Estimating Extent of Mortality Associated with the Douglas-fir Beetle in the Central and Northern Rockies

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ABSTRACT: *Data collected from Douglas-fir* (Pseudotsuga menziesii) *stands infested by the Douglas-fir beetle* (Dendroctonus pseudotsugae) *in Wyoming, Montana, Idaho, and Utah, were used to develop models to estimate amount of mortality in terms of basal area killed. Models were built using stepwise linear regression and regression tree approaches. Linear regression models using initial Douglas-fir basal area were built for all study sites but produce low precision estimates. Regression tree models using initial Douglas-fir basal area or stand density index or both were also built for all sites. Regression tree models provide a more realistic approach to estimate potential mortality by creating more homogenous mortality classes with reduced variance. The models developed provide land managers with a basis for determining the potential mortality should a Douglas-fir beetle outbreak develop. West. J. Appl. For. 14(3):121–127.*

The Douglas-fir beetle (*Dendroctonus pseudotsugae*) is the most important bark beetle affecting Douglas-fir (*Pseudotsuga menziesii*) in the western United States (Furniss and Carolin 1977). Endemic populations usually

attack felled or injured trees in stands predisposed by disturbance agents such as windthrows, defoliation, snow breakage, and fire (Wright and Lauterbach 1958, Lejeune et al. 1961, McMullen and Atkins 1962, Furniss 1965, Rudinsky 1966, McGregor et al. 1974, Berryman and Wright 1978, Wright et al. 1984). Under certain circumstances, which are not completely understood, epidemic populations develop that are able to attack and kill large numbers of apparently healthy trees (Johnson and Bellushi 1969, Furniss et al. 1979).

An important issue for land managers is to be able to estimate the amount of mortality likely to be sustained as a result of a Douglas-fir beetle outbreak. This information can facilitate decision making about how to manage stands to reduce potential mortality.

Some aspects of the biological relationship between the Douglas-fir beetle and its host have been captured in descriptive models. These models seek to explain how various factors affect Douglas-fir beetle abundance and

host susceptibility (Furniss et al 1979, 1981) and to provide a classification system to assist land managers in rating stands for the amount of mortality likely to occur (Weatherby and Thier 1993).

The model proposed by Furniss et al. (1979, 1981) suggests that the Douglas-fir beetle prefers attacking stands of advanced age, high tree density, and a high proportion of Douglas-fir. Weatherby and Thier (1993) describe a system developed by Thier for classifying Douglas-fir beetle-caused mortality. In that system, potential mortality is based on stand basal area, proportion of stand basal area that is Douglas-fir, average stand age, and average diameter at breast height (dbh) of Douglas-fir greater than 9 in. dbh. The highest potential level of mortality is predicted to occur where stand basal area is higher than 250 ft^2/ac, proportion of stand basal area that is Douglas-fir is more than 50%, average stand age is greater than 120 yr, and average Douglas-fir dbh greater than 9 in. is greater than 14 in.

To date there are no published quantitative relationships between stand conditions and Douglas-fir beetle-caused mortality. The objective of this study was to develop models to estimate amount of mortality caused by the Douglas-fir beetle based on stand conditions in various geographical regions.

Methods

Study sites were established in the Shoshone National Forest in Wyoming (hereafter the Shoshone site); the Gallatin, Beaverhead, Helena, and Flathead National Forests in Montana, the Nez Perce and Idaho Panhandle National Forests in Northern Idaho (hereafter the Montana site); the Boise, Payette, and Sawtooth National Forests in Idaho (hereafter the Idaho site); and the Wasatch-Cache, Manti-LaSal National Forests in Utah, and the Bridger-Teton National Forest in Wyoming (hereafter the Utah site) In some instances, different study sites contain areas from the same states; however, the study sites represent areas of geographical proximity and similar ecological conditions. Study sites were selected based on aerial survey detection or ground based information or both. Infested stands were randomly selected and variable radius plots established in each selected stand. Plot location was established by entering the infested portions of the stand and then using a randomly determined distance and azimuth to determine plot location. Data collection for the Shoshone site began in 1992 and was completed in 1995. Data for all other sites were collected in 1994 and 1995

