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A critical assessment of risk classification systems for the mountain pine beetle

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Abstract

Hazard/risk systems developed for mountain pine beetle management traditionally have attempted to describe the potential for timber loss in pine stands due to outbreak phase populations. A variety of stand and site characteristics, as well as climatic conditions, have been used. In this study, four hazard/risk systems were evaluated using data from 105 stands in northern Montana. None of the systems evaluated were found to predict adequately mountain pine beetle induced mortality which occurred in the test stands. Possible reasons for the lack of predictive ability of these systems include: (1) confusion in terminology used in hazard/risk rating for mountain pine beetle; (2) lack of consideration of the mountain pine beetle population phase (e.g. endemic or epidemic) during rating system development; (3) the need to include more information concerning mountain pine beetle population dynamics; (4) the need for inclusion of the spatial nature of both beetle populations and stand conditions.

Introduction

Hazard and risk classification systems are tools used by forest managers to predict future insect activity relative to the location of a forest stand, and conditions within a stand (Hicks et al., 1987). A variety of hazard/risk classification systems have been developed to assist in the forest management process when the mountain pine beetle (MPB), *Dendroctonus ponderosae* Hopkins (Scolytidae: Coleoptera), is an influencing factor. These systems attempt to describe the relationship between MPB populations and forest stand conditions in a quantitative or qualitative manner. Because an MPB infesta-

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tion usually results in the death of the host trees, most systems have related hazard or risk to tree mortality in some manner. Some rating systems were based on regional descriptions such as a historic map depicting the frequency and intensity of MPB infestations (Crookston et al., 1977), and climate-related parameters (Safranyik et al., 1975). Other systems were based on stand and host tree characteristics, including indices of stand competition (Schenk et al., 1980; Anhold and Jenkins, 1987), tree age, diameter, and climatic zone (Amman et al., 1977), host tree growth and vigor (Mahoney, 1978; Waring and Pitman, 1980), tree physiological maturity (Shrimpton and Thomson, 1981), and a combination of several of these factors (Berryman, 1978; Stuart, 1984).

In most instances, MPB hazard/risk systems were developed to provide a predictor of either stand susceptibility or stand resistance to MPB epidemic populations, although exactly what was meant by the terms was not always indicated. The term susceptibility was used by many, although never explicitly defined except by Schenk et al. (1980), who associated susceptibility with current tree/stand vigor. Stand resistance was defined in similar terms by Berryman (1978) as the ability of the average dominant or codominant lodgepole pine in a stand to defend itself against an MPB attack. Use of the terms hazard and risk has also been perplexing. Unfortunately, the melange of terminology has resulted in confusion over what is meant by a particular method and how it should be interpreted.

The objective of this study was to evaluate several MPB hazard/risk rating systems and to determine their applicability in three National Forests in northern Montana. Mixed results have been obtained from previous evaluations of these systems using data from several geographic regions (Mahoney, 1978; McGregor et al., 1981; Stuart, 1984; Amman, 1985; Katovich and Lavigne, 1985; Shore et al., 1989). The purpose of this evaluation was to determine how well each method predicted MPB-caused mortality in forests in northern Montana. Based on our results, new concepts and definitions concerning hazard/risk rating lodgepole pine stands for MPB impact will also be discussed.

Methods

Data

As part of the Canada/United States Mountain Pine Beetle Agreement, 105 stands on the Lolo, Kootenai, and Flathead National Forests (Montana) were surveyed during the summer of 1984. Details concerning data collection and objectives were outlined by a working committee comprised of scientists from Canada and the USDA Forest Service (Amman et al., 1983). Only those stands in areas of climatic suitability (a combination of elevation and lati-

