Susceptibility and risk rating systems for the mountain pine beetle in lodgepole pine stands

T.L. Shore and L. Safranyik

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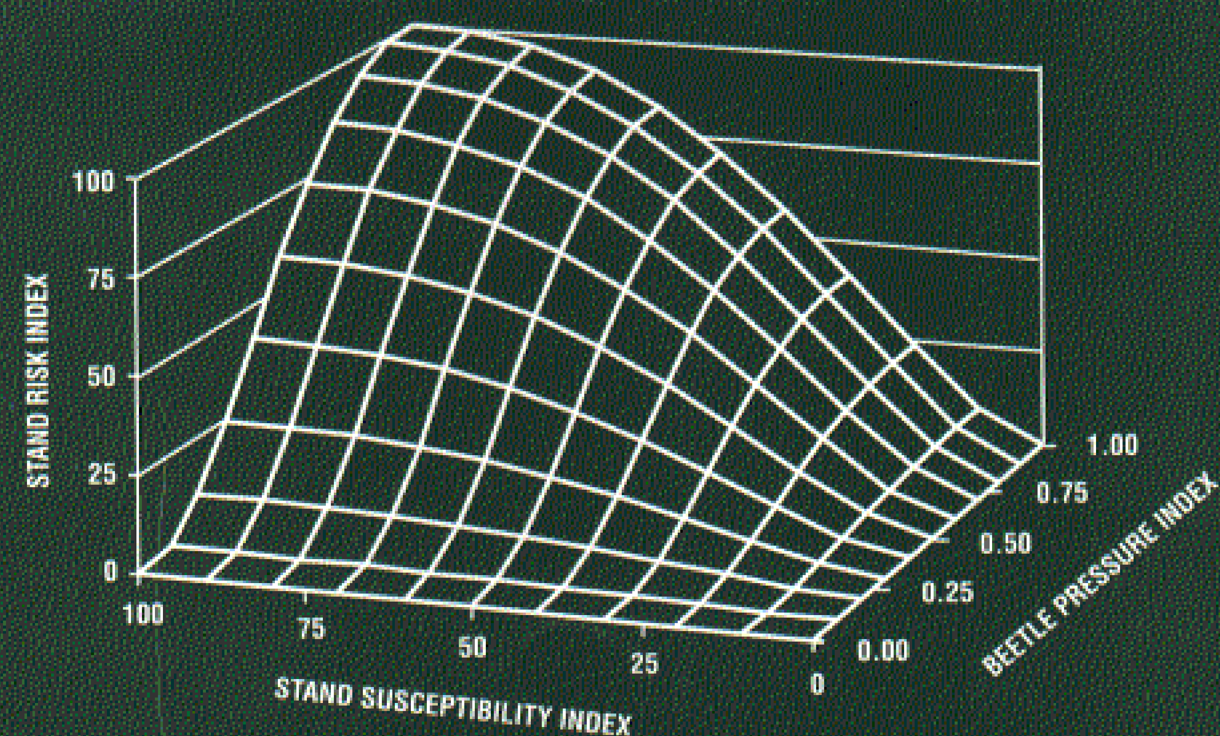

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Contents

Abstract

Systems for rating the susceptibility and risk of damage to lodgepole pine stands from the mountain pine beetle are described. The risk rating system considers both the susceptibility of the stand and the current threat to the stand from neighboring mountain pine beetle populations. A continuous-scale index for both risk and susceptibility can be calculated for any stand. This system provides the forest manager with a framework within which to plan and prioritize mountain pine beetle management activities.

Résumé

On décrit des systèmes d'évaluation de la susceptibilité des peuplements de pins tordus au dendroctone du pin ponderosa et du risque de dommage. Le système d'évaluation du risque tient compte et de la susceptibilité du peuplement et de la menace que font peser les populations avoisinantes de dendroctones du pin ponderosa. On peut calculer pour tous les peuplements un indice sur échelle continue du risque et de la susceptibilité. Ce système met à la disposition du gestionnaire forestier un cadre pour la planification et l'établissement des priorités en matière de gestion du dendroctone du pin ponderosa.

Foreword

Risk and susceptibility rating systems are predictive tools that provide forest managers with a framework within which they can plan and prioritize their stands for treatment. The mountain pine beetle risk and susceptibility rating systems presented in this report have been developed over a number of years; they are based on our analysis and testing of other proposed systems and on our own research and experience with the mountain pine beetle. The susceptibility index has been field tested on a number of stands and found to relate well to the tree mortality that can be expected from a mountain pine beetle infestation (Shore *et al.*, manuscript in preparation). Research on risk and susceptibility rating systems is continuing. Due to strong demand for systems that can be used now, however, we propose these systems for operational use. They may be subject to modification based on future research results and input from users. Although these systems were developed with special reference to British Columbia, they should be generally applicable throughout the range of the mountain pine beetle in lodgepole pine.

