Forest Science, Vol. 34, No. 1, pp. 190–199.

Modeling Long-Term Fire-Caused Mortality of Douglas-Fir

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ABSTRACT. Mortality was determined in a stand of Douglas-fir 8 years after 20 plots were treated with light surface fires. Logistic regression was used to model long-term mortality as functions of morphological variables measured shortly after burning. Independent variables were diameter at breast height, height of needle scorch, percentage of the prefire crown volume scorched, season of burn, and the number of quadrants with dead cambium at 1.4 m bole height. Mortality increased with increasing scorch height, percent crown scorch, and dead cambium. It decreased with larger diameter. The best predictor of mortality was the number of quadrants with dead cambium. Percentage of crown volume scorched was a better predictor than lethal scorch height. For a given level of damage, mortality following fall season fires was slightly higher than following spring fires. Models may be used in planning prescribed fires and for salvaging fire-damaged Douglas-fir. FOR. SCI. 34(1):190–199.

ADDITIONAL KEY WORDS. Fire effects, logistic regression, prescribed fire, *Pseudotsuga menziesii*.

PRESCRIBED BURNING BENEATH STANDING TIMBER has increased in the western United States recently. Fires are prescribed to reduce unwanted fuels for hazard abatement, prepare sites for regeneration, thin overstocked stands, and modify the age structure and species composition of forests. Increased understanding of the relationships between fire damage and tree mortality can lead to more successful use of prescribed fire.

Research on postfire mortality in the western United States has focused largely on ponderosa pine (*Pinus ponderosa* Laws.) and Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) (Connaughton 1936, Herman 1954, Lynch 1959, Wagener 1961, Dieterich 1979, Bevins 1980, Wyant et al. 1986). These studies agree that the level of crown damage is the most useful predictor of mortality because it is physiologically important and easy to observe. Crown damage has been measured in several ways, including percentage of the crown volume killed (Wagener 1961, Dieterich 1979, Mitchell and Martin 1980, Ryan 1982, Peterson 1984, Peterson and Arbaugh 1986), percentage of the crown length killed (Herman 1954, Wyant et al. 1986), and average scorch height (Bevins 1980).

Bole scorch has been used as an indicator of possible stem damage (Ferguson 1955, Storey and Merkel 1960, Dixon et al. 1984, Peterson 1984, Wyant et al. 1986, Peterson and Arbaugh 1986). However, scorching of dead outer bark is not necessarily damaging to a tree (Dominik 1983, Ryan 1982). It is therefore necessary to verify the status of the cambium for each species

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and diameter class of interest before interpreting bole scorch (Storey and Merkel 1960, Wagener 1961, Ryan 1982).

Tree size is widely recognized as a factor in resistance to fire damage. As height increases, a greater proportion of the foliage is likely to be above the height of lethal scorching from a surface fire. Resistance to cambium damage from a surface fire increases with the square of bark thickness (Martin 1963, Hare 1965a). Bark thickness increases with diameter. Large trees are therefore more resistant to both crown and bole damage.

Conifer mortality increases when crown scorch is accompanied by bole and root damage (Connaughton 1936, Miller and Keen 1960, Wagener 1961). The relative importance of multiple damages, however, has not been quantified for Douglas-fir. The relative importance of various damages is also not likely to be the same for all fires. For example, in wildfires the majority of the area is burned in a free-spreading fire, and crown scorch is often severe. It is frequently the only obvious form of damage. In prescribed fires, fireline intensity and crown scorch are controlled by the selected environmental conditions and ignition pattern. Once crown scorch is constrained, damage to the bole and roots can be expected to assume greater relative bearing on tree mortality.

Although the above-cited studies have contributed to our understanding of fire-caused mortality, the influence of cambium damage on long-term mortality and the interaction of multiple damages have not been quantified.

In 1973 Norum (1975, 1976) initiated a prescribed burning study in a western larch (*Larix occidentalis* Nutt.)/Douglas-fir stand in western Montana. Data from this study and followup observations eight years later were used to model long-term mortality associated with cambium and crown damage resulting from fire. The objectives of this study were to determine which mensurational variables and fire damage indicators are important in describing long-term mortality of Douglas-fir following prescribed burning, and to estimate the magnitude of the important parameters and their contribution to the probability of tree mortality.

