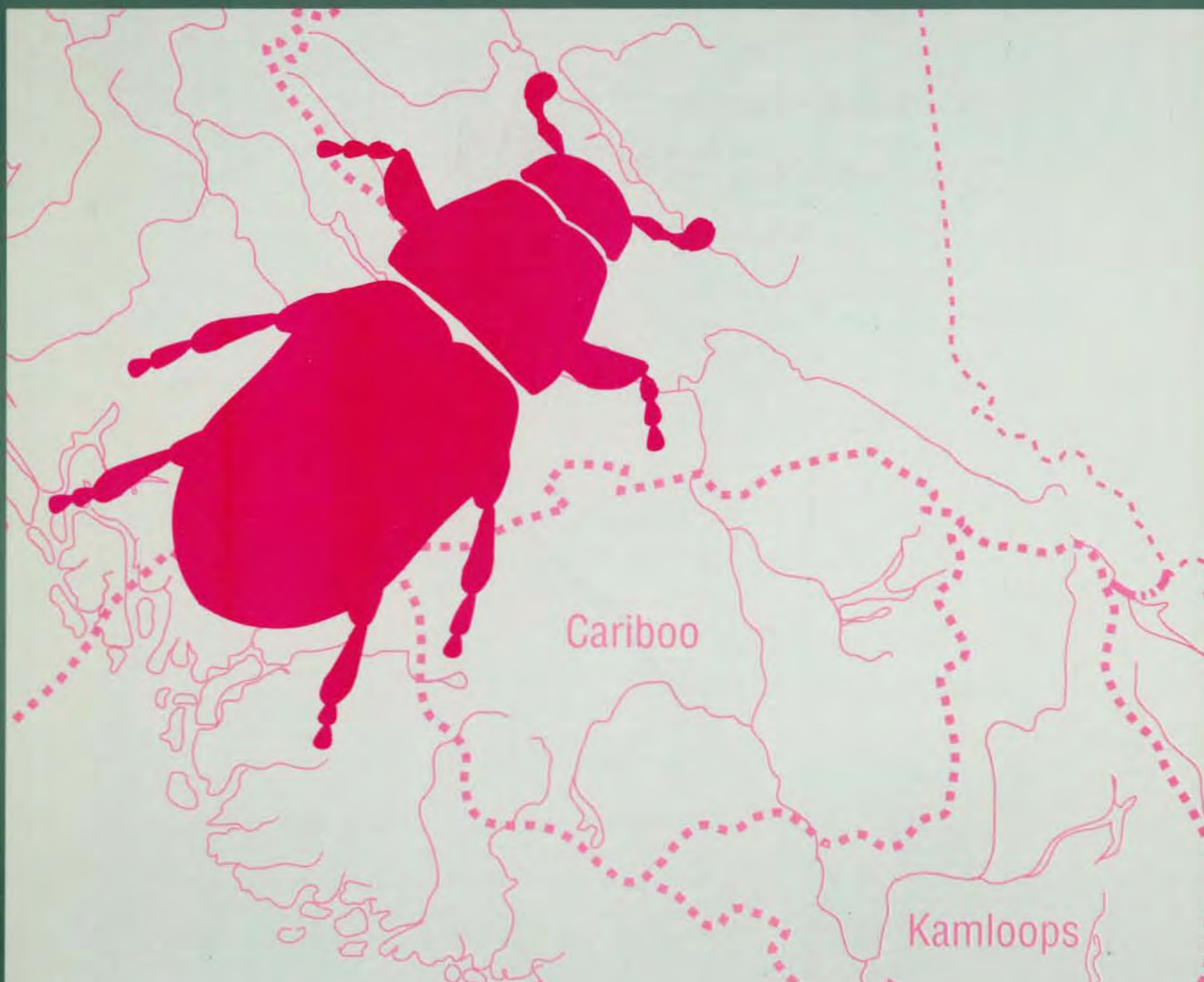
Simulation of mountain pine beetle (*Dendroctonus ponderosae* Hopkins) spread and control in British Columbia

Pacific and Yukon Region — Information Report BC-X-329

A.J. Thomson



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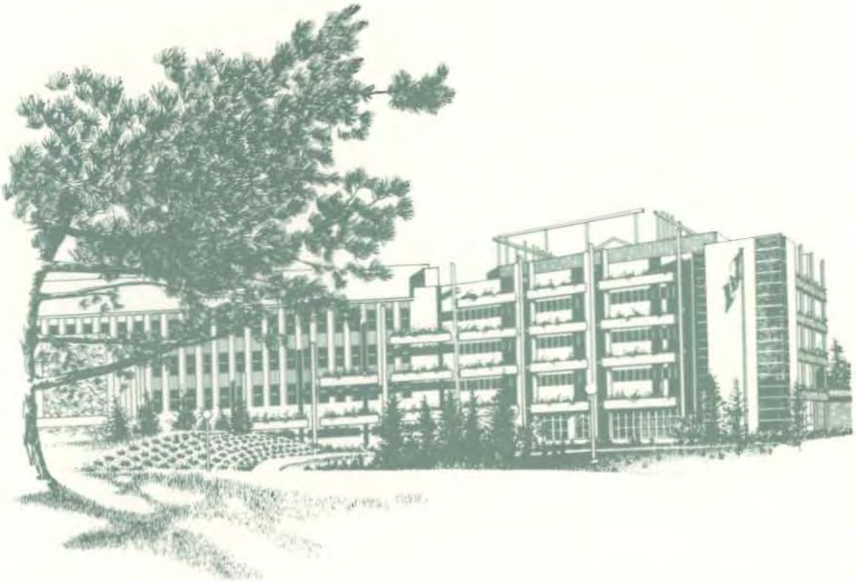

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Contents

Abstract

A method of predicting spread of mountain pine beetle through the use of a simulation model is described, and the assumptions underlying the method are explained. The model was designed to interface with the British Columbia Ministry of Forests forest inventory, and to require only a minimum amount of information about mountain pine beetle (such as the information normally available from operational surveys) to run.

Control by selective harvesting of attacked stands, use of pheromones, and various single-tree treatments is evaluated through a sensitivity analysis of the model parameters; area of attack was the indicator variable for the sensitivity analysis. All control measures were greatly affected by the efficiency of the survey procedure used to determine the extent of the attacked area. In addition, methods such as pheromone baiting and single-tree treatments of various types became relatively ineffective as the area of attack increased, or where there was significant population pressure from neighboring infested areas.

Résumé

Cette étude décrit une méthode permettant de prédire les invasions de dendroctones du pin des montagnes au moyen d'un modèle de simulation et définit les postulats sur lesquels repose la méthode en question. Le modèle a été conçu pour être appliqué a l'inventaire forestier du ministère des Forêts de la Colombie-Britannique et pour ne fonctionner qu'avec un minimum d'information sur les dendroctones du pin des montagnes (comme l'information habituellement tirées des enquêtes opérationnelles).

Les auteurs font une évaluation de la méthode de contrôle par abattage sélectif des peuplements envahis, de l'utilisation de phéromones et de divers traitements sur un seul spécimen en procédant à une analyse de sensibilité des paramètres de modélisation, la variable indicatrice étant la zone attaquée. Cette évaluation révèle que l'efficacité des mesures de contrôle est fonction du degré d'efficacité de la procédure d'analyse utilisée pour déterminer l'étendue de la zone attaquée. L'étude a en outre démontré que les méthodes telles l'emploi de leurres à base de phéromones et les traitements basés sur un seul spécimen devenaient progressivement inefficaces à mesure que la zone attaquée augmentait ou dans les cas où les peuplements étaient très menacés par les attaques voisines.

Acknowledgements: I wish to thank the Forest Insect and Disease Survey unit of the Pacific Forestry Centre for providing the data on damage by supply block.

Introduction

The mountain pine beetle (*Dendroctonus ponderosae* Hopkins) is the major pest of mature pines in western North America (Safranyik *et al.* 1974, 1975; Amman and Cole 1983). The principal host in British Columbia is lodgepole pine (*Pinus contorta* Dougl.). Outbreaks are triggered by the effects of weather on tree resistance (Thomson and Shrimpton 1984; Thomson *et al.* 1985). Initial stages of outbreaks are characterized by small clusters of red-topped trees in stands. The subsequent development of the outbreak is through dispersal of the beetles.

