with the result that it requires more beetles to kill an individual tree than in Alberta (Goodsman and Lewis 2017). We modified an MPB susceptibility curve developed for experienced (BC) pine to represent the greater susceptibility of 'naïve' Alberta pine to MPB colonization (Figure 3).

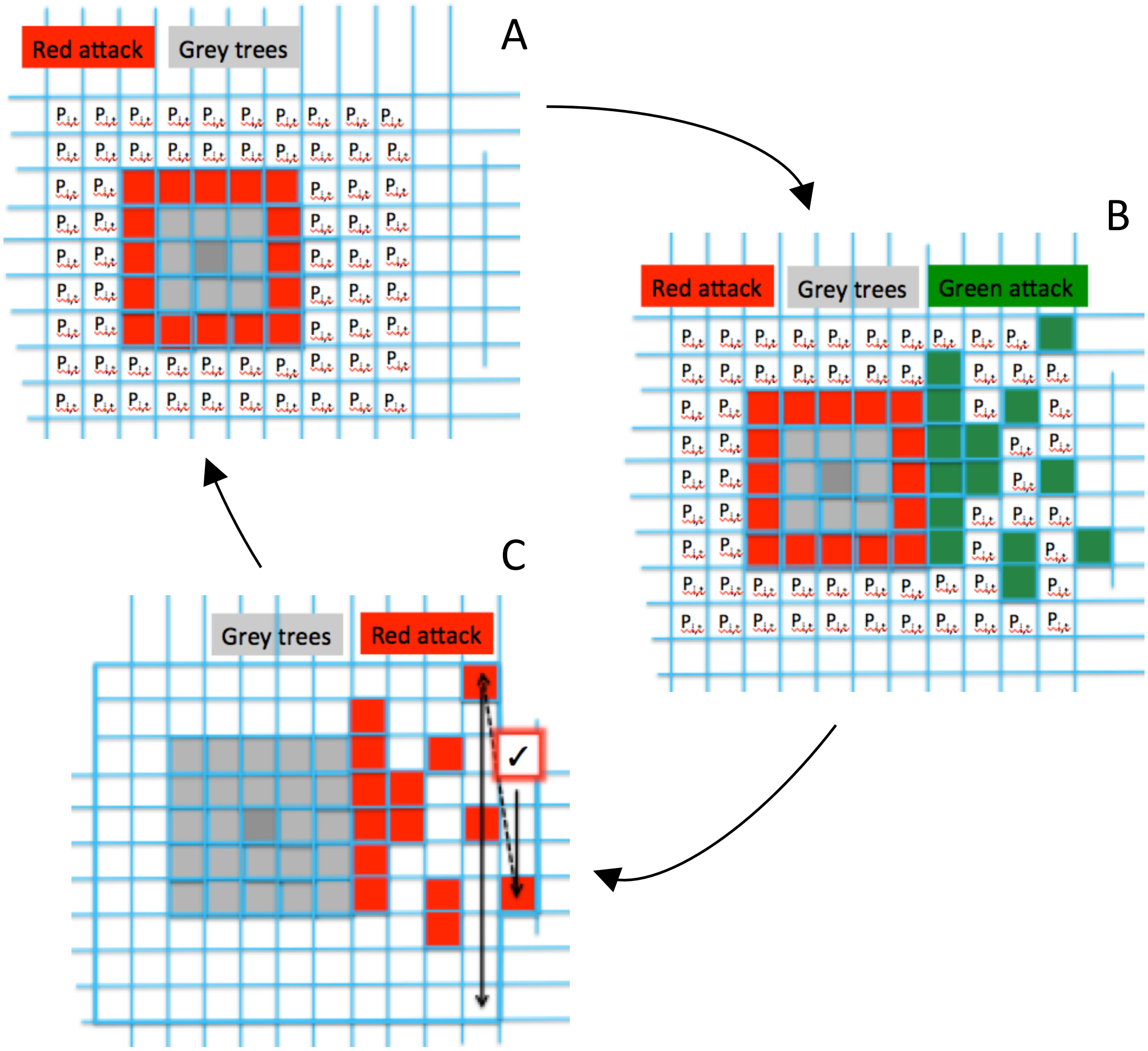

Figure 2. Application of the MPBSpread model. The probability of infestation in a given year for all cells not currently occupied by MPB, $P_{i,t}$, is calculated (panel A). The probabilities ($P_{i,t}$ values) are then assessed for actual colonization events (panel B). Following colonization, control activities are initiated beginning with the cell at the easternmost longitude and corresponding highest latitude within the study area (panel C). Cell sampling to initiate control activities proceeds sequentially by longitude to the southernmost cell within the area and then onto the northernmost cell to the immediate west. This process is continued until all cells within the study area have been sampled or the total area allocated for control in a given year is reached. Trees labelled 'grey' were attacked by MPB in previous years and are already dead. 'Red' trees were killed in the previous year, while 'green' trees are being attacked in the current year. See text for further details.

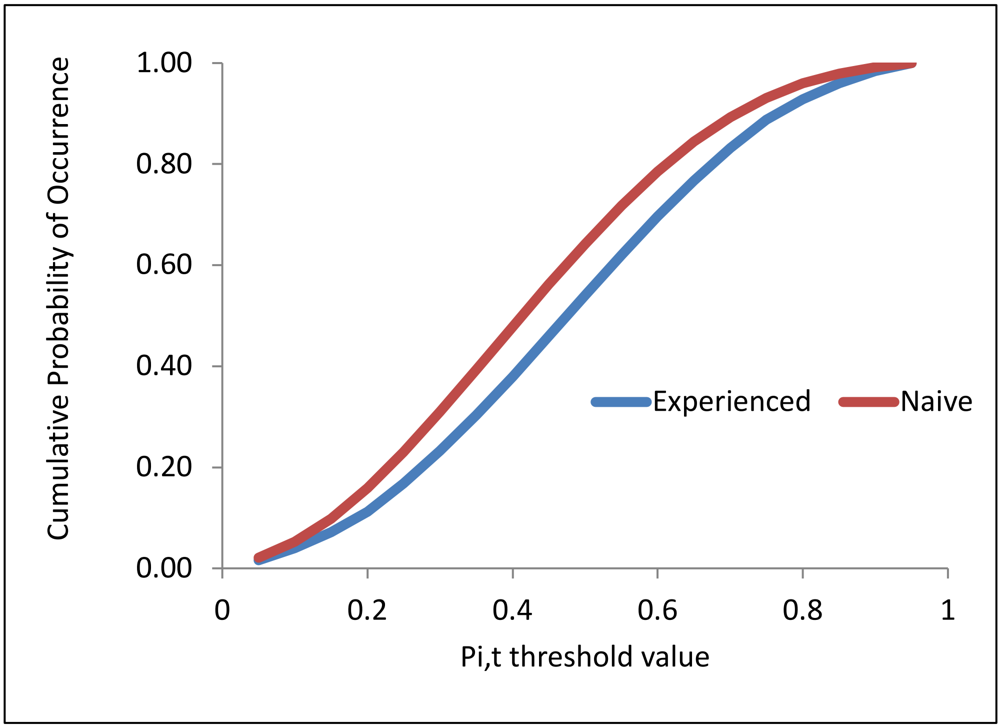

Figure 3. Cumulative probability of occurrence for a given threshold value for $P_{i,t}$. Experienced pine are those in British Columbia have a higher relative threshold than the naïve pine located in Alberta.

Simulating MPB control tactics

Computer-coded cell-based rules were designed to emulate the 'leading edge' approach to MPB control employed in Alberta, Canada (Samis and Eegion 2013). Under this approach, control efforts are focused primarily on eradicating new, isolated outbreaks to prevent the beetle population from becoming established and slow further spread. MPB control tactics in the leading-edge zone comprise either level 1 or level 2 treatments. Within MPBSpread, level 1 was applicable to any cell where an infestation was detected within 2 years of establishment. Cells with infestations of ≥3 years duration and ≤7 km from a road would potentially be treated with level 2 measures. Controls were implemented annually, subject to a detection probability (see below). In all other cases, no treatment occurred and the infestation continued until host availability was sufficiently depleted that further beetle reproduction within the cell was not possible.

Sampling for potential treatment began with the cell at the easternmost longitude and corresponding highest latitude within the study area, and proceeded sequentially by longitude to the southernmost cell (Figure 2, panel c). It was then continued with the northernmost cell to the immediate west, and so on. Each infested cell had a probability of being detected (P_{detect}), and a subsequent probability of successful eradication ($P_{eradicate}$). P_{detect} and $P_{eradicate}$ were derived from Alberta survey data, from which values of 0.9 and 0.65, respectively, were derived. These are similar to those reported in Coggins et al. (2008). With level 1 control, either all or a proportion of green attack was removed. This is determined from a random number (RN) drawn between 0 and 1. Eradication occurred within a cell with RN ≤ $P_{eradicate}$. If eradication was unsuccessful (RN > $P_{eradicate}$), pine mortality for that year was calculated as (M*a* [as per equation 4.10] * (RN - $P_{eradicate}$)). The latter term was designed to account for the decrease in pine mortality within a cell associated with the control effort. Under level 2 control, all trees were removed within a cell (and hence, $P_{eradicate}$ = 1). The sampling process was continued until all cells within the study area had been sampled or the total area allocated for control in a given year was reached. The latter reflects that fact that sampling is expensive and thus is limited by budgetary constraints.