Introduction

The mountain pine beetle, *Dendroctonus ponderosae* Hopk., has caused devastating losses to pine forests in western Canada and the western United States. Mountain pine beetle epidemics have largely been managed by salvaging beetle-killed trees and direct control of currently infested trees and stands. To minimize losses of pine to the mountain pine beetle, management efforts and logging priorities should be assigned to stands based on the likelihood of a mountain pine beetle epidemic and the level of damage expected from the epidemic. The ability to plan provides pest managers with opportunities for preventative management; this is the purpose of risk and hazard rating systems.

A number of hazard rating systems for mountain pine beetle have been developed over the past decade. As part of the Canada/United States Mountain Pine Beetle-Lodgepole Pine Program, a cooperative research project between Forestry Canada and the U.S.D.A. Forest Service was initiated to examine six of these systems. Preliminary results indicated that none of the existing systems provided satisfactory results (Amman and Anhold 1989; Shore *et al.* 1989). Some systems included variables that did not appear to relate significantly to susceptibility; others included variables related to susceptibility but not in the way hypothesized by the system developer. Several of the systems provided predictive indices of limited use to forest managers, such as "susceptible" or "not susceptible." One of the main problems with many of these systems was that they only considered stand susceptibility and not mountain pine beetle population levels. It became evident in assessing stand damage that there is a strong interaction between susceptibility and beetle population levels. For example, very low populations of mountain pine beetle may not be able to overcome the resistance of large, apparently healthy trees and only weakened trees will be attacked. However, if an epidemic population moves into that same stand, or the resistance of the stand decreases due to stress or age, the large-diameter trees as well as many smaller-diameter trees may be overcome by mountain pine beetle (Berryman 1978). A stand can be very susceptible, but if there is no source of beetles it has a low likelihood of damage, whereas a marginally susceptible stand in the path of a raging epidemic may experience heavy damage. For these reasons we chose to include both susceptibility and beetle pressure as components of our risk rating system. This system incorporates several of the concepts found in previous hazard and risk rating systems (e.g. Amman *et al.* 1977; Berryman 1978; Paine *et al.* 1984, 1985; Schenk *et al.* 1980) with modifications based on our research and practical experience with mountain pine beetle in British Columbia.

The terms "hazard" and "risk" have often been used synonymously in the literature, and this has resulted in some confusion. In an attempt to minimize this confusion we will use the more descriptive term "susceptibility" in place of hazard. We define susceptibility as the inherent characteristics or qualities of a stand of trees that affect its likelihood of attack and damage by a mountain pine beetle population. A "stand" is defined as an aggregate of trees or other growth occupying a specific site that is sufficiently uniform in age arrangement, species composition, and density as to be distinguishable within the forest and from other growth on adjoining areas (Hocker 1979). In British Columbia a stand is equivalent to a forest cover polygon in the B.C. Ministry of Forests inventory system. Risk is defined as the short-term expectation of tree mortality in a stand as a result of a mountain pine beetle infestation. Risk is a function of stand susceptibility and "beetle pressure." Beetle pressure is the magnitude of a mountain pine beetle population affecting a stand as determined by the number of currently infested trees and their proximity to the stand being assessed. Beetle pressure relates to the likelihood of a beetle population entering a given stand.

In the following sections we will first explain how to calculate the susceptibility, beetle pressure and risk indices. This will be followed by some practical considerations in applying the system. In the last section we will explain the rationale for the system. Some examples are given in the Appendix to clarify calculation of the indices.

Calculating the susceptibility, beetle pressure and risk indices

Calculating the susceptibility index

The susceptibility index for a given stand is based on four variables: relative abundance of susceptible pine basal area in the stand, age of dominant and codominant live pine, the density of the stand, and the location (latitude, longitude and elevation) of the stand. The expression for calculating the susceptibility index (S) is

$$S = P \times A \times D \times L$$

where

P is the percentage of susceptible pine basal area

A is the age factor

D is the density factor, and

L is the location factor.

The percentage of susceptible pine basal area (P) is calculated as

$$P = \frac{[\text{average basal area/ha of pine} \geq 15 \text{ cm dbh}] \times 100}{[\text{average basal area/ha of all species} \geq 7.5 \text{ cm dbh}]}$$

The age factor (A) is taken from the following table.

If the average age of dominant or codominant pine is:	Then the age factor is:
less than or equal to 60 years	0.1
61 to 80 years	0.6
more than 80 years	1.0

The density factor (D) is taken from the following table.