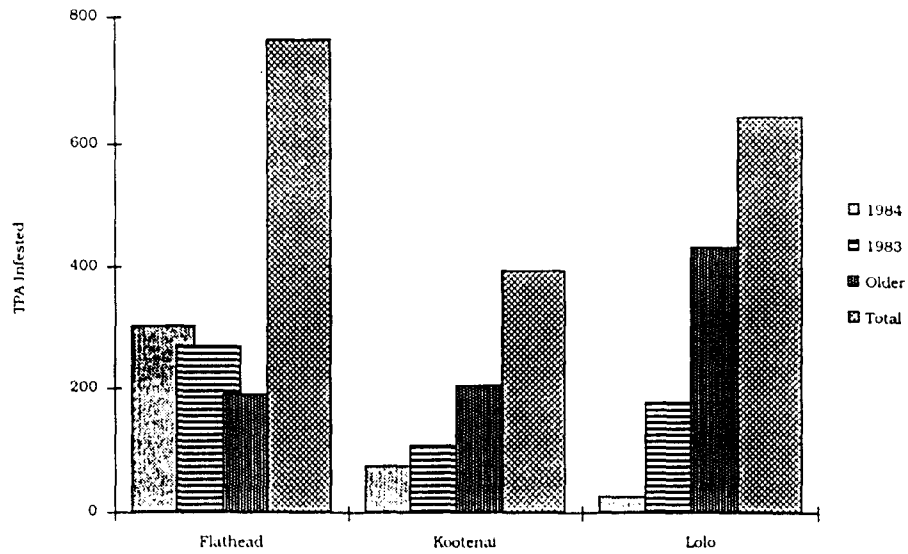

Fig. 1. Trees per acre (TPA) infested by the mountain pine beetle in three forests in northern Montana. Current TPA infested the year of the survey (1984), the previous year (1983) and 3 years prior (Older) are combined to provide a 5 year cumulative total (Total).

tude) for an MPB infestation were included in the study so that all methods to be tested would be based on similar conditions. Stands were selected at random and ranged in infestation history from no recent infestation to those that had recently undergone an outbreak. Only stands with at least 75% lodgepole pine were included in the study. Each stand was sampled using a 10 basal area factor (BAF) variable-radius plot cruising method for ten plots. The plots were located five chains apart in two lines that were also five chains apart. In irregularly shaped stands, plots were located in any pattern that maintained spacing (at least five chains between nearest plots). Variables sampled included: elevation, habitat type, slope, aspect, diameter at breast height (dbh) (only trees 12.7 cm and larger were included), tree species, and MPB mortality code (year killed: current, previous year, or older). Additionally, for several live trees in each plot, increment cores, phloem thickness, crown class and height were obtained. These data were used to evaluate the risk classification methods.

At the time of the stand surveys, the level of MPB infestation in each stand was different. To quantify these differences, the MPB population trend for each stand was categorized as increasing, declining, or static by comparing the trees per acre infested the year of the study to the trees per acre infested the previous year. For example, if the number of trees per acre infested during the previous year was greater than that of the current year, the MPB population trend at the time of the survey was assumed to be declining. Trees coded

Table 1
Descriptive statistics for data used to evaluate the risk classification methods

Variable	Mean	Standard deviation
Flathead National Forest (N = 45 stands)		
TPA	413.02	109.04
LPTPA	310.60	142.82
BA	162.04	36.74
LPBA	115.64	39.21
CCF	213.93	43.80
LPQMD	8.63	1.44
%LPBA	72	0.22
QMD	8.60	1.18
Kootenai National Forest (N = 14 stands)		
TPA	306.00	101.17
LPTPA	217.57	122.59
BA	156.00	30.23
LPBA	105.57	42.03
CCF	181.57	37.52
LPQMD	9.94	2.03
%LPBA	67	0.21
QMD	9.97	1.89
Lolo National Forest (N = 25 stands)		
TPA	458.76	90.95
LPTPA	356.04	119.95
BA	135.60	32.72
LPBA	93.72	28.66
CCF	175.48	30.97
LPQMD	7.04	0.79
%LPBA	71	0.19
QMD	7.36	0.83

TPA, trees per acre; LPTPA, lodgepole pine trees per acre; BA, basal area; LPBA, lodgepole pine basal area; CCF, crown competition factor; LPQMD, lodgepole pine quadratic mean diameter; %LPBA, percentage of the basal area in lodgepole pine; QMD, quadratic mean diameter.

as killed by MPB were included in density calculations to represent the stand structure before the beetle entered the stand. Cumulative mortality included all trees killed by the MPB prior to the survey. Figure 1 provides an indication of the cumulative and yearly mortality in each forest, and descriptive statistics for the initial year are presented in Table 1.

System evaluations

Four systems were evaluated in this study, those of Amman et al. (1977), Mahoney (1978), Berryman (1978) and Schenk et al. (1980). Included here is a brief description of each method. The reader is directed to the original

publications for further details. Each method was originally developed to predict the risk or hazard of a lodgepole pine stand to a MPB infestation. Risk and hazard were defined differently in each method, although both terms were always related to the mortality incurred in a stand. Mortality thresholds were a function of the particular rating method. Evaluations in this study were performed by using the methodology described in each system to predict the risk (or hazard) rating for each stand in the data set. The predicted results were then compared with the actual mortality observed. Evaluations of each system were performed by population trend (when sample sizes were large enough) and for all trends pooled.

