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Mountain pine beetle attack in ponderosa pine: Comparing methods for rating susceptibility

David C. Chojnacky, Barbara J. Bentz, and Jesse A. Logan

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Abstract

Two empirical methods for rating susceptibility of mountain pine beetle attack in ponderosa pine were evaluated. The methods were compared to stand data modeled to objectively rate each sampled stand for susceptibly to bark-beetle attack. Data on bark-beetle attacks, from a survey of 45 sites throughout the Colorado Plateau, were modeled using logistic regression to estimate the probability of attack on individual trees from tree and stand variables. The logistic model allowed flexibility to easily scale results up to a stand level for comparison to the empirical methods. The empirical method, developed by Munson and Anhold, most closely correlated to the logistic regression results. However, the Munson/Anhold method rated all 45 study sites as either moderately or highly susceptible to bark-beetle attack, which raises concern about its lack of sensitivity. Future work on evaluating risk of bark-beetle impact should consider more than stand characteristics.

Keywords: *Dendroctonus ponderosae, Pinus ponderosa,* mortality, hazard rating, risk rating, logistic regression, Colorado Plateau

The Authors

David C. Chojnacky is owner of a USDA Forest Service enterprise unit in Washington, DC. His current interests include biometrics and sampling research on forest measurements, carbon budgets, and wildlife habitat as well as consultation on applications of Forest Inventory and Analysis (FIA) data. He holds a Ph.D. degree in forest biometry from Colorado State University.

Barbara J. Bentz is a research entomologist and project leader of the Interior West Bark Beetle Project in Logan Utah, and an adjunct Assistant Professor in the Forest Resources Department at Utah State University. Her research is focused on the population dynamics and role of bark beetles in forest ecosystems. She received a Ph.D. in Entomology from Virginia Tech and an MS in Forestry from the University of Idaho.

Jesse A. Logan is a Research Entomologist with the USDA Forest Service Interior West Bark Beetle Project in Logan Utah, and a Professor in the Forest Resources Department at Utah State University. His primary research interests are quantitative insect ecology, dynamical systems theory applied to forest insect populations, and disturbance ecology.

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Front cover photos, left to right: beetle-killed ponderosa pine, fading foliage of ponderosa pine attacked at least 2 years before, and live survivor of strip attack, Fishlake National Forest, 1998.

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Introduction

Native bark-beetle species are important to forest ecosystems. Although bark beetles kill trees, dead wood is a necessary component of healthy ecosystems. Dead trees affect carbon and nutrient cycling, wildfire behavior, stream channel morphology, plant reproduction, and wildlife and other organism habitat. However, resource managers face many situations where insect outbreaks warrant intervention. Methods to rate forest stands according to likelihood of bark-beetle outbreak can aid forest management decisions. Silviculturalists can use risk-rating methods to devise harvest strategies that reduce susceptibility to outbreaks in high-value timber stands. Recreation planners and landscape architects need methods to predict tree loss to campgrounds and scenic corridors. Concern over declining forest health and the realized need to manage entire ecosystems are fueling the demand for methods to quickly assess forest insect impacts.

On the Colorado Plateau, two methods are available for rating ponderosa pine (*Pinus ponderosa*) stands for susceptibility to mountain pine beetle (*Dendroctonus ponderosae*) attack. Munson and Anhold (1995) devised a rating technique to classify stands as low, moderate, or high susceptibility (table 1). This method requires stand measurements of basal area, average ponderosa diameter at breast height (dbh), proportion of ponderosa in canopy, and number of currently infested trees. Another similar method for Black Hills ponderosa (Stevens and others 1980) might also be applicable (table 2). Because both methods were developed from professional judgement instead of rigorous data analysis, testing them against objective data is necessary.

However, direct evaluation of the empirical methods is difficult because it is hard to collect suitable data for comparison. One problem is finding field sites to represent a range of stand conditions where bark-beetle history is known for all host trees. The beetle history is needed to separate the non-attacked trees and stands into those that are successfully resistant to attack and those that have not been challenged by bark beetles. This distinction is necessary to clearly characterize stand conditions that are resistant to bark-beetle attack.

An alternative to tree-level historical data, is broad-scale survey of an area under bark-beetle attack to include a range of endemic and epidemic

Table 1. Munson and Anhold risk rating technique for mountain pine beetle attack in ponderosa pine[a].

1) Determine the following stand conditions for live trees 5.0 inches dbh and larger: basal area, average dbh for ponderosa pine (*PP*), proportion of ponderosa pine in canopy, and number of currently infested trees per acre (*TPA*).