If the density of the stand in stems per ha (all species ≥ 7.5 cm dbh) is:	Then the density factor is:
less than or equal to 250	0.1
251 to 750	0.5
751 to 1,500	1.0
1,501 to 2,000	0.8
2,001 to 2,500	0.5
more than 2,500	0.1

There are three possible location factors (1.0, 0.7, and 0.3). The manner in which the location factor varies with the ranges of latitude, longitude, and elevation encountered in British Columbia is shown in Figure 1. To determine the location factor for a particular stand, first determine a parameter (Y) from the following equation:

$$Y = [24.4 \text{ Longitude}]-[121.9 \text{ Latitude}]-[\text{Elevation(m)}]+[4545.1]$$

The location factor is then determined from the value of Y using the following table.

If Y is:	Then the location factor is:
greater than or equal to 0	1.0
between 0 and -500	0.7
less than -500	0.3

Susceptibility indices will range from 0 to 100. The highest values indicate the most susceptible stands.

Determining the beetle pressure index

Beetle pressure is related to the size and proximity of a mountain pine beetle population affecting the stand being rated. To determine the beetle pressure index (B), determine the size category of the infestation from Table 1. After you have determined the size category of the infestation, use Table 2 to determine the beetle pressure index.

Calculating the risk index

The risk index (R) is calculated as follows:

$$R = 2.74[S^{1.77}e^{-.0177S}][B^{2.78}e^{-2.78B}]$$

where: e = Base of natural logarithms = 2.718
B = Beetle pressure index
S = Susceptibility index

Alternatively, the risk index can be found in Table 3. If the exact value of the beetle pressure index or susceptibility index is not represented in the table, an approximate risk index can be determined using the closest values represented or it can be interpolated between the two closest values found in the table. The risk index will range between 0 and 100; the highest values represent stands which would receive the most damage by the mountain pine beetle in the near future.

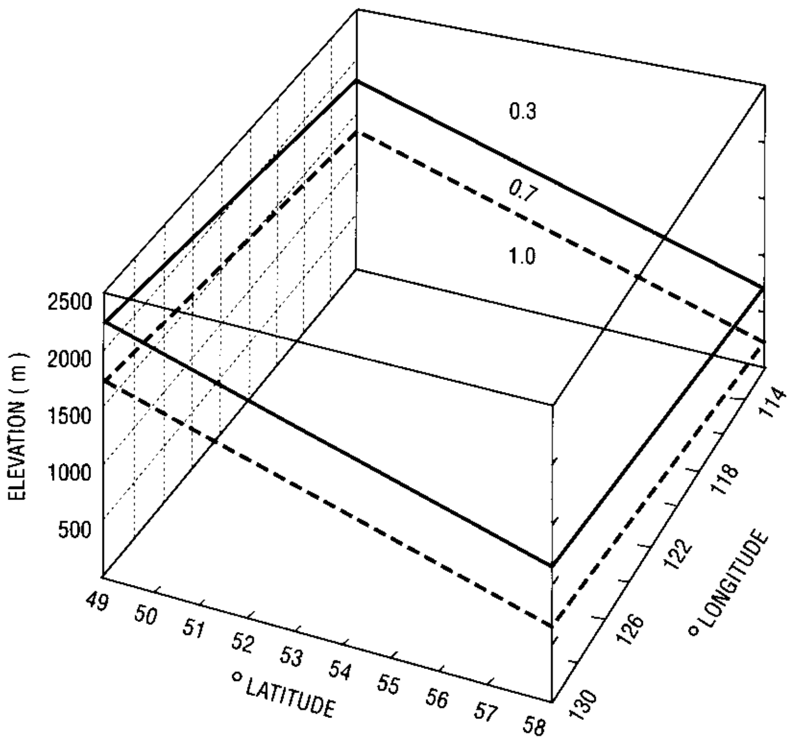

Figure 1. Location weights as a function of elevation, latitude and longitude.

Practical considerations

Interpretation of susceptibility, beetle pressure and risk indices

Susceptibility index

The susceptibility index is an indicator of the susceptibility of a stand if the beetle should attack it. Operationally it may be useful to divide the susceptibility index scale into classes (e.g., 0 - 10, 10.1 - 20, ..., 90.1 - 100), assign a color to each class and map the stand polygons with the appropriate color. This map will provide an overview of an area and facilitate the identification of potential problem areas. It must be remembered, however, that the susceptibility index does not include information on the presence of the mountain pine beetle. A stand may be highly susceptible but without the presence of the mountain pine beetle it is not immediately at risk. For operational planning purposes the location and size of beetle populations must be considered in relation to the stands being assessed. The risk index is proposed as a method of incorporating both susceptibility and beetle population information.

Beetle pressure index

Beetle pressure is a dynamic variable and may change quite suddenly due to factors such as adverse or favorable weather conditions or immigration of beetles from another location. For this reason the beetle pressure index and risk index for each stand should be reviewed every year or two.