Assessing treatment efficacy

A combination of aerial and point survey data are collected annually in Alberta to document the current status of the MPB infestation, and for use in management planning and control. This information was used to calibrate the MPBSpread model by inputting the locations of red-attack trees within a cell and the amount of associated currently infested green-attack trees, for the year 2008. Annual spread of the population to year 2015 was then simulated and parameters adjusted so that model output was consistent with infested cells reported from actual survey data. Thereafter, stochastic simulation runs began in year 2016 and terminated in year 2038, for a total run length of 22 years. A series of control scenarios were evaluated with MPBSpread (Table 2), and each scenario replicated 50 times. The same values from the randomization process (see above) were used in each of the scenarios to ensure any differences were a consequence only of the actual scenario outcomes. We calculated the probability of a 16-ha cell being occupied over the 2016 – 2038 simulation time-interval, as follows. For each simulation, we recorded a positive occupancy in a given cell whenever it became colonized. The duration of occupancy was ignored, except if a cell received a successful Level 1 or 2 treatment, which then eradicated the beetle. In this case, the counter was reset. Some cells may thus have received multiple occupancy within a given simulation. The probability of occupancy for a given 16-ha cell was thus the number of colonization events divided by the total simulation number (n = 50). Finally, we derived an index of extra-provincial spread by tabulating, for each run, the number of (16-ha) cells within a 10-cell 'band' along the Alberta-Saskatchewan border, that was colonized by MPB.

Climate change and an abundance of susceptible pine are two principle factors that underpin the MPB epidemic (Carroll et al. 2004; Taylor and Carroll 2004). Current climate conditions were represented as a random selection from the previous 10-years of historical climate data. These data are then assumed to reflect climate over the subsequent 30-year period of the simulations, which may be a conservative assumption given projected warming trends. In a second case, climate change was approximated by selecting the warmest climate year from the 10-year data set and simply replicating these conditions year-over-year, going forward.

Table 2. Simulation scenarios.

Description	Level 1	Level 2 (2008)	Level 2 (2017)	Control ends
Do nothing[1]	-	-	-	-
BAU[2]	7000	95	190	-
L1*0.7[3]	5000	95	190	-
L1*0.35[4]	2500	95	190	-
BAU_{2020}[5]	7000	95	190	2020
BAU_{2025}[6]	7000	95	190	2025

[1] No controls exercised.
[2] Business-as-usual (BAU; see text).
[3] Level 1 area reduced to 70% of BAU.
[4] Level 1 area reduced to 35% of BAU.
[5] All BAU controls terminated in year 2020.
[6] All BAU controls terminated in year 2025.
Note: Level 1 and Level 2 controls are expressed as the number of 16-ha cells treated per year. In the case of Level 2, the number of cells increases incrementally from 2008 to 2017, and remains constant thereafter (see Carroll et al. 2017).

Measures of connectivity

We used an extension of percolation theory (Stauffer and Aharony 1985), as developed by Keitt et al. (1997), to assess the extent to which a preemptive control strategy might be an effective means of minimizing the risk that the MPB epidemic will cause widespread pine mortality across Alberta. This approach is based on the calculation of a series of connectivity metrics, as follows.

A habitat 'patch' suitable for colonization by MPB was first defined as any 16-ha cell within the study area that contained a minimum 1% pine, from trees with a height $\geq$ 10 m. Cells that did not meet these criteria were assumed to represent 'non-habitat' for MPB.

This 'binary' approach provided only a simple representation of available habitat. Hence, a second patch definition (r_{Hab})was derived that linked habitat availability and climate conditions to MPB reproduction:

$$r_{Hab} = rt_{emp} * rD_{BH} * Pl(\geq 1\%) \quad (16)$$

Where r_{temp} and r_{DBH} are as defined above (see equation 4), and Pl($\geq$1%) refers to cells containing a minimum 1% pine, from trees with a height $\geq$ 10 m. A range of threshold r_{Hab} values were then used to screen cells for eligibility.

A landscape was then constructed of habitat patches of varying size, where patch size is a function of the number of contiguous 16-ha cells that met the habitat criteria defined above.

Two habitat cells were considered to be in the same habitat patch if they were adjacent in any one of the four cardinal directions or diagonally (northeast, northwest, and so on).

An important consideration is that when inventory data are used to classify each 16-ha cell, small habitat patches with relatively few cells are much more likely to be misclassified than are large patches, consisting of many cells (Keitt et al. 1997). By way of example, if errors in assigning pine attributes to each 16-ha cell occur with probability $p << 1$, then the probability of creating a patch of errors of size n is approximately p^n. Random errors are unlikely to produce large patches, because as n increases, p^n becomes very small. On this premise, Keitt et al. (1997) used a method to eliminate the misidentification of small patches, which we applied to the MPB analysis. In essence, the procedure addresses the question, over what patch sizes is the frequency distribution of MPB habitat calculated from the landscape similar to the expected frequency of patches created by random noise? Typically, the two distributions are similar for small patches but diverge at larger patches. The point of diversion represents the minimum patch size above which patches are unlikely to be the result of classification error (see Keitt et al. 1997). The patch assignment exercise was undertaken using both patch definitions described above. Results indicated (data not shown) that, regardless of which patch definition was employed, patches comprising less than 9 16-ha cells (144 ha) were too small for reliable classification. Hence, these were removed from inventory of patches eligible for colonization by MPB (the impact of this removal is illustrated in Figure 10).

Landscape connectivity refers to the ability of an organism to transit a landscape by moving between habitat patches. Patches located within an organism's maximum dispersal distance are 'connected', and groups of patches connected in this way constitute a *cluster*. If a single cluster spans the whole system, this confers complete landscape connectivity, referred to as a *percolation cluster* (see With 2002, for details). Hence, one measure of system connectivity is the probability of forming a *percolation cluster*. Another measure is the *correlation length* (C), the average distance an individual is capable of dispersing before reaching an unbreachable barrier; the longer the correlation length, the more the landscape is connected (Keitt et al. 1997). To assess the effect of dispersal capability on landscape connectivity, we constructed landscape graphs by placing edges between patches only if the minimum distance between them was less than a specified threshold. This created sets of patches on the landscape. By varying the distance threshold, we were able to quantify the connectivity of the landscape across a range of dispersal distances.

The landscape graphs created for each distance (see Keitt et al. 1997) were then used to ascertain visually, which specific patches might be targeted for pre-emptive pine removals in order to reduce connectivity and potentially impede the spread of MPB. These patches were 'removed'

Results and Discussion

1. In the absence of control, will MPB spread across Alberta?

MPBSpread simulations indicate that without ongoing control, MPB is likely to colonize a substantial portion of the pine inventory over the next several decades (Figure 4A). Beetle distribution is heavily concentrated in the lodgepole pine forests along the foothills of the Rocky Mountains, but is expected to move into jack pine and spread eastwards across central Alberta. This trend is reflected in the area colonized by MPB (Figure 4B), which increases rapidly over the 2016 to 2025 period, and begins to level off thereafter, reaching a maximum average (n = 50 runs) of about 1,745,935 ha. MPBSpread is a stochastic simulation model and variation in its input values can generate considerable variation in output. In this case, predictions in the area colonized in the final simulation year ranged from a minimum of 984,544 ha (44% reduction), to a maximum 4,610,672 ha (164% increase), below and above the average, respectfully. Hence, in the absence of control, MPB poses a considerable hazard to the pine inventory.