2) Using the following table and the above stand characteristics total the corresponding rating values enclosed in parentheses:

Basal area (ft^2/acre)		Average PP dbh (inches)		Proportion of PP in canopy (percent)		No. of currently infested TPA (No./acre)	
<80	(1)	<6	(1)	<50	(1)	<3	(1)
80-120	(2)	6-12	(2)	50-65	(2)	3-10	(2)
>120	(3)	>12	(3)	>65.	(3)	>10	(3)

3) Sum ratings (numbers in parentheses) for the four columns to obtain a total rating value:

Total rating value	Potential outbreak rating
1-5	low
6-9	moderate
10-12	high

[a] *Emperical risk-rating method developed in 1995 by S. A. Munson and J. A. Anhold, USDA Forest Service, Forest Health Protection, Ogden, UT.*

stand conditions. These data would provide general trends of bark-beetle activity within stands, and may offer opportunity for modeling to adjust for some of the uncertainty over non-attacked trees.

For this paper, survey data on bark beetles in ponderosa pine were available from a cooperative effort within the USDA Forest Service between Forest Health Protection and Rocky Mountain Research Station. These data were collected to study spatial and temporal relationships of bark-beetle attack in endemic and epidemic situations. Although the data contain much information, this study was limited to a simple evaluation of the 2 existing empirical methods that rate bark beetle susceptibility. Evaluation was done by first modeling the data to objectively rate each sampled stand for susceptibility to bark-beetle attack, comparing the model to the empirical methods.

Field Data Collection

Forty-five sites, representing endemic and epidemic bark-beetle populations, were sampled in Arizona, Colorado, and Utah (table 3, figure 1). Twenty 0.1-acre circular plots were established at each site. Generally, sampling was done with 2 parallel transects where each transect contained 10 contiguous plots. In a few cases, transects were perpendicular or otherwise shifted to fit within a homogenous stand. All tree species were identified and measured for dbh. In addition, Keen's (1943) tree class, mistletoe rating, and past bark-beetle activity were recorded for all ponderosa pine. Field crews estimated year-of-attack for 3 previous years by comparing foliage redness and needle retention to previous observations of tree conditions after beetle attack. The summer of bark-beetle attack pitch tubes are evident and foliage is green. Foliage begins to redden the first year after attack, but none falls. By the second year, foliage is deep red and begins to fall. Most foliage falls between the second and third year after bark-beetle attack.

An 18% subsample of ponderosa pine (the first 2 live trees encountered on each plot) was measured for growth, age, height, and crown characteristics. Crown cover, elevation, topographic features, and geographic coordinates were also recorded for each plot. One plot per transect was permanently established by recording tree distance and azimuth from plot center; the rest were temporary plots.

Of the 45 sites sampled, bark-beetle attacks were found on 38. However, beetle-attacked trees were confined to only 21% of the 760 plots within the 38

Table 2. Stevens, McCambridge, and Edminster (1980) risk rating technique for mountain pine beetle attack in Black Hills ponderosa pine.

1) Determine the following stand conditions for live trees 5.0 inches dbh and larger: basal area, average dbh for ponderosa pine (PP), and stand structure.

2) Using the following table and the above stand characteristics total the corresponding rating values enclosed in parentheses:

Basal area (ft^2/acre)		Average PP dbh (inches)		Stand structure	
<80	(1)	<6	(1)	—	
80-150	(2)	6-10	(2)	1-story	(2)
>150	(3)	>10	(3)	2-story	(3)

3) Multiply (NOT sum) the ratings (numbers in parentheses) for the three columns to obtain a total rating value:

Total rating value	Potential outbreak rating
2-6	low
8-12	moderate
18-27	high

Table 3. Forty-five study sites in Arizona, Colorado, and Utah sampled to determine the presence of bark-beetle populations.

Site no.	National Forest or Park	Area description	Bark beetle status[1]
1	Kaibab	Pleasant Valley	post epidemic
2	Kaibab	Jolly Sink	endemic
3	Kaibab	Telephone Hill	increasing
4	Dixie	Tommy Creek #1	post epidemic
5	Dixie	Duck Creek	increasing
6	Kaibab	Jolly Sink #2	endemic
7	Kaibab	Dog Lake	endemic
8	Kaibab	Crane Lake	increasing
9	Dixie	Cooper Knoll	endemic
10	Dixie	Yellowjacket Spring	increasing
11	Dixie	Tommy Creek Site #2	epidemic
12	Dixie	Bower's Flat	post epidemic
13	Bryce Canyon	Fairyland Point	endemic
14	Bryce Canyon	Horse Creek	endemic
15	Bryce Canyon	Paria View	endemic
16	Bryce Canyon	Daves Hollow	endemic
17	San Juan	Coffee Creek	endemic
18	San Juan	Horse Creek	endemic
19	San Juan	First Notch	endemic
20	San Juan	Sawmill Reservoir	endemic
21	San Juan	First Fork	increasing
22	Manti-La Sal	Twin Springs	increasing
23	Manti-La Sal	Hammond	epidemic
24	Manti-La Sal	Butts	increasing
25	Manti-La Sal	Kigalia G.S.	endemic
26	Manti-La Sal	Corrals	increasing
27	Manti-La Sal	Butts 2	increasing
28	Manti-La Sal	Peavine	increasing
29	Dixie	Willis Creek	increasing
30	Dixie	Strawberry Point	increasing
31	Dixie	Strawberry Knolls	epidemic
32	Dixie	Dry Valley	epidemic
33	Dixie	The Pass	increasing
34	Dixie	Blue Spring Mountain	post epidemic
35	Dixie	Rock Canyon	endemic
36	Grand Canyon	The Basin #1	increasing
37	Grand Canyon	The Basin #2	increasing
38	Grand Canyon	Robber's Roost Sprng	epidemic
39	Uncompahgre	Haley Draw	increasing
40	Uncompahgre	Haley Draw 2	increasing
41	Uncompahgre	Haley Draw 3	increasing
42	Kaibab	Crane Lake West	increasing
43	Fishlake	Little Reservoir	endemic
44	Fishlake	South Creek	epidemic
45	Fishlake	Indian Creek	increasing