Risk index

The risk index will be more closely related to expected stand damage than the susceptibility index in the short term (3 years or less) because it takes beetle pressure into account. The risk index should be updated annually or at least every 2 years because beetle pressure, and therefore the risk index, can change quickly. As with the susceptibility index it may be operationally useful to divide the risk index scale into classes (e.g., 0 - 10, 10.1 - 20, ..., 90.1 - 100), assign a color to each class, and map the stand polygons with the appropriate color. This map provides a visual impression of the areas with the greatest risk of damage by the mountain pine beetle in the near future and therefore can be used as a planning tool.

Table 1. Use this table to determine the relative size of a mountain pine beetle infestation within 3 km of the stand being rated

Number of infested trees outside stand within 3 km	Number of infested trees inside the stand		
	Less than 10	10 - 100	More than 100
<900	Small	Medium	Large
900 - 9,000	Medium	Medium	Large
> 9,000	Large	Large	Large

Table 2. Use this table to determine the beetle pressure index (*B*) from infestation size (determined from Table 1) and the distance from the stand being rated to the nearest edge of the mountain pine beetle infestation.

Relative infestation Size	Distance to nearest infestation (km)					
	in stand	0-1	1-2	2-3	3-4	4+
	Beetle pressure index (B)					
Small	0.6	0.5	0.4	0.3	0.1	0.06
Medium	0.8	0.7	0.6	0.4	0.2	0.08
Large	1.0	0.9	0.7	0.5	0.2	0.10

There are some important subtleties in the interpretation of the risk and susceptibility indices that must be understood when using them to assign priorities for stand management:

- the risk and susceptibility indices describe the potential for loss of a stand's basal area to the mountain pine beetle only, and do not consider socioeconomic or other values that may affect stand management priorities.

- the risk index represents a combination of stand susceptibility and beetle pressure factors and this should be kept in mind when interpreting the index. For example, two stands could have the same risk index, and hence the same expectation of damage at a given time, but one stand may be highly susceptible with moderate beetle pressure and the other may be moderately susceptible with high beetle pressure (see Figure 2).

- the susceptibility and risk indices are relative indicators of a stand's susceptibility or risk, respectively, to the mountain pine beetle. They do not account for the absolute basal area at risk in a stand; rather, they are based on the percentage of a stand's basal area that is susceptible or at risk. Therefore, two stands could have the same susceptibility and risk indices but one may have a total basal area of 1000 m^2 over 20 ha while the other only has a total basal area of 200 m^2 over 5 ha. If total basal area or size of a stand are important criteria for rating management priorities they can be factored into the final decision along with socioeconomic and other values.

- it is important to note that the rating system presented here assesses the risk and susceptibility of the stand as a whole, not just the lodgepole pine component. If large diameter (dbh 15 cm and larger) lodgepole pine do not represent a high percentage of the total basal area of the stand then the stand will not be considered highly susceptible even though the pine component itself may be very susceptible.

Table 3. Use this table to determine the risk index from the susceptibility and beetle pressure indices

Susceptibility index (S)	Beetle pressure index (B) .1	.2	.3	.4	.5	.6	.7	.8	.9	1.
10	<1	<1	2	3	5	6	7	8	8	8
20	<1	2	6	10	14	18	20	22	24	24
30	<1	4	10	17	24	30	35	39	40	41
40	1	6	14	24	33	42	49	54	56	57
50	1	7	18	30	42	52	61	67	70	71
60	2	9	20	34	48	61	70	77	81	82
70	2	10	22	38	53	67	78	85	89	91
80	2	10	24	40	56	71	82	90	95	96
90	2	10	24	41	58	73	85	93	98	99
100	2	11	25	42	59	74	86	94	99	100

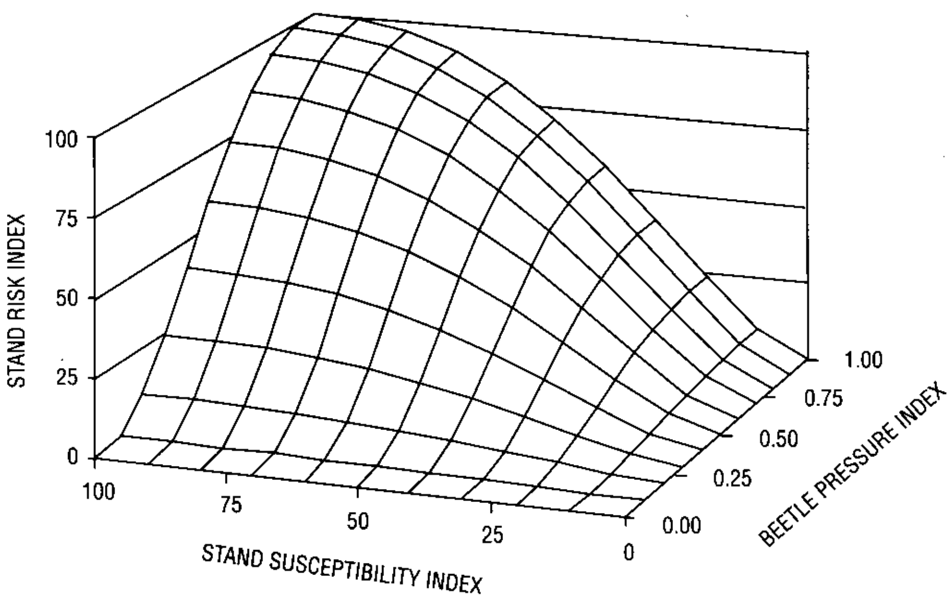

Figure 2. The risk index as a function of the susceptibility and beetle pressure indices