Results

Amman et al. (1977)

The system developed by Amman et al. (1977) includes measures of climatic suitability (a combination of latitude and elevation), and tree characteristics (age and dbh). In this method, hazard is the expected mortality in a stand as measured by the percentage of infested trees. Amman et al. rated these three variables on a scale of 1–3 according to established thresholds. For each stand, the ratings for the three variables are multiplied to obtain a single value for the stand which represents the expected mortality (and subsequent hazard): 1–9 low hazard (less than 25% mortality), 10–18 moderate hazard (25–50% mortality) and 27 high hazard (more than 50% mortality). Only validation data for part of the stands on the Kootenai and Flathead Forests had the required variables necessary for evaluating this method. Of the 49 stands evaluated, only one was predicted to have a low hazard using Amman's system, although 36 stands were observed to have less than 25% mortality, which is indicative of low hazard (Table 2). Thirty-one stands were

Table 2
Comparison of observed and predicted results from Amman et al. (1977) system by population trend

Observed	Predicted			
	Low	Moderate	High	Total
Low	0,1,0[1]	0,5,17	4,1,8	36
Moderate	0,0,0	1,0,6	0,0,3	10
High	0,0,0	0,0,2	0,0,1	3
Total	1	31	17	49

[1]Increasing, static, decreasing population trend.
Low, less than 25% mortality; moderate, 25–50% mortality; high, more than 50% mortality. Mortality is interpreted as the percentage of dead lodgepole pine in the stand.
$\chi^2 = 0.551$, d.f. = 4.

predicted as moderate hazard, although only ten stands observed actually exhibited 25–50% mortality (moderate hazard). Three stands were actually high hazard while this method predicted 17 stands as high hazard. Overall, nine of the 49 stands were correctly categorized (one low, seven moderate, and one high). There were no observable associations between population trend (increasing, static, decreasing) and predicted hazard. One of the stands with an increasing population trend, one stand with a static trend, and seven stands with decreasing trends were successfully predicted. Since most of the error occurred when low hazard stands were rated as moderate or high, predictions from this system tended to be conservative. Observed and predicted values were found to be statistically independent ($\chi^2=0.551$, d.f.$=4$), suggesting that this system lacks predictive capabilities in the stands evaluated.

Mahoney (1978)

In the Mahoney (1978) system, many terms including susceptibility, resistance, and risk were used. Mortality is expressed as the proportion of lodgepole pine in the stand killed by MPB. This method is based on a periodic growth ratio (PGR)

$$\text{PGR}=\frac{\text{Current 5 year radial increment}}{\text{Previous 5 year radial increment}} \quad (1)$$

whereby a stand PGR average of 0.90 or less indicates a decline in overall stand vigor and subsequent susceptibility to an MPB infestation, and a PGR of more than 0.90 suggests that on average the stand is relatively vigorous and should be resistant to MPB attacks. Thus, based on this theory, Mahoney assumed that a stand with a PGR of 0.90 or less, should have greater tree mortality owing to MPB infestation. Not all stands in the validation data set had the required data to evaluate this system. Of the 24 stands tested, 13 were observed to have less than 10% mortality, while the PGR method predicted 17 stands to be resistant (Table 3). Eleven stands exhibited mortality of 10% or more, while seven were predicted to be susceptible. When analyzed by population trend, a slightly higher proportion of stands with increasing trends (4/6) was correctly predicted than in stands with either the static (1/3) or declining (7/15) status. Overall, 50% (12/24) of the stands were correctly rated using this method. Using this system, more stands were rated as resistant than actually exhibited less than 10% mortality, and less stands were rated susceptible than actually had 10% or higher mortality. Observed and predicted values were found to be statistically independent ($\chi^2=0.0352$, d.f.$=1$), suggesting that this rating system lacks predictive capabilities in the stands evaluated.

Table 3
Comparison of observed and predicted results from Mahoney (1978) system by population trend

Observed mortality (%)	Predicted mortality (%)		
	≥10 (susceptible)	<10 (resistant)	Total
≥10	2,0,1[1]	1,0,7	11
<10	1,2,1	2,1,6	13
Total	7	17	24

[1]Increasing, static, decreasing population trend.
PGR ≤0.90 indicates a susceptible stand that should exhibit 10% or higher mortality and PGR >0.90 indicates a resistant stand that should exhibit less than 10% mortality. Mortality is measured as the percentage of lodgepole pine infested.
$\chi^2 = 0.0352$, d.f. = 1.