STUDY AREA

The study area is located on the University of Montana's Lubrecht Experimental Forest 52 km east of Missoula, Montana. Twenty plots were established on a north aspect with 15 to 45% slope at 1460 m elevation (msl). Soils are 1 m thick sandy loams of the Holloway Series overlying talus (Stark 1977). The area is predominantly Douglas-fir/blue huckleberry (*Vaccinium globulare* Rydb.) habitat type (Pfister et al. 1977). Vegetation, soils, and nutrient responses to fire on this site have been previously described (Miller 1977, Stark 1977, Stark and Steele 1977).

Plot average fuels and fire behavior characteristics were previously described by Norum (1975, 1976). Fuel consumption and fire behavior associated with damage to individual trees are unknown. Fuels were natural accumulations of shrub, herbaceous, and conifer litter with some decomposing logs left from harvesting early this century. Fuel mass and moisture content varied, resulting in a range of fire behavior and fuel consumption. The plots were burned using strip head fires, with fireline intensities (Byram 1959) ranging from 100 kW/m^2 to 900 kW/m^2. Plots were burned in May and June ($n = 9$), and in September and October ($n = 11$) 1973.

METHODS

Diameter at breast height (DBH), tree height (HT), average height of needle scorch (SH), and percentage of the prefire crown volume scorched (CS) were measured for 166 burned Douglas-fir trees on the plots a few weeks after the fires. Cambium condition was observed in spring 1974. Four cambium samples were removed from each tree using an increment hammer. Samples were taken at 1.4 m above the groundline from upslope, downslope, and both cross-slope positions. Cores were tested for the enzyme peroxidase with a 1% solution of orthotolidine in methanol and a 3% aqueous solution of hydrogen peroxide (Hare 1965b). Cambial cores were recorded as being alive if there was a blue color change in response to the chemical solutions. The number of quadrants with dead cambium (NDEAD) was recorded for each tree. In 1981, the plots were revisited. Trees with green foliage were recorded as alive.

The multivariate logistic function can be used to classify the status of individual trees (Monserud 1976). The logistic function yields a continuous, nonlinear estimate of the probability of an event, in this case mortality. The model can be interpreted to yield an estimate of the increase in risk of mortality caused by a unit change in an independent variable (Lachenbruch 1975). The logistic function is particularly appropriate when both continuous and discrete independent variables are used to predict or classify and when the assumption of multivariate normality is questionable (Press and Wilson 1978). The Walker and Duncan (1967) algorithm uses the logit transformation of the dichotomous dependent variable and weighted least squares parameter estimation. Hamilton's (1974) program of this algorithm was used to estimate the coefficients of the logistic model:

$$P_m = 1/(1 + \exp(-(b_0 + b_1x_1 + b_2x_2 + \ . \ . \ . + b_ix_i)))$$

where P_m is the probability of mortality, the b's are regression coefficients, and the x's are independent variables.

Descriptive statistics were computed for each variable by 1981 status (0 = alive, 1 = dead) and season of the burn. A two-factor analysis of variance was conducted for each independent variable to determine homogeneous groups by 1981 status and season. Because the normality of some independent variables was questionable, Mann-Whitney U and Kruskal-Wallis one-way nonparametric analyses of variance were also conducted. Variance inflation factors were computed to assess collinearity between independent variables (Sokal and Rohlf 1981).

CS and NDEAD were significantly greater in spring fires (Table 1). Other independent variables were not significantly different by season. The in-

TABLE 1. Independent variable means and multiple comparisons[1] for 166 fire-damaged Douglas-fir.

	1981 status and season of burn			
	Dead		Live	
Variable[2]	Spring	Fall	Spring	Fall
DBH	17.41[a]	18.45[a]	22.61[b]	24.04[b]
HT	12.88[a]	13.98[ab]	15.80[c]	15.17[bc]
SH	7.62[a]	7.39[a]	6.73[ab]	5.38[b]
CS	48.45[a]	27.70[b]	17.39[b]	3.42[c]
NDEAD	2.98[a]	2.23[b]	0.55[c]	0.33[c]

[1] Based on Scheffe's multiple comparison test with F 3, 162 d.f. and α − 0.05. Homogeneous groups have common superscripts.

