Chapter 8

Decision Support Systems

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Abstract

Given the complexity and large number of issues facing forest managers, computerized decision support systems are valuable tools for decision makers. Decision support systems can: provide support for planning, provide rationale for the allocation of scarce resources, allow the exploration of "what if" scenarios, and provide the ability to compare effects of different management strategies. When forest management must consider mountain pine beetle (*Dendroctonus ponderosae* Hopk. [Coleoptera: Scolytidae]), susceptibility and risk rating systems and simulation models are key components of decision support. This chapter reviews mountain pine beetle susceptibility and risk rating systems as well as several different approaches to simulation modelling with a specific focus on products developed and employed as decision support tools in western Canada.

Résumé

Étant donné la complexité et la multitude des problèmes auxquels doivent faire face les gestionnaires des forêts, les systèmes informatisés d'aide à la décision constituent des outils fort précieux pour les décideurs et les décideuses. Ces systèmes peuvent fournir une aide pour effectuer de la planification et une analyse raisonnée de l'allocation de ressources limitées, permettre l'exploration de scénarios de simulation et donner la capacité de comparer les effets des différentes stratégies de gestion. Lorsque la gestion des forêts doit prendre en compte le dendroctone du pin ponderosa (*Dendroctonus ponderosae* Hopk. [Coleoptera: Scolytidae]), les systèmes d'évaluation de la vulnérabilité et des risques d'infestation ainsi que les modèles de simulation deviennent des éléments clés de l'aide à la décision. Dans le présent chapitre, on examine les systèmes d'évaluation de la vulnérabilité et des risques d'infestation de même que différentes approches à la modélisation de simulation, en mettant l'accent sur la gamme de produits développés et utilisés comme outils d'aide à la décision dans l'Ouest canadien.

Introduction

Decision support systems refer to knowledge-based tools, computer-based or otherwise, that provide information to the user to improve the quality and timeliness of decisions. In Figure 1 we show an overview of current decision support systems for the mountain pine beetle. Data requirements include information about the host – forest inventory and geospatial data, and information about the beetle including location and numbers of infested and killed trees. This information can be utilized to develop susceptibility (hazard) and risk rating systems (Fig. 1). Data on climate and management resources, practices and options can be integrated with the beetle and forest inventory information and utilized in various models (Fig. 1). Susceptibility, risk and population dynamics/impact models can be used by managers to set priorities and evaluate management scenarios based on projections of the course of infestations.

The first references to mountain pine beetle (*Dendroctonus ponderosae* Hopk. [Coleoptera: Scolytidae]) in western North America were in 1899 in the United States (Hopkins 1899) and 1912 in Canada (Swaine 1912). Control efforts against the mountain pine beetle were first carried out in Oregon in 1910. From 1910 to the 1970s, most of the focus both in Canada and the USA was on studying the biology of the insect and on direct control activity. Much knowledge was gained on the biology of the beetle and its interaction with its hosts; however, less work was done on packaging this information into tools usable by managers of the forest resource.

Over time this has changed, as systems and models have been developed with the direct goal of supporting management. As computer technology has improved, the ability to encapsulate biological knowledge in tools usable by resource managers has grown in sophistication, leading to the development of decision support systems. Decision support systems typically capture expert knowledge and provide information, risk assessments or projections in a context which facilitates incorporation into the decision making process.

One of the first attempts at producing a management tool for bark beetles in western North America began with the sympatric species western pine beetle, *Dendroctonus brevicomis* Leconte, for which a hazard rating system was developed in the 1930s (Keene 1936). This work related tree characteristics of ponderosa pine to likelihood of western pine beetle attack. Beginning in the 1970s, quantitative work was begun on developing hazard rating systems for the mountain pine beetle. Subsequently, model development began with detailed population dynamics and impact models being produced. Advances in technology have led to spatial modelling tools being incorporated into the mountain pine beetle management environment.

In this chapter we introduce the evolution of mountain pine beetle decision support systems, with emphasis on those used in Canada. These include susceptibility (hazard) and risk rating systems, population dynamics, and impact and management models, both aspatial and spatial, at stand and landscape scales. We include discussion about, and examples of, their use in assisting managers to make informed decisions to minimize the impact of mountain pine beetle on lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) forests.

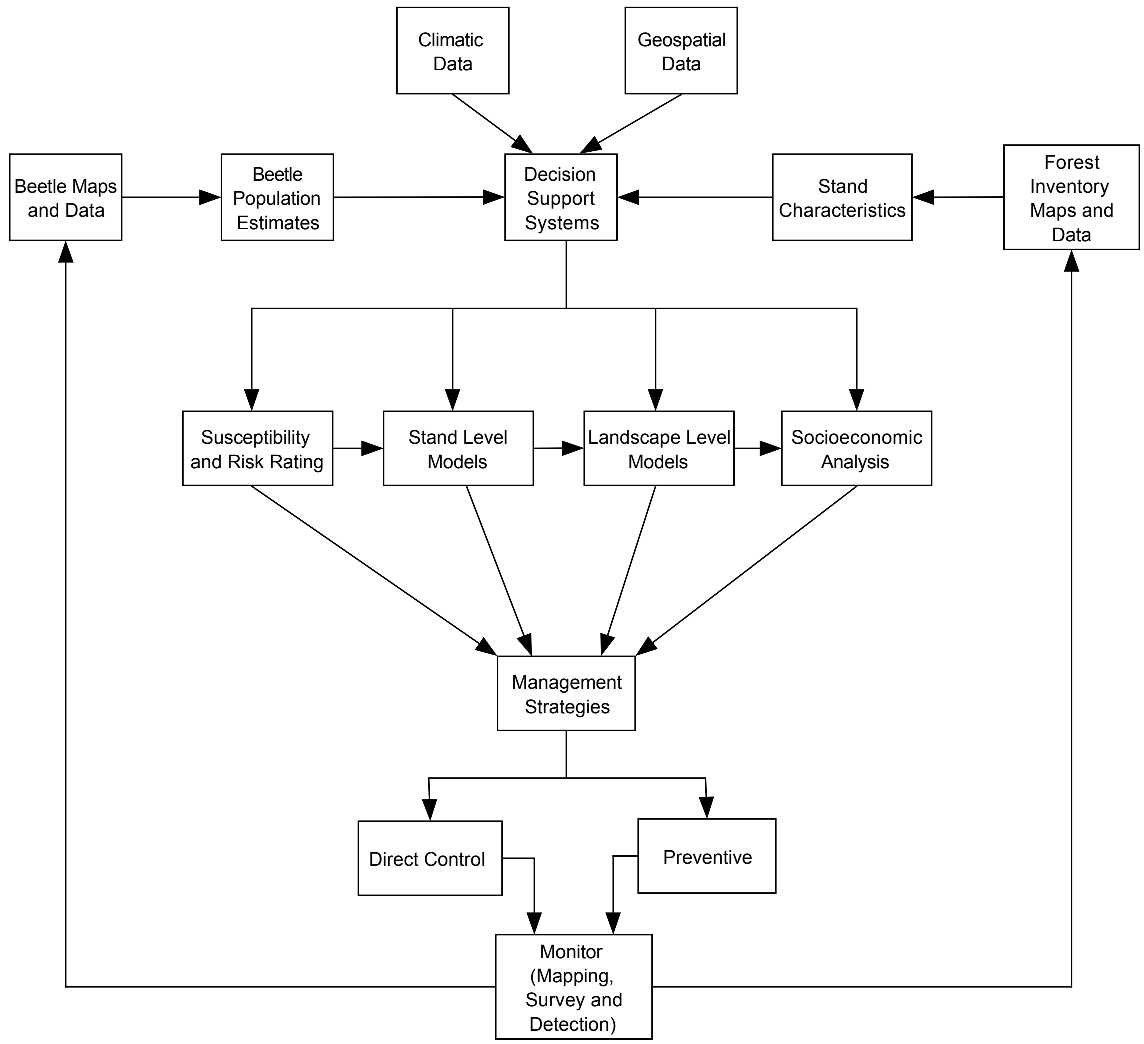

Figure 1. Schematic of decision support systems for the mountain pine beetle.

Susceptibility (Hazard) and Risk Rating Systems

Safranyik et al. (1975) produced a hazard map for mountain pine beetle in British Columbia more than 30 years ago. This map was developed from a model of climatic suitability to the mountain pine beetle based on long-term weather station data. It incorporated a number of climatic variables that were considered important to beetle establishment and survival. A number of hazard or risk rating systems aimed at stand level classification have since been developed for the mountain pine beetle (Amman et al. 1977; Mahoney 1978; Berryman 1978; Schenk et al. 1980; Waring and Pitman 1980; Stuart 1984; Anhold and Jenkins 1987). All of these systems, with the exception of Schenk et al. (1980), were categorical designs where stands would be classified as likely to be attacked or not (Mahoney 1978; Waring and Pitman 1980; Stuart 1984), or assigned to a high, moderate or low (or similar) hazard class (Amman et al. 1977; Berryman 1978; Anhold and Jenkins 1987).

