A test of lodgepole pine hazard rating methods for mountain pine beetle infestation in southeastern Idaho

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Abstract

Five stands of lodgepole pine in southeastern Idaho were rated for hazard to mountain pine beetle infestation by five methods. Losses to mountain pine beetle were correctly identified in three of the five stands using the age-dbh-elevation and PGR methods; in two of the five stands using grams of wood per square metre of foliage and PGR/SHR-phloem methods; and in none of the five stands using the SHR method. The SHR method was invalidated by low crown competition factor in all stands. Mountain pine beetle showed the usual strong preference for trees of large diameter, but showed no consistent preference for trees of low PGR or low grams of wood per square metre of foliage. The less serious error of predicting moderate to high tree losses to moutain pine beetle when low losses occurred was associated with the age-dbh-elevation and grams of wood per square metre of foliage methods. The more serious error of predicting low tree losses to mountain pine beetle when losses were moderate to high was associated with the PGR, SHR, and PGR/ SHR-phloem methods.

Résumé

On a évalué la menace d'infestation du dendroctone du pin ponderosa dans cinq peuplements de pin tordu du sud-est de l'Idaho, grâce à cinq méthodes. Les pertes dues au dendroctone ont été correctement déterminées dans trois des cinq peuplements au moyen de la méthode de croissance périodique (CP) et de celle de l'âge, du diamètre à hauteur de poitrine et de l'altitude (ADA); dans deux au moyen de la méthode CP/MP-phloème (MP=menace posée au peuplement) et de la méthode du nombre de grammes de bois par mètre carré de feuillage (gB/m^2); et dans aucun au moyen de la méthode MP. Celle-ci a été invalidée dans tous les peuplements par le faible facteur de concurrence des cimes. Le dendroctone a montré sa préférence habituelle pour les arbres de gros diamètre, mais aucune préférence constante pour les arbres de faible CP ou d'un faible rapport gB/m^2. L'erreur de prédiction de pertes modérées à élevées d'arbres, alors qu'elles ont été faibles, a été la moins grave avec les méthodes ADA et gB/m^2. L'erreur de prédiction de faibles pertes, alors qu'elles ont été modérées à élevées, a été la plus grave avec les méthodes CP, MP et CP/MP — phloème.

Introduction

Methods for rating hazard of bark beetle outbreaks in forest stands are important tools to the land manager. These methods are designed to help land managers identify high-hazard stands so that action can be taken prior to beetle outbreak. Thus, losses to bark beetles can be minimized and particular objectives can be met, whether they be timber harvest, wildlife, hydrology, aesthetic, or other value.

Since the mid-1970s, a number of hazard rating methods have been developed to rate stands of lodgepole pine, *Pinus contorta* Douglas, to infestation by mountain pine beetles (MPB), *Dendroctonus ponderosae* Hopkins [Coleoptera: Scolytidae]. However, most methods of assessing lodgepole pine susceptibility to infestation by MPB have not been tested widely to determine their geographic zone of applicability. Therefore, to add to the data base of this task already started by McGregor *et al.* (1981) and Shrimpton and Thomson (1981, 1983), five hazard rating methods (Amman *et al.* 1977; Berryman 1978; Mahoney 1978; Schenk *et al.* 1980; Waring and Pitman 1980) were tested in southeastern Idaho. Most parameters needed for these hazard rating methods can conveniently be derived from standard inventory data (Lorio 1978; Hedden 1981).

The area of consideration was the southern portion of the Targhee National Forest because it was undergoing a second MPB infestation. Several stands in this portion of the forest had been surveyed for losses to MPB following the first infestation that occurred in the late 1950s, and ended about 1967 (Amman and Baker 1972). Recently (1977 to 1980) several of the same stands were infested by MPB approximately 20 years after the beginning of the first infestation. Of particular interest were the stand conditions existing now and the applicability of hazard rating methods. The objectives were to determine (1) how well the methods assessed stand susceptibility and (2) the response of beetles to the tree and stand characteristics used in the hazard rating methods.