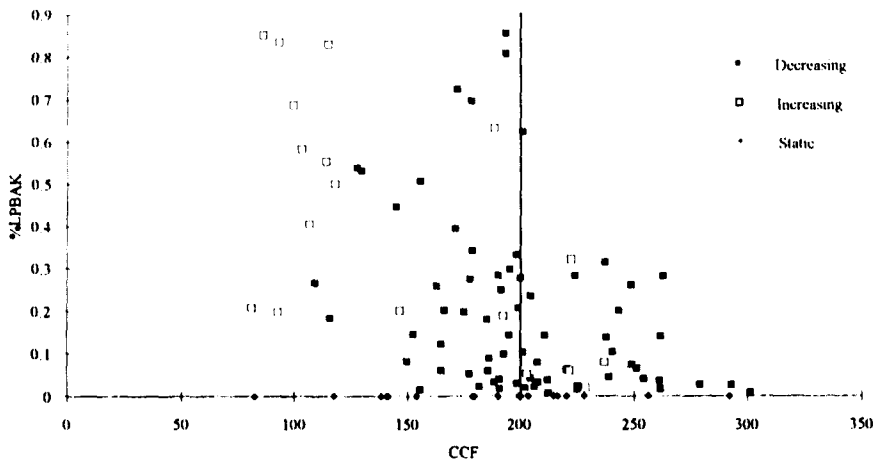

Fig. 2. Observed percentage basal area lodgepole pine killed (%LPBAK) as a function of crown competition factor (CCF) (Schenk et al., 1980).

Schenk et al. (1980)

Schenk et al. (1980) based their system on the hypothesis that stand susceptibility (and subsequent hazard) is a function of average stand vigor and availability of food. Crown competition factor (CCF) (Krajicek et al., 1961; Wycoff et al., 1982) was used as a measure of competitive stress (vigor), and the proportion of stand basal area made up of lodgepole pine (%BALP) was used as an indication of food availability. The interaction between these variables provides a stand hazard rating index (SHR)

$$\mathrm{SHR} = \mathrm{CCF}\frac{\%\mathrm{BALP}}{100} \qquad (2)$$

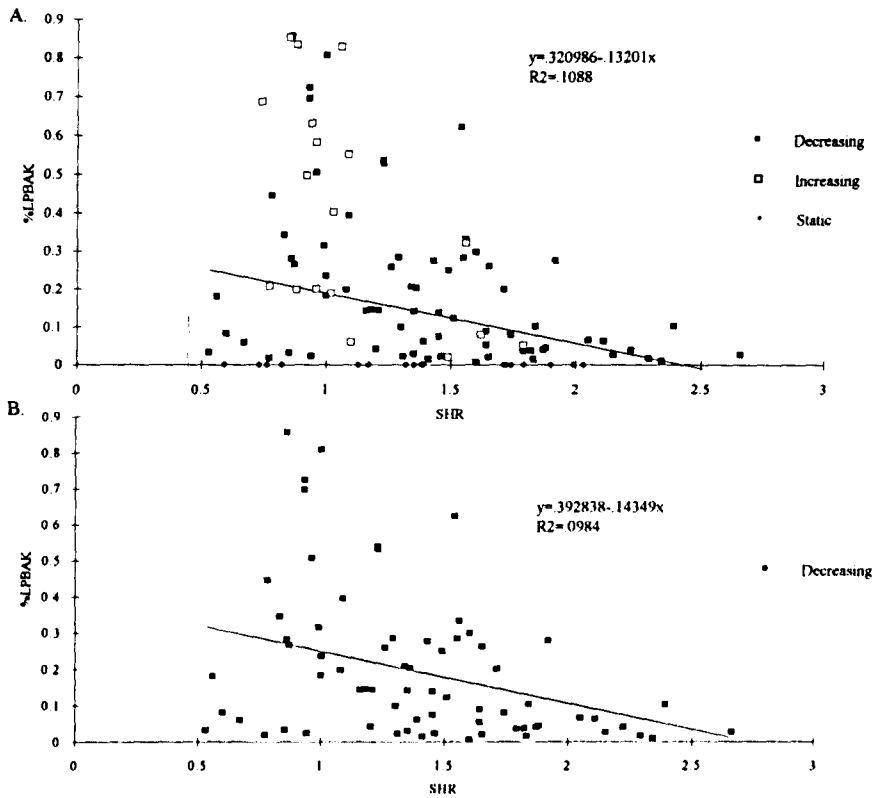

Fig. 3. Observed percentage basal area lodgepole pine killed (%LPBAK) as a function of stand hazard rating (SHR) (Schenk et al., 1980). (A) All population trends (increasing, static, decreasing). (B) Stands with decreasing population trends only.

