Hazard rating of lodgepole pine stands to mountain pine beetle outbreaks in southcentral Oregon

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Stand structure and vigor variables were used to develop a model for predicting the development of a *Dendroctonus ponderosae* Hopk. outbreak in climax *Pinus contorta* Dougl. ex Loud. var. *murrayana* Grev. and Balf. stands in south central Oregon. Stepwise discriminant analysis indicated the significant predictor variables were quadratic mean diameter and the number of rings in the outermost centimetre of radial growth at breast height ($p = 0.00001$, canonical correlation coefficient $= 0.77235$). Ninety-three percent of the stands were correctly classified into their appropriate groups (attacked versus unattacked). None of the five indices of competition tested ((*i*) Waring and Pitman's tree vigor index, (*ii*) Mahoney's periodic growth ratio, (*iii*) Krajicek's crown competition factor, (*iv*) Hegyi's competition index, and (*v*) Curtis's stand density index) were significant discriminators.

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La structure du peuplement et des variables de vigueur ont été utilisées pour la mise au point d'un modèle prédisant le développement d'une épidémie de *Dendroctonus ponderosae* Hopk. dans les peuplements climaciques de *Pinus contorta* Dougl. ex Loud. var. *murrayana* Grev. and Balf. du centre sud de l'Oregon. L'analyse discriminante par étape a indiqué que les variables de prédiction significatives étaient la moyenne quadratique en diamètre et le nombre d'anneaux dans le centimètre externe de la croissance radiale à hauteur de poitrine ($p = 0{,}00001$, coefficient de corrélation canonique $= 0{,}77235$). Quatre-vingt-treize pourcent des peuplements ont été correctement classés dans leurs groupes appropriés (attaqués versus non attaqués). Aucun des cinq indices de compétition évalués ((*i*) indice de vigueur de l'arbre de Waring et Pitman, (*ii*) rapport de croissance périodique de Mahoney, (*iii*) facteur de compétition de cime de Krajicek, (*iv*) indice de compétition de Hegyi, (*v*) indice de densité de peuplement de Curtis) n'avait un pouvoir discriminant significatif.

[Traduit par le journal]

Introduction

Researchers have developed a variety of hazard rating schemes designed to predict if mountain pine beetle (*Dendroctonus ponderosae* Hopk.) (MPB) outbreaks may occur in lodgepole pine (*Pinus contorta* Dougl. ex Loud.) forests. Most hazard rating schemes were developed for *Pinus contorta* var. *latifolia* and are yet untested for *P. contorta* var. *murrayana* stands. The simplest system plots historical infestations on a map from which land managers can determine areas prone to MPB attack (Crookston *et al.* 1977). Other hazard rating systems have been based on the following parameters: climate (Safranyik 1978); tree age, diameter, and climatic zone (Shrimpton 1975; Safranyik *et al.* 1975); habitat types, tree diameter, and elevation (Roe and Amman 1970; McGregor 1978); phloem thickness and diameter (Cole 1978; Cole and Cahill 1976); periodic growth ratio (Mahoney 1978); crown competition factor (Schenk *et al.* 1980); tree vigor (Waring and Pitman 1980); and phloem thickness, tree vigor, and MPB population dynamics (Berryman 1982). Cole and Amman (1980) developed an integrative hazard rating system with the following variables: (*i*) climatic suitability of stand location; (*ii*) average tree diameter 20.5 cm or more; (*iii*) average age 80 years or more; (*iv*) 25% or more of the trees have a diameter at breast height of 20.5 cm or more and a phloem thickness of 2.79 mm or more; (*v*) high crown competition factors and declining periodic growth ratios in some western Montana and northwest Idaho habitat types.

