PRELIMINARY EVALUATION OF HAZARD AND RISK RATING VARIABLES FOR MOUNTAIN PINE BEETLE INFESTATIONS IN LODGEPOLE PINE STANDS

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ABSTRACT: Difficulty in deciding on the most appropriate from among the many methods available for assessing lodgepole pine stand hazard and risk to mountain pine beetle infestation prompted an evaluation of these methods as part of the Canada/United States Mountain Pine Beetle Program. As a first step, some of the variables used in hazard and risk rating methods were analyzed by multiple regression to determine those with which the percent tree mortality was most closely correlated. These variables were found to differ by geographic area. Preliminary results suggest that best results in predicting hazard or risk will be achieved on an individual stand basis, and that tree size (positively related to tree mortality) and stand density (negatively related to tree mortality) will be important variables in any hazard or risk rating system.

INTRODUCTION

Hazard and risk rating methods to assess infestation potential of mountain pine beetle (MPB) (Dendroctonus ponderosae Hopkins) in lodgepole pine (Pinus contorta Douglas) stands are important tools to help deal with the MPB problem. These methods are designed to help land managers identify stands in which MPB epidemics are most likely to erupt and how much loss of timber is likely to occur.

There are many hazard and risk rating methods for assessing mountain pine beetle infestations in lodgepole pine stands. This profusion of methods is confusing--users are uncertain which should be used. Few have been adequately tested in the geographic area where they were developed, much less in other geographic areas. Therefore, as part of the Canada/United States Mountain Pine Beetle Program, a test of the various hazard and risk rating methods was undertaken over the range of mountain pine beetle distribution in lodgepole pine. We report some preliminary results for the western United States. Terry Shore (these proceedings) reported those for western Canada.

The objectives were to determine (1) which of the hazard and risk rating methods does the best job for a given geographic area, and (2) if a different set of parameters would do a better job of predicting hazard and risk than those now in use. The objective of this paper is to examine factors that were most closely associated with lodgepole pine mortality caused by MPB. The objective of determining how well the various hazard and risk rating methods performed cannot be fully assessed until sampled stands are revisited and total tree mortality determined.

RISK AND HAZARD

The terms "hazard" and "risk" are often used synonymously. However, we will follow the definitions given by Waters (1985):

> "Hazard is determined by tree, stand, site, and climatic factors that basically influence the probabilities of tree mortality. For individual trees, this means tree qualities or characteristics that affect the likelihood of successful beetle attack, for example, age or size, vigor, location. For a stand or area, it refers to factors affecting the likelihood of an outbreak occurring in that stand or area, for example, species composition, age-size structure, density, soil type, precipitation, disturbance--or more gross measures such as habitat type, elevation, or landform.
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> "Risk, on the other hand, is a function of beetle abundance and distribution. Regardless of inherent hazard, a significant number of beetles must be in the general proximity for tree mortality to occur. Thus, a high hazard tree or stand may exist for years--to harvest, perhaps--without being infested. Conversely, a low hazard tree or stand may be considered at high risk--and successfully attacked--if within the area of an ongoing outbreak."

Hazard to MPB infestation has been related to a number of tree, stand, site, and climatic factors. These differ by geographic area and include the following: tree age and d.b.h.; latitude and elevation (Amman and others 1977); tree d.b.h.; culmination of current and mean annual increment and weather (Safranyik and others 1974); periodic

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growth ratio (PGR)--current 5 years' radial growth divided by the previous 5 years' radial growth (Mahoney 1978); crown competition factor and percent lodgepole in a stand (SHR) (Schenk and others 1980); PGR divided by SHR and the percent basal area containing phloem 0.1 inch or thicker (Berryman 1978); quadratic mean diameter and number of growth rings in the last centimeter of radial growth (Stuart 1984); stand density index (SDI) (Anhold and Jenkins 1987); habitat type (Cole and McGregor 1983; McGregor 1978; Roe and Amman 1970); and growth efficiency (Waring and Pitman 1980; Waring and others 1980)--grams of stem wood produced per square meter of foliage, using sapwood area as a predictor of foliage area.