SHR is an indication of the percentage of the lodgepole pine basal area which will be killed by the beetle (%LPBAK). Although Schenk et al. originally found SHR to increase with increasing CCF and %LPBAK, Shore et al. (1989) and McGregor et al. (1981) observed that SHR was inversely related to %LPBAK, as was CCF. Similar findings were observed in this study (Figs. 2 and 3). Therefore, since the relationship we observed was the opposite of that found by Schenk et al., the regression models they developed were not considered useful for rating stands in this study. As a consequence, we did not test their equations. However, a linear regression revealed a significant relationship between %LPBAK and SHR ($\alpha=0.0001$), but only 10.88% of the variation observed was explained.

Berryman (1978)

Berryman (1978) developed a model for predicting the risk or hazard of an MPB epidemic starting within the stand being evaluated. In this model,

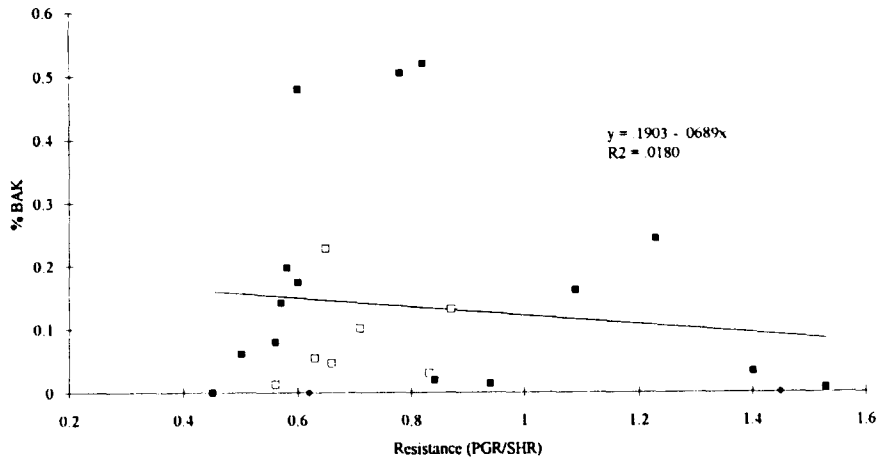

Fig. 4. Observed percentage basal area killed (%BAK) as a function of stand resistance as defined by Berryman (1978).

Berryman proposed that phloem thickness, climatic suitability and host resistance were three variables necessary to describe adequately the interaction between lodgepole pine and MPB. These variables were combined using the ratio of PGR (Eq. (1)) and SHR (Eq. (2)) as a measure of average host resistance, and percentage of the lodgepole pine basal area with a phloem thickness greater than 0.10 in. as a measure of the intensity of the beetle infestation. Of those stands in the validation data set, most had an average phloem thickness of less than 0.10 in. and this variable could not be evaluated. This was perhaps because phloem measurements were made only on surviving trees in a stand and most trees with thick phloem had been killed by the beetle. However, Shore et al. (1989) did not find the percentage of stand basal area with phloem greater than 0.10 in. to be a relevant factor in the model. Based on Berryman's model assumptions, mortality in the stand (%BAK) should decrease with increasing stand resistance. There was a slight trend in this direction, as indicated by a linear regression (slope $= -0.0689$, $R^2 = 0.018$) (Fig. 4). Three stands with high resistance values (1.4 or greater) exhibited less than 10% mortality. However, four stands with low resistance values (0.6 or less) also exhibited less than 10% mortality. All stands with increasing population trends had resistance values between 0.5 and 0.9. Amman (1985) reported that Berryman's method correctly identified susceptibility for two of five stands tested on the Targhee National Forest, although the method rated all stands tested as low susceptibility.