The system of Amman et al. (1977) places the variables of tree diameter, elevation-latitude, and age to rate stands into categories of low, moderate or high hazard. Evaluations of this system generally indicated a low rate of accuracy with a tendency to over-rate stands (Mahoney 1978; Amman 1985; Shore et al. 1989; Bentz et al. 1993). One possible reason for the low accuracy of this system may be the assumption that diameter is related to phloem thickness, the beetle's primary feeding and breeding tissue in the tree. This relationship was not found by other researchers (Katovich and Lavigne 1986; Shrimpton and Thomson 1985).

Mahoney (1978) developed a two-class system based on the variable periodic growth ratio (PGR): the ratio of the most recent 5 years radial growth to the previous 5 years radial growth. Stands having a ratio of 0.9 or less were considered to be in declining vigour and therefore susceptible to attack, and those with a ratio greater than 0.9 were considered resistant to attack. This system was not able to predict losses accurately in subsequent tests (Shrimpton and Thomson 1983; Stuart 1984; Amman 1985; Shore et al. 1989; Bentz et al. 1993). A basic problem with the system is that stands generally decline in growth after about age 30; therefore, a ratio of less than 1.0 would be the norm for stands past this age (Shrimpton and Thomson 1983). Stands less than about 80 years of age, however, are not commonly known to be attacked by mountain pine beetle (Safranyik et al. 1974).

Berryman (1978) developed a theoretical model of stand susceptibility based on phloem thickness and stand resistance. This model had a relatively low rate of success at assigning stands into classes of extreme, high, and low susceptibility in subsequent tests (Amman 1985; Shore et al. 1989; Bentz et al. 1993). A shortcoming in this system may be the variable selected as an index of stand resistance. This variable consisted of the ratio between PGR and stand hazard rating (SHR) (Schenk et al. 1980), described below, and thus inherited the problems described for those indices (Katovich and Lavigne 1986).

The system developed by Waring and Pitman (1980) involves calculating growth efficiency as the ratio of current growth (grams of stemwood produced) to crown leaf surface. These variables are difficult to collect and calculate, and evaluations of this system have produced less than adequate results (Stuart 1984; Amman 1985; Katovich and Lavigne 1986; Shore et al. 1989).

Stuart (1984) developed a discriminant function to describe the probability of a stand falling into a susceptible or non-susceptible class for the mountain pine beetle. This function used the variables of quadratic mean tree diameter and number of rings in the outer one centimetre of radial growth. This relationship can only be considered valid for the small area from which the data was collected.

Anhold and Jenkins (1987) examined the relationship between Stand Density Index (SDI) (Reineke 1933) and beetle-caused tree mortality. They found that SDI was not a good predictor of decreasing or increasing populations; however, ranges of SDI values were found to coincide with low potential for attack, increasing potential for attack, and declining potential for attack. From a theoretical standpoint SDI would not appear to be a useful indicator of stand susceptibility to mountain pine beetle because it is the product of two variables, trees per hectare and quadratic mean diameter. Therefore, a single value of SDI could be determined, for example, by a combination of numerous trees of small diameter or fewer trees of large diameter. It is well known that the beetle shows a preference for larger diameter trees; therefore, it is unlikely that the two stands in this example would have similar susceptibility. It is likely that the findings of Anhold and Jenkins (1987) reflect mainly variations in stand density because only larger diameter trees (>12.7 cm dbh [diameter at breast height]) were included (Safranyik et al. 1974; Amman et al. 1977).

The system designed by Schenk et al. (1980) is the only one that attempted to produce a stand hazard rating (SHR) index that was a continuous variable, and relate it to tree mortality caused by the mountain pine beetle. SHR was calculated using crown competition factor (Krajicek et al. 1961), and the proportion of lodgepole pine basal area in the stand. Tests of this system found that crown competition factor (CCF) and therefore, SHR were inversely related to tree mortality caused by the beetle (McGregor et al. 1981; Shore et al. 1989, Bentz et al. 1993). The problem with the system appeared to be the assumption of a positive relationship between stand density and mountain pine beetle-caused tree mortality (Katovich and Lavigne 1986).

In 1992, Shore and Safranyik published a system incorporating the best features of previous systems. It was considered important to have a continuous variable hazard rating system because a two or three class system is not sensitive enough to provide managers with sufficient information to assign management priorities. Also, it was desirable that the hazard rating index relate to beetle-caused tree mortality. These were features of the Schenk et al. (1980) system. Important variables that are known to affect stand susceptibility are age (Safranyik et al. 1974; Amman et al. 1977; Shrimpton and Thomson 1983), tree diameter (Safranyik et al. 1974; Amman et al. 1977), and climate, which were components of the Amman et al. (1977) system. Some measure of inter-tree competition or stand density was also considered to be important as was attempted in the systems of Berryman (1978), Waring and Pitman (1980), Schenk et al. (1980), and Anhold and Jenkins (1987). In addition, we felt it important from a stand rating perspective to include a measure of the species composition of the stand, as did Schenk et al. (1980).

The Shore and Safranyik (1992) risk rating system incorporated estimators of both stand susceptibility and beetle pressure. The susceptibility rating system provides an index of potential loss of stand basal area in the event of a mountain pine beetle infestation and is, therefore, a long-term rating. The risk rating system provides a short-term index of the likelihood of this event occurring and causing significant losses to the stand.

In British Columbia, Alberta and parts of the western United States, the Shore and Safranyik (1992) system has been incorporated into forest management planning. This system considers stand risk as a function of both stand susceptibility to the mountain pine beetle and beetle population pressure on the stand. The logic behind this is that, from a management perspective, knowledge is required on both the susceptibility of stands and on the size and location of mountain pine beetle populations. A susceptible stand can be at low risk if there is no beetle population present. This general concept of risk as a function of host susceptibility and pest numbers had previously been defined (e.g., Nebeker and Hodges 1985; Paine et al. 1983, 1984). We use the term "susceptibility" synonymously with "hazard" but find it a more self explanatory term to describe the characteristics of a tree, stand or landscape that indicate its level of suitability to the mountain pine beetle. Risk, on the other hand, incorporates a measure of the beetle population into the equation. We define risk as a function of susceptibility and beetle pressure.

In this section we describe the Shore and Safranyik (1992) susceptibility and risk rating system, including a discussion on its use and some modifications. These modifications include the replacement of discrete functions with continuous functions for age, stand density, and beetle pressure, as well as the introduction of an additional susceptibility and risk rating system for the pine component of a stand (pine susceptibility and risk). The rationale for replacing discrete functions with continuous functions for age, stand density, and beetle pressure is to provide more of a gradual transition in susceptibility and risk related to these factors. For example, with the discrete age classes, an 80-year-old stand would be rated considerably less susceptible than an 81-year-old stand with all other factors being equal. With the continuous function for age there will be little difference between the two example stands.

Pine susceptibility and risk are introduced as additional rating systems to address an issue that often causes confusion with the stand susceptibility and risk rating system. In the system, a stand can be rated low and still experience a mountain pine beetle infestation. This is because the stand as a whole is rated; therefore, if only a small part of it is composed of susceptible pine it will be rated low. There will still be a viable stand after the mountain pine beetle. However, this does not address the concern of a forest manager interested in knowing where the susceptible pine is that may contribute to an infestation of mountain pine beetle. By introducing a second system that rates the susceptibility and risk of the pine component of stands, the forest manager can determine where the most susceptible stands are as well as where stands containing susceptible pine are. For further information on the rationale, validation and use of this rating system see Shore and Safranyik (1992) and Shore et al. (2000).

Calculating the stand susceptibility, beetle pressure and stand risk indices

Calculating the stand susceptibility index (SSI)

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 co-dominant live pine, the density of the stand, and the location (latitude, longitude and elevation) of the stand.

The expression for calculating the stand susceptibility index (SSI) is

$$SSI = P \times A \times D \times L \qquad [1]$$

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.

Percentage susceptible pine basal area factor (P)

The percentage of susceptible pine basal area (P) is unchanged from the original system and is calculated as:

$$P = \frac{[\text{average basal area/ha of pine} \geq 15 \text{ cm dbh}] \times 100}{[\text{average basal area/ha of all species} \geq 7.5 \text{ cm dbh}]} \qquad [2]$$

where dbh is diameter at breast height.

Age factor (A)

The age factor (A) from the original system was a categorical variable broken into age classes as follows:

Table 1. Determination of the age factor (A) in original Shore and Safranyik (1992) Stand Susceptibility Index.

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

The age factor ratings from Table 1 are replaced by a series of equations that result in a continuous function that will prevent jumps in values at the class limits (Table 2).

Table 2. Determination of the age factor (A) using current continuous functions

If the average age of dominant or co-dominant pine is:	Then the age factor (A) is:
40-80 years	$0.1 + 0.1[[\text{age}-40]/10]^{1.585}$
81–120 years	1.0
121-510 years	$1.0 - 0.05[(\text{age}-120)/20]$
Less than 40 or greater than 510	0.1

Density factor (D)

The stand density factor (D) from the original system was a categorical variable broken into several classes as follows:

Table 3. Determination of the density factor (D) in original Shore and Safranyik (1992) Stand Susceptibility Index.

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

As with age factor, density factor is now calculated using a series of equations that result in a continuous function that will prevent jumps in values at the class limits (Table 4).