[1]*Subjective rating of general area made by field sampling crew.*

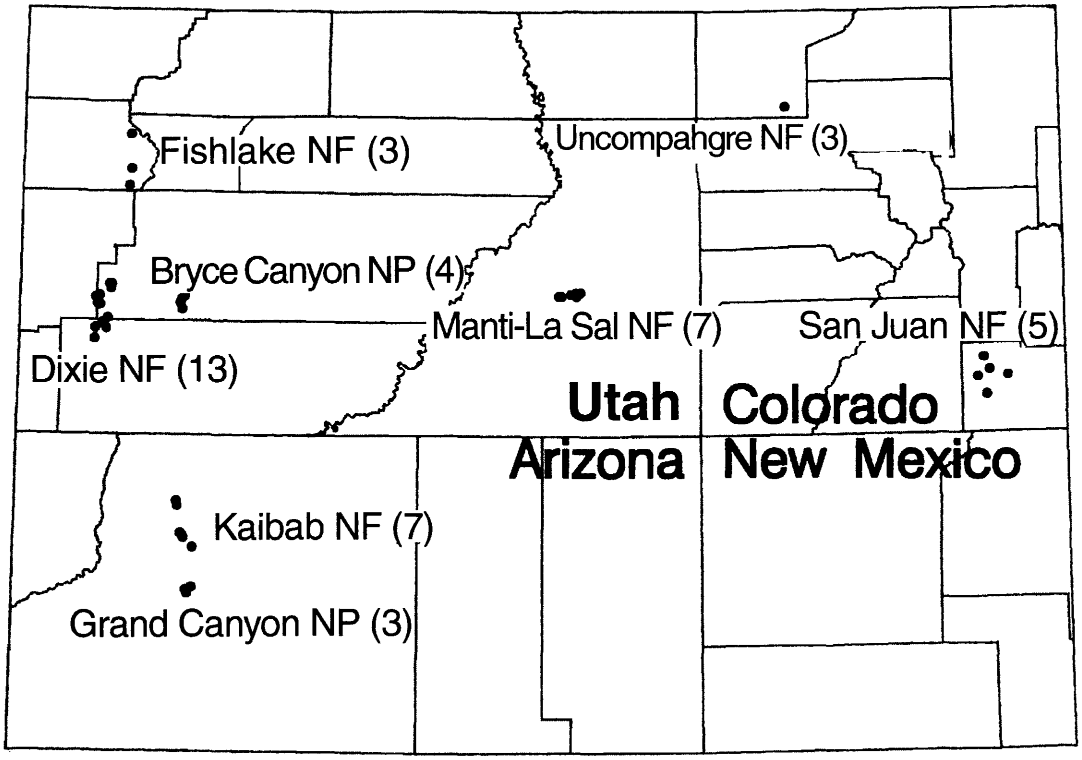

Figure 1. Location of 45 ponderosa pine study sites in national forests (NF) and national parks (NP) throughout the Colorado Plateau.