Methods

Five lodgepole pine stands, at least 22 km apart, were sampled using a systematic random design. Plots were located 200 m apart in a grid pattern. The number of plots per stand ranged between 14 and 20. Living trees were counted on 10 basal area factor (BAF) plots, whereas dead trees were counted on 5 BAF plots. An angle gauge was used to determine which trees were in the plot. Each tree tallied on a 10-BAF plot represents 10 square feet (0.93 m^2) of stem area, and on at BAF plot 5 square feet (0.46 m^2) of stem area/acre. This was converted to m^2/ha.

The diameter at breast height (dbh) was obtained from all trees on the plots. Height and crown length were obtained from the two live dominant and codominant trees closest to the center of the plot, and from all trees killed by the mountain pine beetle from 1977 to 1980. characteristics used to determine year of tree death followed those of Cole and Amman (1969). Two increment cores located 180° apart were obtained at dbh for sapwood and growth measurements. As soon as a core was removed from the tree, sapwood thickness was measured with a ruler graduated in hundredths of inches. The boundary between sapwood and heartwood is easily determined by the wet and darker appearance of sapwood. In trees killed by MPB, the sapwood-heartwood boundary is recognized by blue-staining fungi that penetrate the full thickness of the sapwood by the time MPB emerge. Width of annual rings and tree age were determined using a microscope in the laboratory.

T-tests were used to determine differences in tree characteristics of live and MPB-killed trees. Chi-square tests were used to determine whether MPB-killed trees in the low, moderate, and high susceptibility classes differed from uninfested trees.

Results

Stand and tree characteristics

Stocking was light to moderate, ranging between 361 to 556 trees 12.7 cm dbh and larger per hectare. Lodgepole pine comprised 63.8 to 99.4% of the stands. Douglas-fir, subalpine fir, and aspen were the common associated species. Basal area and crown competition factor (CCF) were light to moderate, ranging between 9.9 and 17.2 m^2/ha and 60 to 103 CCF, respectively. Average diameters for lodgepole pine 12.7 cm and larger dbh ranged from 19.1 to 23.0 cm (Table I).

The average dbh of surviving trees was smaller than that of trees killed by MPB in all stands, but there was no consistent pattern between live and dead trees with respect to age or percent crown. Average age was usually between 60 and 80 years, with only one stand (Pine Creek) averaging older than 80 years (Table II). Averages for percent crown of live trees ranged from 56.4 to 69.8% and for killed trees from 56.5 to 73.1%.

Hazard rating methods

Age-dbh-elevation. The method of Amman *et al.* (1977) bases hazard on average age and average dbh for trees with dbh of at least 12.7 cm, and a measure of climatic suitability of the stand consisting of latitude and average elevation (fig. 1). Each factor is given a value of 1, 2, or 3 (Table III). By multiplying the values for the three factors, hazard rating for a stand is determined (low = 1 to 9, moderate = 12 to 18, high = 27). Expected lodgepole pine mortality of trees with dbh of 21.6 cm or more is less than 25% for low hazard, 25 to 50% for moderate hazard, and greater than 50% for high hazard. A dbh of 21.6 cm was used because that was the smallest size for sawtimber at the time the method was published.

Using age-dbh-elevation, tree loss was correctly identified in three of the five stands—Indian Lake, Packsaddle, and Warm River (Table IV). Tree losses in the Moody Meadows and Pine Creek stands were 3.4 and 4.0% respectively, but, moderate and high hazard, respectively, had been predicted based on the age and average dbh of the stands.

Of the characteristics used in the method, beetle preference for trees of diameter larger than the stand average was consistent in all stands (Table II).