[2] DBH = diameter breast height (cm), HT = tree height (m), SH = average scorch height (m), CS = percentage of the prefire crown volume scorched, NDEAD = number of quadrants with dead cambium at 1.4 m height.

creased number of dead cambium samples in the spring could result from seasonal differences in fires, directly, or it could be an indirect result of the greater elapsed time between spring fires and cambium sampling. To test this latter possibility, regression analysis was used to predict the amount of dead cambium from percent crown scorch and season.

Logistic regression analyses were conducted using DBH (cm), SH (m), CS (%), and NDEAD as independent variables. Equations were developed to predict probability of mortality based on final tree status observed in 1981, using several combinations of independent variables. Since DBH and HT were positively correlated ($r = 0.75$), only DBH was used as an indicator of tree size in logistic models. Season was used as a categorical variable in multivariate models.

Several criteria were used in screening potential models. Student's t-statistic was used to determine whether regression coefficients were significantly different from zero. Each model's goodness-of-fit was tested using the chi-square statistic to compare observed vs. predicted mortality. Predicted and observed mortality were calculated by probability classes. Because predicted mortality is a function of both the probability of mortality and the number of trees in a class it was necessary to vary the degrees of freedom between the different models to avoid artificially inflating the chi-square statistic. Cells were combined until the predicted number of dead trees in each cell was ≥ 5 (Sokal and Rohlf 1981). Small chi-square values indicate no significant difference between the observed and predicted number of dead trees. An analysis of variance F-ratio was used to test whether the model explained a significant portion of the variation in the data. Results of statistical tests were considered significant if $P \leq 0.05$.

Because observed values are either 0 (alive) or 1 (dead), and predicted values are a probability in the interval between 0 and 1, observed values and predicted values cannot be directly compared. In order to assess model performance more explicitly, each regression model was examined on the basis of how often the final 1981 status of individual trees was correctly predicted. An individual tree was classified as dead if the model predicted the probability of mortality (P_m) as ≥ 0.5. The fire-induced mortality classification was then compared to the final observed status. The 0.5 cutoff criterion was used to compute the percentage of individuals classified as alive when actually dead, the percentage of individuals classified as dead when actually alive, the total percentage of trees erroneously classified, and the net percentage of trees in the stand erroneously classified.

RESULTS

Of the 166 trees in the sample, 83 were dead after 8 years. Trees are well distributed between spring ($n = 81$) and fall ($n = 85$). Final observed mortality (O_m) is not significantly different between spring ($O_m = 0.53$) and fall ($O_m = 0.47$) burned trees. Data are not conclusive, but roughly 22 and 20% of the trees died in 1974 and 1975, respectively. The additional 8% appear to have died during the next 6 years. Seven percent of the trees died with no measured crown or bole damage. This may be due to random variation introduced by natural mortality or unmeasured damage.

Both the parametric and nonparametric analyses of variance lead to the same conclusions so only the former is reported (Table 1). Dead trees are significantly smaller in diameter and shorter in height than survivors (Table 1). Surviving fall-burned trees have significantly lower scorch heights than either dead trees or spring survivors. Both CS and NDEAD are significantly greater in the spring burned trees. CS and NDEAD are positively correlated ($r = 0.58$). Linear regression indicates no significant seasonal difference in NDEAD as a function of CS. Thus it does not appear that the increase in elapsed time between spring fires and measurement of NDEAD seriously affected the amount of dead cambium. Norum (1975, 1976) reported that the spring fires were more intense than the fall fires. Apparently these spring fires also caused more crown and bole damage.

The univariate regression models use DBH, SH, CS, and NDEAD, models 1 through 4, respectively, to predict the probability of mortality (Table 2). The chi-square statistic indicates good fit for all four models, and all four models are significant as indicated by the F-ratios. When used with the 0.5 cutoff criterion, the DBH (model 1) and the NDEAD (model 4) models overpredicted total mortality of individual trees, while the SH (model 2) and CS (model 3) models underpredicted it (Table 3). If predictions using this criterion and either the DBH, SH, or CS models were used as a guide for salvaging fire-damaged trees, approximately one-third of the trees would be incorrectly marked. The 0.5 cutoff corresponds to a diameter of 20.3 cm in model 1, a 6.7 m scorch height in model 2, and a 21% crown scorch in model 3.