Similarly, the expectancy of loss (risk) will be higher in a stand with a greater percentage of its basal area in large diameter pine than one with a lower large diameter pine component, all other factors being equal.

Which stands should be rated for susceptibility and risk?

Broad mountain pine beetle susceptibility and risk stratification can be accomplished using a stand inventory database, if such a database is available. All stands with a leading lodgepole pine type that are over 80 years old and have elevation, latitude and longitude attributes which would result in a location factor of 1.0 could be considered top priority for susceptibility rating. Of the most susceptible pine stands, those closest to active mountain pine beetle infestations should receive top priority for detailed risk rating. Other management concerns such as watersheds or wildlife can be used to further rank these top priority stands for detailed susceptibility and risk rating.

All the data required to reliably rate the susceptibility of stands may not be available from existing inventories, or may not be current or specific enough. Where management for the mountain pine beetle is not a high priority, it may be sufficient to estimate some of the system variables based on other available information. Where more accurate stand rating is required, data will have to be obtained by sampling. For this reason the forest manager will want to concentrate the effort needed for detailed susceptibility rating on the highest priority areas. This will involve stratifying the management area based on broad mountain pine beetle susceptibility classification, location of current beetle epidemics, and other management priorities.

Sampling requirements

The data required for calculation of the susceptibility index can be collected quickly with a relatively small number of variable radius sample plots. As a general guideline, if a stand is fairly uniform from plot to plot in terms of tree size and age, species composition, and stand density, 10 plots spaced at 100-m intervals should provide sufficient precision. If the stand is quite variable, at least 20 plots should be sampled. Estimates of the required sample size for a specified level of precision can be obtained by calculating the variances for the required variables from a pilot survey, and utilizing these in sample size formulae such as those found in Freese (1962).

Only live trees should be included in the tally. Dead trees do contribute somewhat to the stand density effect, mainly by their influence on microclimate, but they no longer compete for nutrients and are not susceptible to attack. Trees currently attacked by the mountain pine beetle can be considered dead if successful galleries are found around the bole, if the phloem around the bole has dried out, or if the tree has recently been attacked and there are a total of five or more attacks in two 20 x 40 cm sample areas (one on each of the north and south sides of the tree) taken at breast height.

Only trees 7.5 cm and larger in dbh should be tallied in the survey to make the ratings calculated from field data comparable to those calculated from inventory data.

Record:

- the BAF of the prism used.
- species and dbh of each tree 7.5 cm and larger in a plot; borderline trees must be measured to determine whether or not they are in the sample.
- age of the dominant or codominant pine tree closest to the center of the plot from an increment core. Age should be determined from the point of germination. As sampling this low on the bole is often difficult, a correction factor is generally added to the age obtained from a sample taken further up the bole (Watts 1983). A minimum of 10 trees should be sampled from a stand. If plots do not contain enough pine trees, age samples can be taken from representative trees outside the plots. These sample trees should be clearly marked on the cruise sheet as being outside the plots.
- stand elevation taken with an altimeter or from a topographic map.

From these data the variables required for the susceptibility index can be easily calculated. An aerial survey and/or a fairly intensive ground survey may be needed to determine the number and proximity of currently infested trees for the calculation of the beetle pressure index. In many cases, such as large epidemics or where there are no recorded infestations, the beetle pressure index is obvious and will not require detailed survey information.

If data collection for susceptibility rating can be incorporated into other surveys, costs would be reduced.

Reduction of stand risk through forest and pest management

By understanding the components of the risk index, a number of forest and pest management activities that will lower the risk of a stand being damaged by the mountain pine beetle will become apparent. These can be grouped into two categories related to the two components of stand risk: reduction of stand susceptibility and reduction of beetle pressure.