Table I. Characteristics of five southeastern Idaho stands of lodgepole pine rated for hazard of mountain pine beetle infestation

Locality	Trees/hectare			Lodgepole	Basal area (m^2)		Crown competition factor		DBH (cm) (lodgepole only)		
	n	$\bar{x}$	sme	%	$\bar{x}$	sme	$\bar{x}$	sme	n	$\bar{x}$	sme
Indian Lake	20	361	40.0	91.0	11.2	1.29	60	7.8	126	19.1	0.41
Moody Meadows	14	408	82.7	69.6	17.2	2.39	84	13.0	111	23.0	0.51
Packsaddle	20	457	56.3	63.8	15.4	1.70	81	8.7	115	19.7	0.56
Pine Creek	14	556	102.3	90.0	9.9	1.35	103	14.6	202	21.3	0.28
Warm River	15	516	89.5	99.4	17.2	2.73	87	13.5	211	20.8	0.41

Table II. Mean dbh, age, and percent crown of live and mountain-pine-beetle-killed lodgepole pine in five southeastern Idaho stands rated for hazard of beetle infestation

	DBH (cm)		Age		Percent Crown	
Locality	Live	Killed	Live	Killed	Live	Killed
Indian Lake	19.1	22.4	58.8	59.2	69.8	60.2
Moody Meadows	23.0	28.6	77.2	80.7	59.0	59.0
Packsaddle	19.7	24.3	74.0	56.6	64.4	73.1
Pine Creek	21.3	24.4	82.3	77.4	56.4	56.5
Warm River	20.8	30.6	51.8	76.4	68.0	55.9

Table III. Parameters used to hazard rate lodgepole pine stands by the Amman *et al.* (1977) method. Values in parentheses assigned to stand are multiplied to give a stand hazard rating (low = 1-9, moderate = 12-81, high = 27)[a]

Elevation-latitude		Average age		Average dbh (cm)	
High	(1)	<60	(1)	<17.8	(1)
Moderate	(2)	60-80	(2)	17.8-20.3	(2)
Low	(3)	>80	(3)	>20.3	(3)

[a] One exception occurs when all three feactors are rated moderate, but the value (8) falls within the range of low risk. This should be considered moderate hazard for beetle potential.

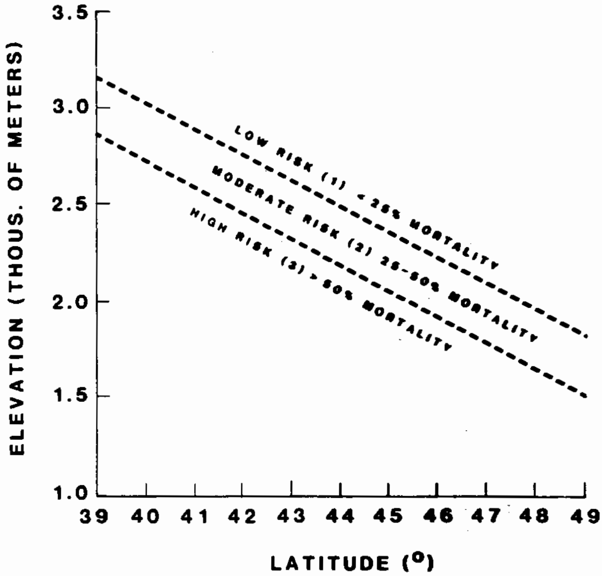

Fig. 1. Expected lodgepole pine losses to mountain pine beetle for different combinations of elevation and latitude.

However, there was no consistent preference shown for older trees. All stands were climatically suitable for MPB.

Periodic growth ratio. The method of Mahoney (1978) is based on periodic growth ratios (PGR) of annual radial increment:

$$\text{PGR} = \frac{\text{current 5 years radial growth}}{\text{previous 5 years radial growth}}$$

Stands having a PGR less than 0.9 are susceptible, whereas those with 0.9 or greater are resistant to MPB. Susceptible stands would be expected to suffer greater than 10% tree mortality, whereas resistant stands would have less than 10% tree mortality among trees with a dbh of 12.7 cm or more.

Tree losses to MPB for three of the five stands were classified correctly using PGR—Moody Meadows, Pine Creek, and Warm River. Both the Indian Lake and Packsaddle stands were expected to have less than 10% tree mortality but had 13.8 and 13.5%, respectively (Table V).

