Susceptibility of lodgepole pine stands to the mountain pine beetle: testing of a rating system

T.L. Shore, L. Safranyik, and J.P. Lemieux

Abstract: A system for rating the susceptibility of lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) stands to the mountain pine beetle (*Dendroctonus ponderosae* Hopkins) was field tested in 38 stands in the Cariboo forest region of British Columbia in a retrospective study. A linear relationship was defined between the percentage of basal area killed by the mountain pine beetle and the susceptibility indices for the sample stands. The system was further tested using an independent data set of 41 stands from across southern British Columbia. Forty of the 41 stands fell within the 95% prediction interval of the original model data for stand susceptibility. This study provides validation for a susceptibility rating model described in 1992. The regression model and associated confidence interval also provide a useful tool for landscape level loss predictions due to the mountain pine beetle.

Résumé : Un système d'évaluation de la susceptibilité des peuplements de pin tordu latifolié (*Pinus ponderosa* Dougl. var. *latifolia* Engelm.) au dendroctone du pin ponderosa (*Dendroctonus ponderosae* Hopkins) a été mis à l'essai sur le terrain, dans 38 peuplements de la région de la forêt Cariboo en Colombie-Britannique, dans le cadre d'une étude rétrospective. Une relation linéaire a été trouvée entre le pourcentage de pertes de surface terrière causées par le dendroctone dans les peuplements échantillonnés et les indices de susceptibilité de ces derniers. Le système a de plus été testé à l'aide d'une base indépendante de données provenant de 41 peuplements du sud de la Colombie-Britannique. Les prédictions de la susceptibilité de 40 de ces peuplements étaient comprises à l'intérieur de l'intervalle de confiance de 95% défini à l'aide des données originales du modèle. Cette étude confirme la validité d'un modèle d'évaluation de la susceptibilité décrit en 1992. Le modèle de régression et l'intervalle de confiance qui lui est associé constituent également un outil pratique pour prédire les pertes imputables au dendroctone du pin ponderosa à l'échelle du paysage.

[Traduit par la Rédaction]

Introduction

The mountain pine beetle (*Dendroctonus ponderosae* Hopkins) is the most destructive insect pest of pine forests in western North America (Wood 1963). Adult beetles fly and attack mature pine trees in middle to late summer. Blue stain fungi, carried by the beetle, are introduced to the host during gallery excavation. The combination of pheromone-induced mass attack and fungal growth quickly kills the tree (Safranyik et al. 1974; Conn et al. 1983). In 1984, at the peak of the most recent epidemic, an estimated 41×10^6 lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) were killed over 482 000 ha (1.19×10^6 acres) in British Columbia (Wood et al. 1985).

Management strategies have historically consisted of salvaging beetle-killed trees or of direct control methods aimed at reducing beetle populations in currently infested trees (McMullen et al. 1986). To set priorities and facilitate planning of access roads for these treatments or to initiate preventative management treatments (Cole 1978), susceptibility and risk-rating systems for predicting the potential for damage to lodgepole pine stands by the mountain pine beetle are required.

For the purposes of this paper we define susceptibility, risk, and beetle pressure as in Shore and Safranyik (1992). "Susceptibility" is the inherent characteristics or qualities of a stand of trees that affect its likelihood of attack and damage by a mountain pine beetle population and is synonymous with the term "hazard." "Risk" is defined as the short-term expectancy of tree mortality in a stand as a result of a mountain pine beetle infestation. Risk is a function of stand susceptibility and beetle pressure. Beetle pressure is the magnitude of a mountain pine beetle population affecting a stand as determined by the number of currently infested trees and their proximity to the stand being assessed. Beetle pressure relates to the likelihood of a beetle population entering a given stand.

A number of hazard or risk rating systems aimed at stand-level classification have been developed for the mountain pine beetle (Amman et al. 1977; Mahoney 1978; Berryman 1978; Schenk et al. 1980; Waring and Pitman 1980; Stuart 1984; Anhold and Jenkins 1987). All of these systems with the exception of Schenk et al. (1980) were categorical designs where stands would be classified as likely to be attacked or not (Mahoney 1978; Waring and Pitman 1980; Stuart 1984), or assigned to a high, moderate, or low (or similar) hazard class (Amman et al. 1977; Berryman 1978; Anhold and Jenkins 1987).