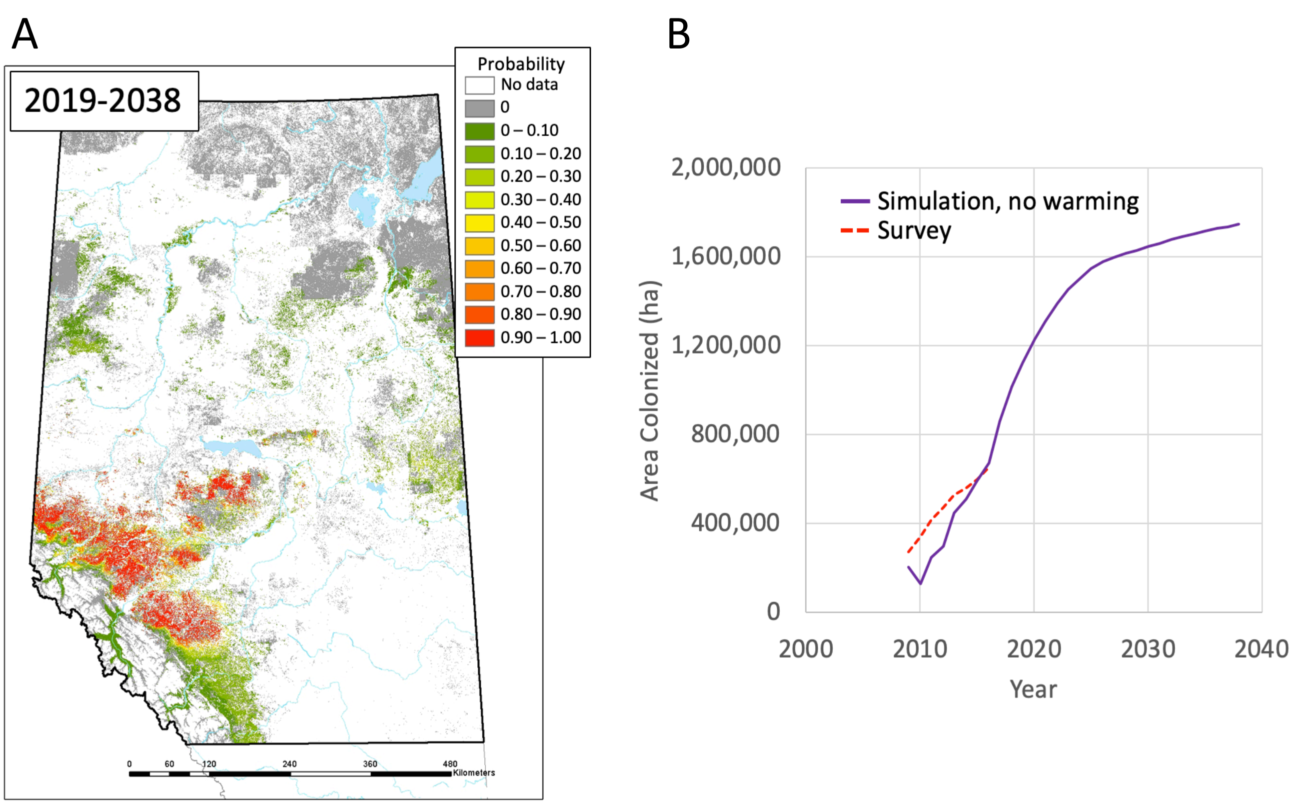

Figure 4. The average probability of MPB colonization in a given 16-ha cell, as derived from MPBSpread simulations (n = 50), over a 20-year period (2019-2038; panel A), and the area colonized (panel B). The latter also shows the average colonized area derived from actual survey data collected in years 2008 to 2016, inclusive (dashed line), used as a means for 'seeding' the model starting conditions. Climate data used in the simulations were derived from the previous 10-year historical records (see text for details).

Lodgepole pine is the historical host of MPB. Though beetles can successfully reproduce in jack pine (Rosenberger et al. 2017, 2018), recent evidence indicates that MPB is capable of persisting as an endemic population only in lodgepole pine (Pokorny and Carroll, *unpublished data*). MPB can therefore only occupy jack pine when population sizes are high enough that large-diameter, healthy trees can be mass attacked (Pokorny and Carroll, *unpublished data*), as is characteristic of epidemic behavior (Safranyik and Carroll 2006). Whether populations can be sustained in numbers sufficient to maintain spread is unknown, and thus represents a source of uncertainty in the predictions.

2. Will climate change exacerbate spread?

Climate is likely to be important in promoting the future spread of MPB in Alberta and exacerbating the hazard to pine health and the overall inventory. Population establishment and its rapid expansion in the province may have been abetted by favorable conditions that occurred during the initial phases of the epidemic when several sizeable immigration events occurred (Raffa et al. 2008; Sambaraju et al. 2012). Beetle larvae are particularly susceptible to cold temperatures in October and November, before becoming fully acclimated to cold. Overall mortality is also higher after prolonged and severe winter temperatures (Cooke 2009). Historically, climate would have been important source of mortality and helped keep MPB populations below threshold levels (Carroll and Safranyik 2004). The high survival rates now recorded in overwintering beetle broods are linked to a trend of warmer-than-usual fall and winter temperatures (Carroll and Safranyik 2004, Taylor et al. 2006). Warm and dry summer temperatures promote adult dispersal (Carroll and Safranyik 2004).

Our simulation results show that climate change will be a contributing factor to beetle spread. The probability of a colonization event over the next two decades was elevated in all regions of Alberta, including the eastern border with Saskatchewan (Figure 5A). Average area colonized reached 2,221,196 ha, at the end of the 20-year simulation period (Figure 5B), a value 27% higher than under the historical climate regime (Figure 4B). The range in predictions under climate change was considerable, varying from 50% (1,106,272 ha) below, to 174% (6,104,080 ha) above, the average. If the future climate is indeed warmer, MPB will pose an even greater hazard to the health of Alberta pine than it does currently.

Climate change, along with an abundance of susceptible pine, are two principle factors that underpin the MPB epidemic in AB (Carroll et al. 2004). Their relative influence on the frequency and intensity of outbreaks, however, is still uncertain. Global Circulation Models differ considerably in the magnitude of their climate projections. While we used an empirically based approach, uncertainty in the future climate serves to constrain the accuracy of model output. As Raffa et al. (2008) point out, the issue is further complicated by the fact eruptions can emerge suddenly when thresholds are surpassed and positive feedbacks amplify across multiple scales. Hence, while localized climate events can trigger a limited outbreak, broad-scale climate events conditions could facilitate synchronized outbreaks (Cullingham et al. 2019) leading to a much wider epidemic. MPB populations in northern British Columbia and Alberta began expanding rapidly in the mid-2000s, with spread proceeding both north through the Rocky

Mountain Trench and east through Pine Pass into the Peace River region (Nealis and Cooke 2014). Spread rates were uneven, however, and varied considerably. In some years, population ranges actually contracted while in other years (2006, for example), spread was exceptionally high.

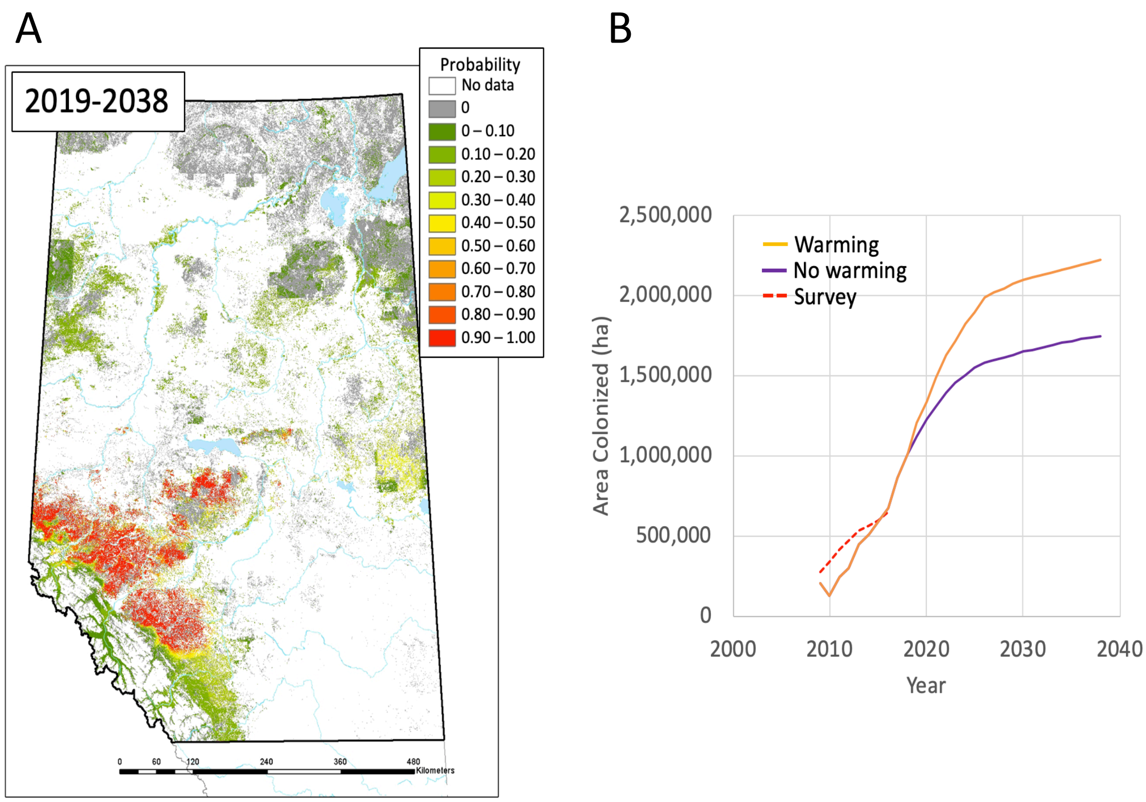

Figure 5. The probability of MPB colonization in a given 16-ha cell, as derived from MPBSpread simulations, over a 20-year period (2019-2038; panel A), and the area colonized (panel B). The latter also shows the average colonized area derived from actual survey data collected in years 2008 to 2016, inclusive (dashed line), as a reference check on model output. Climate change was approximated in the simulations by selecting the warmest climate year from the previous 10-year historical data set and simply replicating these conditions year-over-year, going forward (see text for details).