The resinous response of trees to inoculation of blue-staining fungi (Ceratocystis clavigera [Robinson-Jeffrey and Davidson] Upadhyay) (Raffa and Berryman 1982; Shrimpton 1973) also has been used as a measure of tree susceptibility to MPB infestation. Those trees having the greatest resinous response were considered least likely to be infested by MPB. However, in a field test of the method the tree response to fungal inoculation did not distinguish between susceptible and nonsusceptible trees to MPB infestation (Peterman 1977). The fungal inoculation method was not included in this test because it is quite time consuming.

Regardless of which hazard factors are used, beetle population size (risk) plays a very important role. An illustration of risk was given by Nebeker and Hodges (1983). In this illustration, trees with different abilities to withstand beetle infestation become susceptible to infestation, based on size of the beetle population. Until MPB infest trees suitable for good brood production--that is, trees of large diameter and thick phloem--an epidemic cannot start. Therefore, stands of lodgepole may contain all the elements for an epidemic of MPB, but because beetle numbers are low, an epidemic does not occur. When numbers are large, no tree is likely to be resistant to successful infestation.

Schmitz (in press) observed that during the endemic phase few MPB are present and are usually found in association with secondary bark beetles. These secondary bark beetles usually infest suppressed sapling or pole-size trees that are well below average in growth, have thin phloem, and are often partially girdled by porcupines. However, during an epidemic, the associates infest the tops of limbs of larger diameter trees killed by MPB the previous year. The secondary species usually overwinter in the adult stage in litter on the forest floor. They emerge during spring and infest trees soon after the snow melts. In contrast, the MPB emerge from late June to early September, depending on location. At endemic levels, only a few MPB emerge on any one day. Unless the time required to locate suitable trees to infest is minimized, a large proportion of such sparse populations is likely to succumb during dispersal. By utilizing trees already infested by other secondary scolytids, MPB dispersal losses are reduced. However, selection of trees that are already infested by secondary scolytids results in low MPB production because of small tree size, thin phloem, and infestation of only the basal 1 or 2 feet of the trunk. This behavior assures the MPB population will remain at a low level until the stand matures and beetles infest larger trees having thick phloem that will support high survival rates necessary for an outbreak.

METHODS

Several hundred stands of lodgepole were measured in the western United States. These were limited to the lower elevational levels where stands would be climatically susceptible to MPB infestation, thus making methods more directly comparable, since some have a climatic variable (Amman and others 1977; Safranyik and others 1974), where others do not. Outbreaks are not as likely to occur in the moderate to low areas of climatic suitability, and much of the loss occurring in these hazard zones is the result of beetles emigrating from high-hazard stands at lower elevations.

Stands were selected at random from suitable candidate stands within the zone of climatic suitability for MPB, using a table of random numbers. Stands ranged in infestation history from no recent infestation to those that had just completed an outbreak. Stands that had recently (within the past 10 years) been disturbed by human activity or wind were avoided. Stands that had other species present were sampled, as long as they had 75 percent or more lodgepole pine.

Each stand was sampled, using a 10-BAF variable plot cruising method. Ten plots located 5 chains apart on two lines located 5 chains apart (five plots per line) were used in each stand. However, in the case of odd-shaped stands, plots were located in any pattern that maintained spacing. The following data were recorded for each plot: (1) elevation; (2) habitat type; (3) slope; (4) aspect; (5) diameter at breast height (5 inches and larger) and species of tree; (6) alive or dead; (7) year tree killed (current year: tree green, fresh beetle attacks; 1 year old: most foliage retained and bright orange; 2 years old: one half or more foliage retained and dark brownish orange; older than 2 years); (8) pitch-outs and strip attacks; (9) other insect, disease, or mechanical injury; (10) two increment cores 180 degrees apart; (11) from each bored tree: height, crown length, crown class, sapwood depth, phloem thickness (green trees only); and (12) stand stocking.