Insect dispersal can occur at many different scales, ranging from the movement within a tree of western spruce budworm larvae (*Choristoneura occidentalis* Freeman), to the movement between regions of adult budworm and mountain pine beetle. To evaluate the way in which pest dispersal affects regional forest management, especially timber supply analysis and pest control options, a population model which interacts with the forest inventory is required.

Thomson (1979) developed a simulation model of western spruce budworm population dynamics and impact in the mountainous terrain of British Columbia. One of the goals of the model was to evaluate the consequences of a control program when the wind direction in the major valleys at the time of moth flight, and the pattern of moth dispersal, were uncertain. The budworm outbreak area was partitioned into cells within which the forest cover was defined. The cells were linked by lists of neighbouring cell identifiers created on the basis of relative position within valley systems. The linkage pattern could be varied to reflect different assumptions about wind patterns at the time of dispersal and the allocation of moths dispersing from a source cell across the cells of its linked list could be varied to reflect different hypotheses about the dispersal mechanism. A similar approach to dispersal simulation was used as the basis of a mountain pine beetle spread model.

Model Description

Spread within compartments

The British Columbia Forest Service aggregates the forest inventory in units of different sizes ranging from individual stands to the entire province. An intermediate sized area is the compartment, which represents a topographic unit such as a watershed or a section of a watershed. Compartments are grouped by supply block, and supply blocks are then grouped by timber supply area (TSA).

To guide model formulation, the area of damage over the course of the most recent outbreak was determined for several areas from the annual aerial survey maps of mountain pine beetle damage prepared by the Forest Insect and Disease Survey of Forestry Canada. Damage by mountain pine beetle was categorized by supply block within TSA's of the Cariboo Region (Table 1). Use of such historical data directly for model parameterization has some difficulties. For example, note the appearance of 21 276 ha of damage in the Tatla supply block in 1981. This was due to the absence of any survey in 1980 rather than to immigration of a large beetle population from elsewhere. Such anomalies must be recognized and removed from data sets used to parameterize the model. Also, since damage is expressed in terms of areas with red-topped trees, which normally result from beetle attack in the previous year, the mapped area of red-topped trees actually reflects spread during the previous year.

The present description is based on supply block data, but model development was at the compartment level. The basic model is:

Future damage = f(current damage, host availability, weather)

The procedure followed is then:

a) predict the area attacked next year within the unit
b) apportion the attack among stand types within the unit
c) determine the severity of the attack.

The underlying hypothesis on which the model and the data-fitting procedures are based is indicated in Figure 1. Most models of insect population outbreaks determine numbers of insects in any generation primarily by the numbers in the preceding generation (Barclay et al. 1985). In the present system, the area attacked is used as an index of the population level. The upper dashed line (Figure 1) gives an overall average rate of increase of attacked area for all geographic units (compartments or supply blocks) in a region over all years of the outbreak (i.e. with average weather). The lower dashed line indicates the average spread rate for years in which adverse weather reduces mountain pine beetle brood productivity. In any year, those units with better host conditions will have faster spread than those with poor host conditions; consequently, spread rates in

Table 1. Area (ha) of mountain pine beetle damage in the Cariboo Region based on Forest Insect and Disease Survey records

Timber supply area	Supply block	Year						
		80	81	82	83	84	85	86
Williams Lake	Anahim	6255	11860	45630	34000	22810	6060	4564
	Chezacut	12940	2740	20175	77750	87490	18560	23417
	Tatla	0	21276	72840	105000	60450	0	0
	Chilcotin	2905	3454	19760	30900	7030	0	7
	Kloakut	0	2660	28590	36410	107040	46000	11689
	Gaspard	4125	10409	10400	16000	27100	15690	10870
	Churn	0	4096	3670	3090	8000	2550	1355
	Springhouse	4405	5767	4970	6080	4895	4130	2165
	Palmer Lake	1044	323	3680	25240	27060	63600	26958
	Skelton	645	0	70	1870	1540	750	910
	Moffat	0	0	100	1280	1570	570	125
	Upper Horsefly	0	0	0	190	0	90	45
	Junction	0	0	65	320	0	5	0
	Cariboo	3620	4662	3520	6400	6590	3030	670
Quesnel	South Kluskus	0	0	0	0	180	1390	515
	West Narcosli	0	0	0	1980	1730	5860	11615
	East Narcosli	145	0	5	320	1280	4660	7709
	SSA	0	0	95	250	10	200	234
	Cottonwood	0	0	0	70	0	150	145
	Big Valley	0	0	0	770	0	90	1
	Bowron	0	0	0	3840	0	150	32
	Cunningham	0	0	0	760	0	1040	154
100 Mile	Meadow	0	4939	0	17820	4890	4570	1950
	Loon	0	177	160	1410	625	1200	447
	Bonaparte	0	0	0	130	0	90	17
	Sheridan	0	0	0	0	0	30	39
	Holden	585	89	4110	2370	450	1790	1100
	Rail	0	0	0	190	0	80	43
	Ruth	0	0	0	130	0	50	52
	Canim	0	0	0	510	0	10	114
Tweedsmuir Park		0	0	2560	0	4530	5289	0
Bowron Lake Park		0	0	0	760	1650	870	270
Military Block		0	0	1150	2050	240	910	285

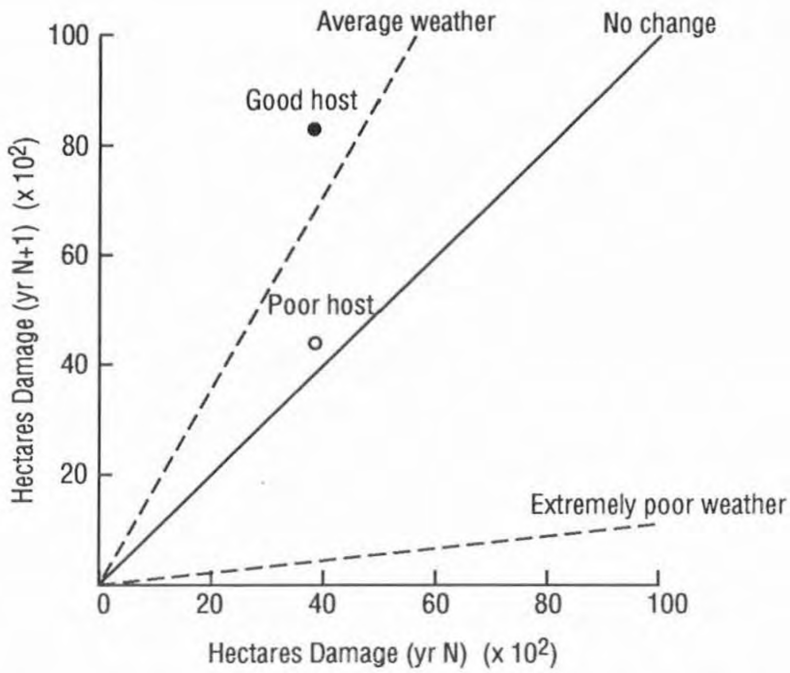

Figure 1. General overview of modeling approach showing the basic dependence of next years damage by mountain pine beetle on this years damage. Weather changes the overall slope of the relationship, and individual units of land will have a residual dependent on the types of stands within the unit. The slopes of the lines will be based on a representative sample of units, or all units, in a region.