3. When will MPB reach Saskatchewan?

There is strong evidence that, over the next 20 years, much of Alberta's central region will be colonized by MPB, including the eastern border with Saskatchewan (Figures 4A, 5A). We calculated the number of (16-ha) cells within a 10-cell edge along the Alberta-Saskatchewan border, that was colonized by MPB, as an index of beetle emigration. Results show that, without MPB control activities, the number of border cells colonized is projected to increase rapidly over the next 5 years (Figure 6). Under historical climate, a peak of 1000 ha (about 60 border cells) will be colonized by 2026, and remains constant thereafter. If the future climate is warmer, however, this will increase substantially. The 1000 ha value is reached 5 years earlier (by year 2021), but continues to increase until year 2038 when its value is about 3600 ha.

Modeling the extra-provincial spread of MPB was not a component of this work, and so we cannot draw firm conclusions in that regard. The emigration index, however, provides a clear indication of the risk of beetle spread into Saskatchewan. The volume of susceptible pine tends to be lower and its distribution less contiguous in Saskatchewan (Safranyik et al. 2010), which could impair population establishment and spread, though this remains an open question.

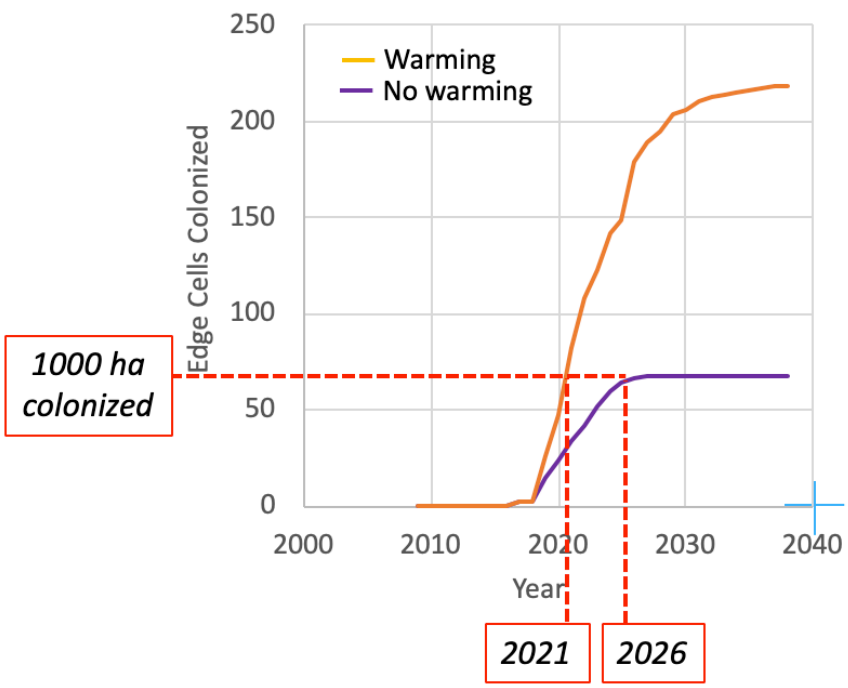

Figure 6. Number of 16-ha edge cells colonized by MPB over the period, 2008 to 2038, as predicted by the MPBSpread model; no controls were implemented. Simulations were conducted using historical climate data and climate warming, respectively. See text for further details.

4. Does the slow-the-spread (StS) strategy work?

The StS strategy is effective in limiting the spread of MPB (Figure 7). It reduced MPB colonization by ~ 535,000 ha (44%) to year 2019, and by ~ 1,560,000 ha (70%) to year 2038, as compared to cessation of control activities in year 2016 (Figure 7B). Reducing spread resulted in a widespread decline in the probability of colonization (Figure 7A). Hence, controls reduce pine mortality within Alberta, as well as the risk of extra-provincial spread.

In previous work (Carroll et al. 2017[1]), MPBSpread was used to evaluate the efficacy of elevating control efforts above the StS level on a subsection of the pine landscape. Model results indicated that doubling Level 1 controls over the period 2008 to 2018 was effective at reducing area colonized, while doubling L2 controls had little impact. We did not evaluate the benefits of enhancing Level 1 controls across the broader landscape because costs would be prohibitive at this scale.

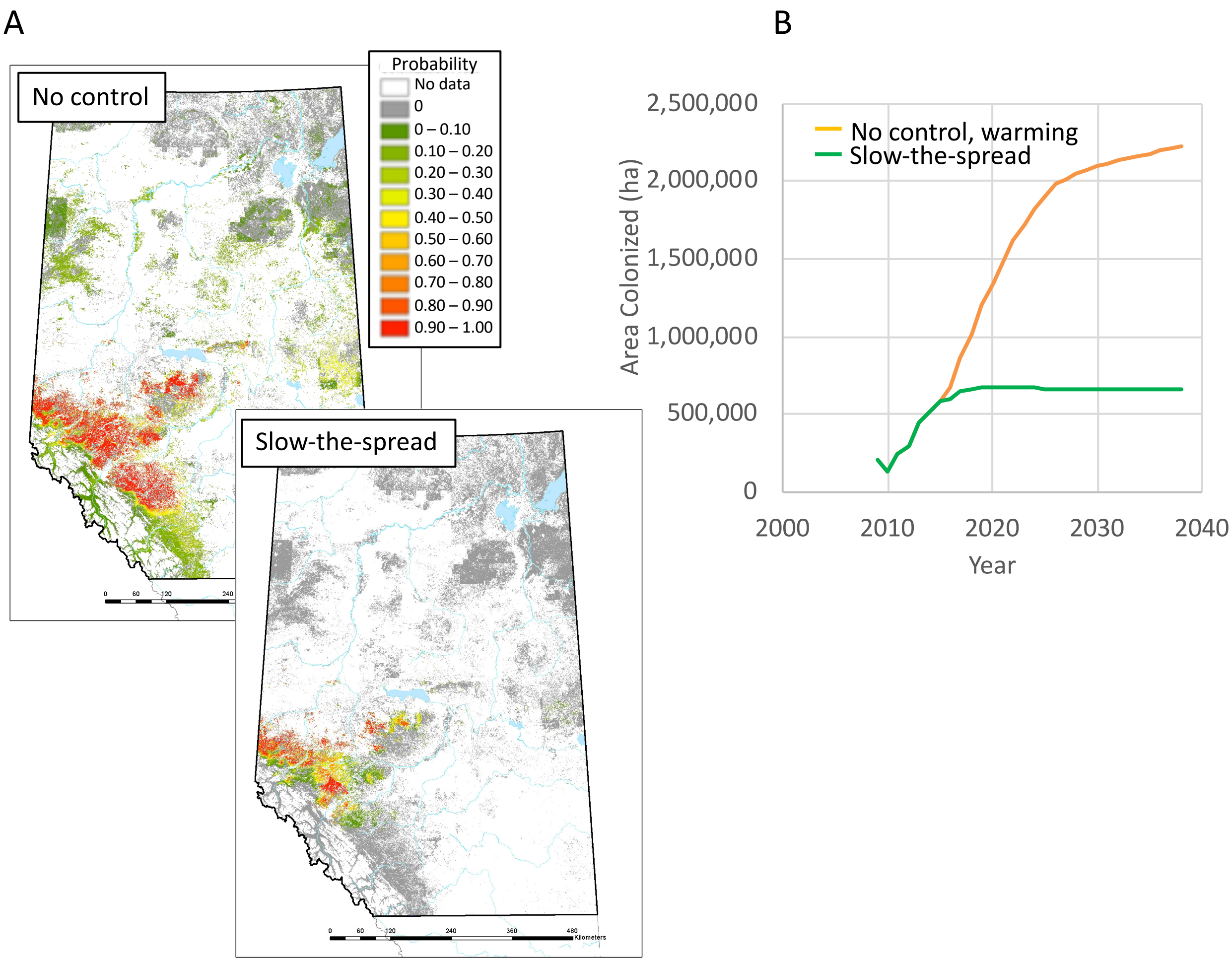

Figure 7. The average probability of MPB colonization in a given 16-ha cell, as derived from MPBSpread simulations (n = 50), over a 20-year period (2019-2038; panel A), and the area colonized (panel B), when no control activities were implemented from 2016 onwards, and a slow-the-spread strategy. Climate change was approximated in the simulations by selecting the warmest climate year from the previous 10-year historical data set and simply replicating these conditions year-over-year, going forward (see text for details).