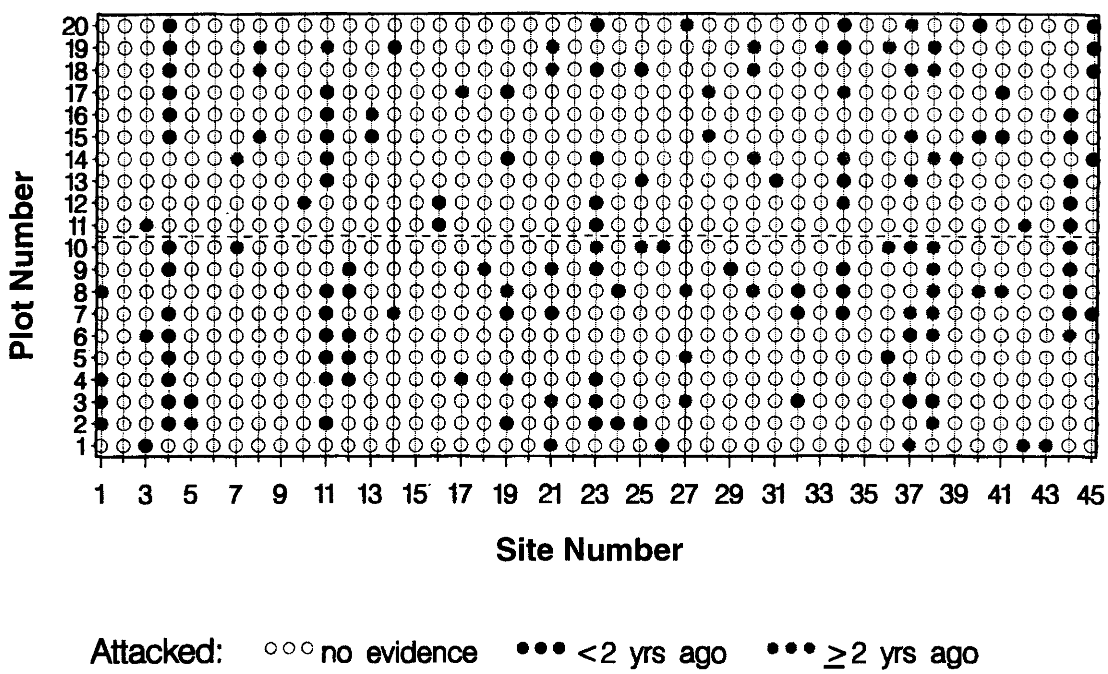

Figure 2. Schematic representation of all plots showing clumped distribution of bark-beetle attacks within transects. At each of the 45 sites, plot numbers 1 to 10 and 11 to 20 are 2 transects (generally parallel) of contiguous 0.1-acre plots.

attacked sites. Also, beetle activity tended to occur among consecutive plots within transects (figure 2).

Data Summary

More than 19,000 trees were measured, of which 10,857 were ponderosa pine. The other 8,900 trees, which were mixed with the ponderosa pine, were either Douglas-fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*), Gambel oak (*Quercus gambelii*), or blue spruce (*Picea pungens*). Aspen (*Populus tremuloides*) occurred on some sites but was not measured.

Bark beetles attacked 719 trees or 7% of the ponderosa. On sites rated as epidemic or post epidemic, about 18% of the ponderosa were attacked. Attack rates were up to 23 and 31%, on epidemic and post epidemic sites, for trees 8 inches dbh and larger. Mountain pine beetle accounted for 79% of the attacks; 15% were round headed pine beetle (*Dendroctonus adjunctus*), and the rest were either western pine beetle (*D. brevicomis*), larger Mexican pine beetle (*D. approximatus*), red turpentine beetle (*D. valens*), or *Ips* species.

Average dbh of attacked trees was 13.2 inches, which was significantly larger than the 10.1-inch average dbh for non-attacked trees (according to paired t-test at 0.5 probability level). More than 10% of the trees in the larger diameter classes (> 10 inches dbh) were beetle-attacked (figure 3). The 4- and 6-inch dbh class had greater mortality from other causes than from bark beetles.

Data were summed for plots and sites into variables describing stand structure. Trees per acre (*TPA*), basal area per acre (BA), stand density index (SDI) (Long and Daniel 1990, eq. 4), and quadratic mean diameter (QMD) were calculated for live and beetle-attacked trees in several diameter groups.

Generally, the stand structure variables showed greater tree density for beetle-attacked plots than for plots that were not attacked. For example, the mean stand density index (SDI) for beetle-attacked plots was 244, which was significantly larger than the mean SDI of 200 for non-attacked plots (from paired t-test with 0.5 probability level) (figure 4).

Model Construction

The most difficult task was selecting a suitable response variable to represent risk or susceptibility of ponderosa pine to bark-beetle attack. The

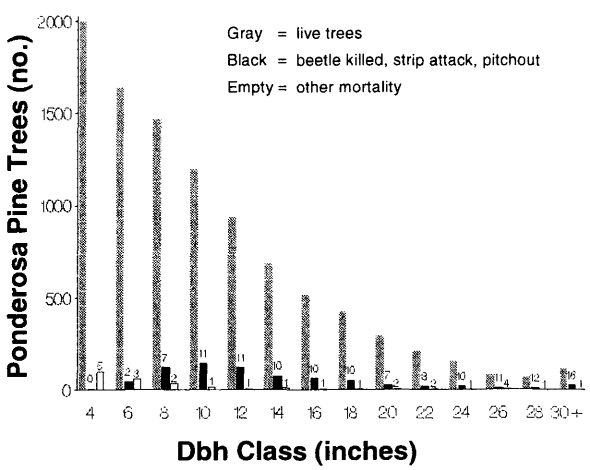

Figure 3. The diameter at breast height (dbh) distribution of beetle-attacked ponderosa pine is not proportional to the live tree distribution, larger dbh trees are more frequently attacked. The number above each bar is the percentage of total trees in the respective diameter class.