Mountain pine beetle showed a preference for trees of average PGR lower than that of surviving trees in four plot years (that is any plot for any one year), a preference for trees of average PGR greater than that of surviving trees in five plot years, and no preference was shown in three plot years. In three plot years when

Table IV. Hazard ratings for mountain pine beetle infestation in five lodgepole pine stands in southeastern Idaho by the method Amman *et al.* (1977)

Locality	dbh (cm)		Age		Elevation (m)		Stand[a]	Tree losses[b]			
	Mean	Rating	Mean	Rating	Mean	Rating	rating	Predicted (%)		Actual (%)	
Indian Lake	19.1	2	59.0	1	1966	3	6	L	<25	L	22.4
Moody Meadows	23.0	3	77.6	2	2012	3	18	M	25-50	L	3.4
Packsaddle	19.7	2	65.5	2	2073	3	12	M	25-50	M	26.3
Pine Creek	21.3	3	81.3	3	1905	3	27	H	>50	L	4.0
Warm River	20.8	3	66.3	2	1737	3	18	M	25-50	M	30.4

[a] Ratings of individual factors are multiplied to give stand ratings.

[b] Losses of trees with dbh of at least 21.6 cm.

Table V. Hazard ratings for mountain pine beetle infestation in five lodgepole pine stands in southeastern Idaho by the method of Mahoney (1978)

Locality and year	Periodic growth ratios: Live trees n	Live trees $\bar{x}$	Live trees sme	Killed trees n	Killed trees $\bar{x}$	Killed trees sme	t-test[a]	Lodgepole killed[c] Predicted %	Lodgepole killed[c] Actual %
Indian Lake									
1977	24	1.39	0.077	2	0.95	0.017	7.802[b]	<10	13.8
1978	24	1.48	0.089	6	1.24	0.091	5.613[b]		
1979	24	1.41	0.082	13	1.30	0.059	4.136[b]		
1980	24	1.27	0.089	0	—	—	—		
Moody Meadows									
1977	22	1.15	0.048	1	1.27	—	—	<10	1.9
1979	22	1.11	0.051	3	0.96	0.062	32.860[b]		
1980	22	1.07	0.051	0	—	—	—		
Packsaddle									
1978	27	0.95	0.050	8	0.97	0.074	0.627	<10	13.5
1979	27	0.92	0.042	14	0.78	0.044	9.354[b]		
1980	27	0.88	0.040	4	0.99	0.128	3.102[b]		
Pine Creek									
1979	22	0.99	0.032	6	0.98	0.057	0.396	<10	2.2
1980	22	0.94	0.028	0	—	—	—		
Warm River									
1977	13	0.86	0.060	4	0.86	0.104	0.004	>10	12.3
1978	13	0.84	0.058	7	0.95	0.091	2.957[b]		
1979	13	0.84	0.062	11	1.03	0.079	6.758[b]		
1980	13	0.83	0.059	1	0.95	—	—		

[a] t-test comparing periodic growth ratios of live and killed trees; <0.9 is susceptible, ≥0.9 is resistant.

[b] Periodic growth ratios significantly different at 0.01 level of probability.

[c] Less than 10% tree mortality, resistant; greater than 10% tree mortality, susceptible for trees with dbh of at least trees 12.7 cm.

preference was shown for trees having PGR less than that of surviving trees, PGR averaged greater for both killed and surviving trees than the 0.9 threshold specified by Mahoney (1978). In only two of the 13 plot years did PGR of infested trees average less than the 0.9 threshold (Packsaddle in 1979 and Warm River in 1977).

The fewest infested trees occurred in the Moody Meadows stand (5.23 trees/ha during the four-year period, or 1.31 trees/ha/year). Even at this low infestation rate, PGR of infested trees ranged between 0.88 and 1.27 ($\bar{x}$ = 1.08). Diameters of infested trees were 25.4 to 48.3 cm, with the largest tree having a PGR of 1.21.