The study described in this paper was made to determine which stand structure variables and (or) hazard rating indices could be used to predict if a MPB outbreak would occur in the study area. Two types of indices were included: (*a*) those used in previous MPB hazard ratings in lodgepole pine forests, and (*b*) those adapted from competition indices used in tree and stand growth simulation. The latter index type was included since competition has been linked to declining tree vigor and a weakening of host defenses (Rudinsky 1962; Schenk *et al.* 1980; Berryman 1982). Two indices based on tree size – density relationships were chosen as examples of this type. The study was limited to the onset of an outbreak. Once an outbreak had started it was felt the predictive value of the stand structure variables and hazard rating indices would be lessened because of confounding effects of MPB population dynamics.

Methods

Study area

The study was conducted in the summer of 1982, in unlogged climax lodgepole pine stands growing at 1800 m elevation near Wickiup Springs on the Fremont National Forest, Oregon. Soils are relatively infertile, well drained, loamy sands, developed from Mount Mazama eolian ash and pumice. The climate during the growing season is characterized by warm, dry days and cold nights. Summer temperatures range from lows of −7°C at night to highs of 41°C during the day. Yearly precipitation ranges from 38–76 cm, with most falling as snow from November through April (Wenzel 1979).

Infestation history

Lodgepole pine forests in south central Oregon have experienced recurring mountain pine beetle outbreaks. Stuart *et al.* (1983) established that outbreaks occurred in climax lodgepole pine stands on the northern portion of the Fremont National Forest in the late 1820's to

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TABLE 1. Year of mountain pine beetle (MPB) outbreak, number of paired plots per outbreak year, density of mountain pine beetle killed trees in outbreak stands, and approximate year of lodgepole pine establishment for sampling sites located near Wickiup Springs, Fremont National Forest, OR

Year of MPB outbreak	Number of paired plots (group 1 + group 2)	Number of MPB-killed trees per group 2 plot	Approximate year of tree establishment
1967	1	5	1899
1968	2	8, 5	1899, 1840
1970	1	4	1750
1972	3	5, 4, 4	1840, 1840, 1840
1973	7	6, 2, 4, 4, 6, 4, 4	1840, 1840, 1750, 1840, 1750, 1840, 1840
1981	1	5	1899

1840's, the 1920's, and from the late 1960's to present. Stuart (1983) suggests that there may have been outbreaks in these stands in ca. 1620 and in ca. 1750. Fires occurred in 1840 and 1899 (Stuart 1983).

The most recent MPB outbreak was first reported in 1956 approximately 10 km south (latitude 43°15′N, longitude 121°22′W) of the study site and encompassed 80 ha. The outbreak area slowly increased northward, peaked in 1968, and covered approximately 75 000 ha (Dolph 1972). By 1981 all of the study area had been affected. Tree mortality was ubiquitous. However, interspersed among the stands which experienced tree mortality were smaller stands having no MPB-killed trees. The intimate mosaic pattern of stands which had outbreaks with those that did not have outbreaks suggests both kinds of stands had an equal opportunity to experience an outbreak.

Study design

The study was located in climax lodgepole pine stands in the general vicinity of Wickiup Springs and Bald Mountain. Sampling sites were located such that plots could be established in stands that (1) escaped an outbreak (group 1), and (2) those that experienced an outbreak (group 2). Paired plots in adjacent stands were used so that tree and stand parameters could be corrected to the year prior to an outbreak (Table 1). All trees in group 2 stands were killed in the same year. Average tree age was identical for each pair of plots, although tree ages differed among sampling sites (83–232 years) (Table 1). Group 1 stands were relatively scarce and were, therefore, used to define the location of sampling sites. Fifteen group 1 stands were identified along United States Forest Service roads 2516 and 256.

After locating the sampling sites, plot centers were randomly located. Data collected from the 15 paired circular 0.01-ha plots (15 group 1 and 15 group 2 plots) included the following: (*i*) the DBHs, to the nearest 0.5 cm, of all trees greater than or equal to 2 cm DBH; (*ii*) MPB-induced tree mortality; (*iii*) the sapwood thicknesses of the five largest trees, determined by measuring the widths of the translucence or the widths of blue stain of increment core samples; (*iv*) information required to calculate Hegyi's index of competition (Daniels 1976), i.e., (*a*) the number of competitors per subject tree; (*b*) the distance, to the nearest centimetre, from the subject tree to each competitor; (*c*) the DBHs, to the nearest 0.5 cm, of subject trees and their competitors. The subject trees were the five largest in each plot. The competitors of each subject tree were those "in" trees found by sighting through a metric wedge prism (basal area factor (BAF) of 2.3) from a point as close to the subject tree as possible.