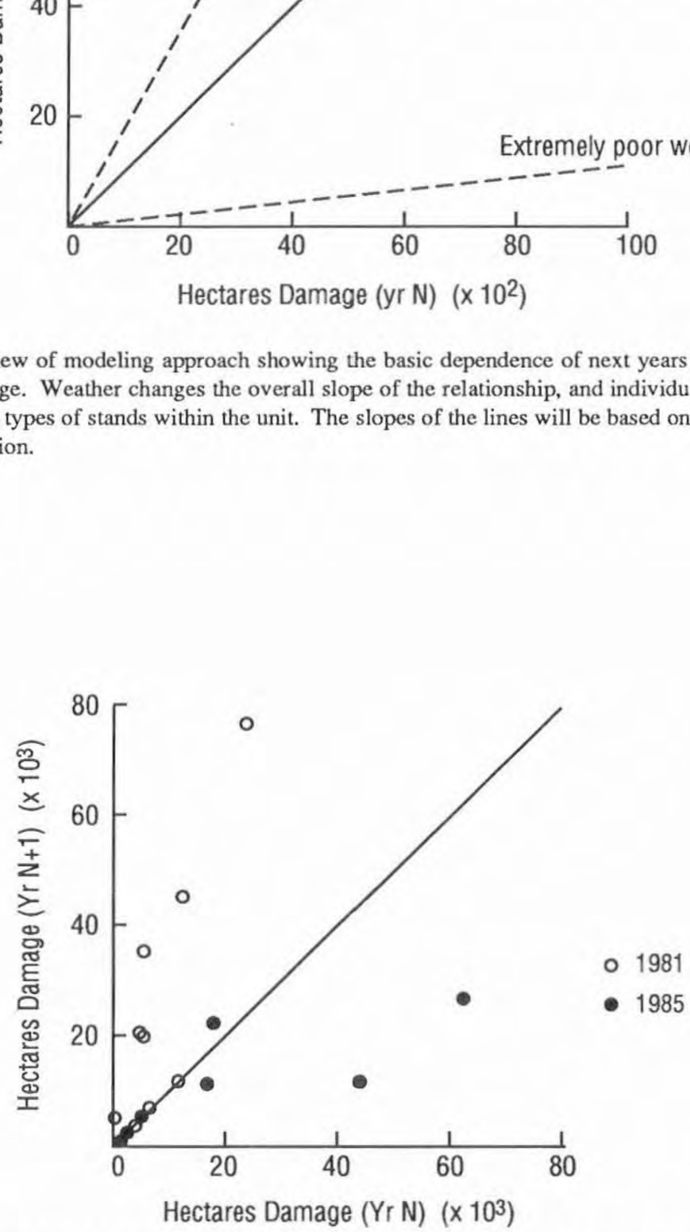

Figure 2. Change in area of attack by mountain pine beetle in the Williams Lake TSA in years with high (1981) and low (1985) spread rates, based on damage per supply block as indicated by the distribution of red-topped trees.

individual units which have a specific attacked area will deviate from the overall spread rate, and the magnitude of the deviation will be related to the forest component of the unit. The lines used to represent spread rates will normally be developed using regression techniques, in which case the deviation of a unit from the line can be equated to the residual.

Examples of high (1981) and low (1985) rate of spread years in the Williams Lake TSA are illustrated in Figure 2; these data conform to the original model postulaes (Figure 1). Note that as a result of the 1-year lag between attack and damage, these data represent the populations in 1980 and 1984, respectively. With a low rate of spread such as that indicated by the 1985 data, one must distinguish between the effect of poor weather and the effect of a lack of available host as the lodgepole pine forest is destroyed. These are easily distinguished by comparing the attacked area with the available inventory.

Using supply blocks as the units of area, there are relatively few data points within a TSA; however, when compartments are used, there are about ten times as many data points per TSA. For the purposes of the sensitivity analyses described herein, an average regional rate of spread of 2.00 is assumed.

Development of mountain pine beetle outbreaks

The transition of populations of mountain pine beetle from endemic to epidemic levels (Shrimpton and Thomson 1983; Thomson and Shrimpton 1984; Thomson et al. 1985) is assumed to have occurred prior to the use of the model, so that populations are sufficiently high to overcome the normal resistance of the host trees.

Two requirements of the model influenced the method of evaluating changes in the population of mountain pine beetle in the model: that the model could interface with the inventory database of the British Columbia Ministry of Forests, and that it require only the most basic description of mountain pine beetle populations to run (i.e., area attacked). The inventory database linkage required that damage be assigned on the basis of stand types; the limitation of population description to area of attack required definition of such areas in relation to stands.

The normal progression of mountain pine beetle attack in a stand is as follows (Figure 3). The first sign of attack is a small patch of red-topped trees where trees attacked in the previous year have died (Figure 3a). Subsequently, this patch expands and new patches may appear (Figure 3b). Eventually, most trees in the stand may be attacked, and attacks may spread into adjacent stands (Figure 3c,d). In exceptionally severe outbreaks, this progression may be compressed into a short period of 1 or 2 years.

Historical records of mountain pine beetle outbreaks include maps of attacked areas, but it is often difficult to interpret such records in a unified manner, as different individuals may record attack in different ways. For example, one individual might record the pattern of Figure 3b as two separate, small but severely attacked areas, while another might record the same pattern as a single area of light or moderate attack severity. Problems in recording attack areas are illustrated in Figures 3c and 3d, where small numbers of attacked trees in one stand are actually at the edge of a major area in a neighbouring stand.

In the model, attack is expressed in terms of *area of stands in which mountain pine beetle attacks have occurred.* Stands of a given type which have been attacked are then classified with respect to the number of years over which attacks have occurred. The intensification of attack within a stand illustrated in Figure 3 is thus a function of attack history. It is assumed that attacks essentially destroy all available host in that stand after a specified number of years, and the stand is then dropped from the inventory of available host. A variable (USEMIN), which may vary from TSA to TSA, represents the smallest stand size in the TSA, and is used to provide a lower limit to the allocation of damage to any stand type; otherwise, allocation of damage on a purely proportional basis might result in unreasonably small attacked areas in some types.

At the start of the simulation, the total area of attack (i.e. total area of stands in which mountain pine beetle has occurred) is specified, as well as the length of time since attacks were first observed in that compartment. The model then estimates the most likely history of attack in forests of the mix of stand types occurring in the compartment, assuming average weather conditions, to give the observed infestation pattern. This estimated history is then used to evaluate the future spread of the outbreak.

Forest cover

The inventory classification system used by the British Columbia Ministry of Forests assigns to each stand a type description which includes the major species, additional species (if any), age class, and site quality. Nine generalized stand types are used in the model (Table 2).

This classification reflects two of the major components of mountain pine beetle hazard rating

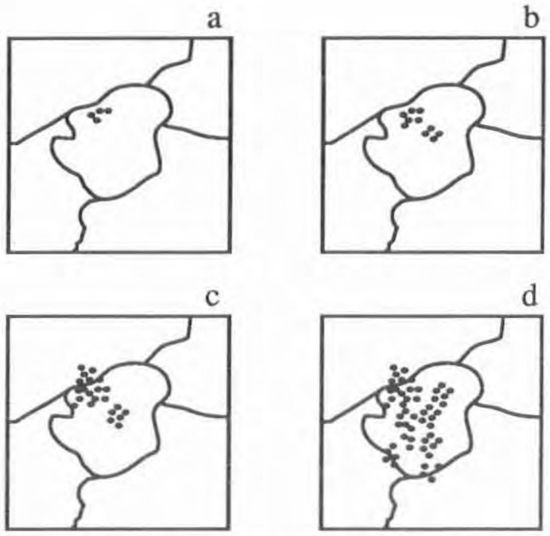

Figure 3. Normal progression of mountain pine beetle attack in a stand. In successive periods (a to d) an increasing proportion of trees succumb to attack, and neighboring stands are also attacked.

systems (Shore *et al.* 1989): percentage of host species, indicated by the species mixture in the stand, and average host size, indicated by the site and the age classes tallied. All mature stands in a compartment are included, and the minimum age class for maturity can be varied with site and species mix.

The percentage of the area covered by forest and percentage of the forest which contains host both influence survival of dispersing insects (Thomson 1979). The total compartment area and total forested area are therefore recorded for each compartment to enable calculation of these proportions to estimate such effects for mountain pine beetle.

The mix of stand types in the forested area of a compartment affects mountain pine beetle spread rates. The residual of a compartment from the regression line describing the regional spread rate (Figure 1) is calculated from the area of each of the nine forest types weighted by a factor which reflects the relative brood productivity in stands of that type under outbreak conditions (Table 2). For the species composition effect, stands where lodgepole pine is the leading species have a relative value of 1.0, and for the site effect, medium sites have a relative value of 1.0. Leading lodgepole pine stands on medium sites are therefore assumed to be the average conditions under which the regional spread rate is achieved.