Overall, tree loss was classified correctly by PGR in three of the five stands, but susceptible and resistant trees could not be distinguished consistently by PGR.

CCF and lodgepole pine basal area. The method of Schenk *et al.* (1980) uses crown competition factor (CCF) and proportion of lodgepole pine basal area (LppBA) in the stand to calculate a stand hazard rating (SHR):

$$SHR = CCF \left(\frac{\text{Proportion LppBA}}{100}\right)$$

A SHR OF 1.00 or above indicates significant lodgepole pine mortality can be expected. Expected mortality for a given SHR can be obtained from the regression presented by Schenk *et al.* (1980).

Stand hazard rating values were low, ranging from 0.50 to 0.93 for the five stands, primarily because of low CCF, which ranged from 59.6 to 103.1. Therefore, no tree mortality was predicted for any of the stands. Actual mortality ranged between 2.9 and 25.5% of lodgepole pine basal area (Table VI). Crown competition factor was lowest in the Indian Lake stand; however, beetles still killed 17.9% of lodgepole pine basal area.

Growth efficiency. The method of Waring and Pitman (1980) is based on the ratio of current basal area growth to sapwood basal area and is a measure of tree vigor stated as grams of wood produced per square metre of foliage (Waring *et al.* 1980). Trees producing less than 50 g of wood per m^2 of foliage are highly susceptible, trees producing 51 to 100 g are moderately susceptible, and trees producing more than 100 g are highly resistant to MPB attack (Gary B. Pitman letter to author, 25 March 1982). Waring and Pitman (1980) state that only lodgepole pine with low vigor indices are apparently attacked, and only those with very low vigor are killed by MPB.

Using grams of wood per square metre of foliage, moderate tree mortality was predicted for all five stands even though there was a wide range in stocking, basal area, CCF, and average tree diameter. Waring and Pitman (1980) did not specify the amount of tree loss expected in stands of different susceptibility.

Mountain pine beetles showed no preference for trees with low growth efficiency in four of the five stands ($P > 0.05$) (Table VII). However, a significant difference was shown for trees with low growth efficiency in the Warm River stand ($P < 0.01$) where surviving trees averaged 120.9 g and trees killed by MPB averaged 63.6 g of wood per m^2 foliage. Most trees producing more than 100 g of wood were less than 35 years old.

Table VI. Hazard ratings for mountain pine beetle infestation in five lodgepole pine stands in southeastern Idaho by the method of Schenk *et al.* (1980)

Locality	CCF	Proportion lodgepole basal area	Proportion lodgepole ÷ 100	SHR	Lodgepole basal area killed	
					Predicted (%)	Actual (%)
Indian Lake	59.6	0.826	0.0083	0.50	0.0	17.9
Moody Meadows	84.3	0.635	0.0064	0.54	0.0	3.0
Packsaddle	80.9	0.615	0.0062	0.50	0.0	13.6
Pine Creek	103.1	0.900	0.0090	0.93	0.0	2.9
Warm River	86.9	0.991	0.0099	0.86	0.0	25.5

In the Moody Meadows stand, where tree mortality was lowest. trees killed by MPB averaged 97.4 g (range 67 to 113) of wood per m^2 of foliage compared to 76 g (range 36 to 121) for live trees. Even at this low rate of tree mortality (1.31 trees/ha/year), only one MPB-infested tree produced less than the threshold of 100 g of wood per m^2 of foliage for resistance to beetle infestation.

Chi-square tests were used to determine whether proportions of trees in the low, medium, and high susceptibility classes differed between live and MPB-killed trees. No significant difference existed in the Moody Meadows, Packsaddle, and Pine Creek stands ($P > 0.05$). Indian Lake and Warm River showed significant differences, and according to expectation, low proportions of trees were killed in the low susceptibility class compared to high proportions killed in the highly susceptible class. However, when live trees smaller than the smallest tree killed by MPB (these were below the diameter range of beetle preference) in the Indian Lake and Warm River stands were deleted from analyses, only Warm River continued to show a significant difference.