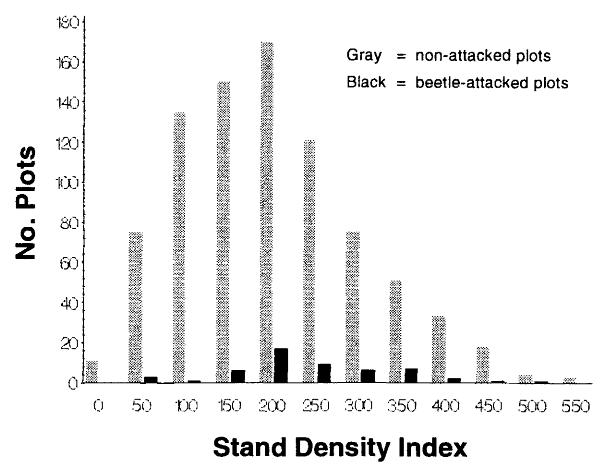

Figure 4. The mean stand density index (SDI) for beetle-attacked plots is 244, which is significantly larger than mean SDI of 200 for non-attacked plots (from paired t-test with 0.5 probability level). Distributions were computed from plot data by averaging backdated SDI across 4 consecutive years.

data were from a sample survey of beetle attacks at various infestation stages. Evidence of beetle attack on individual trees or amount of a plot attacked was easily observed, but unattacked trees and plots posed some uncertainty. Was the unattacked tree or plot less desirable for bark beetles, or was it suitable habitat that was not yet exploited? Also, since trees were sampled at a single point in time, the stage of an outbreak or its final extent was unknown.

With these concerns in mind, data were subset and backdated for analysis to represent plot conditions at the time of the first attack. Out of 900 plots, the subset included only 163 plots showing bark-beetle activity. If at least 1 tree on each plot was attacked, we assumed that all trees within the plot were challenged by bark beetles. Therefore, non-attacked trees were considered less susceptible due to resistant attributes of the individual tree or surrounding stand.

Trees attacked by bark beetles were backdated for analysis to represent a time series from 3 years before sampling. Using estimated year of beetle attack, the plots were reconstructed to correspond to conditions for the first year of beetle entry. This allowed modeling to focus on attacked trees in comparison to the stand conditions that initially attracted the beetles. Annual backdating beyond 3 years was impossible because older beetle attacks could not be readily determined in the field.

The subsetting and backdating of plots to mimic conditions at the time of the first beetle attack reduced data available for modeling. The number of non-attacked trees was reduced from 10,857 to 1,722, since only 163 plots had at least 1 attacked tree. The number of attacked trees was reduced from 719 to 478, since trees attacked in years subsequent to the initial beetle attack were treated as non-attacked. Hence, attacked trees in the analysis were only associated with stand conditions that first attracted bark beetles. If trees attacked in the years after the initial beetle entry had been included, the model would have confounded susceptibility prediction with sustaining an attack. The data supported this distinction, because the average diameter of trees attacked in the years following the initial beetle entry was about 2.0-inches smaller than average diameter of trees initially attacked.

Therefore, we assumed that all trees used in the analysis were challenged by bark beetles and were modeled as a binomial response variable (1 = attacked, 0 = not attacked). Modeling used logistic regression to estimate the probability of attack from the available tree and stand variables. This technique met the need for an objective analysis and allowed flexibility to easily scale results up to a stand level.

Potential predictor variables represented 3 levels of scale resolution: tree, plot, or site. Tree-level variables included dbh, height, growth, age, and Keen's classification. Variables describing plots and sites were computed for the same attributes, but site variables were averaged over 20 plots. Plot variables described each 0.1-acre plot as a microsite. The variable list included slope, aspect, elevation, crown cover, number of trees, basal area, quadratic mean diameter, and stand density index. Plot and site variables for tree attributes were calculated for all live ponderosa and, again, for currently attacked ponderosa. In addition, calculations were repeated to establish variables for all trees larger than threshold diameters of 1.0, 3.0, 5.0, and 9.0 inches. The final list totaled about 50 variables.

Stepwise logistic regression (SAS 1989) was used to select a model from the list of potential variables. The most important variable identified was a plot-level stand density index calculated from only the trees on a plot that were currently under beetle attack (BSDI) (table 4). Next in importance was tree dbh. Other significant variables were plot-level basal area (BA) and quadratic mean diameter (QMD) for live ponderosa pine, which were included with negative coefficients indicating **more likely** beetle attack for smaller BA and QMD. Although somewhat contrary to expectations, Olsen and others (1996) observed similar results for relating the QMD attribute to mountain pine beetle attack in the Black Hills of South Dakota. Finally, a competition variable was included, which corresponded to the amount of SDI on a plot for all trees larger than each subject tree. This variable was zero for the largest tree on a plot, and it progressively increased for each smaller tree until almost reaching total plot SDI for the smallest tree.