Table 4. Determination of the density factor (D) using current continuous functions

If the density of the stand in stems per ha (sph) (all species ≥7.5 cm dbh) is:	Then the density factor (D) is:
Less than 650	$0.0824\ [sph/250]^{2.0}$
650 - 750	$1.0 - 0.7\ [3\text{-}sph/250]^{0.5}$
751 - 1500	1.0
Greater than 1500	$1.0\ /\ [0.9 + [0.1e^{(0.4796[sph/250\text{-}6])}]]$

Location factor (L)

The location factor (L) remains unchanged from the original system. There is ongoing research that may result in this variable eventually being replaced by a climatic suitability index (Carroll et al. 2004).

There are three possible location factors (1.0, 0.7, and 0.3). The manner in which the location factor varies with latitude, longitude, and elevation is shown in Figure 2 (unlike the figure, the relationship is not limited to British Columbia). To determine the location factor for a particular stand, a parameter (Y) from the following equation is first determined:

$$Y = [24.4 \text{ Longitude}] - [121.9 \text{ Latitude}] - [\text{Elevation (m)}] + [4545.1] \quad [5]$$

The location factor is then determined from the value of Y using Table 5.

Table 5. Location factor values.

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

Once the variables P, A, D and L are determined for a stand, the Stand Susceptibility Index (SSI) is calculated as the simple product of the four as defined above: SSI = P x A x D x L

Stand susceptibility indices will range from 0 to 100. The highest values indicate the most susceptible stands (Fig. 3).

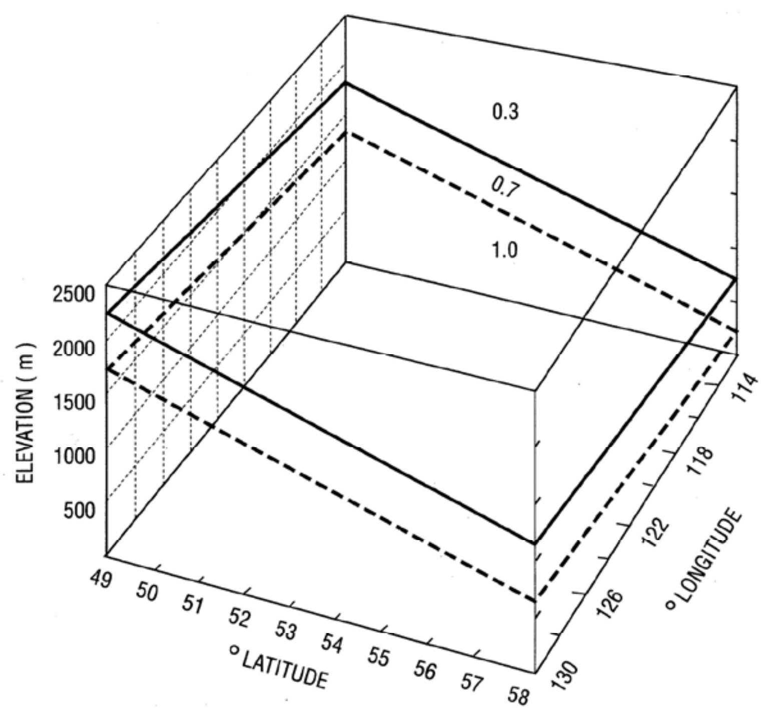

Figure 2. The relationship between latitude, longitude and elevation as related to mountain pine beetle susceptibility in British Columbia (from Shore and Safranyik 1992).

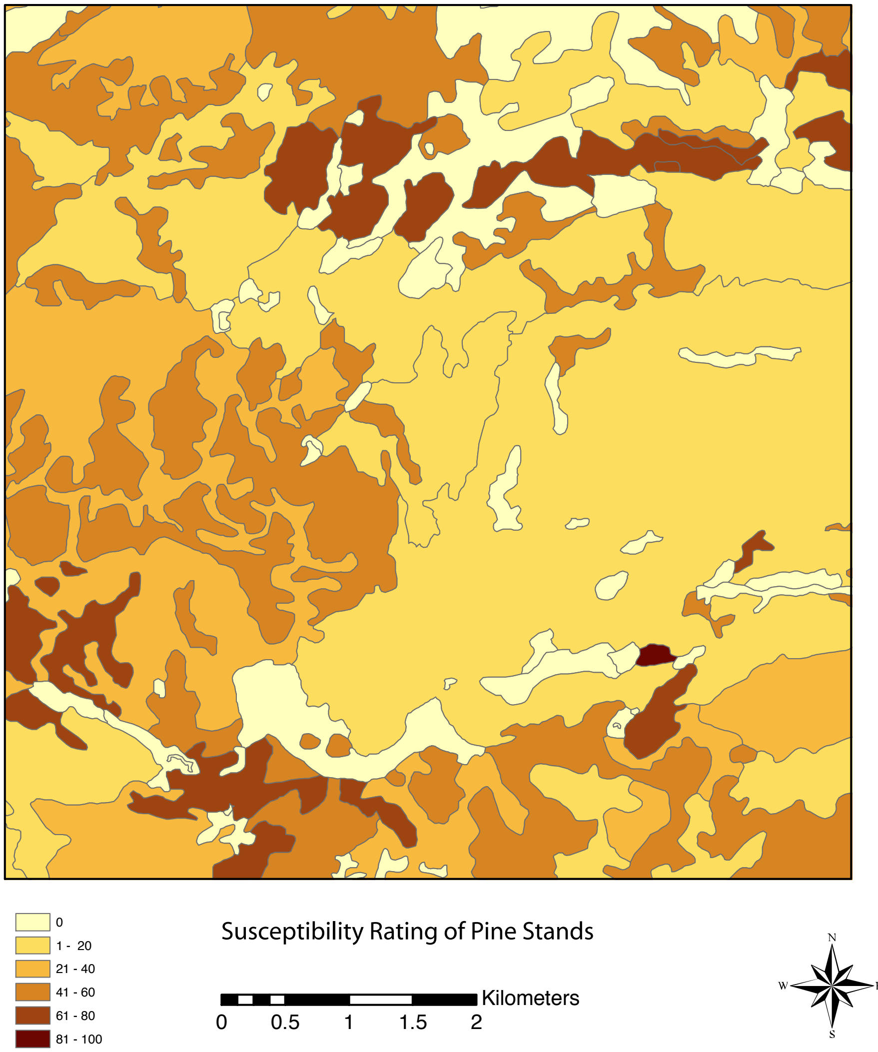

Figure 3. Map showing stand susceptibility index values associated with forest inventory polygons.

Determining the beetle pressure index

Beetle pressure is related to the size and proximity of a mountain pine beetle population that is affecting the stand being rated. To determine the beetle pressure index (B), the size category of the infestation is determined from Table 6. After the size category of the infestation has been determined, the beetle pressure index was previously determined by distance categories in Table 7, but is currently determined using the continuous functions contained in Table 8.

Table 6. 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 to 100	More than 100
Less than 900	Small	Medium	Large
900 to 9,000	Medium	Medium	Large
More than 9,000	Large	Large	Large

Table 7. Categorical table originally used to determine the beetle pressure index (B) from infestation size (determined from Table 6) and the distance from the stand being rated to the nearest edge of the mountain pine beetle infestation.

Relative Infestation Size	Distance to Nearest Beetle Infestation (km)					
	In Stand	0 - 1	1 - 2	2 - 3	3 - 4	4 +
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

Table 8. Continuous functions currently used to determine the beetle pressure index (B) from infestation size (determined from Table 6) and the distance from the stand being rated to the nearest edge of the mountain pine beetle infestation.

Relative Infestation Size	Distance (D) to Nearest Beetle Infestation (km)	
	0 – 4.5	4.5 +
Small	0.582 – [0.123 x D]	0.03
Medium	0.803 – [0.163 x D]	0.06
Large	1.003 – [0.209 x D]	0.07

Calculating the stand risk index

The stand risk index (SRI) is calculated as follows:

$$SRI = 2.74\,[SSI^{1.77}e^{-.0177SSI}][B^{2.78}e^{-2.78B}] \quad [6]$$

where: e = the base of natural logarithms = 2.718

B = Beetle pressure index

SSI = Stand Susceptibility index

Alternatively, the stand risk index value can be found in Table 9. If the exact value of the beetle pressure index or stand 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, with the highest values representing stands that would be expected to receive the most damage by the mountain pine beetle in the near future.

Table 9. The mountain pine beetle stand risk index as a function of the stand susceptibility and beetle pressure indices.

Stand Susceptibility (SSI)	Beetle Pressure (B)									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
10	<1	<1	2	3	5	6	7	8	8	8
20	<1	3	6	10	14	18	20	22	24	24
30	<1	4	10	17	24	30	35	39	41	41
40	1	6	14	24	34	42	49	54	57	57
50	1	8	18	30	42	52	61	67	70	71
60	2	9	20	34	48	61	70	77	81	83
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

Rationale for the stand susceptibility and risk indices

The rationale for selecting the variables, thresholds, weights and models 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 the logic and provide a starting point for further reading.

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

The following criteria were considered 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 co-dominant 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, implying that each variable holds equal weight in its contribution towards stand susceptibility and that the overall effect is multiplicative rather than additive. While this may be arguable in certain situations, overall we considered it to be a reasonable assumption.

Percentage of susceptible pine basal area (P)

Susceptible pine basal area (P) is a complex variable that incorporates the effects of diameter and stand composition on stand susceptibility to mountain pine beetle. Basal area is defined as the cross sectional area of a tree at breast height and is related to volume.