In addition, increment cores were extracted from the subject trees for growth analysis. In the laboratory the cores were sanded to a polish and cross-dated under a microscope to determine when MPBs had been active in the vicinity of the plot. The number of rings, rings per centimetre, and measurements of annual growth were made for those years immediately prior to when MPBs were present. Ring widths were measured on a Bannister incremental measuring machine.

The hazard rating indices used in the analysis were as follows: (*i*) Waring and Pitman's tree vigor index (V) (Waring and Pitman 1980; Mitchell *et al.* 1983); (*ii*) Mahoney's periodic growth ratio (PGR) (Mahoney 1978); (*iii*) Krajicek's crown competition factor (CCF) (Krajicek *et al.* 1961); for lodgepole pine in south-central Oregon Dahms (1971) modified Krajicek's model to:

$$[1]\quad \mathrm{CCF} = 1/A0.0192(n) + 0.0168 \sum_{i=1}^{n} (D) + 0.0036 \sum_{i=1}^{n} (D^2)$$

where A = plot area in acres, n = the number of trees, and D = diameter outside bark. (*iv*) Hegyi's competition index (HEGYI) (Daniels 1976); Daniels proposed a modification of Hegyi's index which would select competitors based on their size and distance from the subject tree; he found that an angle guage with a BAF of 2.3 gave the highest correlations between observed diameter increment and observed total height increment with the calculated competition index value; (*v*) Curtis's stand density index (SDI) (Curtis 1982).

The stand structure variables used in the analysis were as follows: (*vi*) quadratic mean diameter (QUADMN); (*vii*) stand density (DENSITY); (*viii*) mean diameter of the five largest trees in the plot (DBH); (*ix*) mean number of rings in the outermost centimetre of radial growth at breast height for the five largest trees per plot (RINGCM); (*x*) mean number of competitors per plot using Hegyi's index (NUMCOM); (*xi*) basal area per plot (BA); (*xii*) mean basal area of the five largest trees per plot (TREEBA); (*xiii*) mean diameter of all trees in the plot (AVGDBH); (*xiv*) basal area percentage (BAPRCNT), where basal area percentage equals the mean increase in basal area over the past 10 years' growth as a percentage of the basal area for the five largest trees in a plot.

Differences between group means for each variable were determined with 2-tailed *t*-tests.

A discriminant analysis approach was used to develop a stand hazard rating model which would predict, within certain bounds of probability, whether a climax lodgepole pine stand would be susceptible to a MPB outbreak. It was hypothesized that a combination of stand structure characteristics and some hazard rating indices would be significant predictors. The two group discriminant analyses were run using SPSS (Statistical Package for the Social Sciences) procedures (Nie *et al.* 1975). All analyses were done stepwise, with the possibility of entering and removing variables at each step. Some analyses were run in which each of the five indices of competition were "forced in" and could not be removed. The objective was to determine what the relative contribution of these indices would be once all significant variables had been entered.

Results and discussion

Five hazard rating indices and the nine stand structure variables were entered into a correlation analysis to determine which variables would be best to use in the discriminant analysis. From inspection of the pooled within-groups correlation matrix (Table 2), it was judged that four of the stand structure variables (DBH, AVGDBH, TREEBA, and BA) should be removed from subsequent analyses because of their high correlations with other variables: DBH, AVGDBH, and TREEBA with QUADMN; and BA with CCF. Quadratic mean diameter

TABLE 2. Pooled within-group correlation matrix of stand structure and vigor variables used in analysis to assess mountain pine beetle outbreak hazard in climax lodgepole pine stands near Wickiup Springs, Fremont National Forest, OR[a]