Although many site-level variables were available for the stepwise variable-selection process, none were selected by the regression algorithm. This may indicate that individual-tree attack is more influenced by micro sites (i.e., plot-level variables) than by overall stand conditions.

The R^2 goodness-of-fit statistic indicated about half of the total variation explained by the logistic model (table 4), and most of this was due to inclusion of the beetle-attacked SDI variable (BSDI). The

Table 4. Individual tree model[a] for estimating probability of beetle attack (*p*), model developed using stepwise logistic regression. Sample included 478 beetle-attacked ponderosa pine and 1,722 non-attacked ponderosa, R^2=0.47.

Model variable description	Number entered	Parameter estimate	Pr > X^2 (significance)
intercept		$\hat{\beta}_0$: -0.0595	0.9283
X_1 : plot SDI, for current year beetle-attacked ponderosa (BSDI)	1	$\hat{\beta}_1$: 0.0226	0.0001
X_2 : ln(dbh)	2	$\hat{\beta}_2$: 3.0603	0.0001
X_3 : plot ln(BA), for ponderosa	3	$\hat{\beta}_3$: -1.7586	0.0001
X_4 : plot QMD, for 9-inch dbh and larger ponderosa	4	$\hat{\beta}_4$: -0.1604	0.0001
X_5 : plot SDI larger than subject tree	5	$\hat{\beta}_5$: 0.0046	0.0002

[a]Logistic regression model: $\text{logit}(p) = \hat{\beta}_0 + \hat{\beta}_1 X_1 + \hat{\beta}_2 X_2 + \hat{\beta}_3 X_3 + \hat{\beta}_4 X_4 + \hat{\beta}_5 X_5$

$$p = e^{\text{logit}(p)} / (1 + e^{\text{logit}(p)})$$

R^2 for the total model was 0.47, and it was 0.28 when excluding all variables except BSDI. For a model including only 2 most important variables, BSDI and dbh, the R^2 was 0.37.

Model Application

Direct application of the logistic regression model to stand data has the drawback of being highly dependent upon current beetle situation in the stand (BSDI or X_1 in table 4). In other words, the model lacks some practicality because its predictive warning of high beetle attack depends upon whether beetles have already invaded a stand. However, the model does provide an objective means to rank data when simulating different bark-beetle population levels. Ranking is possible by using actual stand data for all variables except X_1, which are defined for different levels of beetle attack. By defining X_1 for a fixed level, the remaining model variables rate stands exclusively from stand characteristics.

To illustrate use of the logistic model (table 4), where X_1 is fixed, the proportion of trees susceptible to attack was calculated for each plot. This was done by multiplying estimated *p* (from *logit (p)* in table 4) times basal area for each ponderosa tree to obtain the percentage of tree basal area attacked and then summing percentages for each site. Actual tree and plot data were used for variables X_2 through X_5, but X_1 was defined as 75% of ponderosa SDI beetle attacked to standardize model ratings for estimating susceptibility in the event of a severe attack. Because different percentages used for defining X_1 will yield different trends (figure 5), such a model rating is a relative index.

Results and Discussion

Of the 2 empirical rating systems, the Munson/Anhold method compared most favorably to logistic-model rating (table 5). For example, Munson/Anhold risk ratings were within ±19 of the logistic regression ratings according to regression analysis (figure 6). This meant the two methods had the same general trend for rating susceptibility from stand characteristics. Although the comparison (figure 6) showed the endpoints of the Munson/Anhold system clumped toward the center rating, which indicates logistic regression rates susceptibility on a wider ranging scale.

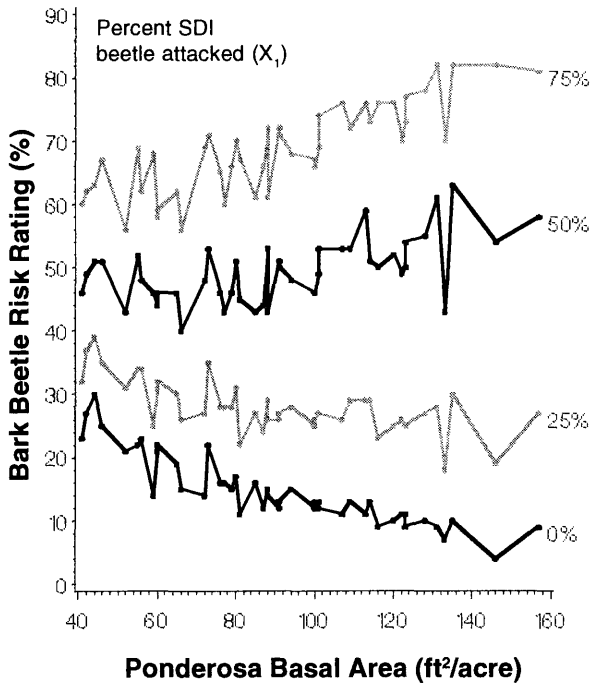

Figure 5. The logistic regression model (table 4) provides different rating scales for different values of percentage of SDI beetle attacked (X_1). Except for X_1, all other variables (X_2-X_5) were calculated from the actual data from the 45 study sites (X_1 = 0%, 25%, 50%, or 75% of ponderosa SDI on study site).