Douglas-fir beetle populations had been active in all study areas for a number of years. Populations had been triggered by a variety of disturbance agents. Primary agents initiating populations were fire in the Shoshone study site, Douglas-fir tussock moth (*Orgyia pseudotsugata*) defoliation in parts of Idaho, and windstorms in the Montana and Utah study sites. Stands sampled varied in infestation history. In the Montana study site, the outbreak had recently collapsed. In the Shoshone site, the outbreak was subsiding, but new mortality was still occurring. In Idaho and Utah, mortality was at outbreak levels in many areas. All our study sites, however, were experiencing decreased mortality levels. We base these observations on current survey information and on the number of plots established that included currently infested trees Habitat types and elevation were variable across all study sites, but most plots were in stands typed in the *Pseudotsuga menziesii* series with similar common habitat types across all sites (Table 1).

At each point established, tree species was determined for all point trees. Data collected for all point trees included dbh, total height, and tree status (alive, infested, or killed by Douglas-fir beetle, or dead from other causes). For the first two to four Douglas-firs in the point starting from the north

Table 1. Number of plots with currently infested trees, range in elevation. and number of plots per habitat type series for each study site.

Site/total plots	Plots with currently infested trees	Elevation (ft)	Habitat type series	N
Shoshone/143	64	6,200–8,400	*Pseudotsuga menziesii*[1]	81
			Abies lasiocarpa	23
			Picea engelmanii	21
			Not typed	18
Montana/85	2	2,760–7,360	*P. menziesii*[1]	66
			A. lasiocarpa	2
			A. grandis	16
			Not typed	1
Idaho/68	12	5,800–6,800	*P. menziesii*[2]	58
			A. lasiocarpa	8
			A. grandis	2
Utah/54	7	6,000–9,120	*P. menziesii*[3]	37
			A. lasiocarpa	11
			A. concolor	4
			P. contorta	2

[1] Most common habitat types *Pseudotsuga menziesii/Symphoricarpus albus, P. menziesii/Physocarpus malvaceous,* and *P. menziesii/Calamagrostis rubescens.*

[2] Most common habitat types *P. menziesii/Acer glabrum, P. menziesii/Spiraea betulifolia* and *P. menziesii/Berberis repens.*

[3] Most common habitat types *P. menziesii/B. repens, P. menziesii/P. malvaceous,* and *P. menziesii/A. glabrum.*

Table 2. Mean (± SEM) for variables measured by study location.

Variable	Shoshone	Montana	Idaho	Utah
Number of points	143	85	68	54
Douglas-fir dbh (in.)	16.6 (0.3)c[1]	18.8 (0.4)b	21.0 (0.7)a	19.5 (0.8)ab
Douglas-fir quadratic mean diameter (in.)	16.4 (0.3)b	19.9 (0.5)a	21.7 (0.7)a	20.2 (0.8)a
Douglas-fir dbh of trees >16 in. dbh (in.)	21.3 (0.3)c	21.7 (0.3)bc	23.7 (0.6)a	23.0 (0.6)ab
Douglas-fir dbh of trees >9 in. dbh (in.)	17.6(0.3)c	19.1(0.4)bc	21.4(0.7)a	20.0(0.7)ab
Percent basal area of Douglas-fir >16 in. dbh	46.3 (2.0)b	59.3 (2.5)a	58.4 (3.0)a	59.8 (3.8)a
Percent basal area of Douglas-fir >9 in. dbh	80.5 (1.7)a	87.2 (1.6)a	82.3 (2.6)a	81.4 (2.6)a
Douglas-fir total height (ft)	69.7 (1.2)b	84.2 (2.2)a	85.3 (2.0)a	75.7 (2.2)b
Total basal area (ft^2/ac)	183.4 (6.4)a	187 (6.2)a	156.8 (7.1)b	153.7 (9.6)b
Douglas-fir basal area (ft^2/ac)	161.5 (6.1)ab	168.6 (6.4)a	134.1 (7.7)c	135.2 (9.6)bc
Basal area killed by Douglas-fir beetle (ft^2/ac)	95.9 (5.4)a	68.8 (4.1)b	82.3 (5.9)ab	87.6 (7.4)ab
Percent basal area represented by Douglas-fir	89.5 (1.5)a	90 (1.6)a	85.7 (2.6)a	86.9 (2.5)a
Percent of Douglas-fir basal area killed by Douglas-fir beetle	59.7 (2.3)a	41.9 (1.9)b	64.0 (3.2)a	66.1 (3.3)a
Trees/ac	121.9 (3.4)b	192.2 (6.3)a	58.1 (5.9)c	68.9 (5.0)c
Stand density index	271.2 (8.2)b	303.8 (9.5)a	204.0 (10.1)c	203.5 (10.0)c
Douglas-fir age	165.2 (4.0)a	157.6 (5.0)a	112.6 (0.7)b	161.9 (5.7)a