Multiple regression analysis was used to determine which variable or set of stand variables best predicted lodgepole pine losses to MPB by broad geographic area. Only variables with F probability of 0.15 or less were considered. Variables included in the regression were: (1) basal area, (2) trees per acre, (3) quadratic mean diameter, (4) stand density index, (5) phloem thickness, (6) basal area of trees having phloem $\geq$ 0.10 inch, (7) age, (8) radial growth during last 5 years, (9) radial growth during previous 5 years, (10) sapwood thickness, (11) number of growth rings in last centimeter, (12) grams of wood per square meter of foliage in killed trees, (13) grams of wood per square meter of foliage in uninfested trees, (14) elevation, and (15) latitude. Stands that had no mortality attributable to MPB were excluded from the analyses. Additionally, seven stands were selected for multiple regression (maximum R^2 procedure) of within-stand factors. However, because of the small sample of increment cores per plot, reliable estimates for variables related to tree growth could not be calculated for individual plots. The dependent variable used was percent of trees killed by MPB. Independent variables were: (1) measures of density, consisting of trees per acre (TPA), basal area (BA), and stand density index (SDI); and (2) measures of tree size, consisting of average diameter for trees $\geq$ 5 inches d.b.h. (AVGD), quadratic mean diameter for trees $\geq$ 5 inches d.b.h. (QMD), and percent of lodgepole 5 to 6.9 inches d.b.h. (%5-6.9). The seven stands were selected on the basis that (1) the current MPB infestation was almost completed, as indicated by current MPB activity, and (2) each stand was in a different National Forest.

GEOGRAPHICAL DIFFERENCES

One of the main objectives of a test of hazard rating methods was to determine if there were strong geographical influences. Stepwise multiple regression was used to determine which variables were most clearly associated with percent cumulative tree mortality by area--Central Rockies, Northern Rockies, and Pacific Northwest. The Central Rockies included the Gallatin National Forest and all National Forests south to Colorado. The Northern Rockies included all remaining National Forests in Montana, northern Idaho, and eastern Washington. The Pacific Northwest includ-ed the remaining National Forests in Washington and all National Forests in Oregon. In the stepwise procedure, variables that were not significant at the 0.15 level were excluded.

In the Central Rockies, the stepwise procedure showed cumulative lodgepole pine mortality was significantly related to two variables, latitude (F probability 0.016) and trees per acre (F probability 0.069). Cumulative mortality was negatively related to both of these factors. The negative relationship to latitude suggests decreased mortality occurs going north from Colorado to southern Montana. The decrease in mortality as latitude increases is probably an artifact related to when beetle infestations occurred. More recent MPB outbreaks have occurred in parts of Colorado and in northeastern Utah, whereas MPB populations farther to the north in the Central Rockies have been low for many years, following earlier outbreaks in the 1960's and 1970's. Past observations show tree mortality was high in the Bridger-Teton, Targhee, and Gallatin National Forests (Amman and Baker 1972; McGregor 1978). Most of these dead trees have been harvested or have fallen down. Therefore, we consider the relationship of less mortality with increased latitude within the Central Rockies to be false. The inverse relationship of mortality with trees per acre is consistent with past observations (Amman 1978), where heaviest tree losses occurred in less dense stands that contained a high percentage of large-diameter trees.

The stepwise procedure for data from the Northern Rockies also showed two variables having F probabilities less than 0.15--phloem thickness ($F = 0.077$) and stand density index ($F = 0.097$). Both were inversely related to cumulative tree mortality. Phloem thickness has in the past been related positively with MPB brood production (Amman 1972). However, once the MPB in the Northern Rockies build up to large numbers, they appear to overwhelm most trees. In many stands, the few remaining live trees on which to measure phloem are usually small-diameter trees that have thin phloem. The inverse relationship of cumulative mortality to SDI is consistent with the findings of Anhold and Jenkins (1987) and with increased mortality as trees per acre decline, as noted for the Central Rockies. Anhold and Jenkins (1987) found generally that mortality was greatest at SDI values between 125 and 250, having losses up to 90 percent at SDI 150. Tree losses in stands having SDI values of 90 to 125 were up to 20 percent. An SDI of 125 corresponds to crown closure, and an SDI of 250 corresponds to the beginning of full site occupancy (McCarter and Long 1986). Anhold and Jenkins (1987) suggested that trees in stands with an SDI above 250, even though of large diameter, would have thinner phloem and thus have less potential for producing beetles. Stands having SDI values below 125 could produce more resin to repel beetle attacks. Recent observations of tree vigor and microclimate in thinned and unthinned lodgepole stands suggest that microclimate plays an important role in reduced infestation of lightly stocked stands (Amman and others 1988; Bartos and Amman 1989).