The relative spread contribution for pure, leading, and secondary lodgepole pine stands is assumed to be 1.5, 1.0, and 0.66, respectively; the relative spread contribution of good, medium, and poor sites is assumed to be 1.5, 1.0, and 0.33, respectively. The overall spread weightings are shown in Table 2. The actual spread is obtained by multiplying the current area by the regional rate,

Table 2. The nine combinations of stand composition and site quality considered in the model, and their spread weight and attack sequence (order of preference by the mountain pine beetle)

Class	Species mix	Site quality	Spread weight	Attack order
1	Pure lodgepole pine	good	2.25	1
2	Pure lodgepole pine	medium	1.50	3
3	Pure lodgepole pine	poor	1.00	5
4	Lodgepole pine leading species	good	1.50	2
5	Lodgepole pine leading species	medium	1.00	4
6	Lodgepole pine leading species	poor	0.66	6
7	Lodgepole pine secondary species	good	0.50	7
8	Lodgepole pine secondary species	medium	0.33	8
9	Lodgepole pine secondary species	poor	0.22	9

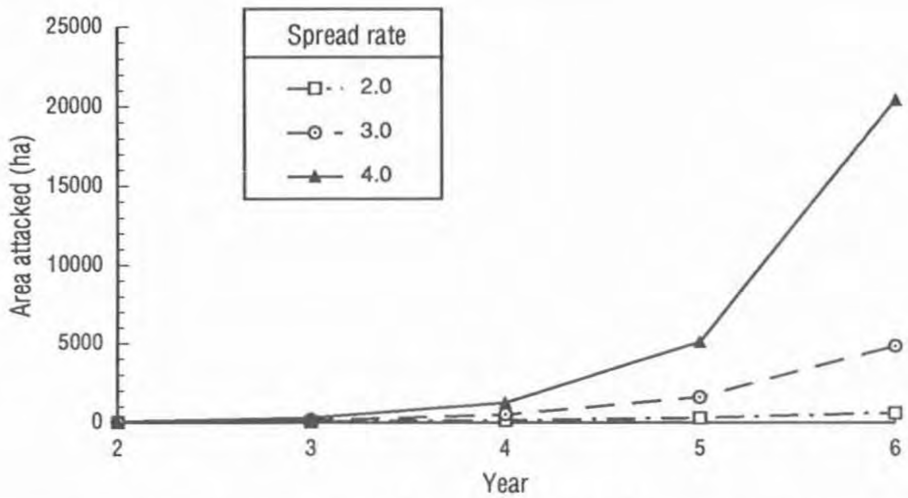

Figure 4. Increase in area of attack by mountain pine beetle from an initial 20 ha up to the sixth year, assuming spread rates of 2.0, 3.0 and 4.0.

modified by weather and the residual of the the spread rate for the compartment from the regional spread rate. Since the calculation is multiplicative, a wide range of combinations of regional rate, compartment residual, and weather effect can result in similar spread rates.

The maximum and minimum values of the residual would be found in compartments consisting entirely of pure lodgepole pine on good sites, and secondary lodgepole pine on poor sites, respectively. The maximum amount by which such residual values can vary from the overall average spread rate are set in the model by the variables RESMAX and RESMIN.

Dispersing beetles have a preference for certain stand types. This preference is reflected in the attack order of each forest type (Table 2); stands composed of pure lodgepole pine on good sites are most preferred, followed by leading lodgepole pine on good sites. Both the spread weightings and the attack order can be varied in the simulation, as well as the maximum and minimum value of the residual.

Dispersal losses where there is a large amount of non-forested land are incorporated by testing the proportion of a compartment which is forested against a threshold value (THRF) which is set at 0.4. If the proportion of a compartment that is forested falls below the threshold, the overall spread in the compartment is reduced by multiplying by a factor (PFOR) which is set at 0.66. Similarly, dispersal losses where much of the forest is compared of non-host species are incorporated by use of a factor (PHOST = 0.66) when the proportion of the forest in a compartment which contains host falls below a threshold (THRH = 0.5). The values of THRF, PFOR, THRH and PHOST can all be changed in the simulation to improve the fit of the model in such compartments.

Spread in the absence of controls

The uncontrolled spread of mountain pine beetle within a compartment is determined by the regional spread rate modified by the compartmental residual from the regional rate related to the forest cover (Figure 1) and weather, and is of an exponential nature. Assuming a regional spread rate of 2.0 (which doubles the attacked area each year), a combined compartmental residual and weather weighting of 1.0, 1.5 or 2.0 was used to give an overall spread rate of 2.0, 3.0 and 4.0 respectively, starting with 20 ha of attack (Figure 4).* In the sixth year of the outbreak the attacked area had increased from 20 ha to 640 ha with a weighting of 2.0, compared to 20480 ha with a spread rate of 4.0.

Changes in initial attack area can have pronounced effects over relatively few years. With an overall spread rate of 4.0, 100 ha initial attack resulted in an attacked area of 6400 ha in year 4; in contrast, 20 ha of initial attack resulted in an attacked area of 1280 ha in the same period (Figure 5). As

* All graphs of system performance prepared for this report were created using a particular version of the system developed specifically for sensitivity analysis. The operational version of the model was transferred to the British Columbia Ministry of Forests Protection Branch and is accessible through their general protection systems user interface. This report is not a user manual: user instructions are part of the Protection Branch system documentation.

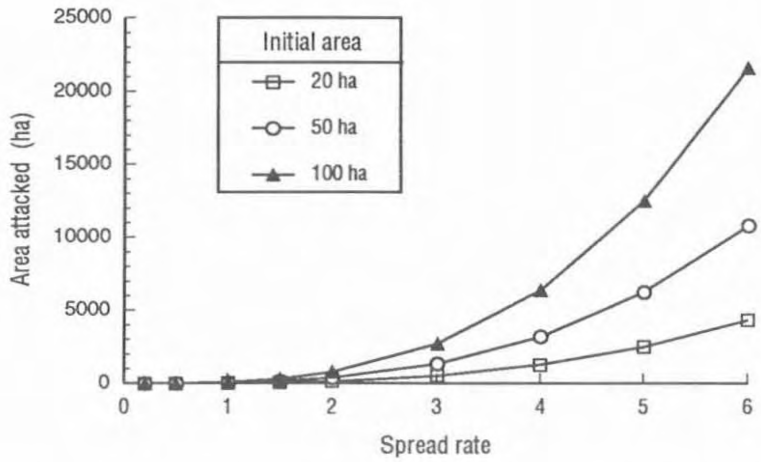

Figure 5. Increase in area of attack by mountain pine beetle over four years resulting from different initial attack areas (20, 50, and 100 ha) and spread rates up to 6.0.

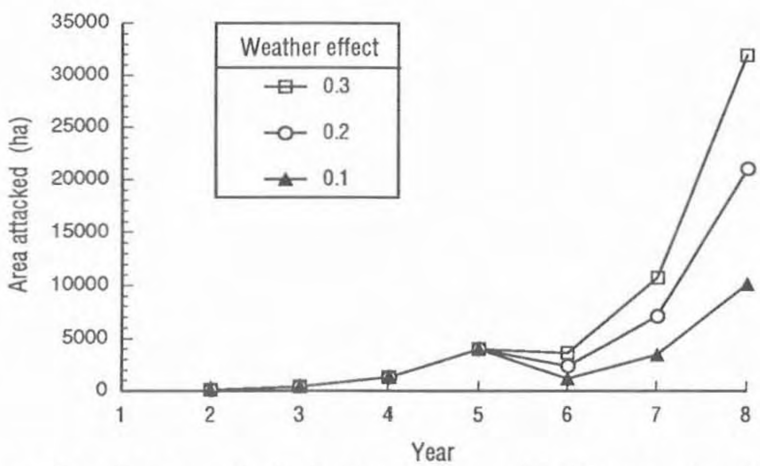

Figure 6. Increase in area of attack by mountain pine beetle over 8 years with different weather effect modifiers (0.3, 0.2, and 0.1) applied to the overall spread rate in year 6.

spread rates increase towards 6.0 under conditions of extremely favorable stand types and weather, the potential for large-scale damage is very high.

Weather effects

An annual weather effect modifier is set for each year of the simulation. Average weather is indicated by a value of 1.0. Conditions favorable for mountain pine beetle populations are indicated by values greater than 1.0, and adverse conditions by values less than 1.0. Figures 1 and 2 illustrate the manner in which weather effects modify the regional rate of spread. To illustrate the consequences of 1 year of adverse weather within one compartment, an initial attack of 50 ha was allowed to spread at an overall rate of 3.0, with adverse weather in year 6. Values of 0.3, 0.2, or 0.1 were used in year 6, giving spread rates in that year of 0.9, 0.6, or 0.3, respectively (i.e. the affected area decreased in size). Increasingly adverse weather reduces the area available for spread in the following year (Figure 6), and subsequent development from that varying area is similar to that illustrated in Figure 5.