The NDEAD model (model 4) is the best univariate predictor of mortality. This model with the 0.5 cutoff criterion correctly predicts the 1981 status of 80.2% of the trees (Table 3). The 0.5 criterion with this model predicts mortality if two or more cambial samples are dead, and survival if zero or one samples are dead. Roughly half of the trees with one or two quadrants of dead cambium in 1974 eventually died. Only one tree with three dead cambium samples lived and no trees survived with four dead samples.

Four multivariate models are also presented in Table 2. Of the possible combinations of independent variables, only those models with significant coefficients are shown. Variance inflation factors indicate no serious collinearity.

Given the assumption that the total classification error is a good indicator of model performance, then multivariate models result in little improvement over univariate models (Table 3). DBH is significant in combination with SH, CS, and NDEAD. SH is not significant in any model which includes either CS or NDEAD. SH is significant with DBH (model 5) but classification errors are similar to the univariate DBH model. DBH is significant with both CS and NDEAD, but the total classification errors are only slightly reduced (Table 3). Season is significant only in combination with DBH, CS, and NDEAD (model 8). The total classification error for this model is 4.8%

TABLE 2. Logistic regression models for predicting the probability of mortality of fire-damaged Douglas-fir 8 years following prescribed burning.

P_m = Model Y =	$1/(1 + e^{-y})$ where: b_o	$+ b_1DBH$	$+ b_2SH$	$+ b_3CS$	$+ b_4NDEAD$	$+ b_5NSEA$[1]	$\chi^2_{d.f.}$	F
1	2.471	−0.122					2.5_7	19.0
2	−0.831		0.123				3.6_7	6.9
3	−0.798			0.038			0.7_7	28.2
4	−1.694				1.263		1.1_4	59.4
5	1.805	−0.156	0.197				3.1_7	14.1
6	1.396	−0.105		0.037			3.8_{10}	17.2
7	0.392	−0.099			1.275		2.6_6	28.9
8	−0.341	−0.106		0.025	1.236	0.955	3.3_5	12.6

[1] P_m = probability of mortality; *DBH* = diameter breast height (cm), *SH* = scorch height (m), *CS* = percentage of the prefire crown volume scorched, *NDEAD* = number of quadrants with dead cambium at 1.4 m height, *NSEA* = season of burn (0 = spring, 1 = fall).

TABLE 3. Logistic model classification errors[1] for fire-damaged Douglas-fir.

Model	Independent variables[2]	Percent classification errors $C_D O_L$	$C_L O_D$	Total	Net
1	*DBH*	20.5	11.4	31.9	9.1
2	*SH*	15.7	21.7	37.4	−6.0
3	*CS*	7.2	24.1	31.3	−16.9
4	*NDEAD*	12.0	7.8	19.8	4.2
5	*DBH, SH*	17.5	13.6	31.1	3.9
6	*DBH, CS*	11.4	18.7	30.1	−7.3
7	*DBH, NDEAD*	7.2	10.2	17.4	−3.0
8	*DBH, CS, NDEAD, NSEA*	5.4	9.6	15.0	−4.2

[1] Trees were classified alive (C_L) if the predicted probability of mortality <0.5. Trees were classified dead (C_D) if the predicted probability of mortality was ≥0.5. O_L = observed alive in 1981, O_D = observed dead in 1981.

[2] P_m = probability of mortality; *DBH* = diameter breast height (cm), *SH* = scorch height (m), *CS* = percentage of the prefire crown volume scorched, *NDEAD* = number of quadrants with dead cambium at 1.4 m height, *NSEA* = season of burn (0 = spring, 1 = fall).

less than for the univariate NDEAD model. Three of the four multivariate models underpredict mortality.