5. What effect will reducing StS have on spread?

Implementing MPB control activities is costly. It is tempting therefore to reduce control efforts below 'business-as-usual' (BAU) investment. Under StS, the area colonized by MPB in year 2038 was 726,712 ha, but there was only a small increase (15%; 833,070 ha) when controls were reduced to 70% of StS (Figure 8). Reducing controls to 35% of StS increased area colonized by 56% (1,132,963 ha). These values were still substantially below the 'no control' option (2,221,196 ha, in year 2038). Volume loss prevented with level 1 controls showed similar trends. A total of approximately 128 million m^3 of pine were preserved (to year 2038) under

StS, 119 million (93%) m^3, and 94 million 73%) m^3 at 70%, and 35% levels of StS, respectively (Figure 9A). The net present value (NPV) of preventative loss is illustrated in Figure 9B. The NPV associated with StS delivers the highest return at a given discount rate (from 200 to 400 million dollars) but is only marginally more favorable than the 70% StS level (between 4 and 7%, at the 4% and 8% discount rates, respectively). Anticipated or realized increases in the discount rate result in increased investment in level 1 controls to maintain NPV (Figure 9B).

Taken together, results indicate diminishing returns in efficacy and economic returns with increasing investment in MPB control activities above 70% StS (Figures 8, 9). Conversely, eliminating controls entirely as a cost-cutting measure entails considerable risk since it might permit unchecked population growth resulting in major pine mortality, particularly under a warming climate (Figure 7).

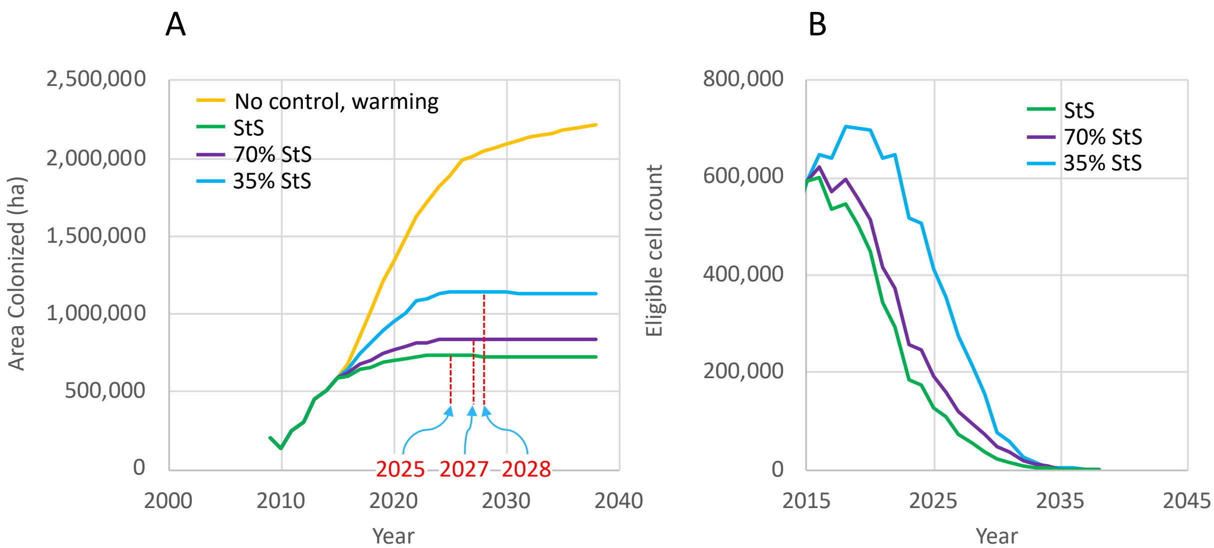

Figure 8. A. Area colonized by MPB, when no control activities were implemented from 2016 onwards (yellow line), a slow-the-spread strategy (StS; green line), 70% of StS (blue line), and 35% of StS (purple line). Arrows indicate the years when area colonized was at its peak. B. Newly colonized pine. Climate change was approximated in the simulations by selecting the warmest climate year from the previous 10-year historical data set and simply replicating these conditions year-over-year, going forward (see text for details).

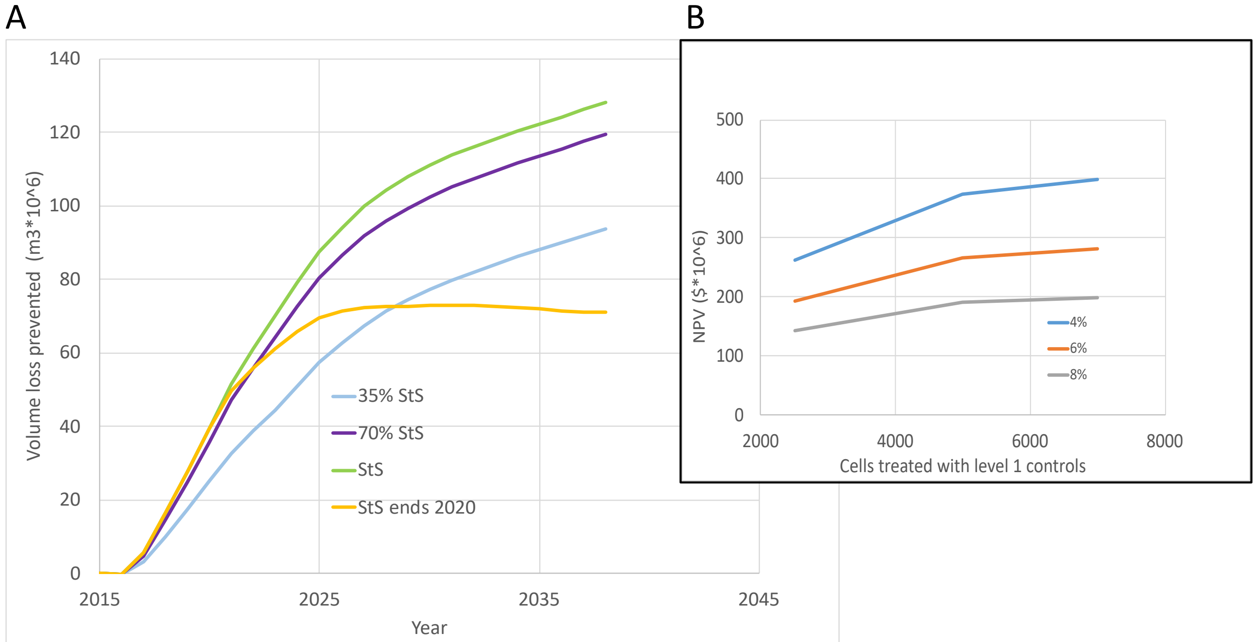

Figure 9. A. The benefits of Level 1 control (pine volume loss prevented) when activities were implemented from 2016 onwards under a slow-the-spread strategy (StS – 7000 cells treated); green line), 70% of StS (5000 cells treated; blue line), 35% of StS (2500 cells treated; purple line), and StS ending in year 2020 (yellow line). B. Net present value (NPV) of level 1 controls at level 1 treatment levels of 7000, 5000, and 2500 cells, under three discount rates.

6. Would spread continue if StS was reduced before MPB collapse?

Question 5 evaluated the veracity of the MPB program using a historical perspective to assess the efficacy of prior investments in beetle control. Here, we address the implications of curtailing controls in the near future, specifically at years 2020 and 2025, respectively. Maintaining the control program does matter if slowing the eastward spread of MPB is a principal objective, and the termination date is important (Figure 10). If controls are terminated in 2020, for example, area colonized increases rapidly, reaching 1,302,241 ha by year 2038. Prevention of pine volume loss is reduced by 45% (Figure 9, upper panel) and area colonized is 79% higher (Figure 10), than if controls were maintained through this period. The latter is, however, 41% below the area colonized in year 2038, if no controls had been implemented (see Figure 8). Delaying termination to 2025 results in an area colonized of 853,049 ha (at year 2038), 17% higher than full control. Early abandonment thus risks a much greater spread of MPB than delaying even 5 years.

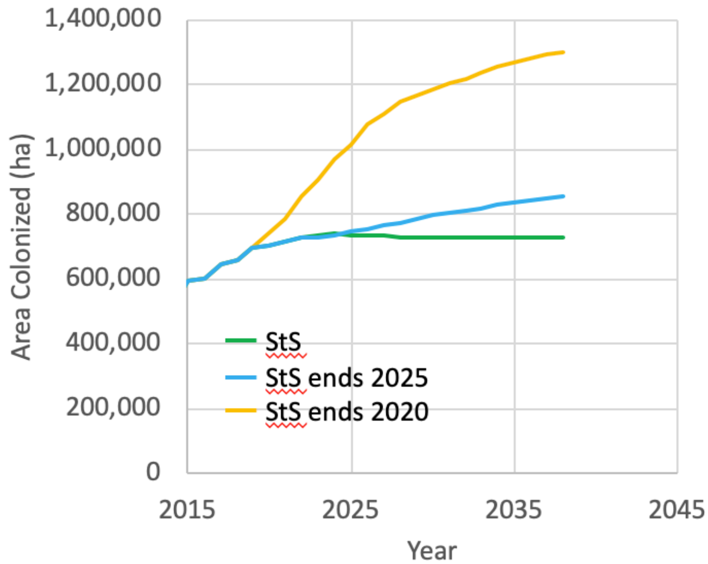

Figure 10. Area colonized by MPB under a slow-the-spread strategy (StS; green line), and termination of of StS in year 2020 (yellow line), or year 2025 (blue line). Climate change was approximated in the simulations by selecting the warmest climate year from the previous 10-year historical data set and simply replicating these conditions year-over-year, going forward (see text for details).