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The system of Amman et al. (1977) uses categories of the variables tree diameter, elevation-latitude, and age to rate stands as low, moderate, or high hazard. Evaluations of this system generally found that it had a low rate of accuracy with a tendency to overrate stands (Mahoney 1978; Amman 1985; Shore et al. 1989; Bentz et al. 1993). One possible reason for the low accuracy of this system may be the assumption that diameter is related to phloem thickness, the primary feeding and breeding tissue of the tree for the beetle. This relationship was not found by other researchers (Katovich and Lavigne 1986; Shrimpton and Thomson 1985).

Mahoney (1978) developed a two-class system based on the variable periodic growth ratio (PGR), which is the ratio of the most recent 5 years radial growth to the previous 5 years radial growth. Stands having a ratio of 0.9 or less were considered to be in declining vigor and, therefore, susceptible to attack, and those with a ratio greater than 0.9 were considered to be resistant to attack. This system was not able to predict losses accurately in subsequent tests (Shrimpton and Thomson 1983; Stuart 1984; Amman 1985; Shore et al. 1989; Bentz et al. 1993). A basic problem with the system is that stands generally decline in growth past about age 30, and therefore, a ratio or less than 1.0 would be the norm for stands past this age (Shrimpton and Thomson 1983).

Berryman (1978) developed a theoretical model of stand susceptibility based on phloem thickness and stand resistance. This model had a relatively low rate of success at assigning stands to classes of extreme, high, and low susceptibility in subsequent tests (Amman 1985; Shore et al. 1989; Bentz et al. 1993). A shortcoming in this system may be the variable selected as an index of stand resistance. This variable consisted of the ratio between PGR and stand hazard rating (SHR) (Schenk et al.1980), described below, and thus inherited the problems described for those indices (Katovich and Lavigne 1986).

The system developed by Waring and Pitman (1980) involves calculating growth efficiency as the ratio of current growth (grams of stemwood produced) to crown leaf surface. These variables are difficult to collect and calculate and evaluations of this system have produced less than adequate results (Stuart 1984; Amman 1985; Katovich and Lavigne 1986; Shore et al. 1989).

Stuart (1984) developed a discriminant function to describe the probability of a stand falling into a susceptible or nonsusceptible class for the mountain pine beetle. This function used the variables quadratic mean tree diameter and number of rings in the outer 1 cm of radial growth. This relationship can only be considered valid for the small area from which the data was collected.

Anhold and Jenkins (1987) examined the relationship between stand density index (SDI) (Reineke 1933) and beetle-caused tree mortality. They found that SDI was not a good predictor of decreasing or increasing populations; however, ranges of SDI values were found to coincide with low potential for attack, increasing potential for attack, and declining potential for attack. From a theoretical standpoint, SDI would not appear to be a useful variable as an indicator of stand susceptibility to mountain pine beetle, because it is the product of two variables, trees per hectare and quadratic mean diameter. Therefore, a single value of SDI could be arrived at, for example, by a combination of numerous trees of small diameter or fewer trees of large diameter. It is well known that the beetle shows a preference for larger diameter trees; therefore, it is unlikely that these two stands would have similar susceptibility. It is likely that the findings of Anhold and Jenkins (1987) reflect mainly variations in stand density, because only larger diameter trees (>12.7 cm diameter at breast height (DBH)) were included, and larger trees are the most susceptible to the mountain pine beetle (Safranyik et al. 1974; Amman et al. 1977).

The system designed by Schenk et al. (1980) is the only one proposed that attempted to produce a SHR index that was a continuous variable and relate it to tree mortality caused by the mountain pine beetle. SHR was calculated using crown competition factor (Krajicek et al. 1961) and the proportion of lodgepole pine basal area in the stand. Tests of this system found that CCF and, therefore, SHR were inversely related to tree mortality caused by the beetle (McGregor et al. 1981; Shore et al. 1989, Bentz et al. 1993). The problem with the system appeared to be with the assumption that there was a positive relationship between stand density and mountain pine beetle caused tree mortality (Katovich and Lavigne 1986).

In 1992, Shore and Safranyik published a system that attempted to incorporate the best features of previous systems. It was considered important to have a continuous variable hazard rating system because a two- or three-class system is not sensitive enough to provide managers with sufficient information to assign management priorities. Also, it was considered a desirable feature that the hazard rating index should relate to beetle-caused tree mortality. These were features of the Schenk et al. (1980) system. Important variables that are known to affect stand susceptibility are age (Safranyik et al. 1974; Amman et al. 1977; Shrimpton and Thomson 1983), tree diameter (Safranyik et al. 1974; Amman et al. 1977), and climate, which were components of the Amman et al. (1977) system. Some measure of intertree competition or stand density was also considered to be important as was attempted in the systems of Berryman (1978), Waring and Pitman (1980), Schenk et al. (1980), and Anhold and Jenkins (1987). In addition we felt it important from a stand-rating perspective to include a measure of the species composition of the stand as did Schenk et al. (1980).