In the Pacific Northwest, as in the other geographic areas, only two variables had F probabilities less than 0.15--grams of wood per square meter of foliage in killed trees ($P < 0.112$) and elevation ($P < 0.038$). Cumulative tree mortality was positively related to grams of wood. Increased tree mortality, with an increase in grams of stem wood produced per square meter of foliage, is opposite of observations by Waring and Pitman (1980) in Oregon. Therefore, additional work, particularly within stands, needs to be done to verify the relationship of grams of stem wood to tree mortality. Trees producing high wood-to-foliage ratios were just as likely to be infested as those producing lower wood-to-foliage ratios in the Central (Amman 1985) and Northern Rockies (Amman and others 1988). The inverse relationship of tree mortality to elevation is consistent with observations in southeastern Idaho and northwestern Wyoming (Amman and Baker 1972), and in northern Utah (Amman and others 1973). As elevation increases, weather is generally cooler and the MPB life cycle becomes delayed and out of synchrony with weather conditions for best brood survival (Amman 1973; Reid 1962).

WITHIN-STAND DIFFERENCES

When analyzing data obtained over a large geographic area, unexplained variance tends to be large. Therefore, the seven selected stands were analyzed to determine which of six variables explained the largest amount of variance in cumulative tree mortality within each stand.

The variable accounting for the greatest amount of variance in the percent of lodgepole pine mortality differed by stand. Measures of density were strongest in three of the stands--TPA in one, BA in one, and SDI in one. Measures of tree diameter were strongest in four stands--percent of trees 5 to 6.9 inches d.b.h. in one, QMD in two, and AVGD in one. The largest amount of variance explained by the regressions of individual factors within individual stands ranged between 9.4 and 68.6 percent (table 1). In multivariable models, variance explained in two variable models ranged between 34.5 and 79.9 percent; three-variable models ranged between 44.8 and 84.3 percent; four variable models ranged between 45.3 and 86.7 percent; five-variable models ranged between 60.5 and 95.4 percent, and six-variable models between 59.3 and 96.8 percent (table 2).

Going from the broad areas (Pacific Northwest, Northern Rockies, and Central Rockies) to the individual stand, much of the variance associated with the broad areas is eliminated and a much better prediction of mortality can be obtained. Tree size (QMD and AVGD) was positively correlated with tree mortality in five of the seven stands. This is consistent with observations that MPB show preference for lodgepole of large diameter (Cole and Amman 1969; Hopping and Beall 1948). These are the trees in which reproductive success is best (Amman 1969; Cole and others 1976; Reid 1963), probably because of generally thicker phloem, the food of developing larvae (Amman 1972), and greater moisture retention during beetle development (Cole and others 1976). Stand density (BA, TPA, SDI) was negatively correlated to tree mortality in five of the seven stands and always opposed (negative or positive) correlations with tree size. As basal area and SDI increase, tree competition increases and phloem thickness declines, thus beetle production declines. This is consistent with Anhold and Jenkins (1987), except at SDI values below 100, where high mortality occurred in our observations. Although SDI is made up of tree size and stand density, it often appears as a significant variable with BA and QMD. The percent of trees 5 to 6.9 inches d.b.h. is that portion of the stand that is not very susceptible to beetle infestation. Tree mortality was negatively correlated with trees 5 to 6.9 inches d.b.h. in five of the seven stands. Of the two positive correlations, one occurred when mortality was negatively correlated with stand density but positively correlated with tree size, and the second occurred under opposite conditions. When trees are infested in these diameters, few beetles are produced, on the average, resulting in a population deficit.

Although there are additional factors that will be explored for use in predicting lodgepole pine mortality when stands have been revisited and radial growth measures completed, these analyses suggest that a good combination may consist of a measure of (1) tree size (QMD), (2) stand density (BA), (3) percent of trees 5 to 6.9 inches d.b.h., and (4) an SDI that integrates tree size and stand density.