Diameter

The beetles show a visual preference for wider objects (Shepherd 1966). Attack correlates positively with diameter, and trees less than 12.5 cm in diameter are rarely attacked (Hopping and Beall 1943). 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 from desiccation, cold, and enemies than thin bark provides. Diameter is generally correlated with age and older trees are less resistant to the beetle (Shrimpton 1973). 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 in significant numbers and if they are, they will not support significant brood production.

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 attacks the pine component of mixed lodgepole pine stands as readily as it does pure lodgepole pine stands (Amman and Baker 1972). Nonetheless, it seems logical that the probability of beetles successfully finding and attacking a lodgepole pine tree would diminish as the number 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 number of non-host trees in a stand. Hopping (1961) states that mountain pine beetle outbreaks seldom originate in mixed stands, although we have seen situations where this is the case. The potential for basal area loss to the stand as a whole will be less in a mixed stand than in 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 resulted in the removal of the large diameter pine.

Age of the dominant and co-dominant 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 and introduced into successfully attacked trees by the mountain pine beetle (Shrimpton 1973). These fungi quickly penetrate the conductive tissues thereby killing the tree in 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, as mentioned earlier, 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 are rarely reported in stands less than 60 years of age (except in cases of severe epidemic). Similarly, beetle-caused mortality is less common between 60 and 80 years of age, but 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 old have an intermediate age component of susceptibility, and stands over 80 years old have a high age component of susceptibility. Lodgepole pine older than about 150 years, although relatively rare in British Columbia, seem to be less often attacked by the mountain pine beetle. This may reflect the reduced growth rate and relatively thinner phloem associated with these older trees. Our age model reflects this gradual reduction in susceptibility in older stands.

The age model is theoretical and not empirically derived. The equation presented is not meant to imply precision of knowledge of the relationship between age and susceptibility, but to provide smooth interpolation between generally understood relationships as described above.

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 vigour through the increasingly adverse effects of competition for light and nutrition. 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 vigour (Mitchell et al. 1983) and by altering the microclimate (Amman et al. 1988a; Bartos and Amman 1989). Vigourous 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 occurs when mortality is plotted against stand density (Anhold and Jenkins 1987), indicating low mortality at low stand densities, rapidly increasing mortality at intermediate stand densities, 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 2,500 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. Our observations of basal area mortality suggest that the highest mortality occurs in intermediate stand densities of 750 - 1500 stems per hectare. We considered all of this information in developing our stand density model.

The stand density model is theoretical and not empirically derived. The equation presented is not meant to imply precision of knowledge of the relationship between stand density and susceptibility, but to provide smooth interpolation between generally understood relationships as described above.

Location (elevation, latitude, longitude)

Elevation, latitude and longitude influence stand susceptibility through their effects on mountain pine beetle survival. 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 (Fig. 2). It is not possible to visually determine the location weighting of a stand from Figure 2 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 that could have been included such as beetle population trend, prevailing wind direction, and the size of the stand that, 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 6, 7 and 8 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 large rather than just a few trees in size. If, however, just a few trees are infested in the stand, the likelihood of infestation becomes 100 percent. The threshold numbers of trees and distances were based largely on observations made during population and dispersal studies over the past 30 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 calculated using equation [6], which is based on the susceptibility index and beetle pressure index. This non-linear relationship between these three variables is seen in Figure 4.

Calculating the pine susceptibility and pine risk indices

Pine susceptibility and pine risk rating systems serve a different purpose than stand susceptibility and stand risk rating systems. Pine susceptibility and risk indicate the susceptibility and risk of the pine component of a stand, whereas stand susceptibility and risk rate the stand as a whole. For example, a stand containing a small percentage of mature pine will have low stand susceptibility. In this case, even if mountain pine beetle were to kill all the pine, the stand as a whole would suffer only low levels of mortality. The pine susceptibility would be higher than the stand susceptibility, indicating that there is potential in that stand for mountain pine beetle to become established and cause some level of mortality. This concept will be discussed further in the section, Practical Considerations.

Calculation of the pine susceptibility index (PSI)

Pine susceptibility is defined as the inherent characteristics of the pine component of a stand that affect its likelihood of attack and damage by the mountain pine beetle. It is calculated as follows:

$$PSI = 100.0/(1+EXP(-(P-22.7)/5.3)) \times A \times L \times D \quad [7]$$

Where:

EXP = base of natural logarithms

P = Percentage of susceptible pine basal area

A = Age factor

L = Location factor

D = Density factor

SSI = Stand susceptibility index

The variables defined above have the following restrictions:

If PSI < SSI then PSI = SSI; if SSI = 0 then PSI = 0

Rationale for the pine susceptibility index

This equation was developed on the premise that the P factor in Shore and Safranyik (1992) reflects the proportion of a stand's total basal area that is composed of susceptible pine. The degree of susceptibility of that pine component is related to the magnitude of this proportion (P) in a non-linear fashion (see Table 10). The following examples illustrate the basis for this relationship. Assume A, L and D = 1 (most susceptible): When P is 100 then all of the pine is deemed susceptible, therefore PSI is also 100. If P is greater than 50 (meaning 50% of the stands basal area is composed of susceptible pine), the susceptibility of the pine component changes very little and remains close to 100%. As the percentage of susceptible pine decreases below 50% however, it is assumed that the mountain pine beetle will have increasing difficulty locating suitable host trees in the stand. This dispersion of host trees in the stand can also disrupt the timing and success of breeding and subsequent dispersal. As a result, the pine component of the stand decreases in susceptibility (PSI) more rapidly as P takes on values lower than 50% (Table 10).

Table 10. The relationship between P (percentage of susceptible pine basal area) and PSI (pine susceptibility index) assuming A, D and L values of 1.

A	D	L	P	SSI	PSI
1	1	1	0	0	0
1	1	1	5	5	5
1	1	1	10	10	10
1	1	1	20	20	37.5
1	1	1	30	30	79.9
1	1	1	40	40	96.3
1	1	1	50	50	99.4
1	1	1	60	60	99.9
1	1	1	70	70	100.0
1	1	1	80	80	100.0
1	1	1	90	90	100.0
1	1	1	100	100	100.0

Pine risk: The short term expectation of pine tree mortality in a stand as a result of a bark beetle infestation.

Calculation of the pine risk index:

$$PRI = 2.74\ [PSI^{1.77}e^{-.0177PSI}][B^{2.78}e^{-2.78B}] \quad [8]$$

Where:

PSI = Pine Susceptibility Index (above)

B = Beetle Pressure Index (from Shore and Safranyik 1992)

This equation simply replaces SSI with PSI in the risk equation used for calculating stand risk index.

Practical considerations

Interpretation of susceptibility and risk indices

The stand susceptibility index (SSI) is an indicator of the potential loss in stand basal area or volume that could occur if mountain pine beetle infested a particular stand. This index can be used in preventive management to identify which stands, or groups of stands on a landscape, should receive management priority to reduce potential loss to the beetle (Fig. 3 and see Chapter 7). It could also be considered an index of a stand's capacity to produce beetles in the event it is attacked. In this sense, it could be used to set priorities for direct control treatment during incipient or early epidemic mountain pine beetle infestations.

Susceptibility indices are longer-term than risk indices and need to be periodically updated to reflect changes in stand structure due to growth or depletions. Risk indices incorporate both the susceptibility indices and the beetle pressure indices (Fig. 4).

Stand susceptibility and risk indices indicate the potential for loss to the stand as a whole from the mountain pine beetle. Pine susceptibility and risk indicate the potential for loss to the pine component of a stand. By definition, stands with high stand susceptibility will also have high pine susceptibility. By looking at stands with medium to low stand susceptibility, the pine susceptibility index highlights stands where the mountain pine beetle could build up or spread to other stands. The indices should be used together to provide a more complete picture of potential loss and habitat for the mountain pine beetle on which to base preventive management or direct control decisions.

The range of values for these indices will vary by geographic region so we have not defined ranges of discrete categories such as low, moderate, and high. The highest values may only be in the 40 or 50 range in some areas, whereas in others they may be in the 80 or 90 range. Also, depending on the intended use of the ratings, the sensitivity of the system may be lost by going from a 100-point rating system to a small number of broad categories. Therefore, we have left interpretation to the discretion of the user. Through local knowledge and observation of the relationship between index values and resultant mountain pine beetle-caused tree mortality, logical categories can be derived locally which will relate to operational management decisions.

One important consideration that has become increasingly evident during the current enormous mountain pine beetle epidemic in British Columbia is that the stand susceptibility rating system is not intended for use under such unusual beetle population pressure conditions (Ebata 2004). Susceptibility and risk rating systems are planning tools used to reduce stand and landscape level susceptibility to the beetle during endemic, incipient or early epidemic population conditions or to reduce beetle pressure in expanding population situations. Once a large-scale epidemic is in motion, it is not uncommon for beetles to attack trees as small as 8 to 10 cm, in younger age classes, and in a variety of density classes where hosts become limited in relation to the population of beetles. The mountain pine beetle will not successfully reproduce in most of these stands and the net effect will be that these stands are a "sink" rather than a "source" for beetle populations. Nevertheless, the usefulness of susceptibility and risk indices under these circumstances is diminished.