7. What if controls were implemented in the direction opposite to StS?

Implementing controls along the leading edge of the MPB epidemic (to the east and northeast of the province), as is the current StS policy, is more effective at limiting the spread of MPB than if controls had been were implemented in the direction opposite to StS, i.e., beginning at the western edge ("back-treated") focussing on potential "source" populations. Employing StS reduced the area colonized across the province by at least 25%, compared to the alternative option (Figure 11). The likely explanation for these results is that only a relatively small proportion of beetles, carried by favorable winds, emigrate from their natal stands (Chen and Jackson 2017); the majority of dispersion is within-stand (Robertson et al. 2007). Hence, beetles located in stands far removed from the leading edge would likely have little impact on the rate of spread. These stands, however, would always be subject to controls under the back-treatment approach. Finally, although StS is the more effective strategy, employing controls from west to east still offers considerable benefits over no control (Figure 11).

8. Is there an end in sight - what does the future hold?

The principal objective of the provincial MPB control program is to contain infestations and minimize eastward spread. Ostensibly, this should minimize the impact of MPB on the timber supply and give licensees time to develop and implement harvest plans targeting their most vulnerable pine stands. The effectiveness of the program is illustrated in Figure 8. Under the full StS strategy, the peak in area colonized is reached earlier (year 2025) and at a lower point than when StS is scaled back to 70% (year 2026), or 35% (year 2028) (Figure 8A). The same trends are evident with newly colonized areas (Figure 8B). StS then has a lower rate of beetle spread and the overall mortality in the pine inventory is reduced. Regardless of which control strategy is employed, however, on average the MPB outbreak in Alberta is expected to persist until at least year 2035 as infestations continue to deplete volume within colonized areas.

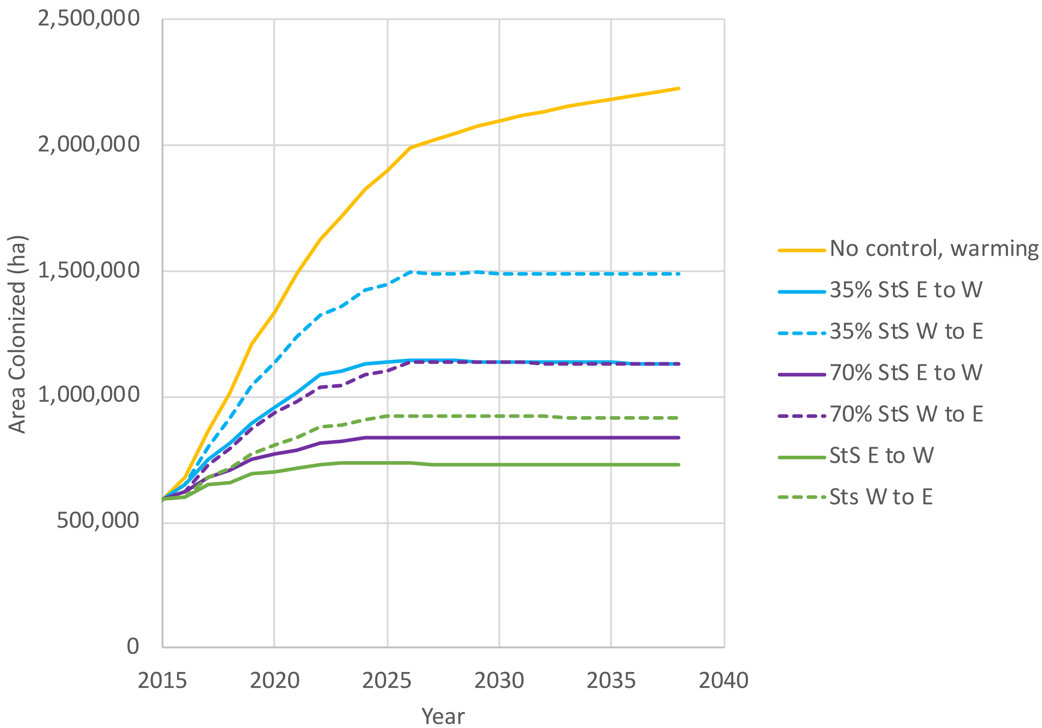

Figure 11. A. Area colonized by MPB, when no control activities were implemented from 2016 onwards (yellow line), a slow-the-spread strategy (StS; green lines), 70% of StS (purple lines), and 35% of StS (blue lines). Solid lines indicate treatments applied from east to west, while dashed lines indicate the converse (i.e. control of potential western “source” populations). Climate change was approximated in the simulations by selecting the warmest climate year from the previous 10-year historical data set and simply replicating these conditions year-over-year, going forward (see text for details).

9. How ‘connected’ is the pine landscape?

Groups of cells (patches) comprising less than 9 16-ha cells (i.e., 144 ha) were deemed too small for reliable classification (see Methods for a description of this definitional procedure). After their removal, the landscape constituted 497,215 16-ha cells eligible for colonization by MPB (14.1% of the total cells in the landscape), when eligibility was defined as $\geq$ 1% pine, with a height $\geq$ 10 m (the pine index), or 323,874 cells, with an R_{Hab} threshold of 0.5 (as defined per equation 16). The distribution of eligible cells is shown in Figure 12. Eligible cells are concentrated in the lodgepole pine forests along the western and, to a lesser degree, the eastern provincial boundaries. The former area is where the MPB epidemic became established initially, while the latter is of concern with respect to extra-provincial spread. In central Alberta, pine is less concentrated and more widely distributed (Figure 12). This region of the province offers the best opportunity to increase resistance to beetle spread from pine removals (see question 10).

As noted above, two modes of dispersal have been identified in mountain pine beetle: short-distance (Safranyik et al. 1992, Robertson et al. 2007) and long-distance (Safranyik and Carroll 2006). The former is the predominant flight mode and occurs under the forest canopy, usually at distances of 50–100 m (Robertson et al. 2007). From a flight mill study of MPB, Evenden et al. (2014) recorded a mean flight distances of 2.12 to 5.95 km, though the longest total flight was >24 km. This represents the physiological dispersal potential. Where beetles are carried into the atmosphere on convective winds (Jackson et al. 2008), dispersal distances can be much longer, in excess of 20, to several hundred, km (Safranyik and Carroll 2006, Cooke and Carroll 2017). Correlation length (CL), the average continuous distance an individual is capable of dispersing, is an index of habitat connectivity that scales directly with dispersal capability. When the simple pine index was used to define eligible cells (see 'Measures of connectivity'), CL increased sharply at the 10 km dispersal distance, and again (though at lesser amounts) at distances of 18 and 24 km (Figure 12). A sudden change in connectivity at a threshold distance is commonplace and indicative of a "phase transition" (Stauffer and Aharony 1985). This transition divides the landscape of eligible pine habitat into a connected phase and a disconnected phase. Hence, at the 10 km dispersal distance, CL jumps by 70%, and at 24 km, it reaches its maximum value. The latter indicates that the landscape is fully connected. Given that during epidemics, beetles are capable of dispersing distances well in excess of 10 km in numbers sufficient to overcome tree defenses, a majority of the Alberta landscape likely constitutes a single, interconnected habitat patch (a percolation cluster; see Keitt et al. 1997). This suggests that if population growth continues unabated, MPB should have little difficulty in colonizing all areas of the province, and beyond.

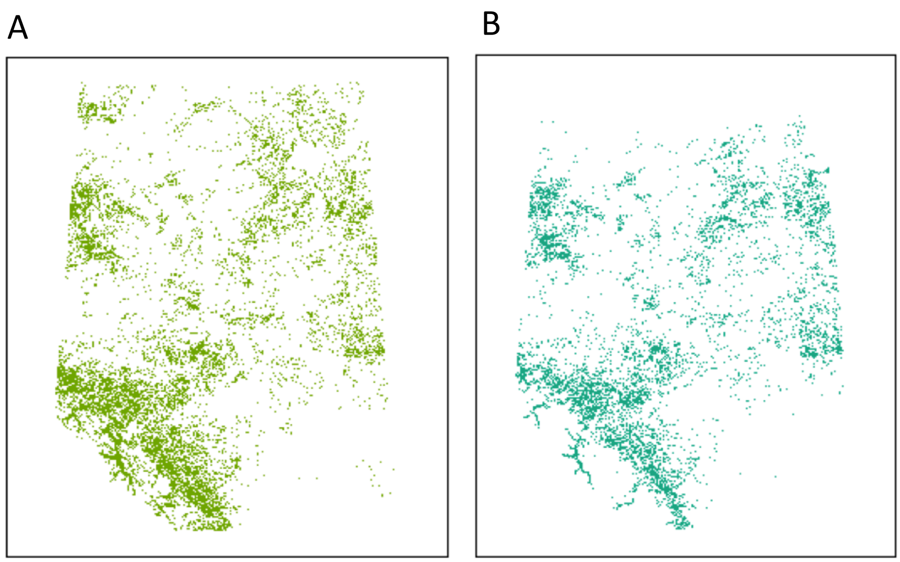

Figure 12. The distribution of 16-ha cells within the study landscape eligible for colonization by MPB, where eligibility was defined as $\geq$ 1% pine, with a height $\geq$ 10 m (A), or as per equation 16 but only including cells where $R_{Hab} \geq 0.5$ (B). See text for details.