The Shore and Safranyik (1992) risk-rating system incorporated estimators of both stand susceptibility and beetle pressure. The susceptibility-rating system provides an index of potential loss of stand basal area in the event of a mountain pine beetle infestation and is, therefore, a long-term rating. The risk-rating system provides a short-term index of the likelihood of this event occurring and causing significant losses to the stand. Although this system has been in widespread use throughout British Columbia for a number of years and appears to work satisfactorily in terms of an observational correlation between the stand susceptibility rating and tree mortality caused by mountain pine beetle, it has never been officially evaluated.

This paper reports the results of a retrospective study in which the relationship between the Shore and Safranyik (1992) susceptibility index and tree mortality caused by the mountain pine beetle was examined for stands that had been exposed to mountain pine beetle epidemics that had naturally subsided. The risk-rating index was not evaluated because to do so would involve annual assessments of beetle pressure, stand susceptibility, and tree mortality for a large number of stands from the beginning of each infestation. The stand susceptibility index, however, was developed as an indicator of the final level of tree mortality that could occur in a stand over the course of an infestation. All stands studied were exposed to high beetle pressure for an extended period of time and, therefore, reflect the final levels of tree mortality expected from a mountain pine beetle infestation.

As a further test, data on stand susceptibility and mortality from an independent set of data covering a broader geographic area were utilized to see if they fit the model developed from the original data set.

Methods

The Shore and Safranyik susceptibility-rating system

The Shore and Safranyik (1992) susceptibility index (S) for a given stand is the product of four variables:

$$[1] \qquad S = P \times A \times D \times L$$

where *P* is the percentage of the stand basal area composed of susceptible pine, i.e., the basal area of pine greater than or equal to 15 cm DBH (diameter at breast height, 1.3 m), expressed as a percentage of the basal area of all species in the stand greater than or equal to 7.5 cm DBH; *A* is a factor for the average age of dominant and codominant pine in the stand (defined as <60 years = 0.1, 61–80 years = 0.6, >80 years = 1.0); *D* is a density factor for the number of stems per hectare of all trees greater than or equal to 7.5 cm DBH (<250 stems = 0.1, 251–750 stems = 0.5, 751–1500 stems = 1.0, 1501–2000 stems = 0.8, 2001–2500 stems = 0.5, >2500 stems = 0.1); and *L* is a location factor determined by inserting the longitude, latitude, and elevation of the stand into the following equation and calculating the variable *Y*:

$$[2] \qquad \mathrm{Y} = (24.4 \times \text{longitude (degrees)}) - (121.9 \times \text{latitude (degrees)}) - (\text{elevation (m)}) + 4545.1$$

which is then used to calculate L ($Y > 0$, then $L = 1.0$; $0 > Y > -500$, then $L = 0.7$; $Y < -500$, then $L = 0.3$).

To calculate values of *P*, stand basal area, which is is the sum of the cross-sectional area of trees as measured at breast height, was determined. This variable is considered important for a stand-level rating system, because it indicates how much of the total basal area of the stand is composed of larger diameter pine. The DBH limit of 15 cm was selected, because this is generally the lower diameter limit at which trees are commonly attacked (Safranyik et al. 1974) unless the stand is under severe beetle population pressure. The 7.5 cm DBH threshold for all species represents the minimum diameter included in most inventory surveys in British Columbia. The variable *A* accounts for the mountain pine beetles' preference for older trees (Safranyik et al. 1974; Amman et al. 1977; Shrimpton and Thomson 1983). For *D*, studies have shown that stands at low densities receive little or no attack both because of increased tree vigor (McGregor et al. 1987; Amman et al. 1988*a*, 1988*b*) and alteration of microclimate (Amman et al. 1988*a*; Bartos and Amman 1989). An inverse relationship between tree mortality caused by the beetle and stand density as measured by CCF has been shown for higher density stands (McGregor et al. 1981; Shore et al. 1989). Anhold and Jenkins (1987) found a left-skewed relationship between SDI and beetle mortality. Our personal observations have shown that most mountain pine beetle caused tree mortality occurs in stands between 750 and 1500 trees per hectare. The location variable, *L*, accounts for the effect of climate on beetle development and survival and is an adaptation of the model presented by Amman et al. (1977) expanded to include longitude as the third dimension and extended to more northerly latitudes. It also utilizes Hopkins (1919) bioclimatic law. More detailed explanations of the variables and the rationale for their values and inclusion in the index can be found in Shore and Safranyik (1992).