Control options

Control options may be evaluated in the system in the following manner:

a) Clearcutting of infested stands would reduce the area attacked in a particular year and thus reduce subsequent damage (Figure 1).

b) Selective harvest of high risk unattacked stands would reduce the carrying capacity of the compartment and create a lower compartment residual from the regional spread rate, slowing down the rate of spread.

c) Treatment of single infested trees (e.g. use of the chemical MSMA or pile-and-burn) removes stands from the infested category without destroying the stand, and has an effect similar to option (a), through reduction of the area attacked.

d) In the early years of an outbreak, before such options become unfeasible due to swamping by dispersing beetles, spread rate within a compartment may be decreased to account for reduction in the population of dispersing beetles through control methods such as pheromones and trap trees, inundation of parasitoids or predators, or the use of microbials.

e) The consequences of varying the species composition may be explored through the weightings which define the relationship of the compartmental residual from the overall regional spread rate to forest type.

Selective harvesting of attacked stands

Selective harvesting of stands attacked by mountain pine beetle reduces the area available for contributing insects to spread in the next year (Figure 1), and this lowers the spread rate. However, harvest can only be carried out on stands where the beetle has been detected. Foliage normally does not discolor until the year following attack, so the first year of attack in a stand can only be detected by ground examination. Stands in which attack was observed in previous years are assumed to be fully detected. The ground-based sampling procedure for determining the spread of mountain pine beetle is known as the probe.

When red-topped trees are detected by aerial survey, attack by mountain pine beetle is confirmed by ground examination, then the area around the red trees is examined for green-attacked trees. The radius of the survey is increased until no more attacked trees have been located within a specified distance. The efficiency of the probe is therefore related to the spread rate of the beetle. When spread rates are low, most new attacks will be close to the old attacks, and so will be easily detected. As the spread rates increase, new attacks will occur further from the old attacks and will be more easily missed by the probe.

At spread rates less than or equal to 1.0 there are no new attacked areas, so all attacked areas are assumed detected. As spread rate increases, a decreasing rate of detection is assumed. For the purposes of the sensitivity analysis, probe efficiencies higher and lower than the standard values were also tested.

Range of overall spread rate (x)	Probe efficiency		
	Low	Standard	High
$0.0 < x < 1.0$	1.000	1.000	1.000
$1.0 < x < 1.5$	0.900	0.950	0.975
$1.5 < x < 2.0$	0.800	0.900	0.950
$2.0 < x < 2.5$	0.600	0.800	0.900
$2.5 < x < 3.0$	0.300	0.600	0.800
$x > 3.0$	0.100	0.200	0.600

An initial attack of 200 ha was used, and the area of attack at the end of year 5 examined, assuming selective harvest of all detected attacked stands and a spread rate from stumps (CUTAO) of 0.15. As spread rates increase, only the most efficient probe procedure allows selective harvesting to keep the outbreak under control (Figure 7). With less efficient probes, there is a threshold spread rate, around 3.5, above which selective harvesting of attacked stands does not control the outbreak.

Spread of mountain pine beetle when attacked stands are harvested does not only come from undetected attacked areas. Mountain pine beetle also spreads from the stumps left by the logging at a rate (CUTA0) proportional to that from uncut stands. A standard value of 0.15 was assigned to CUTA0, implying that spread from stumps was 15% of that from stands. A lower value (0.1) and a higher value (0.25) were also examined, assuming the standard probe efficiency described above. Figure 7 illustrates the effect of spread rate on harvest with CUTA0 = 0.15. The effect of varying the proportional spread rate from stumps was also examined. In Figure 8, the area attacked after 5 years is given as the percentage of the area attacked assuming the highest value of CUTA0 (0.25) at varying overall spread rates (Figure 8).

When the spread rate from the stumps is low, complete control can be achieved by selective harvesting over a wider range of overall spread rates. Accurate determination of the spread rate from stumps is important only when the overall spread rate is relatively low; at higher overall spread rates, spread from areas missed by the probe becomes more important than spread from the stumps left in the cutblocks.

Pheromones may be applied around the cutblocks to reduce the spread from stumps. A pheromone percentage efficiency (CUTAP) of the untreated spread rate from stumps is used in such situations. A standard value of CUTAP of 50 is used, implying that pheromones reduce spread from stumps by 50%. The effect of such treatments is analogous to the lower CUTA0 spread rate in Figure 8; more control is possible at the lower overall spread rates (Figure 9). In practice, the efficiency of pheromone treatments around cutblocks might vary with cutblock size and overall spread rate, but as there is little information about this variability a constant value is used at present.

Selective harvesting of stands at risk

As indicated earlier, selective harvesting of the unattacked stands that are at risk would decrease the compartmental residual of the spread rate by altering the stand composition, thus slowing spread through the compartment. The effects of reducing the compartmental spread rate in this way may be evaluated from Figures 4 and 5. The harvest also reduces the carrying capacity of the compartment (as does selective harvest of the attacked areas), reducing the potential spread to adjacent compartments later in the outbreak, as discussed in the section on inter-compartment spread.

Pheromones

When beetle populations are low, pheromones may be used successfully to reduce the spread from attacked stands. However, as the population builds, enough beetles are available to escape the traps and the effect on spread is lessened. The contribution of stands to the residual of the compartment from the regional spread rate is decreased when pheromones are used to influence the weightings. However, it is assumed that the amount of the decrease diminishes as the area of attack increases. Two threshold areas (area of attacked stands in a compartment) are defined: if the current attack is less than the lowest threshold area, then pheromones have the greatest effect on spread rate; if current attack is above the highest threshold area, then the effect of the pheromone is minimal. Threshold areas of 100 ha and 300 ha are used, with pheromone efficiency values of 66%, 50% and 10%.

As with other controls, pheromones can only be used in stands where outbreaks have been detected; thus, their effectiveness varies with the efficiency of the probe. Starting with 20 ha of attack, and using the standard pheromone efficiency of 66% with treated areas less than 100 ha, decreasing to 10% when the treated area exceeds 300 ha, a high efficiency probe is required to achieve much control after 5 years (Figure 10). Using the standard probe efficiency, even an increase of pheromone efficiency does not achieve much control if the overall spread rate increases above 3.5 (Figure 11).

In this example, pheromone efficiency was varied by changing the threshold areas. The low efficiency pheromone had threshold areas of 50 and 200 ha, while the high efficiency pheromone had threshold areas of 200 and 500 ha. The standard and low pheromone efficiency curves coincide at a spread rate of 6.0 (as might occur with a high regional spread rate in a compartment with mostly pure lodgepole pine on good sites, during a year of better than average weather), due to the pattern of increase in relation to the threshold areas for pheromone efficiency (Figure 12). In the second year, the attacked area lies between the lower and

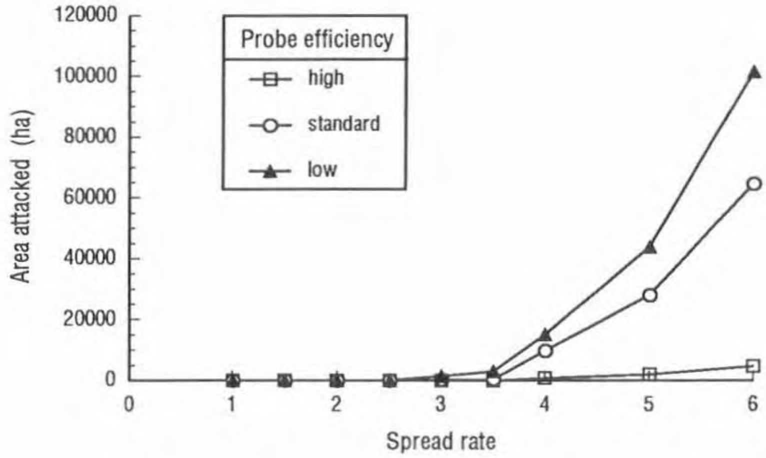

Figure 7. Increase in area of attack by mountain pine beetle after 5 years with different probe efficiencies (high, standard, and low) when selective harvesting of attacked stands is used to control the outbreak. A spread rate from stumps (CUTA0) of 0.15 was assumed.