Reduction of stand susceptibility

Of the variables composing the susceptibility index, age, density and the percentage of the stand's basal area represented by susceptible pine can be altered through silvicultural practices. Through stocking control in young stands, thinning in specific situations, and organized clearcuts, age, size, and species mosaics can be created which will break up the large, homogeneous, susceptible forest type that has resulted in major mountain pine beetle epidemics (Cole 1978). Reducing the ratio of large-diameter pine to other size and species components by thinning "from above" will reduce the susceptibility index of the stand by reducing the relative abundance of susceptible pine, possibly reducing the average age of the pine component of the stand, and by lowering stand density. This approach is perhaps best suited to mixed stands where species other than pine could be left and would respond well to the removal of the overstory. In pure pine stands removal of the larger pine could result in "high-grading", leaving inferior trees which will produce a poor stand. Also, the residual, smaller diameter pine are susceptible to wind and snow breakage. Through stocking control in young stands and partial cutting in older stands, densities can be lowered below 750 stems per ha to reduce stand susceptibility. At these low densities larger and older pine can be left standing and the susceptibility will be relatively low (see the following discussion of System Rationale).

Reduction of beetle pressure

Beetle pressure is determined by the size and proximity of the nearest group of trees infested by the mountain pine beetle to the stand being rated. Both the number and proximity of infested trees to a stand can be altered through "direct control" pest management techniques such as fell and burn, treatment with silvicides or insecticides, mechanical debarking and sanitation logging. The effectiveness of these treatments can be improved by the strategic use of semiochemicals such as pheromones (McMullen *et al.* 1986).

System rationale

The rationale for selecting the variables, thresholds, weights and models that we included in the risk rating system are presented here. This section is not a literature review on any of the system components, but a few key references are provided to substantiate our logic and provide a starting point for further reading.

In developing our risk rating system we chose an heuristic rather than a statistical approach. That is, we selected variables we felt would be key factors and assigned weights to these on the basis of current knowledge, logic, and experience with the beetle.

The following criteria were considered to be important components of an operational risk rating system:

- it should account for both the beetle pressure and stand susceptibility components of mountain pine beetle damage.
- most of the required data should be obtainable from existing forest inventory data and minimal field work should be required to obtain the remainder.
- a continuous-scale index value should be provided for each stand.
- the risk index should relate directly to basal area and volume killed by mountain pine beetle.
- most of the variables included in the stand susceptibility index should be manipulable by silviculture.
- the beetle pressure component of the risk index should be manipulable by direct control pest management methods.

Susceptibility index

For the stand susceptibility component of our model we chose four variables as indicators of a stand's susceptibility to mountain pine beetle: relative abundance of larger diameter pine, age of dominant and codominant pine, stand density and location. All four variables may not be key factors for any given stand but their inclusion in the model provides a responsive system that we believe is generally applicable. The weights for these four variables are simply multiplied together which implies that each variable holds equal weight in its contribution towards stand susceptibility and that the overall effect is multiplicative rather than additive. While

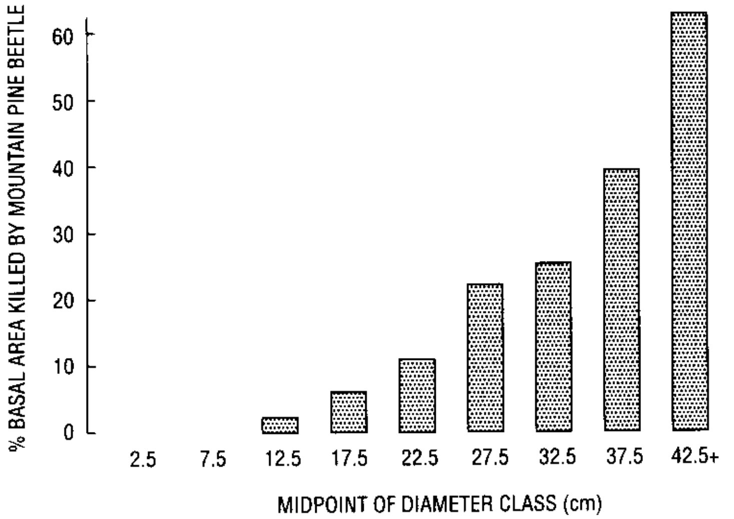

Figure 3. The percentage of total basal area within a diameter class killed by the mountain pine beetle based on 38 stands in the Cariboo Forest Region of British Columbia. (T.L. Shore, unpublished data)

this may be arguable in certain situations, overall we considered it to be a reasonable assumption.

Percentage of susceptible pine basal area

This is a complex variable which incorporates the effects of diameter and stand composition on stand susceptibility to mountain pine beetle.