[1] Means within rows followed by the same letter are not significantly different at the 0.05 level, Tukey's HSD test.

and counting clockwise, an increment core was extracted at dbh and used to determine tree age. Data collected were then used to generate metrics, such as average Douglas-fir dbh, Douglas-fir quadratic mean diameter, average Douglas-fir total height, average Douglas-fir dbh of trees ≥ 9 and ≥ 16-in. dbh, Douglas-fir basal area, proportion of basal area in Douglas- fir, proportion of basal area of Douglas-fir ≥ 9 and ≥16 in. dbh, trees per acre (dbh ≥ 5.0 in.), and stand density index (Avery and Burkhart 1994).

Statistical differences were detected among the sites for all variables except the percent of basal area represented by Douglas-fir or the percent of Douglas-fir basal area represented by trees larger than 9 in. dbh (Table 2). In general, stocking levels were higher in the Shoshone and Montana study sites when compared to the Idaho and Utah study sites. Tree diameters were somewhat reduced at the Shoshone and Montana study sites when compared to the Idaho and Utah study sites, but the difference was less when only trees ≥ 9 or ≥ 16 in. dbh are considered. Tree heights were also somewhat lower at the Shoshone and Utah study sites. Percent basal area represented by trees ≥ 16 in. dbh was lower at the Shoshone site. Average age was lower at the Idaho study site, and percent basal area killed by the Douglas-fir beetle was lower at the Montana site.

Data were analyzed using two approaches. At first, the amount of basal area killed by Douglas-fir beetle was modeled by using a linear regression analysis that utilized the variables generated and a stepwise regression approach (SAS® 1990). The second approach employed a technique called Classification and Regression Trees

(CART) (Breiman et al. 1984). A module developed for use with SYSTAT® was used to conduct the CART analysis (Steinberg and Colla 1992). The result is a binary tree that uses the best predictor variables as splitting rules and terminal nodes with a node-specific average of the dependent variable, which in this case is the amount of basal area killed by Douglas-fir beetle. Coefficients of determination (R^2) were calculated for the regression tree models by calculating the residuals and constructing an analysis of variance table.

Results

Linear regression analysis indicated that initial basal area of Douglas-fir was the best predictor variable for basal area killed by the Douglas-fir beetle at all four locations. Relationships were significant at all sites, and coefficients of determination (R^2) ranged from 0.26 to 0.65. Positive slopes indicated increased tree mortality with increasing Douglas-fir basal area. Regression coefficients indicated unit increases in basal area killed, with increases ranging from 0.33 to 0.63 ft^2/ac of basal area (Table 3).

The first of two regression tree models resulting from the analysis of the Shoshone data set used Douglas-fir basal area and stand density index as splitting variables (Figure 1a; $R^2 = 0.49$). By removing stand density index during model construction, another regression tree using only Douglas-fir basal area as the splitting variable was produced ($R^2 = 0.46$). In this second model (no figure

Table 3. Y-intercept, slope, coefficient of determination, mean square error, and significance level for estimate of mortality prediction equations, $y = b_0 + b_1 x$, where y is Douglas-fir mortality in terms of ft^2/ac of basal area, and x is Douglas-fir basal area in terms of ft^2/ac.

Site	y-intercept (b_0)	Slope (b_1)	Coefficient of determination (R^2)	Mean square error	Significance P
Shoshone	−0.52	0.6	0.46	47.2	< 0.0001
Montana	13.2	0.33	0.26	32.4	< 0.0001
Idaho	15.8	0.5	0.41	37.5	< 0.0001
Utah	2.8	0.63	0.65	32.2	< 0.0001

presented) the first split is the same as shown in Figure 1a. The second split uses Douglas-fir basal area to split node 2b into two terminal nodes. With Douglas-fir basal area $\leq$ 300 ft^2/ac, average basal area killed was 126.5 (SEM $\pm$ 7.9) ft^2/ac and included 62 cases. With Douglas-fir basal area > 300 ft^2/ac, average basal area killed was 270 (SEM $\pm$ 19.1) ft^2/ac and included four cases. Higher stand density index in the first model and higher Douglas-fir basal area in both models were associated with higher Douglas-fir beetle-caused mortality levels. Both regression tree models and the linear regression model had comparable coefficients of determination.