Experimental procedures

Thirty-eight stands in the Cariboo forest region of British Columbia were selected for testing the susceptibility index. These stands were in areas that had recently experienced mountain pine beetle epidemics (Chilko and Choelquoit Lakes). Stands were selected that, based on inventory and pest survey information, would provide a range of susceptibility indices because of age, species composition, tree diameter, and stand density differences (Figs. 1*a*–1*d*). Each stand was sampled with between 8 and 18 (mean 10.5) variable-radius plots depending on its area. Tree species, DBH, tree condition (live or dead), and cause of death (mountain pine beetle or other) were recorded for all sample trees in each plot. The age of the nearest dominant or codominant pine to plot center was determined by increment core and corrected for sample height (Watts 1983). Elevation, latitude, and longitude were obtained for each stand from maps. Stand density, basal area per hectare for each tree species, and average age were calculated for all stands. Trees killed by the mountain pine beetle were included in the calculations of basal area and density to recreate the stand conditions that existed prior to the recent beetle epidemic.

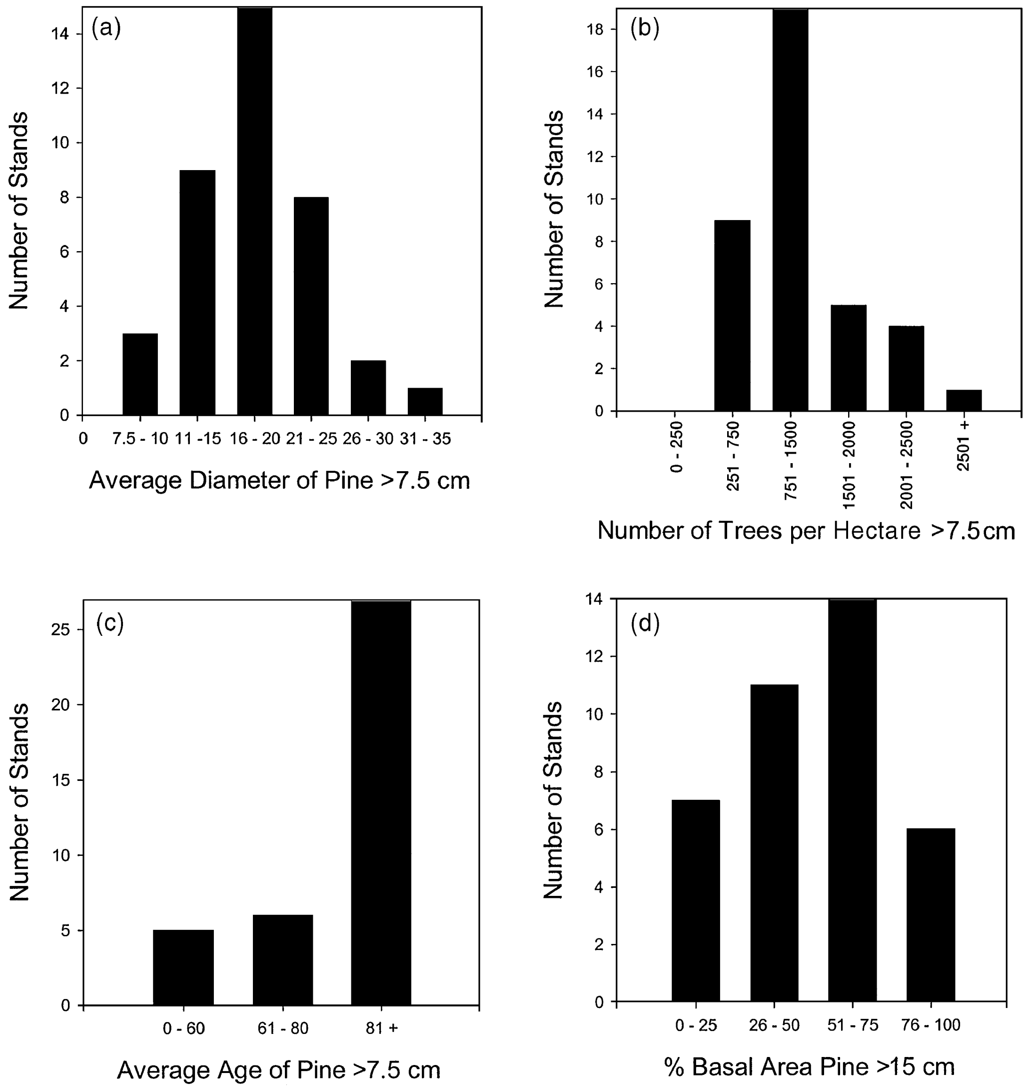
Susceptibility indices were derived for the 38 stands based on the sample data assuming that all trees were still alive. The susceptibility indices were then compared with the tree mortality resulting from mountain pine beetle infestation using regression analysis (SPSS Inc. 1997*a*).