Terry Shore (these proceedings) has already progressed into assessing the performance of individual hazard rating methods in British Columbia. The next step in hazard rating analyses in western United States is to revisit plots to record any additional mortality and then test all existing methods and any new combinations, such as those in this paper. Until these tests are completed, managers should feel safe in using lodgepole pine diameter and a measure of climatic suitability to assess stand susceptibility to MPB (Amman and others 1977; Cole and McGregor 1983; Safranyik and others 1974).

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Table 1--Proportion of variance in percent tree mortality caused by mountain pine beetle (dependent variable) explained by different combinations of tree and stand factors

	National Forest							
Independent variable	Flathead	Lolo	Colville	Kootenai	Deschutes	Freemont	Winema	Forests combined
<u>One-variable model</u>:								
Trees per acre	0.438	0.266	0.018	0.183	0.071	0.023	0.369	0.0064
Basal area	0.061	0.223	0.094	0.066	0.008	0.001	0.454	0.00001
Stand density index	0.171	0.237	0.070	0.100	0.021	0.002	0.501	0.0003
Percent trees 5-6.9 inches DBH	0.534	0.061	0.054	0.299	0.111	0.289	0.001	0.058
Quadratic mean DBH	0.223	0.011	0.006	0.331	0.686	0.005	0.245	0.077
Average DBH	0.243	0.004	0.016	0.330	0.674	0.012	0.170	0.082

Table 2--The best one- to six-variable models based on maximum R^2 procedures

Number of variables	National Forest															
	Flathead		Lolo		Colville		Kootenai		Deschutes		Freemont		Winema		Forests combined	
	Model	R^2	Model	R^2	Model	R^2	Model	R^2	Model	R^2	Model	R^2	Model	R^2	Model	R^2
1	[1]%5-6	0.534	TPA	0.266	BA	0.094	QMD	0.331	QMD	0.686	%5-6	0.289	SDI	0.501	AVGD	0.082
2	[2]%5-6 BA	0.652	TPA %5-6	0.365	BA SDI	0.345	QMD %5-6	0.423	QMD TPA	0.799	%5-6 AVGD	0.540	BA AVGD	0.534	AVGD TPA	0.098
3	%5-6 SDI TPA	0.722	%5-6 TPA QMD	0.518	BA SDI %5-6	0.672	%5-6 QMD AVGD	0.448	AVGD %5-6 SDI	0.843	%5-6 AVGD QMD	0.626	QMD BA SDI	0.555	AVGD SDI BA	0.126
4	%5-6 TPA SDI BA	0.749	BA %5-6 QMD AVGD	0.529	AVGD QMD BA SDI	0.829	%5-6 QMD AVGD TPA	0.453	%5-6 BA AVGD QMD	0.867	%5-6 AVGD QMD TPA	0.647	QMD BA SDI TPA	0.582	AVGD BA SDI TPA	0.152
5	SDI BA QMD AVGD TPA	0.871	TPA SDI BA AVGD %5-6	0.954	AVGD QMD BA SDI TPA	0.908	%5-6 BA SDI TPA AVGD	0.566	TPA SDI BA AVGD QMD	0.886	%5-6 AVGD QMD SDI BA	0.651	AVGD BA SDI TPA %5-6	0.605	BA SDI TPA AVGD QMD	0.152
6	QMD AVGD BA SDI TPA %5-6	0.871	BA SDI TPA AVGD %5-6 QMD	0.968	AVGD QMD BA SDI TPA %5-6	0.924	%5-6 TPA SDI BA AVGD QMD	0.593	AVGD BA QMD TPA SDI %5-6	0.910	%5-6 AVGD QMD BA SDI TPA	0.655	BA SDI TPA AVGD %5-6 QMD	0.613	BA SDI TPA AVGD QMD %5-6	0.152

[1]Abbreviations stand for the following: %5-6 = percent of lodgepole in the 5 to 6.9-inch d.b.h. class; TPA = number of trees per acre; BA = square feet of basal area, all tree species; SDI = stand density index; QMD = quadratic mean d.b.h. of all lodgepole; AVGD = average d.b.h. of all lodgepole 5 inches and larger d.b.h.

[2]Variables in multivariable models are listed from most to least significant.

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