Overall, tree loss was correctly identified in two of the five stands using grams of wood per square metre of foliage, but the method did not distinguish between susceptible and nonsusceptible trees.

PGR/SHR-phloem. Berryman (1978) proposed the use of PGR/SHR as a measure of stand susceptibility. PGR and SHR are derived by the methods of Mahoney (1978) and Schenk *et al.* (1980). The percent of the stand basal area contained in trees having phloem thickness of at least 2.5 mm is used as a measure of the stand's potential to support MPB. Figure 2 shows the limits for low, high, and extreme susceptibility classes for different combinations of PGR/SHR and percentage of basal area contained in trees having phloem at least 2.5 mm thick. The

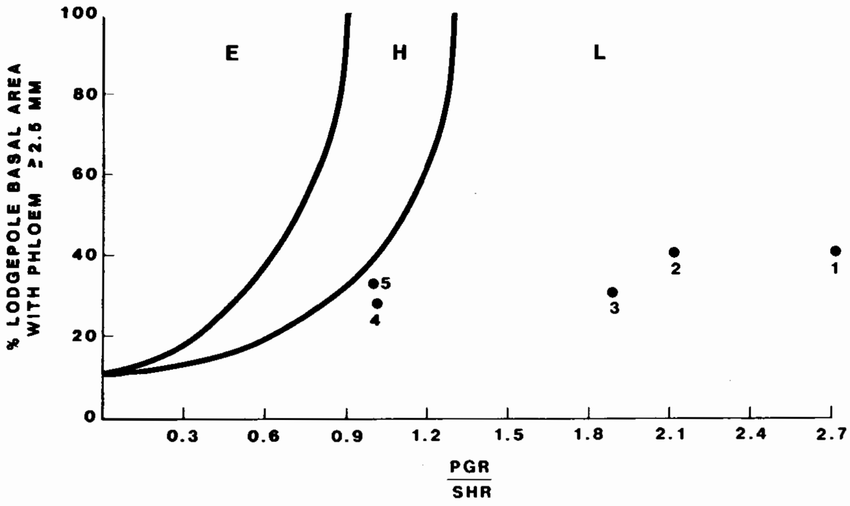

Fig. 2. Hazard rating of five lodgepole pine stands to mountain pine beetle infestation by Berryman (1978) method. Letters refer to hazard: E = extreme, H = high, L = low. Numbers refer to areas: 1 = Indian Lake, 2 = Moody Meadows, 3 = Packsaddle, 4 = Pine Creek, and 5 = Warm River.

probability of an outbreak decreases as the percentage of basal area in trees having phloem at least 2.5 mm thick decreases. Stands that contain less than 10% of their basal area in trees with phloem at least 2.5 mm thick have little or no chance of MPB outbreak.

The PGR/SHR-phloem method correctly identified loss in two of the five stands—Moody Meadow and Pine Creek. The other three stands also were rated low for susceptibility even though 22.4 to 30.4% of the lodgepole pine with a dbh of at least 21.6 cm, or 17.9 to 25.5% of the lodgepole pine basal area, was killed.

Discussion

This study has not demonstrated conclusively that one stand hazard rating method is superior to another. However, some problems with the hazard rating methods are suggested, possibly related to lodgepole pine stands undergoing a second outbreak within a short time. The methods tested were developed in unmanaged lodgepole pine stands that either had not undergone an MPB outbreak or were experiencing their first one.

Average diameter, average age, and a measure of climatic suitability rated tree loss correctly in three of the five stands. Stands apparently can experience a

Table VII. Hazard rating for mountain pine beetle infestation in five lodgepole pine stands in southeastern Idaho by the method of Waring and Pitman (1980)

Locality	Grams of wood/m² foliage							t-test[a]	Lodgepole killed[b]	
	Live trees			Killed trees			Live and killed		Predicted	Actual
	n	$\bar{x}$	sme	n	$\bar{x}$	sme	$\bar{x}$			
Indian Lake	23	91.2	6.00	22	75.3	5.90	83.4	$P > 0.05$	M	L
Moody Meadows	23	76.0	5.60	3	97.4	15.22	78.5	$P > 0.20$	M	L
Packsaddle	12	56.4	10.52	23	58.9	6.10	58.0	$P > 0.50$	M	M
Pine Creek	22	67.0	4.10	6	60.0	5.66	65.5	$P > 0.40$	M	L
Warm River	15	120.9	10.60	20	63.6	6.26	88.2	$P < 0.01$	M	M

[a] t-test comparing grams of wood per m² foliage of live and killed trees.