The first regression tree model constructed with the Montana data selected stand density index as the splitting variable, with higher stand density index resulting in higher Douglas-fir beetle-caused mortality (Figure 1b; R^2 = 0.23). By removing variables during model construction, a second regression tree model was generated in which Douglas-fir basal area was the driving variable (Figure 1c; R^2 = 0.33). This model made two splits based on Douglas-fir basal area, with higher levels of basal area associated with increased Douglas-fir beetle-caused mortality. Coefficient of determination for the Douglas-fir basal area-based model was higher than for the stand density-based model or the linear regression model.

The first regression tree produced for the Idaho data set includes one split made based on Douglas-fir basal area (Figure 1d; R^2 = 0.39). A second tree (no figure presented) used two consecutive splits on Douglas-fir basal area and had three terminal nodes (R^2 = 0.44). In the second tree, the first split is the same as the first tree, but Node 2 becomes an intermediate node and is split again into two terminal nodes. With Douglas-fir basal area $\leq$ 110 ft^2/ac, average basal area killed was 49.6 (SEM $\pm$ 4.2) ft^2/ac and included 27 cases. With Douglas-fir basal area > 110 ft^2/ac, average basal area killed was 76.5 (SEM $\pm$ 8.4) ft^2/ac and included 17 cases. In both regression tree models, higher Douglas-fir basal area resulted in higher levels of mortality caused by Douglas-fir beetle. Coefficients of determination for both regression tree models and the linear regression model are similar.

The first of two regression trees for the Utah data set makes only one split on Douglas-fir basal area (Figure 1e; R^2 = 0.58). An alternate regression tree with three terminal nodes (no figure presented) was also produced (R^2 = 0.69). Once again, in this second tree the first split is the same, but Node 2 becomes an intermediate node and is split into two terminal nodes. With Douglas-fir basal area $\leq$ 115 ft^2/ac, average basal area killed was 45.7 (SEM $\pm$ 3.9) ft^2/ac and includes 23 cases. With Douglas-fir basal area > 115 ft^2/ac, average basal area killed was 87.1 (SEM $\pm$ 8.9) ft^2/ac and includes 17 cases. In both regression trees, higher Douglas-fir basal area was associated with higher mortality levels. Coefficients of determination for the two regression tree models and the linear regression model for the Utah data set all have comparable values.
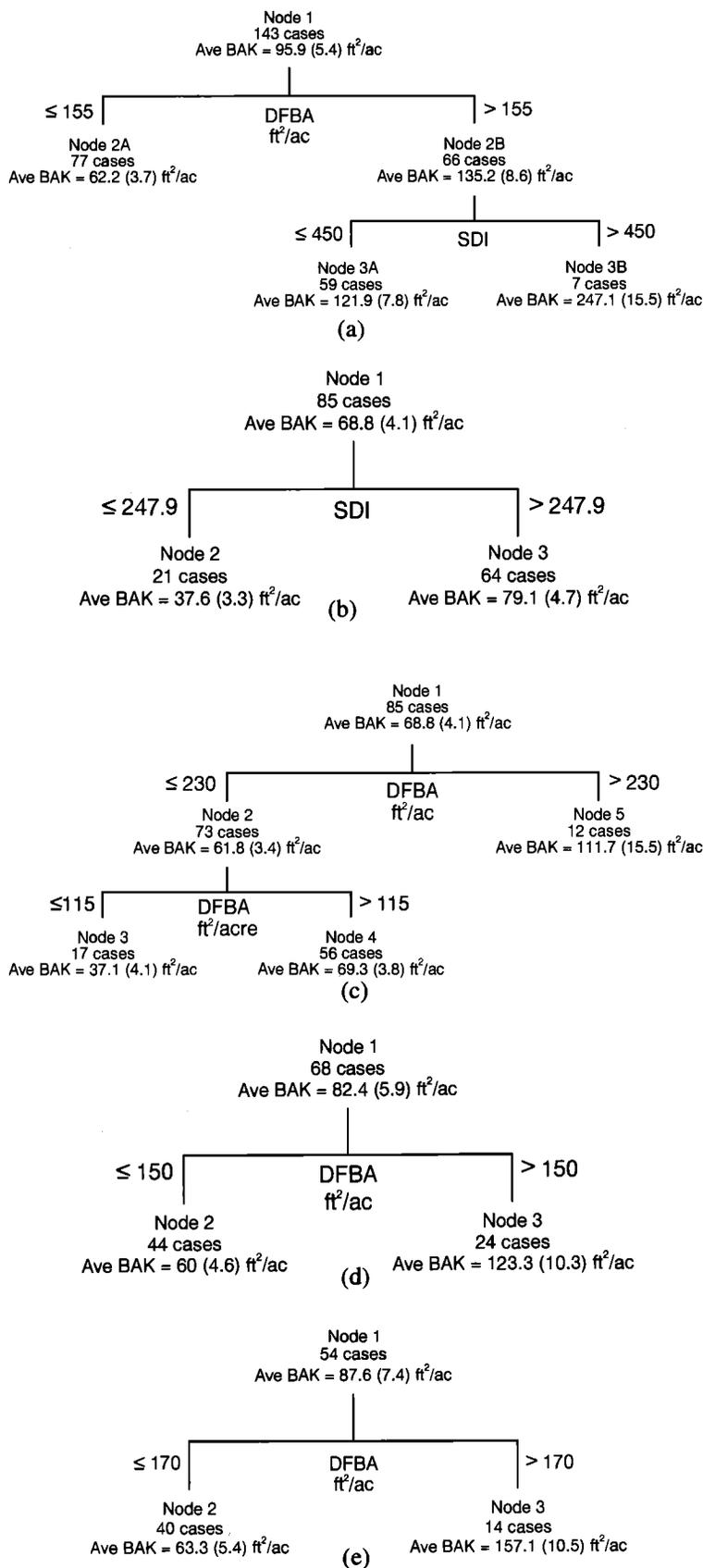
Results from the regression tree analysis were used to develop damage class levels for each location (Table 4).