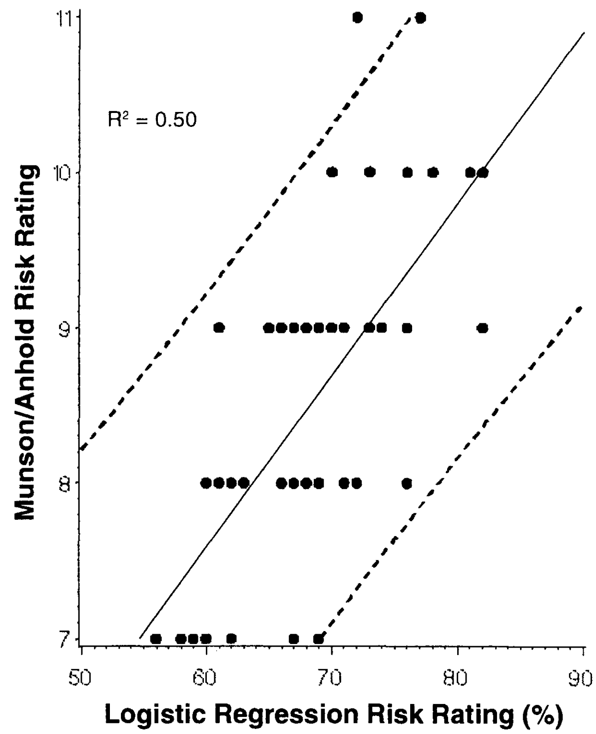

Figure 6. For the 45 study sites, Munson/Anhold risk ratings can be estimated to within 19 from the logistic regression rating percentage (according to 95% confidence intervals for individual predictions).

A similar regression analysis between Stevens/McCambridge/Edminster and logistic methods showed less agreement. The 95% confidence ranged from 50% to over 100%, and there was little evidence to suggest that 2 methods rate in a similar trend.

The Munson/Anhold method seems to rate a rather broad range of ponderosa pine stand conditions as either moderate or high (table 5). Perhaps factors other than stand conditions alone should be considered in rating stands for bark-beetle impact. Anhold and Jenkins (1987) had difficulty explaining population trends for mountain pine beetle only in terms of lodgepole pine stand density (SDI), and others have shown that a measure of susceptibility that considers only stand conditions is just a first step in the process (Bentz and others 1993; Shore and Safranyik 1992). For example, a highly susceptible stand could have a very low risk until the appropriate weather conditions occur and a beetle population in the area increases beyond endemic stage. At this point, the stand would have a high risk due to the nearby beetle population and susceptible stand conditions.

Future work on rating bark-beetle impact should consider more than stand characteristics. Maybe bark-beetle population dynamics and weather are more important than host-tree density for sustaining an outbreak (Bentz and others 1991; Bartos and Amman 1989; Raffa and Berryman 1982). Results from this study indicate that increasing beetle attack is correlated with increasing SDI, but high SDI may not be a significant factor for outbreak initiation. For example, beetle attack within SDI classes showed steady increase (from 1.9% to 29.5%) as SDI increased, but the total percentage of plots attacked from SDI class-to-class increased much less (from 0.2% to 4.9%) as SDI increased (table 6). Other unknown factors independent of stand density may initially draw bark beetles to a stand, but once in a stand the beetles seek out the pockets of higher SDI.

Table 5. Munson/Anhold bark-beetle risk rating for 45 study sites compared most favorably to rating from logistic model. The logistic rating was computed with variable X_1 (beetle-attacked SDI) equal to 75% of ponderosa SDI on each plot. Other data are site averages backdated to time of first beetle attack.