Validation and interpretation of the stand susceptibility index

The key question, "Does the stand susceptibility index relate to tree mortality caused by the mountain pine beetle?" and the related question, "What does a particular stand susceptibility index value mean?" were addressed by Shore et al. (2000). As stated above, the SSI is a relative value, the range of which could vary widely between forest management units. To a degree, experience with the system and the mountain pine beetle will give a forest manager a sense for which values of SSI may be more cause for concern than others in his or her management unit. Shore et al. (2000) examined 38 stands in which a mountain pine beetle infestation had come and gone and rated the SSI for the stands as they would have been before the beetle infestation. The SSI was then related to the percentage of stand basal area killed. The resultant regression was:

Percent basal area killed = 0.68 x SSI [9]

This equation reduced the variation in the dependent variable, uncorrected for the mean, by 86% (Steel and Torrie 1980) (Fig. 5).

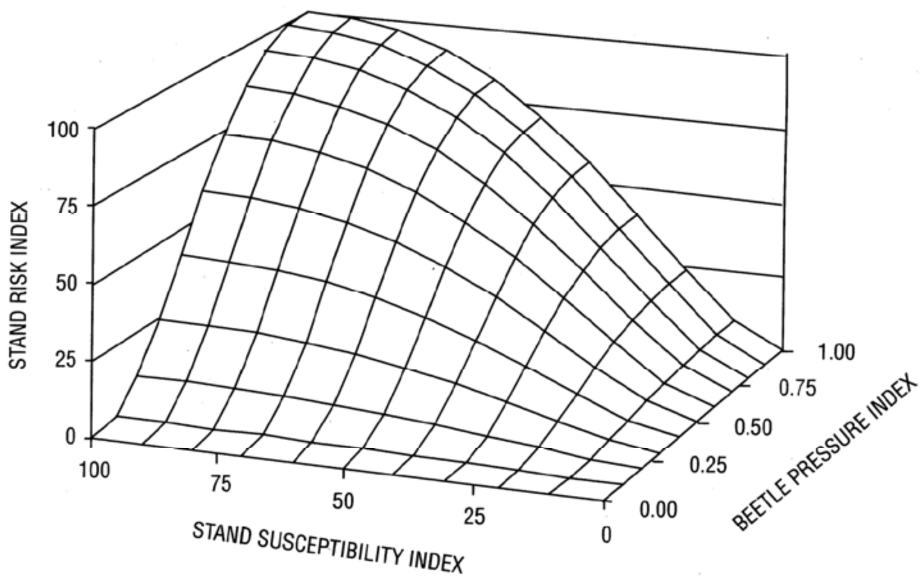

Figure 4. The stand risk index as a function of the stand susceptibility index and the beetle pressure index.

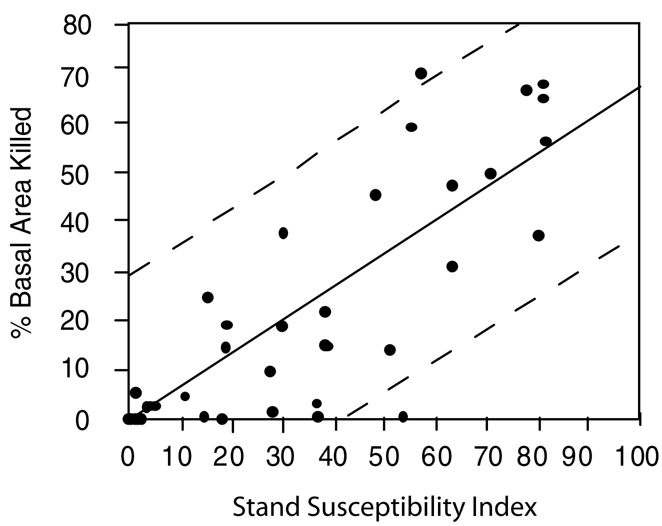

Figure 5. The relationship between the stand susceptibility index and percent basal area killed for 38 stands in the Cariboo region of British Columbia. Solid line represents the regression and broken lines represent the 95% prediction interval.

Putting a 95% prediction interval around this regression, and overlaying an independent data set consisting of data from 41 stands across British Columbia, 40 stands fell within the prediction interval (Fig. 6).

These results indicate that the stand susceptibility index is directly related to the susceptible basal area of the stand and is an index of the maximum mortality (in terms of percentage of stand basal area) a stand would receive in the event of a mountain pine beetle infestation under normal circumstances (see discussion above regarding major epidemic populations). It is useful as a long-term indicator of potential loss in the event of a beetle epidemic.

It is likely that a portion of the variation about the susceptibility versus percent basal area killed regression line is due to variability in mountain pine beetle population levels between stands. Additional variation would likely be attributable to differences in host resistance (Berryman 1978).

The susceptibility versus percent basal area killed model (equation 9) can be used to estimate the potential loss of stand basal area for stands that have been rated with a susceptibility index. A prediction interval can be assigned to the estimate. The 95% prediction interval shown in Figure 5 is rather broad (approximately ± 30 m^2 per ha) for single stand estimates with 95% probability, but this can be reduced considerably if a lower level of confidence is acceptable (e.g., approximately ± 19 m^2 per ha at the 80% probability level). In practice, use of the regression at the individual stand level is limited by its variability. The most likely way this relationship would be used is as an estimator of potential loss of basal area at the landscape level where the average susceptibility of a large number of stands is calculated. A confidence interval would then be constructed about the predicted mean basal area mortality. In such a situation, for a given probability level, the confidence interval around the mean would be considerably less than the prediction level in Figure 5 (Shore et al. 2000).

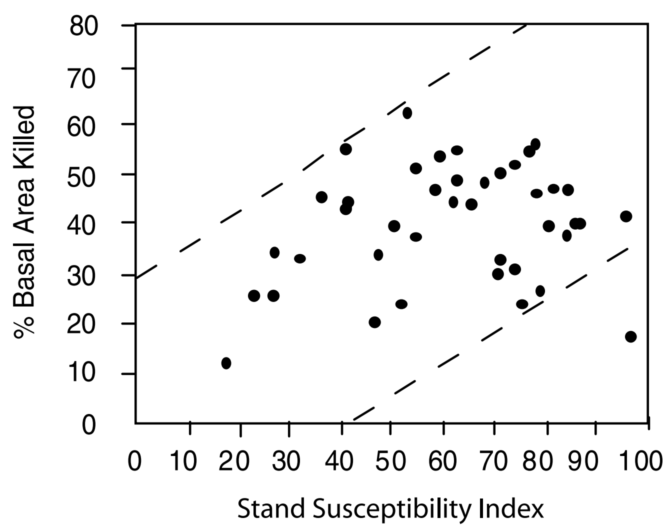

Figure 6. Overlay of data from 41 stands from across British Columbia on the 95% prediction interval shown in Figure 5.

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 four variables composing the susceptibility index, the variables of age, density and 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 applying organized clearcuts, age, size, and species mosaics can be created to 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 lowering stand density. This approach is perhaps best suited to mixed stands where species other than pine could be left that would respond well to removal of the overstory. In pure pine stands removal of larger pine could result in "high-grading", leaving inferior trees to produce a poor stand. The residual, smaller diameter pine may be 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 Whitehead et al. Chapter 7 for more complete discussion).

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). See Carroll et al. (Chapter 6) for further discussion of direct control of mountain pine beetle.

Population dynamics, impact and management models

Models simulating mountain pine beetle activity have long been an important component of decision support, and many different types of models have been developed. With improvements in computer technology, more sophisticated modelling approaches have been used, and it is expected that this trend will continue. Following is a brief discussion on some of these approaches and models. This is not intended to be an exhaustive review of mountain pine beetle simulation models, but rather a brief exploration of some of the different modelling approaches that have been employed.

Empirical models based on life tables and life stages have been developed and used (Cole et al. 1985), and are often components of other modelling approaches. More theoretical models have also been developed. Burnell (1977) developed a dispersal-aggregation model based on the following three assumptions:

1. Pioneer beetles attack with random distribution over the available bark surface.
2. Every tree has a threshold of aggregation which is required to trigger aggregation.
3. Any tree which becomes an aggregator (as in assumption 2) will be mass attacked and killed.

Assumption 1 meant that trees would be attacked in proportion to the "barrier" presented to the flying beetles; there would be no active selection on the part of the beetle. However, larger diameter trees would tend to be attacked earlier due to the larger basal area presented. Assumption 2 was not meant to be a measure of the number of insects required to kill a tree, but rather the number and distribution of attacking beetles required to trigger aggregation. Assumption 3 may not be true in some cases, but simplified the model development. This theoretical model was fit to data from four stands that had been attacked by mountain pine beetle and found to provide a reasonable account for tree mortality by diameter class during an outbreak.

Cole and McGregor (1983) used a more empirical approach, and developed a rate of tree loss model that projected tree and volume losses per year and for the duration of an epidemic. At its time of development, this model differed from many other mountain pine beetle models because it did not follow a continuous-infection assumption, something common to models of epidemic processes. In analyzing and verifying this model it became clear that different habitat types displayed different tree mortality patterns during outbreaks. This led to the development of different rate of loss projections for differing habitats. One of the major strengths of this model was the ability to integrate it into existing forest management planning software. This design philosophy is common today (Beukema, et al. 1997; Fall et al. 2004, Riel et al. 2004) and is an important consideration for the development of decision support tools.