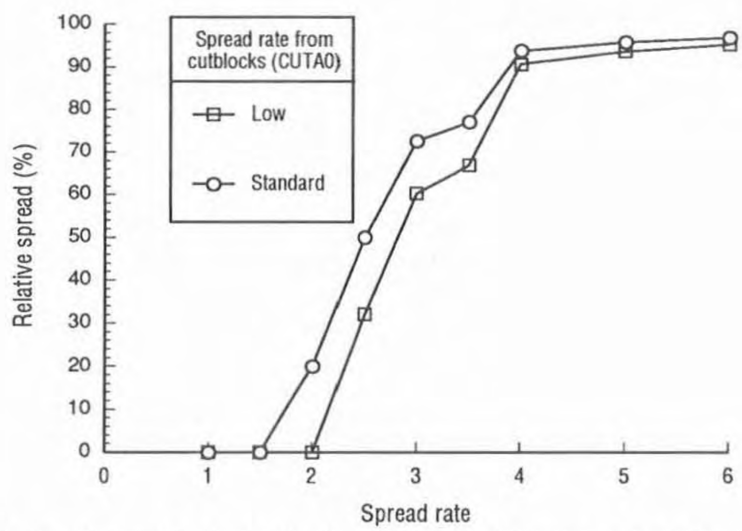

Figure 8. Reduction of spread of mountain pine beetle after 4 years with different spread rates from stumps when selective harvesting of attacked stands is used to control the outbreak. Relative spread is the percentage of the area that would have been attacked with the highest spread rate from stumps (CUTA0 = 0.25)

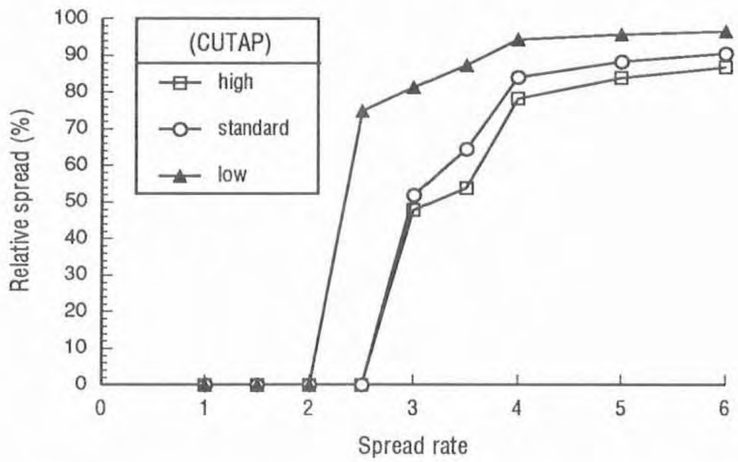

Figure 9. Reduction of spread of mountain pine beetle after 5 years with different pheromone efficiencies (17, 50, and 66%) when pheromones are used to control spread from stumps. Relative spread is the percentage of the area that would have been attacked had no phermones been used.

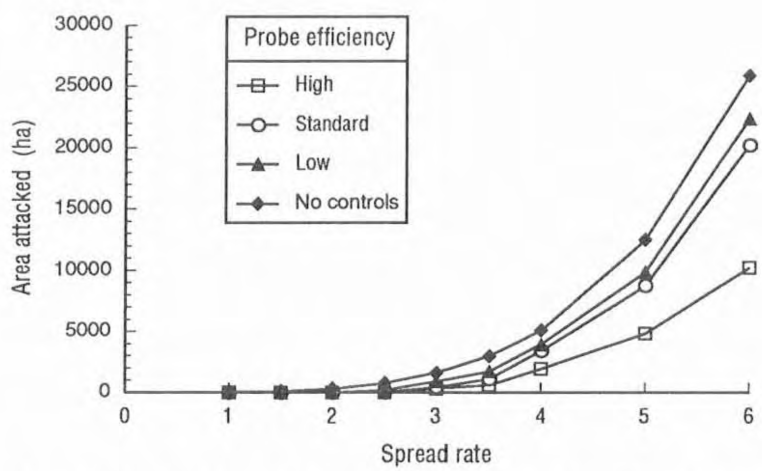

Figure 10. Increase in area of attack by mountain pine beetle after 5 years with different probe efficiencies (high, standard, and low) when phermones are used to control the outbreak.

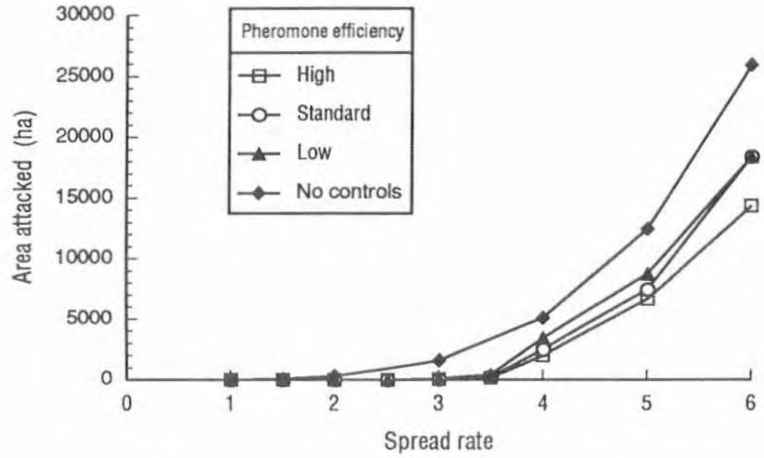

Figure 11. Increase in area of attack by mountain pine beetle with different pheromone efficiencies (high, standard, and low) when pheromones are used to control the outbreak. A standard probe efficiency was assumed.

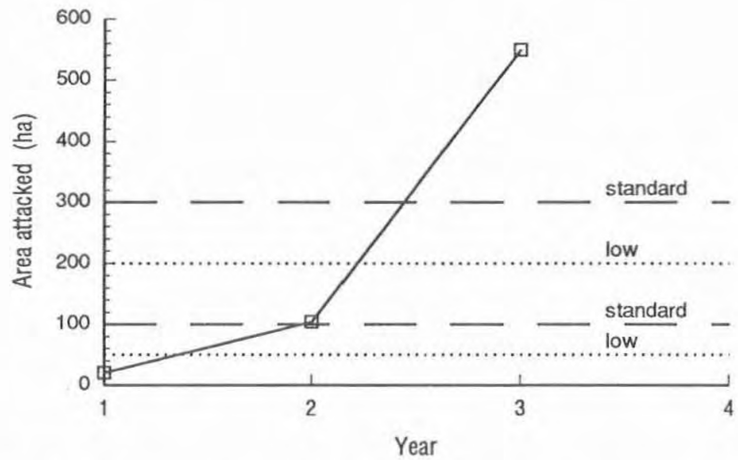

Figure 12. Increase in area of attack by mountain pine beetle over four years in relation to two pheromone effectiveness threshold configurations. In the low configuration, the thresholds are 50 and 200 ha; in the standard configuration, the thresholds are 100 and 300 ha. The level of pheromone effectiveness in each year is the same whether the low or the standard configuration is used.

upper threshold area of both the standard and low efficiency pheromone levels, and by year three, the area exceeds the upper threshold area in both cases. Pheromone efficiency, expressed in relation to effective area, therefore has no effect in this instance.

Single-tree treatments

Any treatment which destroys the brood in individual trees is considered in this category. Success of single-tree treatments is influenced by two main factors (apart from the probe efficiency which identifies stands for treatment). First, effectiveness is modified by the efficiency (EFF) of the treatment in killing the brood in treated trees; for example, pile-and-burn leaves the brood in the stumps. Secondly, a proportion (DETP) of green-attacked trees in stands missed by the probe are assumed to turn red prior to the treatment, making them detectable in time for treatment.

Especially with treatments which destroy the whole attacked tree, efficiency of single-tree methods is high, most spread is from newly attacked stands missed by the probe and from trees within treated stands missed by the treatment. A standard value of efficiency (EFF) of 90% is used in all stands where attack is detected by the probe. In stands missed by the probe, 50% of trees are assumed to change color in time for treatment, and the treatment is also assumed to be 90% efficient in killing the brood in these detected stands.