	Empirical ratings			Ponderosa pine						All species	
				(3-inch dbh and larger)					9+ dbh	3+ dbh	
Site No.	Munson Anhold	Stevens McCam. Edmin.	Log. model rating @ 75%	Live trees (No./acre)	Attacked trees (No./acre)	Live BA (ft^2/acre)	Live SDI	Live QMD (inches)	Live QMD (inches)	Live trees (No./acre)	Live SDI
13	Mod-7	Low -6	56	91	1	52	87	10	14	93	87
16	Mod-7	Low -4	56	176	1	66	116	8	15	193	126
19	Mod-7	Low -4	58	105	4	60	103	10	13	138	114
43	Mod-7	Low -6	59	70	1	60	92	13	16	135	133
14	Mod-7	Low -4	60	91	1	41	73	9	13	101	78
22	Mod-8	Low -6	60	99	0	77	119	12	17	103	120
40	Mod-9	Mod-12	61	74	3	85	120	15	19	191	157
42	Mod-8	Mod-12	61	115	2	88	131	12	19	282	255
15	Mod-7	Low -6	62	75	0	42	72	10	13	123	109
28	Mod-8	Low -6	62	50	1	56	79	14	19	61	83
44	Mod-8	Hi -18	62	101	28	65	109	11	14	216	187
35	Mod-8	Low -6	63	42	1	44	68	14	15	56	75
18	Mod-9	Mod-12	65	85	1	76	119	13	15	248	169
9	Mod-8	Mod-12	66	164	0	87	154	10	12	175	162
33	Mod-8	Hi -18	66	119	1	79	133	11	13	220	192
41	Mod-9	Mod-12	66	68	2	100	140	16	19	185	170
17	Mod-9	Mod-12	67	51	2	100	136	19	20	113	150
29	Mod-7	Mod -8	67	87	2	46	78	10	14	284	231
36	Mod-8	Hi -18	67	45	2	81	103	18	25	220	265
8	Mod-8	Mod-12	68	47	3	59	80	15	22	252	233
27	Mod-9	Mod-12	68	70	3	94	139	16	17	72	140
5	Mod-7	Mod-12	69	74	6	55	88	12	15	368	267
6	Mod-9	Mod-12	69	80	0	101	143	15	19	88	159
30	Mod-8	Mod-12	69	105	4	72	118	11	14	246	233
1	Mod-9	Mod -8	70	220	9	122	192	10	18	286	227
4	Mod-9	Hi -27	70	127	34	80	133	11	14	446	323
37	Hi -10	Hi -18	70	78	6	133	173	18	24	312	296
7	Mod-8	Hi -18	71	44	1	73	102	18	19	288	343
38	Mod-9	Hi -18	71	46	8	91	124	19	20	177	247
23	Hi -11	Mod-12	72	98	25	109	163	14	17	104	164
25	Mod-8	Mod-12	72	110	3	88	140	12	15	242	211
34	Mod-8	Hi -18	72	186	26	91	159	9	14	414	297
2	Hi -10	Mod-12	73	103	0	123	176	15	19	112	183
31	Mod-9	Hi -18	73	138	1	114	185	12	13	143	189
39	Mod-9	Mod-12	74	101	1	101	151	14	17	216	186
12	Mod-9	Hi -18	76	187	13	116	202	11	12	197	210
20	Mod-8	Hi -18	76	155	0	107	177	11	14	182	195
26	Mod-9	Mod-12	76	126	2	113	174	13	16	127	174
32	Hi -10	Hi -18	76	152	10	120	195	12	14	187	221
11	Hi -11	Mod-12	77	232	38	123	207	10	14	344	264
3	Hi -10	Hi -18	78	125	2	128	181	14	20	184	228
21	Hi -10	Hi -18	81	138	3	157	233	14	16	143	236
10	Mod-9	Mod-12	82	529	1	146	285	7	13	626	350
24	Hi -10	Mod-12	82	125	4	131	205	14	15	149	210
45	Hi -10	Hi -18	82	151	4	135	210	13	16	248	259

Table 6. Number of plots by stand density index (SDI) class that are beetle attacked. Maximum SDI for ponderosa pine is 450.

SDI class	Percent of max SDI	Total plots	Plots beetle attacked within SDI class		
				Percent of SDI class	Percent of total
<45	<10	107	2	1.9	0.2
45-90	10-20	166	21	12.7	2.3
90-135	20-30	181	27	14.9	3.0
135-180	30-40	153	33	21.6	3.7
180-225	40-50	144	36	25.0	4.0
225-450	50-100	149	44	29.5	4.9
Total		900	163		18.1

Management Implications

Although native bark-beetle species kill trees that input important dead wood into ecosystems, resource managers face many situations where insect outbreaks warrant intervention. Methods to rate forest stands according to likelihood of bark-beetle outbreak are useful to silviculturalists, recreation planners, forest health specialists, and others.

This study indicates the Munson/Anhold rating system is reasonable for use in ponderosa pine stands in the Colorado Plateau region. The Stevens/McCambridge/Edminster method, developed for the Black Hills, is less appropriate for the Colorado Plateau. The logistic regression method offers another rating system for simulating projected stand conditions for different beetle population levels. However, use any mountain pine beetle risk-rating method with caution because no method based on stand characteristics alone is likely to rate risk of beetle entry into a given stand. The methods are trustworthy in predicting that once beetles enter a stand, the more dense stands with larger stand density index (SDI) can be expected to have greater beetle attack.

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