	DBH	RINGCM	NUMCOM	HEGYI	DENSITY	BA	TREEBA	PGR	CCF	QUADMN	SDI	BAPRCNT	AVGDBH	V
DBH	1.00000													
RINGCM	−0.33633	1.00000												
NUMCOM	−0.16032	0.03193	1.00000											
HEGYI	−0.56556	0.12515	0.76133	1.00000										
DENSITY	−0.38044	−0.00061	0.54870	0.63047	1.00000									
BA	0.46274	−0.27464	0.61985	0.32447	0.49148	1.00000								
TREEBA	0.97945	−0.35785	−0.22098	−0.54434	−0.37379	0.44523	1.00000							
PGR	0.03604	−0.07893	−0.26069	−0.22247	−0.13753	−0.12489	0.06457	1.00000						
CCF	0.30993	−0.29433	0.66026	0.39325	0.64006	0.98057	0.29277	−0.16463	1.00000					
QUADMN	0.81975	−0.28599	−0.27720	−0.56616	−0.63778	0.19884	0.82541	−0.05687	0.06026	1.00000				
SDI	0.13843	−0.13457	0.71869	0.56064	0.73541	0.91997	0.11743	−0.13074	0.91341	−0.16834	1.00000			
BAPRCNT	−0.26892	−0.55239	−0.20150	0.12554	−0.07984	−0.25334	−0.18019	0.12512	−0.17688	−0.07178	−0.26629	1.00000		
AVGDBH	0.78358	−0.19762	−0.17718	−0.45930	−0.60295	0.25827	0.77938	−0.08154	0.08901	0.97505	−0.07503	−0.15042	1.00000	
V	0.02037	−0.45033	−0.27682	−0.07121	−0.14509	−0.10934	0.11665	0.57413	−0.12332	−0.00020	−0.15918	0.69231	−0.07408	1.00000

[a]See Methods section for variable descriptions.

TABLE 3. Means of variables used in analysis to assess mountain pine beetle (MPB) outbreak hazard in climax lodgepole pine stands near Wickiup Springs, Fremont National Forest, OR (group 1, stands not attacked by MPBs; group 2, stands attacked by MPBs)

Group No.	Group means													
	DBH**	RINGCM**	NUMCOM	HEGYI*	DENSITY**	BA	TREEBA**	PGR	CCF	QUADMN**	SDI	BAPRCNT**	AVGDBH**	V**
1	20.45333	21.57333	10.84000	3.28027	27.63333	3555.64067	345.33404	0.93014	217.96355	13.75936	3.20972	9.95243	12.66723	30.22736
2	24.87333	27.22667	10.14667	2.59827	12.33333	3598.65133	511.60531	0.89564	205.73965	20.08135	2.71571	6.84259	18.67978	22.87541
Total	22.86333	24.40000	10.49333	2.93027	19.93333	3576.14600	428.46968	0.91280	211.85160	16.92036	2.96271	8.29750	15.67350	26.55139

NOTE: See Methods section for variable descriptions. *, 5% significance level; **, 1% significance level.

TABLE 4. Discriminant function classification coefficients used in analysis to assess mountain pine beetle hazard in climax lodgepole pine stands near Wickiup Springs, Fremont National Forest, OR

	GRPNUM	
Variables	1	2
QUADMN[a]	1.268654	1.779806
RINGCM[b]	1.369873	1.774615
(CONSTANT)	−24.19745	−42.72203

[a]Quadratic mean diameter.
[b]Rings per centimetre.