Raffa and Berryman (1986) developed a mechanistic model exploring mountain pine beetle population interactions with lodgepole pine stands. This model was based on laboratory and field studies from which equations and model assumptions were developed. This model was not intended to project numerical levels of beetle attack or damage, but rather patterns of population development of both *D. ponderosae* and other primary bark beetle species. It was used to evaluate management practices for controlling mountain pine beetle, and the results suggested that control efforts that directly influence stand vigour were the most effective long term strategies for reducing damage from beetle outbreaks.

Beyond the stand level, landscape scale simulation models have also been developed as decision support tools. Earlier technology did not permit spatially explicit modelling, thus aspatial landscape scale models have been developed. Thomson (1991) published a landscape scale model that explored the general impacts of various management strategies on a mountain pine beetle outbreak. Since then, spatially explicit approaches have become practical. The Westwide Pine Beetle Model (Beukema et al.1997) is one example of such an approach, designed to work within the framework of the Forest Vegetation Simulator (Wykoff et al. 1982) using a contagion paradigm to simulate beetle spread among stands, and to and from the "outside world" (i.e., the area surrounding the target landscape).

In addition, sophisticated mathematical approaches to modelling mountain pine beetle spatial dynamics have been employed. Polymenopoulos and Long (1990) developed a model of population growth with spatial diffusion that allows evaluation of the spatial spread of mountain pine beetle populations and the resulting damage. The variables used in the model are insect density, food availability, and insect diffusivity (spatial spread). For modelling mountain pine beetle dynamics, the density of killed (red-topped) trees was used as an index of population density. The model design is based on spatially discrete areas of mountain pine beetle habitat. Exchange of beetles among stands is assumed to be accomplished through random movement of individuals and an "attractive force" that directs movements toward a favourable environment. Two models were developed: a) a simple diffusion model that describes the number of lodgepole pine that would be killed if mountain pine beetle spread was a passive diffusion process, and b) a diffusion-convection model that describes the density of lodgepole pines that would be killed if mountain pine beetle were attracted to stands with thick phloem trees and if the rate of population increase was a function of the density of living lodgepole pine. The models were used to construct maps of density surfaces for killed lodgepole pine and were compared to a map showing the actual density surface for the same area. The initial results indicated that a 3-year history of mountain pine beetle dynamics (i.e., damage) is adequate for a 1-year projection of the spatial distribution and density of damage.

Powell et al. (1998) developed a spatially dynamic, forest-scale model (referred to as the global model) for mountain pine beetle dispersal and interaction with pine hosts. This is a probabilistic model based on a system of partial differential equations, and represents an attempt to capture the complex host tree-beetle interactions including chemical ecology, attack dynamics, beetle dispersal, resin outflow and resin capacity of individual trees. This model is well suited to broad descriptions of dispersal and attack but it is difficult to make comparisons with field data to assess whether or not the model represents a reasonable description of observed events.

Later, a "local" model, a system of ordinary differential equations, was developed to represent the consequences of the global model at the individual tree level to allow analysis of switching mountain pine beetle attacks from initial foci to nearby hosts (Powell et al. 1998). This theoretical analysis of a two-tree system strongly suggested that stand thinnings are successful mainly because of interference with the mountain pine beetle communication system. Tree vigour was found to play a major role only at very low emergence densities.

Logan et al. (1998) developed a spatially explicit model, based in part on the global model, of forest level interaction between the mountain pine beetle and its host. The model system describes the temporal dynamics of beetle attraction: as a function of the concentration of pheromones, change in the numbers of flying and attacking beetles, host tree resistance, and recovery of trees from attack. This model was used to explore the evolution of the spatial pattern of attacks by simulation. The main results indicated that, at endemic levels, the pattern of successful attacks is determined mainly by the spatial distribution of susceptible hosts. During development of an outbreak, the spatial pattern of successful attacks is driven by the pattern of a self-generated semiochemical landscape. Synchrony of adult emergence was critical for overcoming host resistance and spatial proximity to brood trees was an important factor in subsequent successful attacks.

Powell et al. (2000) combined different mathematical approaches to develop a method for assessing the risk of attack by mountain pine beetle on individual hosts. The dispersal and focusing behaviour of the beetle is achieved by the density-based global model, and local projection of this model predicts the consequences of the density equations at individual trees. Natural division of risk into categories of high, medium and low is accomplished by the so-called bifurcation diagram of the density equations. Preliminary results from this model suggested that host vigour and stand age has much less affect on the risk of mountain pine beetle attack than stand microclimate.

Modelling in western Canada

While models of various scales and approaches have been developed and applied in many locations within the range of mountain pine beetle, we will focus specifically on models developed for (and in current use) in western Canada.

Thomson's (1991) landscape scale model was developed in direct response to a mountain pine beetle outbreak in British Columbia in the 1970s to mid 1980s. This was an aspatial model that operated at a relatively large scale. One advantage of this model was that data requirements were relatively simple and easy to acquire. The model was limited, however, in that the spatial dynamics and interaction between the beetle and management could not be captured. Its main strength was the ability to assess the sensitivity of the mountain pine beetle outbreak to various management strategies.

During the early 1990s, a stand level mountain pine beetle population dynamics model was developed to address questions at a much finer scale than the Thomson model (Safranyik et al. 1999). Even though operating at a much smaller scale, the processes captured in this model later allowed its use as a component in a spatially explicit landscape simulation.

The Safranyik population dynamics model

This population dynamics model (hereafter referred to as the "Safranyik model") is a complex process-based simulation of mountain pine beetle activity on a one hectare stand of pure lodgepole pine. The model simulates the process of host colonization, brood development and survival, predation and parasitism of mountain pine beetle as well as tree mortality (Safranyik et al. 1999). It can be used to explore and compare the effects of various management treatments on both the beetle and host stand.

The Safranyik model is composed of four main sections: two biological sections – the forest stand model and the mountain pine beetle biology model, and two non-biological sections – a management submodel and a section that controls input, output and interactive simulation. The original model was written in FORTRAN to run on a VAX 8650 under VMS. It has since been converted to the Windows platform and possesses a simple to use graphical user interface.

The forest stand submodel is based on variable density yield tables for lodgepole pine developed by Johnstone (1975) and simulates the growth (diameter at breast height, height, natural mortality) and yield of a pure, unmanaged lodgepole pine stand as a function of site quality, initial density, and age. The mountain pine beetle biology and management submodels simulate the processes of host colonization, brood development and survival, tree mortality, and control interventions (direct control, host density manipulation and biological control). The model simulates the course of a beetle infestation in a one hectare stand using a daily time step.

Although the number of adult beetles dispersing out of the area is calculated for each beetle generation, the fate of these beetles is not considered in the model. Stand parameters, temperature regime, host resistance, the initial size of the beetle population, and control interventions by type, magnitude, and duration, can all be specified at the beginning of each run.

The development of this model involved two approaches: 1) empirical models from published sources, and 2) conceptual models. The empirical models were based on regressions such as surface area equations or growth and yield functions, or they consisted of tabular data from which intermediate values were interpolated, such as the data for brood development as a function of temperature. The general structures of conceptual models and their parameters were based on published sources whenever data were available. The functions relating egg and larval survival to attack density were derived in this manner. Where data were not available, the parameters were derived from the known or assumed limits of the dependent variable and its rate of change with respect to the explanatory variable. In situations where only general information was available, the structure and parameters of submodels were developed on hypothetical grounds. For example, to examine the effects of bait on attack density and tree mortality, it was assumed that the inter-bait distance commonly used in operational programs was the practical limit for attraction or repellency, and that relative bait effects increase exponentially with bait density.

Model outputs are in the form of tables showing changes through time in a number of stand and insect variables, which can be plotted against each other, or as functions of time. A large number of variables are included in the simulation; only a subset of these variables, of interest mainly to forest managers and students of insect population dynamics, are output. Figure 7 shows a simplified flow chart, which demonstrates program flow.