An independent data set, collected from 41 stands from across southern British Columbia (30 in the Cariboo Forest Region, 5 in the Kamloops Forest Region, and 6 in the Nelson Forest Region) was used to further test the system. These data were from a study aimed at evaluating mountain pine beetle impact on lodgepole pine stands and, therefore, included only stands that had experienced mountain pine beetle epidemics. Data were collected as described above. Because the data were not originally intended for the purpose of evaluating the relationship between the stand susceptibility index and percentage basal area killed, stands with low susceptibility levels were not included. The lack of data across the full range of susceptibility values precludes comparison of regression lines between the original and validation data sets. Thus, to determine how well this data fit the model developed from the original data, a scatterplot of the susceptibility index versus percent basal area killed for the independent data set was overlaid on a graph of the 95% prediction interval (SPSS Inc. 1997*b*) of the original susceptibility index versus percent basal area killed model.

Results

Data from two stands were identified as outliers (studentized residual 3.04, 3.40) and, therefore, removed from the analysis. A linear relationship ($r^2 = 0.67$; $p < 0.0001$) was found between the percentage of the total stand basal area killed by the mountain pine beetle and the susceptibility index. The coefficients of the regression included a slope of 0.73 and an intercept of –2.9. The coefficient for the intercept was not significantly different from zero ($p = 0.46$); therefore, the regression was forced through the origin. This procedure is theoretically valid, because a susceptibility index of zero is possible only if there are no pine

Fig. 1. Frequency distribution of stands sampled at Chilko and Choelquoit lakes with respect to (*a*) average diameter of pine ≥7.5 cm DBH; (*b*) number of trees per hectare ≥7.5 cm DBH; (*c*) average age of pine ≥7.5 cm DBH; and (*d*) percent of stand basal area composed of pine ≥15 cm DBH.



greater than or equal to 15 cm in a stand, in which case mortality from mountain pine beetle would be unlikely (Safranyik et al. 1974). The regression equation (Fig. 2) was

[3] Percent basal area killed

$$= 0.68 \times \text{stand susceptibility index}$$

This equation reduced the variation in the dependent variable, uncorrected for the mean, by 86% (Steel and Torrie 1980). The 95% prediction interval for the stand susceptibility index versus percent basal area killed data was determined (Fig. 2) (SPSS Inc. 1997*b*). Stand susceptibility indices and corresponding percent basal area killed data were plotted for the 41 stands from the independent data set and overlaid on the prediction interval from the original data (Fig. 3). Data points from 40 of the 41 stands (98%) fell within this prediction interval.

Discussion

The stand susceptibility index is directly related to the susceptible basal area of the stand and is an index of the maximum mortality (in terms of percentage of stand basal area) a stand would receive in the event of a mountain pine beetle infestation. It is useful as a long-term indicator of potential loss in the event of a beetle epidemic.

The stand susceptibility rating system is not to be confused with an infestation rating system. It is designed to rate the susceptibility of the stand as a whole, not just the lodgepole pine component of the stand. The lodgepole pine component of a stand may be attacked by the mountain pine beetle, but if lodgepole pine represents only a minor component of the stand, it would be rated as low susceptibility.

It is likely that a portion of the variation about the susceptibility versus percent basal area killed regression line is due to variability in mountain pine beetle population levels between stands. Additional variation would likely be attributable to differences in host resistance (Berryman 1978). Also,

Fig. 2. The regression, and 95% prediction interval, of percentage of total stand basal area killed by the mountain pine beetle on the stand susceptibility index for stands sampled at Chilko and Choelquoit Lakes (n = 36, percent basal area killed = 0.68 × stand susceptibility index).