Single tree treatments were evaluated based on the attacked area after 5 years, with an initial attack area of 20 ha. At lower spread rates, the probe efficiency is high so subsequent color change (DETP) is less important (Figure 13 a); when the probe is less effective at higher spread rates and more attacks are missed (Fig 13 b,c), subsequent color change is more important. At all spread rates, the efficiency of the treatment (EFF) plays a major role in determining the final attacked area, and spread rate itself plays a major role in determining the final outcome.

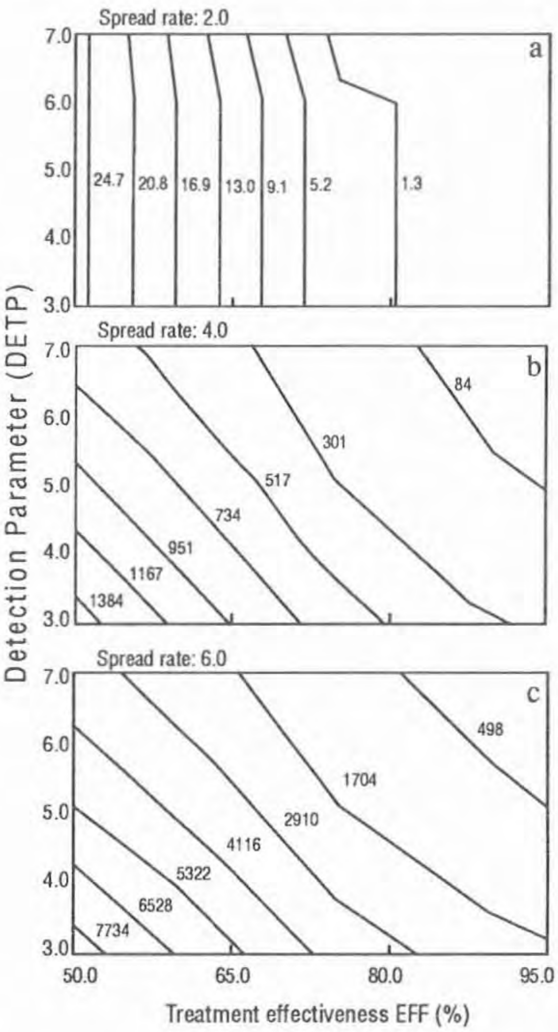

Figure 13. Area attacked by mountain pine beetle after 5 years with different levels of the effectiveness of single-tree treatment (EFF) and different proportions of green-attacked trees that change color in time to be treated (DETP). Contour lines join points of equal attack area, and the area associated with each line is given to the right of the line. Initial attack area was 20 ha.

Partial treatments

In all the above discussions of control methods, it is assumed that all the attacked forest in a compartment is treated. Partial treatments within a compartment are equivalent in effect to a low probe efficiency in that spread from untreated areas is similar to spread from areas missed by the probe. An important consequence of this observation is that a highly efficient probe is not likely to be cost-effective unless all detected attacked stands in a compartment are to be treated. If some stands are to be left untreated, then a less intensive probe may be appropriate.

In addition, it is assumed in these analyses of control options that there is no influx of beetles from neighbouring compartments. Effectiveness of controls may be negated by such dispersal effects.

Spread between-compartments

The above discussion has concentrated on the intensification of an outbreak within an area. Spread into a new area may also be examined. The amount of spread will be a function of the host availability in the new area, the extent of the outbreak in the new area's neighbors, and the topographic relationship of the area to these neighbors with respect to prevailing wind patterns.

A hypothetical two-compartment scenario was developed to investigate spread between compartments. The two compartments were identical: they were both 50 000 ha in size, and they were completely forested with leading lodgepole pine on medium sites. An initial infestation of 20 ha of attack was started in one compartment; spread between compartments was measured as the number of years required for the outbreak to first appear in the neighboring compartment.

The boundary between compartments generally represents a topographic feature, especially a ridge line. Such topographic features may limit spread to varying degrees. The boundary of a compartment in the Cariboo, for example, may be much less a barrier to spread than the topography represented by a compartment boundary in TSA's in the Rocky mountains. The proportion of the potential dispersal from a compartment that actually spreads to a neighbour in spite of topographic constraints (DPROP) should thus be lower in high mountain areas.

Within compartments, the location of stands is not specified. Stands at risk could be close to the boundary where spread from a neighbor would be easy, or they could be at the opposite end of the compartment, where spread would be difficult. It is assumed that on average, the bigger the area of a compartment, the greater is the population pressure from all neighboring compartments required to start a new outbreak in the compartment. A dispersed area threshold (DTHRA) is set to reflect such effects of compartment size and distribution of host within compartments of a TSA; this threshold is larger in TSAs which have large compartments than in those with small compartments.

In practice DPROP and DTHRA interact to modify spread between compartments (Figure 14). Consequently, the setting of these parameters is somewhat arbitrary; a combination was selected to reasonably approximate the historical pattern of spread. Current default values for DPROP and DTHRA are 0.04 and 10 respectively, with which 5 to 6 years must elapse before a 20 ha outbreak spreads to a neighboring compartment.

Within a TSA, each compartment actually has a number of neighboring compartments, each with its own orientation. Spread within a TSA is normally under the influence of prevailing winds or major topographic features. Spread in a preferred direction can be set through the use of weightings associated with the eight principal compass directions (DISPW). An eastward spread is illustrated in Figure 15, where an outbreak was initiated in a compartment on the western edge of the supply block and allowed to develop for 10 years.

Outbreak collapse

When the area of attack is low in a compartment in which host conditions are poor for beetle development, or there are other effects which reduce spread rates such as adverse weather or pheromone control programs, the mountain pine beetle population can collapse in that compartment. The threshold area below which the outbreak collapses in that compartment is assumed to vary linearly with spread rate and a parameter (BVAL) represents the slope of that relationship.

For example, if the spread rate falls to 0.3, and if BVAL is equal to 100 (the default value), then a total attacked area of less than 30 ha in that compartment will result in collapse of the outbreak. Increasing BVAL makes outbreaks less likely to collapse, and decreasing BVAL makes outbreaks more likely to collapse. A decreased BVAL would enhance the importance of pheromones, as the induction of collapse would be an effect in excess of the normal reduction in spread.

Discussion

The method of predicting mountain pine beetle spread described in this study focused on two primary considerations: the requirement that the model interface with forest inventory data of the British Columbia Ministry of Forests, and that it be usable with a minimum amount of information about beetle infestations - specifically, the area of attack and number of years of attack history. Relationships in the model were formulated on the basis of the research-based knowledge of scientists at the Pacific Forestry Centre.

Accurate estimation of many of the parameters in the model will require detailed study of historical mountain pine beetle outbreaks and control programs, and such studies are presently in progress. In addition, validation of the model requires that its use be closely monitored in an operational environment. Comparison of the observed and the predicted area of attack over the course of an outbreak is an appropriate test; comparison of the observed and predicted areas missed by the beetle is not. The basic algorithm assigns attack in accordance with weightings based on stand types in a manner that leads to loss of all the best stands in the course of an outbreak; in practice, a

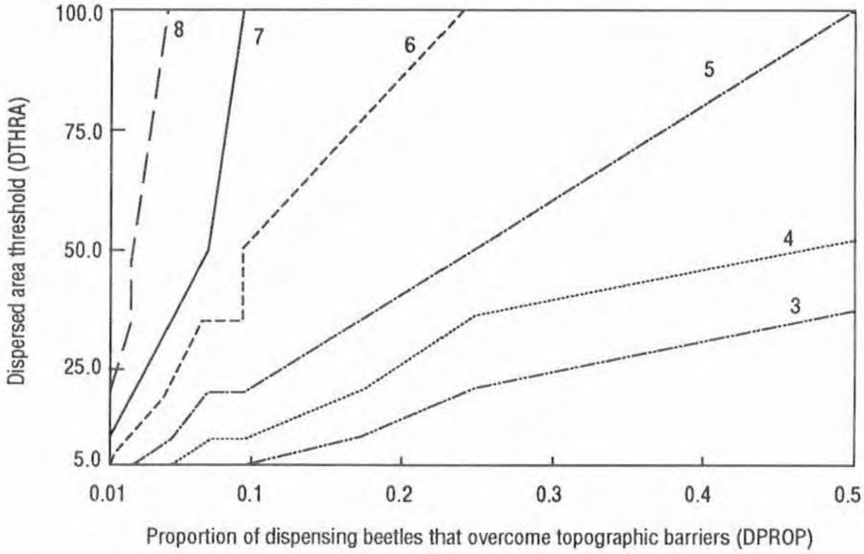

Figure 14. Number of years before an outbreak will spread to a neighboring compartment for different proportions of dispersing beetles that overcome geographic obstacles (DPROP) and compartment size effects (represented by the dispersed area threshold, DTHRA, which is larger for TSAs with larger compartments).