The presence of 'red-attack' trees and/or pheromone baiting are used to select stands suitable for treatment. If control operations treat at least 50 per cent of infested trees, the MPB population will remain static. Not all stands can be treated, however, particularly when the epidemic has become widespread. Resources might be utilized more effectively therefore by focusing on areas where control efforts have their maximum impact on population growth and spread. For example, if low-quality stands contribute little to the spread of MPB, control efforts might be reallocated towards better-quality stands. We investigated this idea by eliminating stands with low r-values (calculated as per equation 16) from the pool of available stands, and then re-calculating the CL for a range of threshold distances. Results are shown in Figure 13. When the r-value threshold was set at $\geq$ 0.5, the first phase transition distance increased from 10 to 16 km (compared with the 'all pine' case), with subsequent step increases at 18 and 22 km (Figure 13). Increasing the r-value threshold to $\geq$ 1, added a further 4, 4, and 10 km, respectively to the threshold distances. The threshold distances were sensitive then to the removal of low-quality pine stands thus highlighting their contribution to the spread of MPB. Prioritizing high-quality stands for harvest has important economic benefits but control efforts must target the broader spectrum of available pine stands to minimize MPB spread.

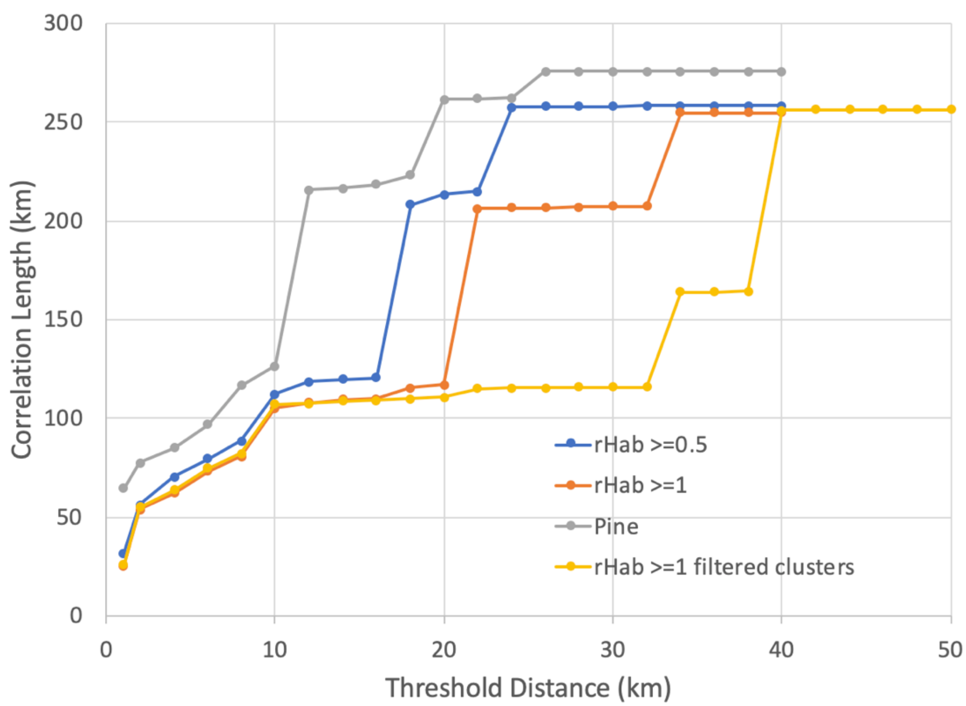

Figure 13. Correlation length (CL) in relation to threshold dispersal distance for cells defined as pine presence or absence (Pine), and r_{Hab} values $\geq$ 0.5 and 1, respectively. Also shown is the CL when habitat cells were 'removed' from the landscape ($r_{Hab} \geq$ 1 filtered clusters) and thus unavailable for colonization by MPB. See text for details.

10. Can pine habitat 'connectivity' be impaired enough to disrupt the spread of MPB?

Pine distribution across Alberta is heterogeneous. Lodgepole pine forests are concentrated in a more-or-less continuous band along the eastern Rocky Mountains. The transition to jack pine-dominated stands towards the eastern border occurs in conjunction with a more scattered, less dense distribution, particularly in the central region of the province (see Figure 4A, for example). One management option is to enlarge the 'gaps' between suitable habitat through pre-emptive harvesting. Reducing habitat connectivity, in conjunction with current practices, could help to further slow MPB spread rates along with the benefit of realizing harvest volume before any mortality occurs. A key question in implementing this approach, is which stands should be selected for removal? We addressed this question using a two-stage approach. First, a map was created across the study area from all stands with an $r_{Hab} \geq 1$. Next, a series of 50 runs was conducted using MPBSpread, over years 2019 to 2039, but with no controls implemented. From this set of runs, an average probability of colonization ($P_{i,t}$; see equation 1) was calculated for each of the selected stands. The r_{Hab} and $P_{i,t}$ values were then overlaid to identify stands with the highest reproductive and colonization potential. From this, a group of stands were selected for 'removal' (Figure 14). MPBSpread was then re-run with the following management scenarios: No control, Level 1 controls at 2500, 5000, and 7000 16-ha cells, respectively, and Level 1 control at 7000 cells, terminating in year 2020. Run output was compared with MPBSpread simulations of equivalent management scenarios but without excluding the filtered cells.

Area colonized by MPB was always reduced after habitat removal (Figure 15). The treatment effect was not substantial, however, and likely reflects the fact that, as this was a 'test' analysis, only a relatively small area was subtracted from the available pine cells (see Figure 14). Additionally, the removals were aggregated spatially in an area where MPB was anticipated to be heavily concentrated. At least some of the border colonization, however, could have occurred from the spread of more northerly populations (Figure 14).

In relative terms, Level 1 controls had a much more substantial impact on the spread of MPB than did selective removal. This likely reflects the fact that, on an area basis, Level 1 was implemented to a far greater extent. In that regard, the benefit of pre-emptive harvesting was reduced as the amount of Level 1 control increased (Figure 15). Although this provides strong support for the efficacy of Level 1 controls in slowing the spread of MPB, whether a more comprehensive application of pre-emptive harvesting would also be highly effective, remains an open question.