[b] Trees producing ≤50 grams of wood per m² foliage highly susceptible, 51-100 grams moderately susceptible, > 100 grams, resistant (M = moderate, L = low)

second infestation at a younger age when stand density is light and large diameter trees occur at an earlier age. The preference of beetles for lodgepole pine larger than the stand average was apparent in all stands regardless of MPB population level. Shrimpton and Thomson (1983) found average stand dbh in stands undergoing outbreaks of MPB in Western Canada was closer to 25.4 cm rather than 20.3 cm specified in the Amman *et al.* (1977) method. This may be a geographic difference because in my study the three stands that experience outbreaks ranged from 19.1 to 21.3 cm in diameter.

The PGR method also rated three of the five stands correctly on a stand basis. However, beetles showed no consistent preference for trees of low PGR, suggesting that a factor other than PGR is involved. Shrimpton and Thomson (1981) point out that, on the basis of normal tree growth, PGR is less than 1.0 most of the time after trees reach age 20. Additionally, Shrimpton and Thomson (1983) found PGR generally too high to indicate susceptibility during the five years prior to MPB outbreak. Earlier in the life of stands, PGR lower than the threshold of 0.9 was not associated with beetle attack.

The SHR values did not rate any stand correctly because CCF in all stands was low. Therefore, SHR values will probably need to be calibrated for the lighter stocking found in the stands undergoing a second MPB infestation. McGregor *et al.* (1981) found tree losses to MPB in pure lodgepole pine stands increased with decreased CCF in Montana, the reverse of that reported by Schenk *et al.* (1980). Shrimpton and Thomson (1983), on the other hand, found SHR values well above 1.0 in all stands with expanding MPB outbreaks, suggesting perhaps a geographic difference in applicability of the SHR method.

Using grams of wood per square metre of foliage, two of the five stands were rated correctly. However, all stands were rated as moderate even though a wide range in tree and stand characteristics existed. The moderate risk category is probably too broad and needs to be divided into smaller units. Beetles in four of the five stands did not show a preference for trees having low growth efficiency, suggesting beetles are responding to conditions other than growth efficiency. However, Mitchell *et al.* (1983) observed less tree loss to MPB in thinned than in unthinned lodgepole pine stands in Oregon. Stands were thinned 7 to 15 years prior to beetle outbreak and growth efficiency was better than in the unthinned stands. Therefore, a geographic difference in the usefulness of the growth efficiency method also is indicated.

The PGR/SHR-phloem method placed all stands in the low susceptibility class with two of the five stands rated correctly. Neither stand experienced an outbreak of MPB. Moderate losses of trees in the other three stands, although rated low, suggest that beetles are responding to something other than PGR/SHR, unless they are responding to high values of PGR/SHR rather than low values as expected in the development of the method. Because SHR alone predicted no loss in any stand, the division of PGR by SHR appears to have eliminated some of the predictability of PGR.

The age-dbh-elevation and grams of wood per square metre of foliage methods erred by predicting moderated to high tree losses to MPB when low losses actually occurred—the less serious error. The PGR, SHR, and PGR/SHR-phloem methods erred by predicting low tree losses to MPB when losses were actually moderate to high—the more serious error.