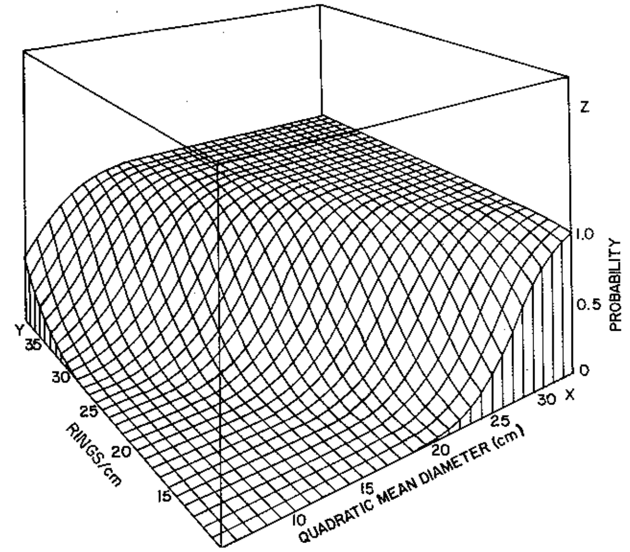

FIG. 1. Three dimensional surface indicating the probability a climax lodgepole pine stand near Wickiup Springs, Fremont National Forest, OR, may incur a mountain pine beetle outbreak based on the quadratic mean diameter and the number of rings per centimetre.

was expected to best represent the diameter classes preferred by the MPB and, since phloem thickness has been shown to be positively correlated with diameter (Amman 1969, 1975; Cole 1973), to best represent phloem thickness. Two of the hazard rating indices (CCF and SDI) had a high correlation coefficient ($r = 0.913$), but since a primary objective of the study was to compare the effectiveness of these indices as discriminators, they were left in the analysis.

A comparison of the means of the 14 variables (Table 3) showed that the stands which did not experience the recent MPB outbreak (group 1) had trees which were denser ($p = 0.0016$) and smaller in diameter ($p = 0.0004$) than stands attacked by MPBs (group 2). The basal area of both groups was essentially the same ($p = 0.916$). Two variables based on tree vigor showed that group 1 stands experienced less competition (Waring and Pitman's index, $p = 0.0068$; number of rings per centimetre, $p = 0.0020$). Another vigor variable, Mahoney's periodic growth ratio, showed no statistical difference between groups ($p = 0.368$). The variables based on mensurational parameters such as diameter−density relationships (CCF), quadratic mean diameter and basal area (SDI), and intertree distances and diameters of trees selected by a wedge prism (HEGYI) gave inconclusive results. Hegyi's index showed that group 1 stands experienced greater competition ($p = 0.0471$), while the crown competition factor and the stand density index showed no statistical differences between groups ($p = 0.605$ and $p = 0.161$, respectively). The vigor variables were thought to better represent competition, as they directly measure tree growth. The other indices of competition are indirect measures of competition, and are therefore not as reliable.

The five remaining stand structure variables and the five hazard rating indices determined to be suitable for further analysis were entered in a stepwise discriminant analysis. The most significant variable (highest F, equal to or greater than 1.0) was entered at each step. It was possible to remove previously entered variables if, because of the addition of new variables, their significance levels fell below an F value of 1.0.

The variables that the discriminant analysis selected as statistically significant discriminators of groups were measures of tree diameter (quadratic mean diameter) and of tree vigor (rings per centimetre), ($p = 0.00001$, canonical correlation coefficient = 0.77235). Group centroids were separated by 2.35 standard deviations.

The selection of quadratic mean diameter and of the number of rings per centimetre as variables to predict whether a lodgepole pine stand would be attacked by MPBs is consistent with what Cole and Amman (1980) found.

The adequacy of the derived discriminant functions was tested by classifying the stands used to derive the functions in the first place, and comparing these predicted group memberships with actual group memberships. Using coefficients from Fisher's linear discriminant functions (Table 4) it was possible to calculate probabilities of group membership for each stand. A stand was classified into a particular group if its probability of membership was greater than 0.5. An incorrect classification occurred if a stand was classified into group 1, for example, yet actually belonged to group 2. In this analysis 93.33% of the stands were correctly classified.