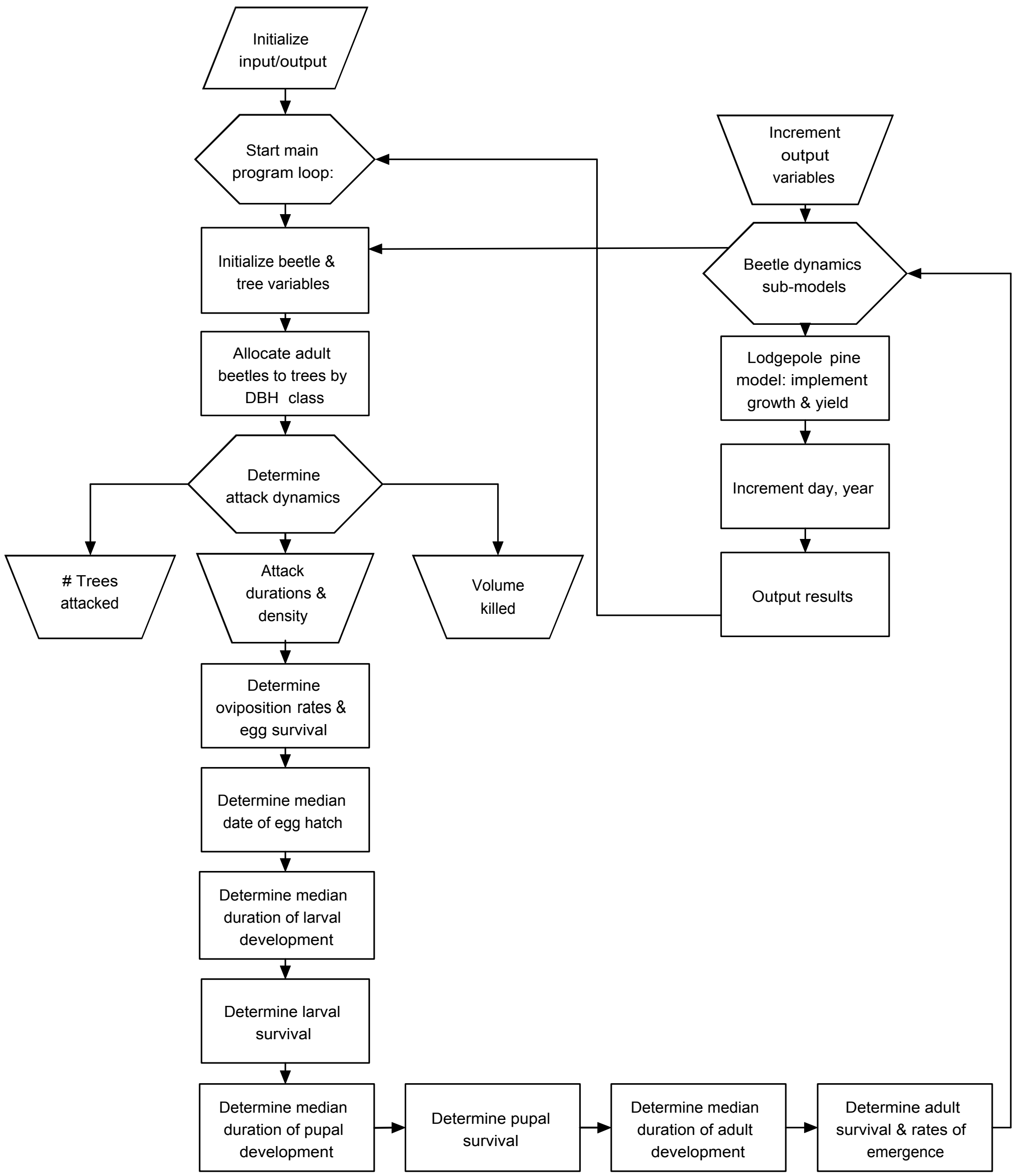

Figure 7. Safranyik model flow diagram (Safranyik et al. 1999).

Stand level simulation: MPBSIM

The Safranyik model represents a sophisticated approach to modelling mountain pine beetle activity and for exploring effects of management intervention at the scale at which it operates. However, the scale of the simulation restricts its utility as a tool for forest managers who must deal with larger stands and stands of mixed tree species. For these reasons, a new simulation called MPBSIM has been developed (Riel et al. 2004). MPBSIM is a stochastic, process based simulation of mountain pine beetle activity at the stand level. Host stands can be mixed species and can range in size from 1 ha to 50 ha. MPBSIM is a much coarser simulation than the Safranyik model; it simulates host selection, brood development and survival and beetle emergence and dispersal out of the stand on a yearly time step. Tree mortality is tracked on a year-by-year basis by different diameter at breast height (dbh) classes.

Similar to the Safranyik model, MPBSIM is composed of four main components: a mountain pine beetle population dynamics sub model, a stand sub model, a beetle management sub model and a graphical user interface for collecting inputs and displaying projected outputs.

MPBSIM input requirements include stand parameters and beetle information. Specifically, the following inputs are necessary for running the simulation:

- Stand size (in hectares);
- Stand age (in years);
- Stand site index (for lodgepole pine, expressed in metres at 50 years breast height age);
- Percent pine;
- Stand density (stems per hectare); and
- Number of attacking beetles (or number of currently attacked trees).

Even though the stand inputs are coarse stand parameters, MPBSIM requires diameter class structure and can use real or simulated tree lists. In the absence of such information, the stand sub model will generate a diameter class structure for the host pine based on the broader stand parameters.

The outputs generated by MPBSIM include:

- Projected duration of outbreak (in years);
- The number of trees killed each year;
- The volume of trees killed each year by diameter class;
- The number of beetles emerging each year; and
- The number of beetles dispersing out of the stand each year.

A highly simplified flow diagram depicting overall program flow in MPBSIM is shown in Figure 8.

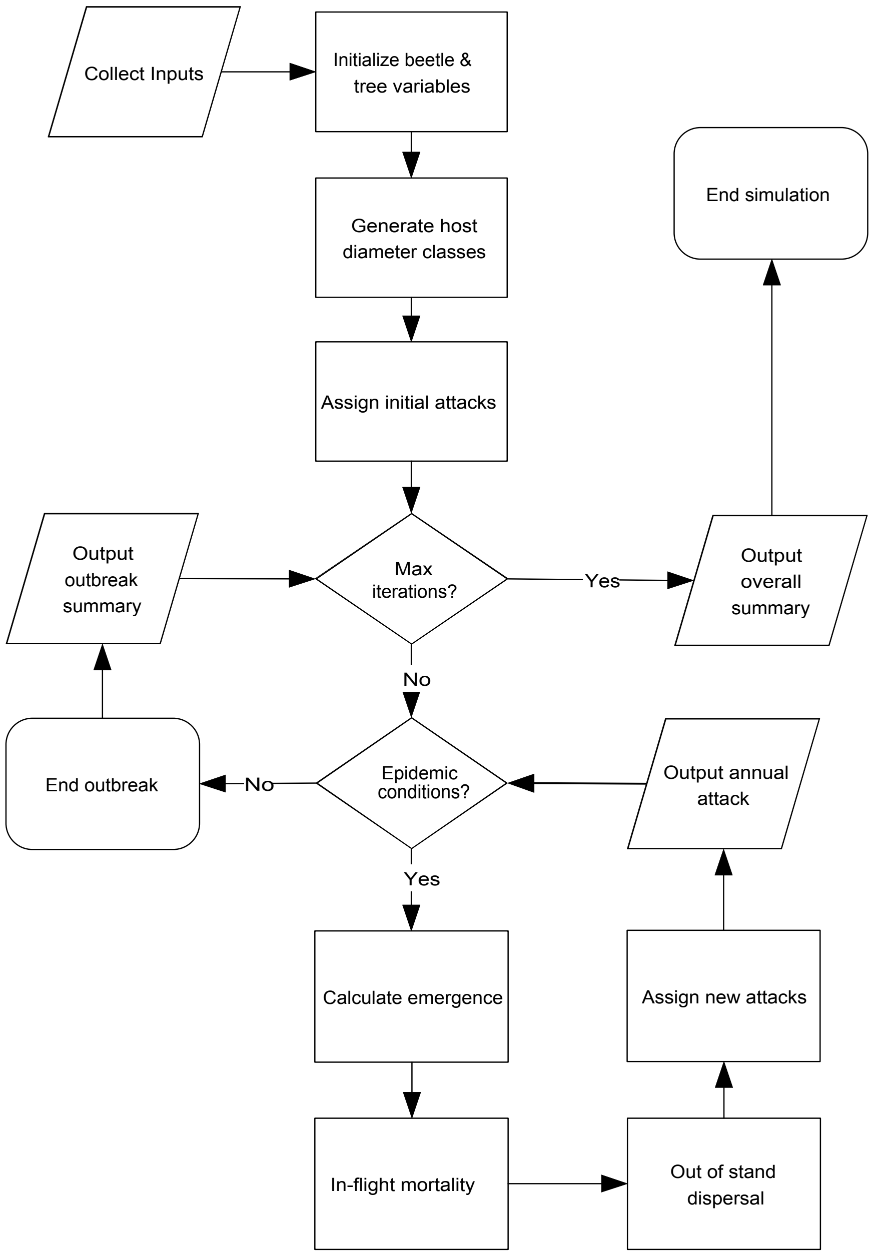

Figure 8. MPBSIM flow diagram.

Landscape level simulation: SELES-MPB

To effectively simulate a mountain pine beetle epidemic, a landscape scale simulation is important. A spatially explicit simulation allows a better platform for evaluating mountain pine beetle impacts and comparing various management strategies because it places the stands in a real world context with geospatial and beetle information. For these reasons, a spatially explicit landscape scale model has been developed using the Spatially Explicit Landscape Event Simulator (SELES) as a development platform (Fall and Fall 2001). SELES is not a model, but a raster-based platform in which to build and execute spatially explicit landscape models (Fall and Fall 2001). Every SELES model consists of three components:

1. Raster layers. These are the landscapes on which the simulation is executed. Layers can be base maps, forest inventory, road networks, etc.
2. Global variables. Global variables describe the state of the system.
3. Landscape events. Landscape events are the dynamic models that operate on (sometimes modifying) the landscape (raster layers). Landscape events can communicate indirectly through modifying the landscape.