The damage class levels are based on Douglas-fir basal area and are associated with average basal area killed by Douglas-fir beetle. These estimates exhibit reduced variability and increased precision as observed by the small standard errors of the mean. It should be noticed that differences in percent Douglas-fir basal area killed do not vary drastically among damage classes across all four sites. Increased Douglas-fir mortality, however, is associated with increased Douglas-fir basal area levels. On average, substantial losses of at least 41% of the Douglas-fir basal area were observed in all infested stands relative to initial Douglas-fir basal area. For the Shoshone study site, because only four plots had Douglas-fir basal area higher than 300 ft^2/ac, it may be advantageous to create a medium-high category when the Douglas-fir basal area is greater than 155 ft^2/ac, with average Douglas-fir beetle mortality being 135.2 (SEM $\pm$ 8.6) ft^2/ac.

Discussion

Relationships were built in this study primarily using Douglas-fir basal area and, to a lesser degree, stand density index as independent variables to model basal area killed by the Douglas-fir beetle. The models explain from 26 to 63% of the variation in mortality. This is fairly strong when the wide range of factors that may influence Douglas-fir beetle populations and the extent of mortality associated with outbreaks are considered. Mortality levels associated with Douglas-fir beetle outbreaks are influenced by multiple factors, such as tree densities, stand age, percent basal area in Douglas-fir, stand basal area, and average diameter of Douglas-fir (Furniss et al. 1979, 1981, Weatherby and Thier 1993). Abiotic agents, such as weather patterns, elevation and aspect of the stand, or position on the slope, may also affect beetle populations due to differential microsite conditions in which infestations develop.