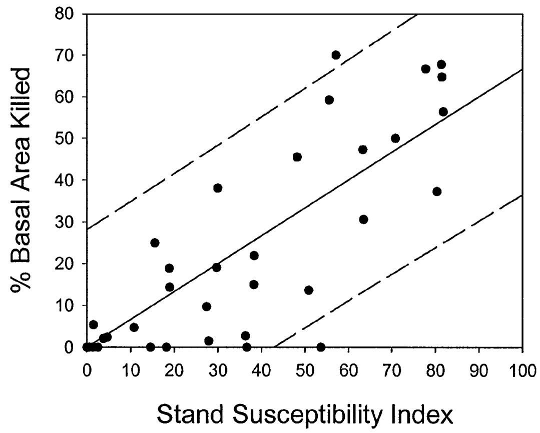
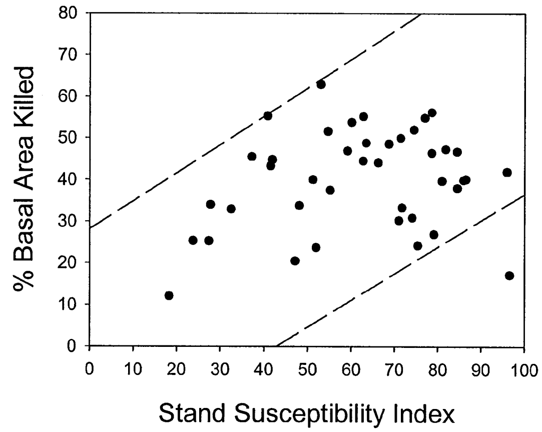


Fig. 3. Overlay of the independent data set on the 95% prediction interval of the original data set. Variables are the percentage of total stand basal area killed by the mountain pine beetle versus the stand susceptibility index for 41 stands from the Cariboo, Kamloops, and Nelson forest regions.



the stepwise function of the variables age, stand density, and location in the susceptibility index likely contributes to this variation. A continuous function model is currently in development that should reduce this source of variability.

We believe there are several reasons why the Shore and Safranyik (1992) susceptibility-rating system appears to provide more accurate estimates over a broader geographical area than previous systems. This system was developed using a process model approach rather than the empirical model approach used in systems such as that of Stuart (1984) and Anhold and Jenkins (1987). The limitations of the empirical model approach are that the resultant model is generally valid only for the geographical area from which the data for its development were collected. For example, Amman and Anhold (1989) found that the variables included in regression models describing tree mortality caused by mountain pine beetle differed by geographic area. Variables included in the Shore and Safranyik (1992) system are well known to be associated with mountain pine beetle infestations, as described above. Perhaps the most significant improvement in the Shore and Safranyik (1992) system over its predecessors, however, was the choice and form of stand density as a variable reflecting stand resistance (Berryman 1978; Schenk et al. 1980), vigor (Mahoney 1978; Waring and Pitman 1980; McGregor et al. 1987; Amman et al. 1988*a*, 1988*b*), microclimate (Amman et al. 1988*a*; Bartos and Amman 1989), and phloem thickness (Cole and Amman 1980). Other authors that have included measures of stand density such as crown competition factor (Schenk et al. 1980) and stand density index (Anhold and Jenkins 1987) have had some success in showing a relationship between these variables and tree mortality caused by the mountain pine beetle. In the former case, however, the assumptions about the form of the relationship seem to have been erroneous (McGregor et al. 1981; Shore et al. 1989; Bentz et al. 1993), and in the latter case, stand density index is a complex variable that also includes quadratic mean diameter and, therefore, may not be appropriate for reasons described above. We believe the form of the relationship and the ranges assigned to the stand density variable in our model make sense from both a theoretical and observational standpoint for reasons described above and, therefore, should have general applicability.

The susceptibility versus percent basal area killed model (eq. 3) can be used to estimate the potential loss of stand basal area for stands that have been rated with a susceptibility index. A prediction interval can be assigned to the estimate (Fig. 2). The 95% prediction interval presented in this paper is rather broad (approximately ±30 m^2/ha) for single-stand estimates with 95% probability, but this can be reduced considerably if a lower level of confidence is acceptable (e.g., approximately ±19 m^2/ha at the 80% probability level). In practice, the most likely way this relationship would be used would be at the landscape level, where the average susceptibility of a large number of stands is calculated. A confidence interval would then be constructed about the predicted mean basal area mortality. In such a situation, for a given probability level, the confidence interval around the mean would be considerably less than the prediction level presented here.

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