Diameter. The beetles show a visual preference for wider objects (Shepherd 1966). Attack has been shown to correlate positively with diameter, and trees less than 12.5 cm in diameter are rarely attacked (Hopping and Beall 1943 and Figure 3). Trees of larger diameter are attacked to a greater height (Cahill 1960) and more intensely (Cole and Amman 1969) than smaller trees. Mountain pine beetle reproduces and survives better in trees of larger diameter (Cole and Amman 1969) and the beetles produced in these trees are larger and perhaps of better quality (Safranyik and Jahren 1970). Trees of larger diameter generally have thicker phloem which results in more food for the beetles. They also tend to have thicker bark which provides better protection than thin bark from dessication, cold and enemies. Diameter is generally correlated with age and older trees are less resistant to the beetle. On average, the number of emerging brood beetles only exceeded the number of attacking parent beetles in trees 25 cm dbh and larger (Safranyik *et al.* 1974). We selected 15 cm as a threshold for the susceptible pine component because trees less than this diameter are not commonly attacked and if trees of this size are attacked they will not produce significant numbers of beetles. This threshold may seem low in some regions but significant mortality can occur in smaller trees during a major epidemic and we felt it was better to be conservative than to underestimate stand susceptibility. The threshold of 7.5 cm for basal area of all species in the stand was selected because this is a common minimum tree diameter for inclusion in forest inventories.

Stand composition. Mountain pine beetle has been found to attack the pine component of mixed lodgepole pine stands as readily as it does pure lodgepole pine stands (Amman and Baker 1972). Nonetheless, it would seem logical that the probability of beetles successfully finding and attacking a lodgepole pine tree would diminish as frequency of non-host species in a stand increases. Also the probability of an epidemic arising from an endemic situation in a stand would likely decrease with the frequency of non-host trees in a stand. Hopping (1961) states that mountain pine beetle outbreaks seldom originate in mixed stands. The potential for basal area loss to the stand as a whole will be less in a mixed stand than a pure stand. In other words, even if all the larger diameter pine are killed in a mixed stand it will still have live basal area in other species or in smaller diameter pine; therefore, risk of loss in the stand is lower than that of a pure stand. Depending on the proportion of the pine killed, a release effect may occur on surviving pine and on the non-host trees which may lessen the impact in mixed stands (Heath and Alfaro 1990). The *P* variable in the susceptibility index indicates what percentage of a stand's total basal area is susceptible to the beetle or, conversely, whether or not a viable stand would still exist if a mountain pine beetle epidemic removed the large-diameter pine from the stand.

Age of the dominant and codominant pine component of the stand

Age has been shown to be directly related to a tree's ability to resist infection by the fungi carried by the mountain pine beetle (Shrimpton 1973). These fungi are introduced into successfully attacked trees by the beetles and quickly penetrate the conductive tissues thereby killing the tree in a matter of a few weeks (Safranyik *et al.* 1974). Trees 31 to 50 years old were found to be the most resistant to fungal infection;

resistance declined progressively in older trees (Shrimpton 1973). Diameter is generally related to age and beetles prefer larger trees. For stands, the point of physical maturity determined by the intersection of current annual increment and mean annual increment can be considered as an age threshold for attack (Shrimpton and Thomson 1981; 1983). In British Columbia, outbreaks have not been reported in stands less than 60 years of age, are rarely reported in stands between 60 and 80 years of age, but are common in stands older than 90 years (Safranyik *et al.* 1974). We therefore assigned values to the pine age component of our susceptibility index such that stands less than 60 years of age have a low age component of susceptibility, stands between 60 and 80 years of age have an intermediate age component of susceptibility, and stands over 80 years of age have a high age component of susceptibility.

Stand density

There are a number of ways in which stand density affects the susceptibility of pine stands to the mountain pine beetle. Stand density affects tree diameter: dense stands produce small-diameter trees and low-density stands produce trees of larger diameter. Density also affects tree vigor through the increasingly adverse effects of competition for light and nutrition in denser stands. Thinned stands have been shown to be more resistant to mountain pine beetle damage (McGregor *et al.* 1987; Amman *et al.* 1988a,b) both through improvement in tree vigor (Mitchell *et al.* 1983) and by altering the microclimate (Amman *et al.* 1988a; Bartos and Amman 1989). Vigorous trees are more able to resist beetle attacks by producing copious flows of resin to "pitch out" attacking beetles (Reid *et al.* 1967). Mountain pine beetle is affected adversely by microclimate changes in thinned stands including increased light and temperatures on the bole, and increased wind movement in the stand (Bartos and Amman 1989). An inverse relationship between tree mortality caused by the beetle and stand density, as measured by crown competition factor, has been shown (McGregor *et al.* 1981; Shore *et al.* 1989). When low density stands are included, a left-skewed distribution can be shown when mortality is plotted against stand density (Anhold and Jenkins 1987) indicating low mortality at low stand densities rapidly increasing at intermediate stand densities and then tailing off at high stand densities. From thinning studies we know that little mortality from the beetle occurs in stands with fewer than 250 stems per ha (Amman *et al.* 1988a,b) or in very dense stands of more than 2500 stems per ha. From a theoretical standpoint, the relationship between beetle-caused tree mortality and stand density has to go through the origin because when there are no trees there can be no mortality. We have observed differences in basal area mortality related to stand density suggesting that the highest mortality occurs in intermediate stand densities of 750 - 1500 stems per hectare. We considered all of this information in assigning weights to the stand density classes.