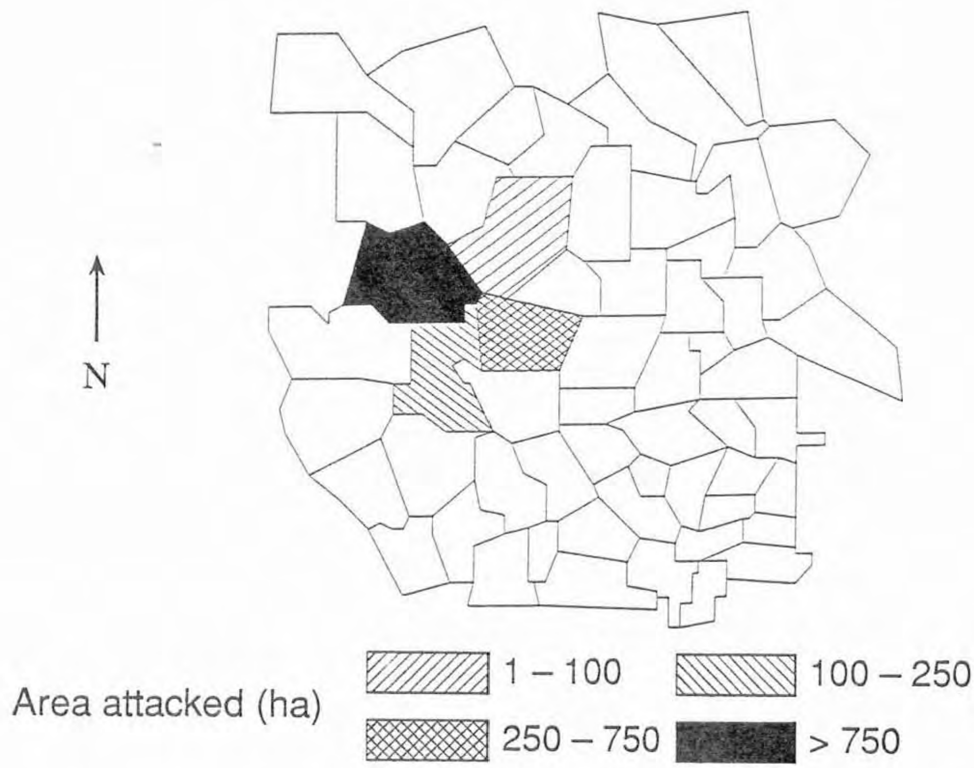

Figure 15. Extent of a mountain pine beetle outbreak in the mosaic of compartments in the 100 Mile House TSA 10 years after a hypothetical outbreak, using a hypothetical forest inventory, began in a compartment on the western border of the supply block. Prevailing winds were from west to east.

few good stands in isolated parts of the compartment may escape attack.

In the absence of statistically based estimates of parameters and validation of the model, which will require a considerable time to develop, evaluation of the model must rely on sensitivity analysis such as that described here. The sensitivity analysis was based on a highly structured use of the model, and results should be interpreted in this light. For example, all control options were evaluated in a single compartment, with no consideration of the possibility of spread from adjacent compartments, which could severely disrupt the controls. However, in the sensitivity analysis, control effect was generally evaluated with different within-compartment spread rates, and immigration from neighboring compartments would have an effect equivalent to high within-compartment spread.

In addition, all sensitivity analyses of control options assumed that the controls were applied to all attacked stands in the compartment; partial control was not evaluated. However, controls can only be applied where attacks are detected, and the sensitivity analysis did include varying efficiencies of the probe (the ground sampling procedure for mountain pine beetle). Partial control would therefore be equivalent to a probe of low efficiency which misses many areas of attack. A corollary of this idea is that probe effort should be reduced if it is known that controls will not be applied throughout the attacked compartment.

In the sensitivity analysis, controls were applied in each year within the test compartment, but in practice, decisions on control must be made on a year-by-year basis within the mosaic of compartments that comprise the area being simulated. In the model, two approaches to control were made available. Firstly, the status of the outbreak could be displayed for the year as in Figure 15, and controls could be specified by the user for specific compartments. Alternatively, a control policy could be established at the start of a simulation run, and the computer program itself would monitor the status of the outbreak and assign controls to compartments where appropriate under the policy. These two approaches to control reflect the way in which different types of users (operational *versus* planning personnel) might interact with the program.

In the sensitivity analysis, area of attack by the mountain pine beetle was the only indicator of system performance, but in practice many other indicators would be important, such as the number of compartments attacked, total area treated, cost/benefit values of control programs, salvage, and the area of forest at risk. Development of the appropriate user interface to make such indicators readily accessible will play a key role in the acceptability of the system.

A method of incorporating effects of mountain pine beetle dispersal in forest-level loss prediction was proposed by Hamilton *et al.* (1985), based on the procedure described by Thomson (1979) for budworm. The model described by Hamilton *et al.* was based on details of stand-to-stand movement of beetles, rather than the more abstract approach to beetle dispersal used in the present study.

The method described by Hamilton *et al.* (1985) has several basic assumptions :

a) Beetle dispersal is related to wind direction. A wind/topography rosette gives the proportion of dispersing beetles moving in a particular direction.

b) The spatial positions of stands are included in a geographic information system such that the size and neighbors of each stand are known, and the distances between stand centers can be established. From the neighbor list and the wind/topography rosette, the sequences of stands entered by dispersing beetles may be determined.

c) As dispersing beetles pass through a stand, a proportion, based on some stand hazard index, is "absorbed" by the stand, and another proportion is removed from the system to reflect dispersal mortality.

This approach requires a very detailed knowledge of the forest cover. In addition, a stand hazard system and appropriate "absorption" relationships are required, as well as detailed knowledge of dispersal mortality effects. In spite of this level of model detail, the authors indicate that the system cannot predict which stands will be attacked, but can only indicate relative rates of spread through different types of stands and topographies. However, this may simply be a reflection of the hazard system; little real advantage was gained for considerable additional effort.

The approach developed for British Columbia uses relative rates of spread through different stands as a starting point to estimate forest-wide losses over the course of an outbreak. In addition, the parameters and relationships of the model may be obtainable from historical records. The success of this approach remains to be evaluated through the ongoing studies of parameter values and the operational validation of the model.

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Appendix

Definition of model variables* described in the text.**

Variable	Definition
BVAL	The slope of the relationship between spread rate and threshold area for outbreak collapse.
CUTA0	The spread rate from stumps in cutblocks as a proportion of the expected rate from unharvested stands.
CUTAP	The percentage by which the spread of mountain pine beetle from stumps in cutblocks is reduced when pheromones are applied around the cutblocks.
DETP	The proportion of green-attacked trees in stands missed by the probe which become detectable through color change in time for treatment.
DPROP	The proportion of potential dispersal from a compartment that actually spreads to a neighbor under topographic constraints.
DTHRA	The compartment size inter-compartment dispersal modifier, which has a larger value in TSAs with larger compartments.
EFF	The efficiency of single-tree treatments in changing the attack status of stands from attacked to unattacked.
PFOR	The spread rate modifier when a compartment has a low forested area.
PHOST	The spread rate modifier when forested area has a low proportion of host species.
R1	The average regional spread rate.
RESMAX	The maximum amount by which the compartmental residual can vary from the average regional spread rate.
RESMIN	The minimum amount by which the compartmental residual can vary from the average regional spread rate.
THRF	The threshold proportion of forested area within a compartment below which there is an effect on spread rate through PFOR.
THRH	The threshold proportion of host forest area of the total of forested land in a compartment below which there is an effect on spread rate through PHOST.
USEMIN	The smallest stand area for which damage is allocated.

* Many effects are controlled through arrays rather than single variables; these array names are not indicated, although their effects are described in the text.

** This appendix is provided to assist users of the system to interpret the parameters which can be changed through user input.