The spatio-temporal model of mountain pine beetle spread and impact that was developed consists of several landscape events, including a spatially explicit mountain pine beetle spread model, a spatial timber harvesting model, a spatial mountain pine beetle management model, and an aspatial mountain pine beetle impact simulation. This model is referred to as SELES-MPB.

Model scaling and integration

To provide a satisfactorily detailed projection of mountain pine beetle impacts and to evaluate management effectiveness, it is preferable to generate stand level details of mountain pine beetle impacts even in a landscape model. For this reason, MPBSIM has been linked with the SELES landscape model as a landscape event. Because the purpose of SELES-MPB is to simulate beetle impacts and management strategies on real landscapes with unique climate and topography, it is important that MPBSIM projects beetle development and survival consistent with those conditions. To do this, MPBSIM is calibrated for the specific landscape using the Safranyik model.

The Safranyik model is capable of utilizing recorded daily temperatures for projecting mountain pine beetle development and survival as influenced by climate. To calibrate MPBSIM, temperature data from several weather stations located within the landscape are collected and adapted as inputs to the Safranyik model. A number of simulations are performed in a variety of stand conditions using these temperature data, and the resulting development and survival rates are used to calibrate MPBSIM.

Once MPBSIM has been calibrated to the local landscape climate, it can be incorporated into the landscape model using a loose coupling methodology (Chang 2001). This is accomplished by collecting a complete range of inventory data for the landscape in question and pre-running MPBSIM for as many conditions as possible at a large number of different initial beetle attack levels. This can amount to well over one million different combinations. A variety of values and indicators are output and collated in a large table which includes stand information (number of stems per hectare, stand age, percent pine, site index) and beetle activity information (number of attacking beetles, number of dispersing beetles, number of beetles emerging next year, trees killed and tree volume killed). This table reflects MPBSIM's projection of mountain pine beetle activity for any condition that exists on the landscape. (Fig. 9).

The MPBSIM generated table is integrated into SELES-MPB as a landscape event, along with the spatial harvesting model and management model (Fig. 10). These landscape events do not directly communicate with each other, but can impact each other by making changes on the landscape (spatial landscape layers).

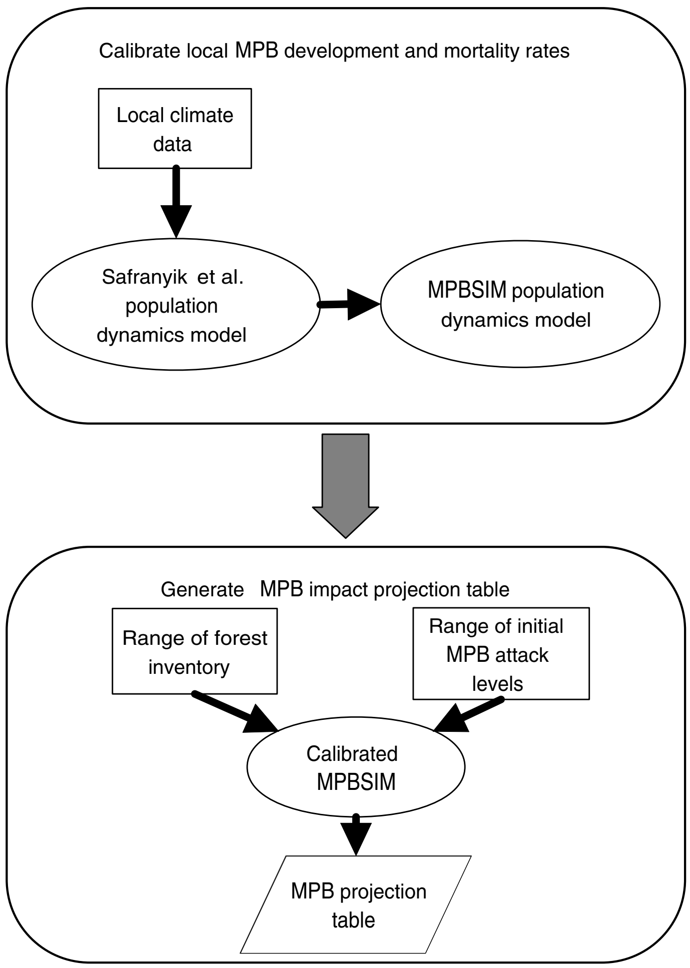

Figure 9. MPBSIM Calibration and table generation for SELES-MPB.

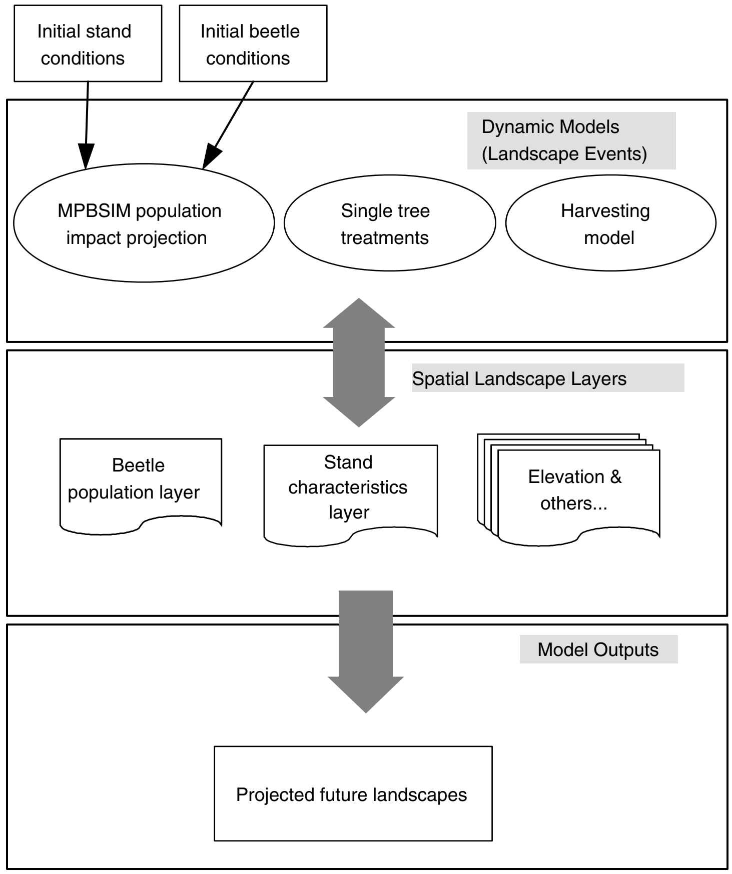

Figure 10. Overview of SELES-MPB.

Model applications

The modelling approach described above has been successfully applied in several districts within the provinces of British Columbia and Alberta (including the Kamloops, Lakes and Morice timber supply areas and the Foothills model forest), exploring the effectiveness of mountain pine beetle management, the impacts of mountain pine beetle on timber supply and other concerns (Fall et al. 2004). In each landscape the questions may be quite different, thus requiring different simulation scenarios, but in every case a "base" scenario is generated and used to compare against other scenarios.

Base scenarios are designed to address primary questions regarding the expected impact of beetle management. These can differ by study area, based on information obtained in workshops held with operational and management personnel. Some common features include application of current forest management policy, operational constraints (e.g., in one forest district, the amount of pine that could be harvested was constrained by a need to address concurrent outbreaks of balsam fir bark beetle [*Dryocoetes confusus* Swaine] and spruce bark beetle [*Dendroctonus rufipennis* Kirby]). Other differences encountered in different landscape simulations include the level of fine-scale treatments applied, harvest levels, differing forest cover constraints, etc. To put the effect of beetle management on the mountain pine beetle in a broad context, base scenarios are compared against a variety of scenarios, including those where no harvesting takes place, where beetle management is abandoned, and where forest policy constraints are disabled.

Outputs are typically tables, graphs and maps that can show a number of indicators including the following:

- Effectiveness of current management,
- Effects of altering harvest level,
- The likely trajectory of the mountain pine beetle across the landscape.

Conclusions

Decision support systems are valuable tools that make the accumulated knowledge of experts available to forest managers to assist them in making good decisions. The essential ingredients to mountain pine beetle decision support systems are reliable data on the forest resource and the location and size of the mountain pine beetle (Fig. 1). These data can be used to develop and assign hazard and risk rating values to stands in the management areas, which enables the manager to begin to set priorities for stand or beetle treatments. As a component of a decision support system, risk rating has a role in both long and short term planning and management.

Data on the forest resource and the beetle are also used as inputs to models, as well as other inputs such as geospatial, climate and management information. Within the context of decision support, modelling mountain pine beetle activity at different scales is important for different management questions. Many different approaches can and have been employed to build valuable decision support tools. Integrating models of different scales allows for a more detailed simulation of finer scale impacts and permits evaluation of management at appropriate levels of detail. For example, SELES-MPB has been used to address many questions surrounding mountain pine beetle activity and its management at relevant scales. Examples of questions addressed include:

- Where should different beetle management strategies be applied?
- What is the effect of an epidemic on the future timber supply?
- Would improved detection help the beetle management effort?
- What are the other resource implications of this epidemic and subsequent harvesting?
- Do any of the policy rules cause difficulties for beetle management?

Through the use of decision support systems we are able to better assign current priorities as well as forecast possible futures under different management scenarios. These models can only improve in the future as new knowledge and technologies become available to us.

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