Location (elevation, latitude, longitude)

Elevation, latitude and longitude influence stand susceptibility through their effects on survival of the mountain pine beetle. At higher elevations, or more northerly latitudes, or easterly longitudes, the beetle's development cycle will be extended (Hopkins 1919) and it is more likely to be exposed to cold temperatures during vulnerable stages, which increases mortality (Amman 1973). Also, the extended development cycle exposes the beetle to natural enemies for a longer period of time. Tree mortality from beetles is inversely related to elevation (Amman *et al.* 1973). The elevation zones between which we have observed differences in beetle survival were adjusted for latitude and longitude using Hopkins' bioclimatic law (Hopkins 1919) to arrive at three location classes (Figure 1). It is not possible to visually determine the location weighting of a stand from Figure 1 unless the stand is at an extreme point on the graph; therefore, the thresholds between classes were described by a mathematical equation.

Beetle pressure index

We included two variables in our measurement of beetle pressure: beetle population size and proximity of infested trees to the stand being assessed. There are many other variables which could have been included such as beetle population trend, prevailing wind direction, and the size of the stand which, perhaps, would improve the accuracy and precision of this component of the model. The variables we selected represent a compromise between ease of use and potential accuracy and precision.

Tables 1 and 2 contain several thresholds relating to the size and proximity of infestations surrounding the stand being rated. These attempt to express, in the form of an index, the interaction between number and proximity of infested trees and their relationship to the likelihood of a mountain pine beetle population entering the stand. The likelihood of beetles entering a stand from an infestation 3 km away is obviously greater if that infestation is a large one rather than just a few trees. If those few trees are in the stand, however, the likelihood becomes 100 percent. The threshold numbers of trees and distances were based largely on observations made during population and dispersal studies over the past 20 years (e.g., Safranyik 1969; Safranyik *et al.* 1989).

Risk index

The risk index is an indicator of the short-term risk of loss of stand basal area to the mountain pine beetle. It indicates risk only in the short term because beetle pressure changes annually, and once a stand is being attacked its susceptibility will drop annually as the larger live pine component is reduced.

The risk index is based on the susceptibility index and beetle pressure index. The relationship between these three variables can be seen in Figure 2. The reason the final calculation is based on a relatively complex equation is that we see stand susceptibility and beetle pressure relating to stand risk in a non-linear way.

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APPENDIX

Examples of Susceptibility and Risk Index Calculations

(The tables and formulae used in these calculations are found on pages 2 to 5 of this report.)

STAND A. Data

- Average age of dominant-codominant pine = 65 years
- Average basal area per ha of pine with DBH greater than or equal to 15 cm = 13.5 m^2
- Average basal area per ha of all species with DBH greater than or equal to 7.5 cm = 35 m^2
- Number of trees per ha of all species with DBH greater than or equal to 7.5 cm = 950
- Longitude = 122°, latitude = 52°, elevation = 1500 m
- No infested trees in stand. Between 900 and 9000 infested trees within 3 km and closest infestation is approximately 2.5 km away.

I. Susceptibility index: $S = P \times A \times D \times L$

$$S = ((13.5/35) \times 100) \times (0.6) \times (1) \times (0.7) = 16.2$$

II. Beetle pressure index: $B = 0.4$

III. Risk Index: $R = 2.74 \times [S^{1.77} \times e^{-.0177S}] \times [B^{2.78} \times e^{-2.78B}]$

$$R = 2.74 \times [16.2^{1.77} \times 2.718^{-.0177 \times 16.2}] \times [0.4^{2.78} \times 2.718^{-2.78 \times 0.4}]$$

$$R = 7.3$$

STAND B. Data

- Average age of dominant-codominant pine = 120 years
- Average basal area per ha of pine with DBH greater than or equal to 15 cm = 34 m^2
- Average basal area per ha of all species with DBH greater than or equal to 7.5 cm = 40 m^2
- Number of trees per ha of all species greater than or equal to 7.5 cm = 740
- Longitude = 118°, latitude = 50°, elevation = 800 m
- Infested trees in the stand. More than 9000 infested trees within 3 km.

I. Susceptibility index:

$$S = ((34/40) \times 100) \times (1) \times (0.5) \times (1) = 42.5$$

II. Beetle pressure index: $B = 1.0$

III. Risk index:

$$R = 2.74 \times [S^{1.77} \times e^{-.0177S}] \times [B^{2.78} \times e^{-2.78B}]$$

$$R = 2.74 \times [42.5^{1.77} \times 2.718^{-.0177 \times 42.5}] \times [1.0^{2.78} \times 2.718^{-2.78 \times 1.0}]$$

$$R = 61.1$$