The problem remains as stated by Shrimpton and Thomson (1981): "At the present we can define when a stand becomes prone to outbreak but still cannot define when the outbreak may commence." Comparisons of existing stand conditions with threshold parameters used in the various hazard rating methods (Shrimpton and Thomson 1983) offer considerable promise in future evaluations. Many stands will need to be examined to determine which hazard rating method is best in a given geographic area, or if a new combination of factors will be a better predictor of MPB outbreak and tree loss. Such work is planned as part of the Canada/US MPB agreement.

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References

Amman, G.D. and B.H. Baker. 1972. Mountain pine beetle influence on lodgepole pine stand structure. J. For. 70:204-209.

Amman, G.D., M.D. McGregor, D.B. Cahill, and W.H. Klein. 1977. Guidelines for reducing losses of lodgepole pine to the mountain pine beetle in unmanaged stands in the Rocky Mountains. U.S. Dep. Agric. For. Serv. Gen. Tech. Rep. INT-36.

Berryman, A.A. 1978. A synoptic model of the lodgepole pine/mountain pine beetle interaction and its potential application in forest management, pp. 98-105. *In* A.A. Berryman, G.D. Amman, and R.W. Stark, Eds. Theory and practice of mountain pine beetle management in lodgepole pine forests. Symp. Proc., For., Wildl. and Range Exp. Sta., Univ. Idaho, Moscow.

Cole, W.E., and G.D. Amman. 1969. Mountain pine beetle infestations in relation to lodgepole pine diameters. U.S. Dep. Agric. For. Serv. Res. Note INT-95.

Hedden, R.L. 1981. Hazard-rating system development and validation: An overview, pp. 9-12. *In* R.L. Hedden, S.J. Barras, and J.E. Coster (Coordinators). Hazard-rating systems in forest insect pest management. Symp. Proc., U.S. Dep. Agric. For. Serv. Gen. Tech. Rep. WO-27.

Lorio, P.L., Jr. 1978. Developing stand risk classes for the southern pine beetle. U.S. Dep. Agric. For. Serv. Res. Pap. SO-144.

Mahoney, R.L. 1978. Lodgepole pine/mountain pine beetle risk classification methods and their application, pp. 106-113. *In* A.A. Berryman, G.D. Amman, and R.W. Stark, Eds. Theory and practice of mountain pine beetle management in lodgepole pine forests. Symp. Proc., For. Wildl. and Range Exp. Sta., Univ. Idaho, Moscow.

McGregor, M.D., G.D. Amman, and W.E. Cole. 1981. Hazard-rating lodgepole pine for susceptibility to mountain pine beetle infestation, pp. 99-104. *In* R.L. Hedden, S.J. Barras, and J.E. Coster (Coordinators), Hazard-rating systems in forest insect pest management. Symp. Proc., U.S. Dep. Agric. For. Serv. Gen. Tech. Rep. WO-27.

Mitchell, R.G., R.H. Waring and G.B. Pitman. 1983. Thinning lodgepole pine increases tree vigor and resistance to mountain pine beetle. For. Sci. 29:204-211.

Schenk, J.A., R.L. Mahoney, J.A. Moore and D.L. Adams. 1980. A model for hazard rating lodgepole pine stands for mortality by mountain pine beetle. For. Ecol. and Manage. 3: 57-68.

Shrimpton, D.M., and A.J. Thomson. 1981. Use of physiological maturity to identify hazard of lodgepole pine stands from mountain pine beetles, pp. 149-153. *In* R.L. Hedden, S.J. Barras, and J.E. Coster (Coordinators), Hazard-rating systems in forest insect pest management. Symp. Proc., U.S. Dep. Agric. For. Serv. Gen. Tech. Rep. WO-27.

Shrimpton, D.M., and A.J. Thomson. 1983. Growth characteristics of lodgepole pine associated with the start of mountain pine beetle outbreaks. Can. J. For. Res. 13:137-144.

Waring, R.H., and G.B. Pitman. 1980. A simple model of host resistance to bark beetles. Oreg. State Univ. For. Res. Lab. Res. Note 65.

Waring, R.H., W.G. Thies and D. Muscato. 1980. Stem growth per unit of leaf area: A measure of tree vigor. For. Sci. 26:112-117.