The relationship suggested in this study between Douglas-fir basal area and subsequent mortality is consistent with other studies for other bark beetle species. McCambridge et al. (1982) indicated that there was a positive correlation between initial basal area of ponderosa pine (*Pinus ponderosa*) and the number of trees killed by the mountain pine beetle (*D. ponderosae*) in north-central Colorado. Sartwell and Stevens (1975) indicate that high stand densities (in excess of 150 ft^2/ac) are among stand conditions that favor mountain pine beetle outbreaks in ponderosa pine. Basal area killed by the spruce beetle (*D. rufipennis*) in Alaska in Lutz spruce (*Picea* $\times$ *lutzii*) stands and in Lutz and Sitka spruce (*Picea sitchensis*) has been shown to be related to total stand basal area, percent of total basal area comprised by spruce, and the percent of spruce basal area composed of trees > 9.8 in. (Reynolds and Holsten 1994, 1996). More recently, ponderosa pine basal area has been used to estimate mortality caused by the roundheaded pine beetle (*D. adjunctus*) in south-central New Mexico (Negron 1997) and Douglas-fir beetle basal area to estimate mortality caused by the Douglas-fir beetle in the Colorado Front Range (Negron 1998).

(a)

Node 1
143 cases
Ave BAK = 95.9 (5.4) ft²/ac

DFBA ft²/ac

≤ 155

Node 2A
77 cases
Ave BAK = 62.2 (3.7) ft²/ac

> 155

Node 2B
66 cases
Ave BAK = 135.2 (8.6) ft²/ac

SDI

≤ 450

Node 3A
59 cases
Ave BAK = 121.9 (7.8) ft²/ac

> 450

Node 3B
7 cases
Ave BAK = 247.1 (15.5) ft²/ac

(b)

Node 1
85 cases
Ave BAK = 68.8 (4.1) ft²/ac

SDI

≤ 247.9

Node 2
21 cases
Ave BAK = 37.6 (3.3) ft²/ac

> 247.9

Node 3
64 cases
Ave BAK = 79.1 (4.7) ft²/ac

(c)

Node 1
85 cases
Ave BAK = 68.8 (4.1) ft²/ac

DFBA ft²/ac

≤ 230

Node 2
73 cases
Ave BAK = 61.8 (3.4) ft²/ac

> 230

Node 5
12 cases
Ave BAK = 111.7 (15.5) ft²/ac

DFBA ft²/acre

≤ 115

Node 3
17 cases
Ave BAK = 37.1 (4.1) ft²/ac

> 115

Node 4
56 cases
Ave BAK = 69.3 (3.8) ft²/ac

(d)

Node 1
68 cases
Ave BAK = 82.4 (5.9) ft²/ac

DFBA ft²/ac

≤ 150

Node 2
44 cases
Ave BAK = 60 (4.6) ft²/ac

> 150

Node 3
24 cases
Ave BAK = 123.3 (10.3) ft²/ac

(e)

Node 1
54 cases
Ave BAK = 87.6 (7.4) ft²/ac

DFBA ft²/ac

≤ 170

Node 2
40 cases
Ave BAK = 63.3 (5.4) ft²/ac

> 170

Node 3
14 cases
Ave BAK = 157.1 (10.5) ft²/ac

Figure 1. Regression trees for estimating mortality associated with the Douglas-fir beetle across all study sites [Ave BAK (± SEM) = Average basal area killed; DFBA = Douglas-fir basal area; and SDI = stand density index]: (a) Shoshone; (b) Montana 1; (c) Montana 2; (d) Idaho; (e) Utah.

Table 4. Damage classes obtained from regression tree estimates for each study location showing observed average amount of basal area killed and average percent Douglas-fir basal area killed by the Douglas-fir beetle with indicated Douglas-fir basal area levels.

Site	Douglas-fir basal area (ft²/ac)	Douglas-fir basal area killed by Douglas-fir beetle	
		ft²/ac (±SEM)	% (±SEM)
Low			
Shoshone	DFBA≤155	61.9(3.7)	58.4(3.2)
Montana	DFBA≤115	37.1(4.1)	44.5(4.4)
Idaho	DFBA≤110	49.6(4.2)	68.6(5.2)
Utah	DFBA≤115	45.7(3.9)	66.4(5.5)
Medium			
Shoshone	155<DFBA≤300	126(7.8)	59.9(3.7)
Montana	115<DFBA≤230	69.3(3.8)	40.9(2.4)
Idaho	110<DFBA≤150	76.5(8.4)	59.0(6.5)
Utah	115<DFBA≤170	87.1(8.9)	62.1(6.4)
High			
Shoshone	DFBA>300	270(19.1)	70.5(7.4)
Montana	DFBA>230	111.7(15.5)	43(5.9)
Idaho	DFBA>150	123.3(10.3)	62.4(5.3)
Utah	DFBA>170	157.1(10.4)	70.6(5.3)

Although coefficients of determination suggest a fairly strong linear relationship between Douglas-fir basal area and basal area killed, the predicted estimates from the equations yield low precision estimates. As an example, Figure 2 presents the relationship for the Shoshone study site with 95% confidence band for the estimation of individual observations. The wide range of the confidence band is reflective of the low precision in the estimates.