Discussion

None of the systems evaluated here provided adequate estimates of stand susceptibility (measured as percentage lodgepole pine mortality) on the Lolo,

Flathead or Kootenai Forests. If all the systems had overestimated stand mortality, a plausible explanation for the lack of predictability would be that a beetle population simply had not entered a particular stand. Only the Amman system predicted greater mortality than was observed (in two of three classes) (Table 2). Instead, it seems the relationships used in the evaluated systems to describe the MPB–lodgepole pine association are neither inclusive nor fully appropriate. Also, because predictive results from the PGR, CCF and SHR relationships were affected by beetle population trends, stand data used both to develop and evaluate empirically based systems should be an important consideration. In this evaluation, we used data from stands in several MPB population phases (increasing and decreasing) and stands with no infested trees (static). Stuart (1984) used only data from stands in the onset of an outbreak, and Katovich and Lavigne (1985) used data from stands with endemic MPB populations. Ideally, stands used to evaluate a particular system should be in the same beetle population phase as the stand where data were collected to develop the system. This is to aid evaluation as well as biological reality. If an empirical system was developed using data from stands at the end of an outbreak, for example, it would not be appropriate to evaluate the system using mortality measures (e.g. trees per acre (TPA) killed) from stands in which an epidemic was just beginning. Unfortunately, publications describing the original systems evaluated in this study did not always fully describe the data used for system development.

Stands in the final stages of an epidemic (total mortality throughout the outbreak period) were used for development of model relationships in the Schenk et al. (1980) system. When only stands in our data with a declining trend are considered, both CCF and SHR (Eq. (2)) are significantly related to %LPBAK although a very low percentage of the observed variation was explained and the relationship was found to be the opposite of that observed by Schenk et al. (1980). In our data, the majority of stands with increasing population trends had SHR (Eq. (2)) values of between 0.75 and 1.10 (Fig. 3). Conversely, Shrimpton and Thomson (1983) found stands with expanding MPB populations to have SHR values well above 1.0. Perhaps, as suggested by Amman (1985), there is a geographic difference in the applicability of SHR, or Shrimpton and Thomsons' expanding populations and our increasing populations are actually not the same population phase.

The relationship between CCF and the percentage of lodgepole basal area killed (%LPBAK) is similar to that found between lodgepole pine mortality and stand density index (SDI) described by Anhold and Jenkins (1987). Both CCF and SDI are relative measures of stand density which take into account the size of the trees in the stand. CCF is based on the relationship of crown area and dbh of open-grown trees and can be estimated using dbh and the trees per acre represented by each tree (Krajicek et al., 1961; Wycoff et al., 1982). Conversely, SDI is estimated using the average quadratic mean di-

ameter (QMD). Beetle-caused mortality decreased in stands with CCF values of over 200 (Fig. 2; McGregor et al., 1981). Anhold and Jenkins (1987) observed a similar density threshold using SDI, and Amman and Anhold (1989) found a negative correlation between SDI and beetle-caused tree mortality. These observations seem to demonstrate that extremely dense stands, with consequently thinner phloem, are less favorable to MPB populations. Although our data did not include many low density stands (e.g. CCF < 100), Anhold and Jenkins observed that low density stands also had fewer trees attacked per hectare. Therefore, although stand density has consistently been shown to be an important factor associated with MPB populations (Shrimpton, 1978; Berryman, 1982; Mitchell et al., 1983; Amman et al., 1988; Bartos and Amman, 1989), it is not necessarily a linear relationship. Owing to the wide range of infestation levels in our data, attempts to fit a nonlinear distribution were unsuccessful.

The characteristics used in Amman's system provide a good indication of the climatic regions favorable to MPB population growth. However, attributes used in this system do not seem to provide enough detail specific to a particular stand to differentiate between low, moderate, or highly susceptible stands. Because only those stands within the zone of climatic suitability for MPB populations were surveyed, the effect of climate was discounted in this data set, and therefore the applicability of the Amman et al. (1977) system was perhaps not adequately evaluated.

Mahoney's system is based on the assumption that vigorous stands will be resistant to MPB infestations. We feel, however, that this assumption is dependent upon the number of beetles in the area. Stands with high vigor usually have a higher proportion of trees with thicker phloem (Cole, 1973). Because phloem is the food of the developing brood, these stands are favored by beetle populations and provide optimal conditions for increases in population size once an epidemic is initiated (Amman, 1972). Therefore, although endemic populations usually will not start in highly vigorous stands (theoretically with a PGR greater than 0.90), these stand types provide optimal conditions for rapid population growth once the transition to the epidemic population phase occurs in nearby, less vigorous stands. The theory behind Mahoney's system, therefore, seems more applicable to predicting stands with conditions conducive to low level populations of MPB, rather than epidemic populations. When beetle population trends were considered, the PGR method correctly predicted four of the six stands with an increasing trend, split equally between the susceptible and resistant categories (Table 3). Additionally, there are situations where PGR values greater than 0.90 are not necessarily indicative of resistance to MPB attacks. For example, in periods of drought and in stands where MPB mortality has recently occurred (Amman, 1985), PGR values may be more than 0.90. Also, growth in radial increment tends to de-

cline after about 30 years of age (Shrimpton and Thomson, 1981). Therefore, on average, after a tree reaches 30 years of age, the PGR value may be less than 0.90, independent of resistance capability.