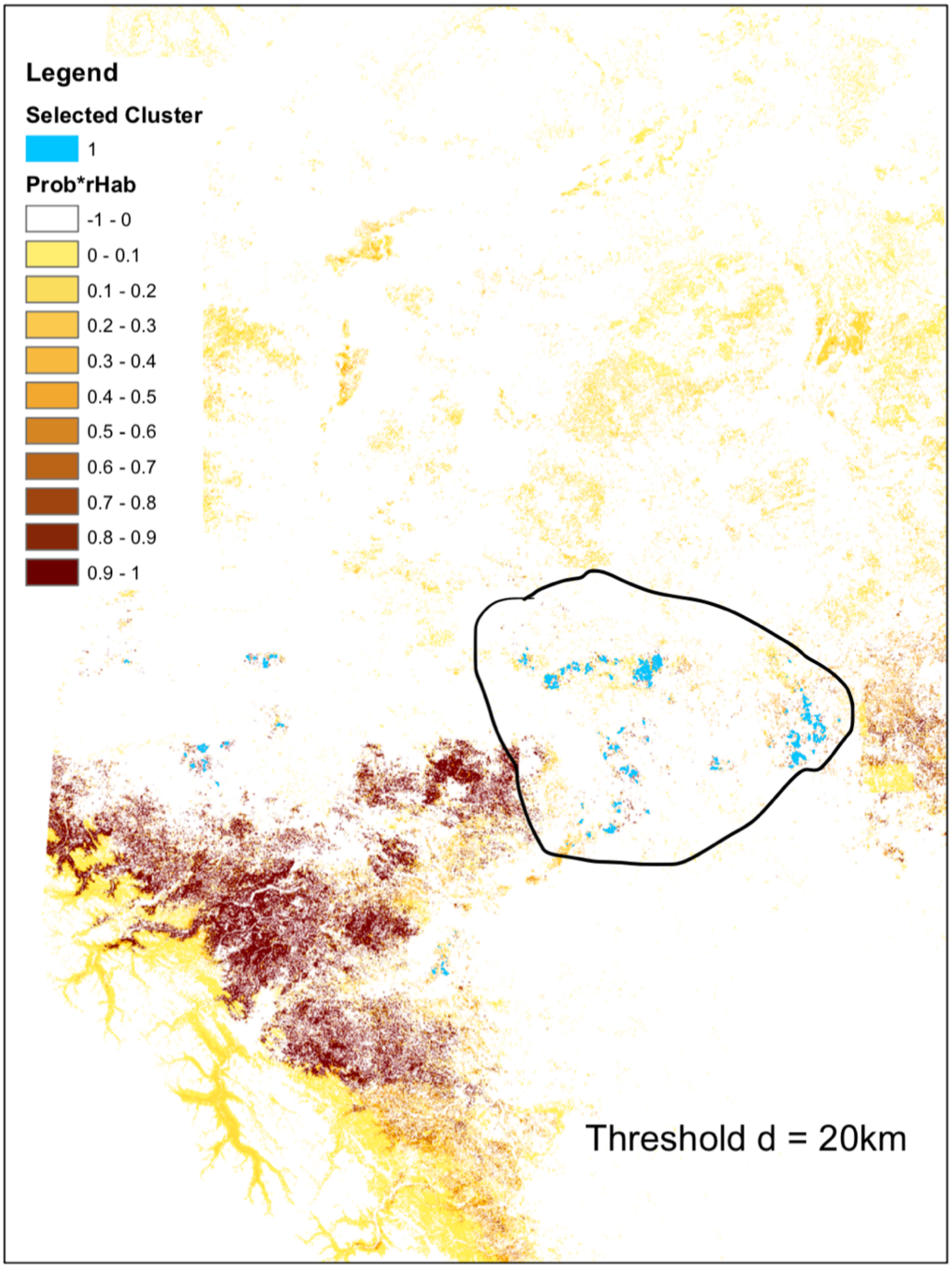

Figure 14. Map of the r_{Hab} and $P_{i,t}$ overlay (see text) classes across the Alberta study area. Black line encircles the 16-ha pine cells 'removed' from MPBspread simulations (blue cells) to enhance habitat discontinuity.

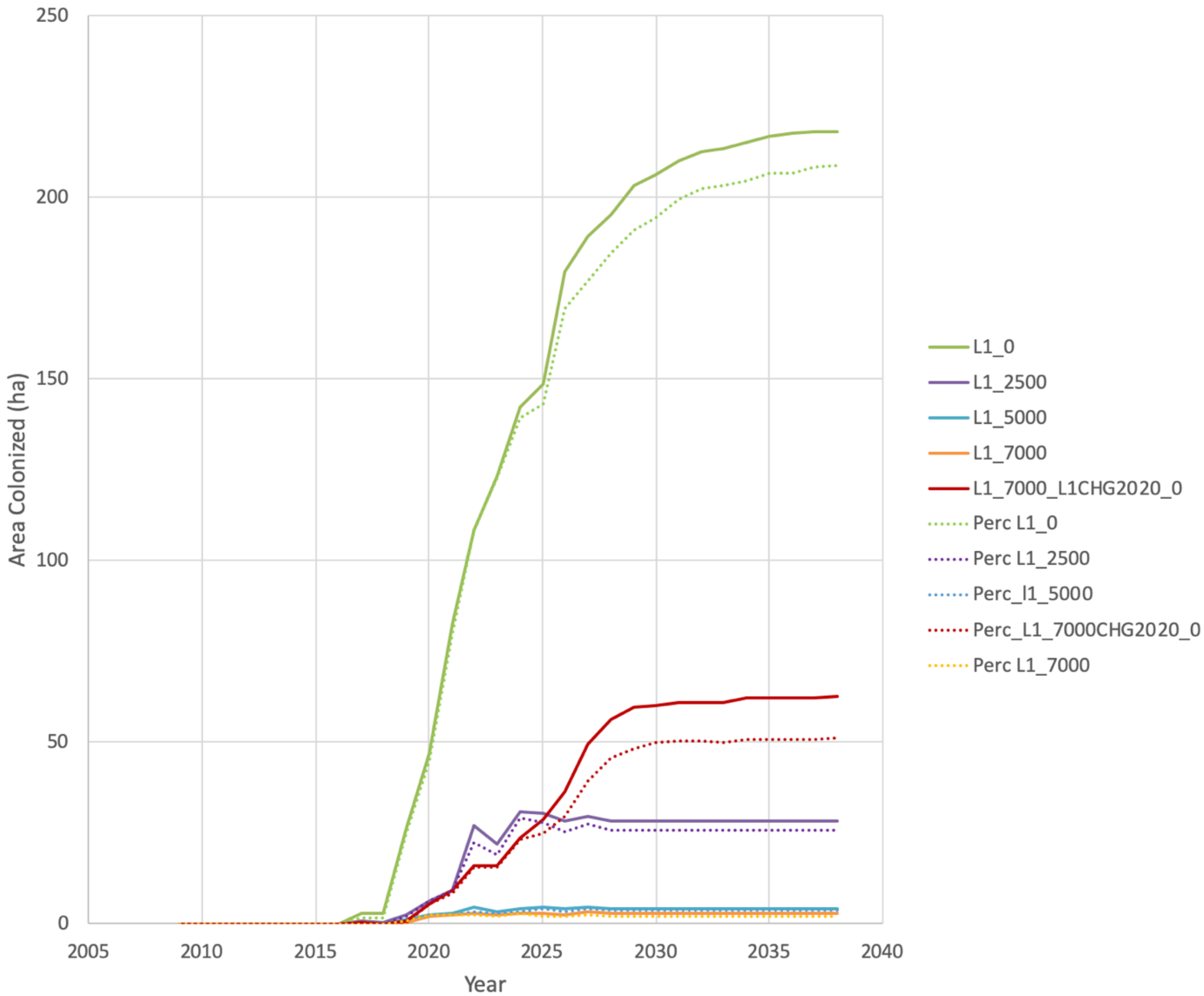

Figure 15. MPBSpread simulations of area colonized on the eastern border of Alberta by simulation year, under management scenarios of: No control (L1_0), Level 1 controls at 2500 (L1_2500; 35% of StS), 5000 (L1_5000; 70% of StS), and 7000 (L1_7000; StS) 16-ha cells, respectively, and Level 1 control at 7000 cells, terminating in year 2020 (L1_7000_L1CHG2020_0). Lines denoted with 'Perc' were derived from simulations with habitat removal (see text).

Conclusions

1. Control efforts are necessary to reduce MPB spread across Alberta.
2. Spread will be worsened with additional warming.
3. In the absence of control, significant populations will reach the Saskatchewan border within 2 – 7 years.
4. The StS strategy has reduced the rate and extent of MPB spread.
5. Eliminating or reducing MPB controls going forward (cutting program costs in years 2020 or 2025) still results in new colonization, though at reduced rates relative to that expected under current control.

6. To achieve maximum effectiveness, StS should be continued until epidemic collapse.
7. By 2030, there should be no new net colonized areas with Alberta.
8. The pine landscape in Alberta is highly connected - suitable pine stands are in close enough proximity that they can be easily colonized if current MPB population levels are maintained.
9. Pre-emptive harvesting has the potential to reduce habitat connectivity thereby limiting the spread of MPB and, consequently, pine mortality.

Final considerations

The aim of this project was to assess the efficacy of the Alberta 'StS' strategy in limiting the impact of the MPB invasion at the provincial scale. The strategy targets the 'leading-edge' in an effort to eliminate new colonisation events, and thus contain the geographic range and impact of the epidemic. Additional modeling results using MPBSpread (from an external project) indicate that an ancillary benefit of this approach is that, in addition to broader-scale benefits, StS has/will continue to reduce colonization within pine-dependent FMAs. Prior work (Carroll et al. 2017[1]) also indicates that more effective spread control can be achieved at all spatial scales with increased Level 1 treatments.

Although MPBSpread has provided immediate answers regarding spread-control efficacy over the regions of Alberta invaded by MPB, its projections were limited to the northern portion of the province. Its representation of climate was also relatively simply and likely does not capture the dynamic nature of the changes projected over the next several decades. Both elements limit its application and accuracy. The next iteration of its application should span the full range of spatial scales (FMA to province) and include a more detailed representation of climate and climate change scenarios. Another consideration is that model simulations incorporate constraints on control activities associated with conservation areas, and tradeoffs with competing resource objectives (particularly, caribou management). These additions to MPBSpread would greatly improve assessments of future MPB population dynamics and outbreak risk. Finally, how licensees might best manage their individual forest management areas (FMAs) to limit MPB impacts within the context of constraints and tradeoffs, has received only cursory analysis. This is significant because it has a direct impact on present and future timber revenues and the annual allowable cut, and could also inform strategies for pine regeneration that minimize the risk of subsequent outbreaks.

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