Mortality estimates obtained with the regression tree approach are more realistic. The regression tree approach used in this study is less effective when used with data where there is linear structure (Breiman et al. 1984). This is the case with the data sets presented in this study, as indicated by the significant linear equations built for all study sites. Under these circumstances, regression tree analysis yields results with successive splits using the same variable, which is what we obtained with our data. In this study, however, we were able to use this feature of the tree regression analysis to develop mortality categories

Figure 2. Relationship between Douglas-fir basal area (ft²/ac) and basal area killed by the Douglas-fir beetle (ft²/ac) for the Shoshone study site. Shaded area represents 95% confidence interval for individual observation prediction.

(Table 4). These mortality categories generated with CART represent relatively homogeneous clusters with reduced variance (Steinberg and Colla 1992).

The verbal model presented by Furniss et al. (1979, 1981) to explain factors that affect Douglas-fir beetle abundance and host susceptibility includes high tree densities and a high proportion of Douglas-fir. The rating system described in Weatherby and Thier (1993) also includes the proportion of Douglas-fir in the stand and total stand basal area. These metrics are related to Douglas-fir basal area, which was found to be the best variable to predict mortality due to Douglas-fir beetle. The data presented confirm that mortality levels associated with Douglas-fir beetle, as with other bark beetles, are an indication of stand stress caused in this case by overstocking.

All study locations had stand conditions suitable for the development of Douglas-fir beetle epidemics. That is, stands contained tree diameter classes, percent host type, and stocking levels that made the stands susceptible to the development of a Douglas-fir beetle outbreak. High Douglas-fir stocking levels alone do not increase the potential for mortality unless other conditions, such as the availability of large diameter trees, exist. Suitable conditions for the development of epidemics seem to vary somewhat from one site to another. When stand conditions exist for the development of an epidemic, however, results from this study suggest that Douglas-fir basal area then becomes an important driving factor in the amount of mortality likely to occur.

Land managers may use the linear regression equations presented here where there is a need to estimate the actual mortality likely to occur in a stand as a result of a Douglas-fir beetle outbreak. In using the linear regression models, however, the user needs to be aware of the relatively low precision estimates generated, as exemplified by the confidence bands in Figure 2. When a characterization of whether mortality in a stand is likely to be high, medium, or low is needed, the results from the regression tree approach are adequate and more reliable.
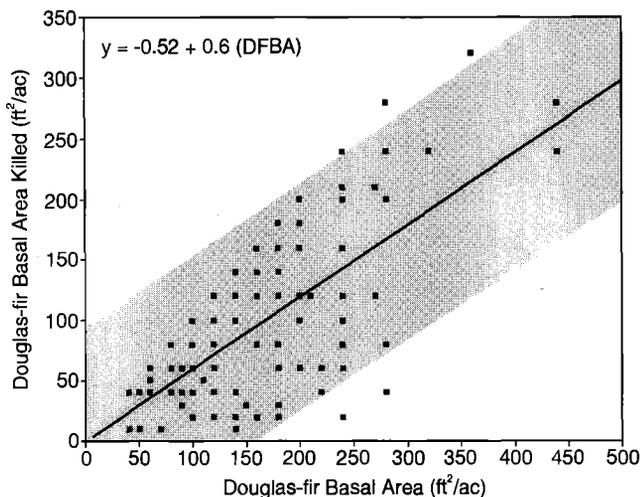
There was variation in infestation history across the study sites except for perhaps the Montana sites, where outbreaks had clearly subsided. This suggests that relationships built for the Idaho, Utah, and probably to a greater extent the Shoshone site, may underestimate the amount of potential mortality since the outbreaks had not completely subsided.

The simple models presented in this study provide land managers with empirically derived projections of potential mortality due to Douglas-fir beetle. This information can assist in developing priorities for stand treatments based on estimates of potential mortality from Douglas-fir beetle.

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