The risk and hazard rating systems evaluated in this study were originally developed to use stand characteristics to predict the likelihood of an MPB epidemic. Evaluation of these systems using data from regions other than where they were developed emphasizes that empirically based systems developed using data from a single region will not be robust enough to capture the complexity of the MPB–lodgepole pine relationship over a wider geographic area. Because the relationship between lodgepole pine and the MPB is a complex interaction of both host and beetle population attributes, as well as weather, more than a few site and stand variables will be necessary to describe the association. The likelihood of an MPB epidemic occurring in a stand is dependent not only on tree and site characteristics and the beetle population within the stand being evaluated, but also upon immigrating MPB and conditions within the surrounding stands. A spatial measure of the beetle population in the vicinity and surrounding stand conditions therefore needs to be included in a rating system. This concept has been previously emphasized by others including Paine et al. (1984) and Shore and Safranyik (1992). Because temperature is a significant driver of MPB populations (Safranyik, 1978; Thomson et al., 1983), incorporating the effect of weather patterns, in particular that of temperature, on beetle development may also enhance predictability of MPB population trends (Bentz et al., 1991).

An additional problem identified in this and other studies is the confusion in terminology used in hazard/risk systems. Historically, in MPB research and management, the terms hazard and risk have been used in a variety of ways. Initially, risk was applied to individual trees and hazard to stands or areas (Waters, 1985). More recently, hazard and risk have been used interchangeably, even within the same sentence (e.g. the systems evaluated in this study). One consequence of this is that authors have not been consistent in the meanings attached to the concepts of the rating system developed. A related problem which added further to the lack of consistency and poor predictive value of the systems is that the MPB population phase was not always considered.

Historically, rating systems have clumped together the complexity of MPB population dynamics when, in fact, factors controlling endemic and epidemic population dynamics are different. Stand conditions required for occurrence and maintenance of the endemic population phase are not necessarily the same as the requirements for initiation and spread of the epidemic population phase. Typically, a vigorous host tree is only successfully attacked (killed) if beetle densities are high (Berryman, 1976; Raffa and Berryman, 1980; Cates and Alexander, 1982; Thomson et al., 1983; Gara et al., 1985). At low endemic levels, suitable breeding sites are limited in both space and time to those trees which have been affected by various stress factors, thereby lowering their re-

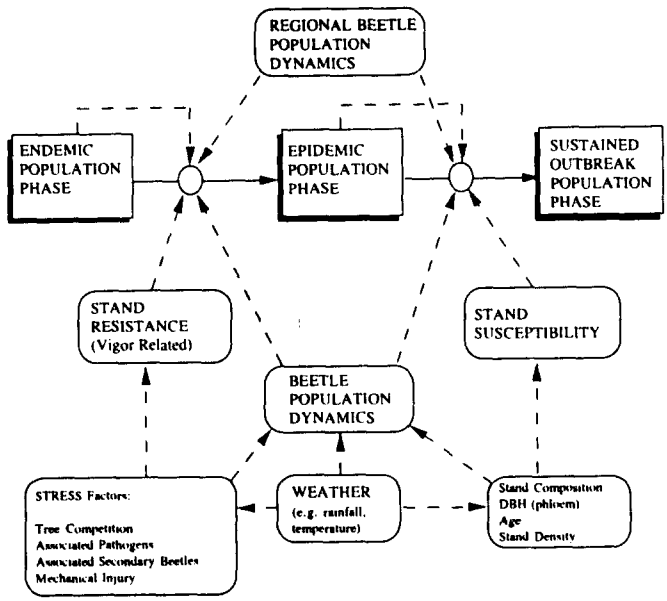

Fig. 5. Components of the dynamic relationship between mountain pine beetle populations and lodgepole pine stands. Two separate phases are important, the endemic and epidemic. The transition from the endemic to epidemic population phase is dependent on vigor related tree resistance factors, whereas stand and site conditions promoting large trees with healthy, thick phloem are more important for sustaining an epidemic phase population. The two transition phases are also dependent on beetle survival, weather, and regional population dynamics. 0 is the transition probability.