Given that the discriminant analysis did a good job of separating the groups, and that the predictor variables were ecologically appropriate, a model based on the classification scores was developed to predict whether a particular stand would be susceptible to MPB attacks. The model calculates the posterior probabilities that a stand belongs to group 2 based on the Fisher linear discriminant function classification coefficients. By using the quadratic mean diameter and the number of rings per centimetre for a climax lodgepole pine stand from the general vicinity of Wickiup Springs, it was possible to determine the posterior probability that the stand would be attacked by MPBs. Posterior probabilities were calculated by

$$[2] \quad P = \exp(S_{ij}) / \sum_{k=1}^{a} \exp(S_{ij})$$

where S = the classification score for stand i of group j, and a = the number of groups (Dixon and Brown 1981).

For example, the posterior probability that a stand belongs to group 2 is

$$[3] \quad P = [\exp(-42.722 + 1.779(\mathrm{QUADMN}) + 1.775(\mathrm{RINGCM}))]/[\exp(-42.722 + 1.779(\mathrm{QUADMN}) + 1.775\,(\mathrm{RINGCM})) + \exp(-24.197 + 1.269(\mathrm{QUADMN}) + 1.369(\mathrm{RINGCM}))]$$

By calculating an array for posterior probabilities for the two variables, it was possible to develop a three-dimensional representation of the probability surface (Fig. 1). Estimating the probability that a stand will be attacked by MPBs is easier and

TABLE 5. Contributions of five hazard rating indices used in discriminant analysis models to predict if a mountain pine beetle outbreak will occur in a climax lodgepole pine forest near Wickiup Springs, Fremont National Forest, OR

Index of competition	Wilks lambda	R^2	F	Added contribution to canonical correlation coefficient with all significant variables in the model
Waring and Pitman	0.7660	0.234	0.0068	0.0020
Hegyi	0.8665	0.134	0.0471	0.0014
Stand density index	0.9312	0.069	0.1613	0.0001
Periodic growth ratio	0.9709	0.029	0.3675	0.0001
Crown competition factor	0.9903	0.009	0.6045	0.0015

faster by interpolation from Fig. 1 than by using the formula. If it is necessary to know the exact probability of MPB attack, the formula should be used.

Users of the results of this discriminant analysis and prediction equations should note that the numerical relationships are valid only for stands in the general vicinity of Wickiup Springs. If one needed to know the probability that a stand will be attacked by MPBs in a different region, a new set of data would have to be collected and the corresponding predictive equations developed using the method outlined above.

The relative importance of the hazard rating indices was determined by forcing them into separate stepwise discriminant analyses. In each analysis the first variable entered was one of the hazard rating indices. Subsequent steps brought in the next most significant (F equal to or greater than 1) variables. It was possible for a variable to be removed from the analysis if its significance level dropped below an F of 1.0. The hazard rating index, however, could not be removed from the analysis, regardless of its F value. By examining the summary table for the first step in each analysis, it was possible to determine the significance level and the percentage of the explained variation [(1 − Wilk's lambda) (100)] for each index of competition. Waring and Pitman's tree vigor index and Hegyi's index were the only indices that were statistically significant ($p = 0.0068$ and $p = 0.0471$, respectively), although they explained less than 25% of the variation in the data (23.4 and 13.4%, respectively) (Table 5). The other indices explained even less of the variation, with the stand density index accounting for 6.9%, the periodic growth ratio accounting for 2.9%, and the crown competition factor explaining only 0.93%. The contribution of the hazard rating indices as discriminators was negligible once all the significant variables had been entered. Waring and Pitman's index was the best of the five, although it improved the canonical correlation index by only 0.0020. The added contributions of the other four indices were, in descending order: crown competition factor (0.0015), Hegyi's index (0.0014), periodic growth ratio (0.0001), and stand density index (0.0001).

Conclusions

The variables determined to be significant predictors of whether a climax lodgepole pine stand will be attacked by MPBs were the quadratic mean diameter and the number of rings in the outermost cm of radial growth. None of the other hazard rating indices were significant. A possible reason why the hazard rating indices were not significant could be that none of them incorporated both vigor (growth) and tree size: Waring and Pitman's and Mahoney's indices were based on growth, Curtis's index was based on tree size, Hegyi's and Krajicek's indices were based on tree size and density. It may be possible to develop a better predictive model if one of the vigor indices were modified to incorporate tree size.

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