sistance (Berryman, 1982; Schmitz, 1988). We consider resistance to be related to the vigor of individual trees, and based on physiological and chemical properties of the trees in a stand, weather, and the occurrence of pathogens and associated secondary bark beetle species. Therefore, although the exact conditions which cause the transition from an endemic to epidemic population are still unclear, we can assume that the probability of transition is affected by factors which enhance, maintain, and favor the endemic level population which is influenced mostly by host resistance factors. Once the population has reached the epidemic level, stand and tree conditions which dictate the growth of the population are typically independent of the resistant capabilities of an individual tree. At this point, epidemic populations are essentially food-limited, and even very resistant host trees can be overcome if beetle numbers are high enough (Safranyik et al., 1975; Amman, 1984). Therefore, the ability of a stand to sustain an epidemic population, leading to the sustained outbreak level, is more dependent upon factors such as stand density, dbh distribution, phloem depth, and age of the trees. The effect of weather on beetle development and stand conditions is important in both transition probabilities. Figure 5, which graphically depicts these concepts,

includes only those factors affecting the transition probabilities which we feel are important for discriminating between the two. Obviously, other factors such as natural enemies are important to the entire MPB–lodgepole pine system.

Conclusions

A risk rating system for the MPB is not intended to be a panacea, but a guideline to help managers in the forest planning process. Risk models are not intended to exactly reproduce the complexity of nature, but to identify and relate key biological features important in the MPB–lodgepole system which may have predictive value. One important relationship that has only recently been considered in MPB risk-rating systems is the spatial nature of both host stands and beetle populations (Shore and Safranyik, 1992). Until a spatial measure of the beetle population is routinely included, the utility of risk rating systems cannot be fully realized nor can they be accurately evaluated. Validation in particular, will continue to be difficult. A stand rated as highly susceptible (based on stand and site characteristics) which has no beetle-caused mortality will consistently be improperly evaluated until it is known whether sufficient beetle numbers have occurred in the area to 'test' the stand. Techniques for sampling and monitoring MPB populations routinely, both aerially and on the ground (e.g. using semiochemical traps), are needed. Additionally, including the effect of microclimate and large-scale weather patterns on beetle development will most likely be of assistance in predicting MPB population behavior in a stand. Risk-rating systems which include spatial relationships at the landscape level will help fulfil a much needed forest-wide perspective.

The manager is interested in predicting whether or not an epidemic beetle population will get into a stand. The hazard systems tested here do not address this problem. Although the concept of predicting timing has plagued bark beetle researchers for decades, current research in the spatial and temporal movement of beetle populations will provide a much needed perspective. As noted by Mawby et al. (1989), consideration of the different phases in bark beetle dynamics is also important when making stand management decisions. There are two distinct phases in the MPB–lodgepole pine system. The concepts important in describing population transition from the endemic to epidemic phase are different from those necessary to measure the ability of a stand to sustain a large outbreak MPB population. Until biological/ecological knowledge concerning the former is unraveled, risk rating systems for the MPB will contribute the most to decision-making if an estimate of stand susceptibility and ensuing risk is provided.

We define susceptibility as the ability of a stand to support an epidemic MPB population. Susceptibility measures are independent of the beetle pop-

ulation level, and include factors relating to stand and site characteristics. Risk, which is the likelihood of an outbreak population occurring in a stand and concomitant loss during a specified period of time, includes a measure of the MPB population within the stand and vicinity, as well as susceptibility. Stand resistance factors, which are related to the vigor of individual trees and are important in describing the transition from the endemic to epidemic population, will also be useful for determining stand risk as more information becomes available regarding the endemic population phase.

With the recent advances in computerized technologies, a risk-rating system which includes the complexity inherent in the MPB–lodgepole pine relationship is feasible. We should no longer be limited to systems such as those evaluated in this study which are based on a few stand characteristics. As has been shown, these types of systems are not capable of adequately describing the diversity of interactions between MPB populations and their hosts. Owing to differences in regulating influences on endemic and epidemic populations, models for rating stands should be contingent upon the population phase of interest. Lastly, it is important that individuals working in both management and research retain consistent terminology relating to MPB prediction and loss assessment. Historically this has not been true. To avoid confusion with past traits, we propose that the term hazard be dropped from use and replaced with the terms susceptibility, resistance, and risk as they have been defined here.

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