DISCUSSION

The number of dead cambium samples is the most important predictor of mortality of these trees. The amount of fire-induced girdling that Douglas-fir can withstand has not been previously quantified. These data indicate there is a high probability of mortality if more than one quadrant is dead at breast height. Although it is generally thought that nearly complete girdling is necessary to kill trees (Noel 1970) these results do not confirm this. However, it is possible that trees with more than one dead cambium sample at 1.4 m were completely girdled near the ground. Because most of the fuel that burns and, therefore, the greatest energy release, in prescribed fires is near the ground, additional damage should be expected below 1.4 m on the bole. Also, damage that occurs a few meters up on the bole is thought to be more critical to survival than a similar amount near the base (Miller and Keen 1960, Wagener 1961). Wagener (1961) observed that trees with severe cambial damage were poor candidates for survival. He defined cambial damage as severe if more than one-quarter of the circumference was girdled at the stump height or if damage occurred to more than narrow strips of cambium beneath bark crevices above the stump. These results confirm his observation.

Because bole damage cannot be determined without destructive sampling, models that require quantification of these damages (e.g., models 4, 7, and 8) may have little applicability in forest management. Managers can seldom afford to intensively sample fire-damaged stands. They should, however, be aware that a large number of trees may be inappropriately marked if cambium damage is not considered.

In addition to cambium damage on the bole, root damage may have also affected survival. Douglas-fir frequently has major lateral roots at or near the boundary between the organic and the mineral soils. These can be damaged if the organic layer burns. Indeed, several exposed, damaged, or dead roots were noted in the 1981 survey of these trees. It is not known how much of the variation in tree mortality could have been explained by the timely quantification of these additional damages.

Partial basal girdling and root damage may lead to moisture stress (Chambers et al. 1986) and reduced resistance to insects and disease (Geiszler et al. 1984). These may have been factors in the mortality of 12 trees that died without any measured damage.

Because cambium injury can be important in some fire situations, there appears to be a great value in predicting it from readily available site variables. In future studies, quantification of the maximal extent of girdling and, possibly, the surface area of dead cambium would appear to be preferable to point samples at 1.4 m.

These results confirm the common observation (Wyant et al. 1986, Bevins 1980, Lynch 1959) that diameter is inversely related to mortality. Diameter is, however, only an indicator of resistance to fire injury. Models based on diameter cannot be extrapolated to trees of significantly different bark thickness or to fires significantly different from those used to build the model. Thus they have limited management applicability.

This study also confirms recent results that show that crown scorch is a better predictor of tree mortality than scorch height (Wyant et al. 1986, Peterson 1985, Peterson and Arbaugh 1986). The portion of the prefire crown that is killed directly affects a tree's photosynthetic capacity and, therefore, its capacity for growth (Chambers et al. 1986) and resistance to insects and disease (Miller and Keen 1960, Furniss 1965).

Crown scorch ranged from 0 to 80% for living trees and 0 to 100% for dead trees. The average percent crown scorch for dead trees in this study was 39%. This level of crown scorch is not usually considered serious in the absence of other damages (Herman 1954, Miller and Keen 1960, Wagener 1961, Dieterich 1979). Light scorching to the lower canopy may reduce transpiration and maintenance respiration of marginally productive foliage resulting in a more favorable carbon balance (Chambers et al. 1986). Moderate to heavier scorching may, however, be expected to affect a tree's physiological condition adversely.

Models based on percent crown scorch and diameter are easy to apply in the field and are, therefore, potentially valuable to managers. The linear combinations of crown scorch and diameter that lead to a range of probable mortalities predicted by model 6 are presented in Figure 1. Following light to moderate surface fires, model 6 may be used for salvaging Douglas-fir ranging from about 12 to 36 cm DBH and over the full range of percent crown scorch.

Scorch height does not directly relate to any physiological function of a tree. Scorch height in a fire depends primarily on fireline intensity, wind speed, and air temperature (Van Wagner 1973) and to a lesser extent on crown morphology (Byram 1948) and phenology (Wagener 1961). If scorch height is less than the base of a tree's crown, then it has no predictive value for salvaging fire-damaged trees because it is not detected.

Since scorch height can be related to predicted fire behavior (Albini 1976), models based on it may be useful for planning prescribed fires. Models based on scorch height (e.g., models 2 and 5) should not be extrapolated to trees of different heights or crown ratios than those used to build the model.

Given the same level of fire damage, model 8 (Table 2) predicts slightly higher mortality following fall fires. However, trees burned in spring fires experienced more crown and cambium damage and were more likely to die than those burned in the fall (Table 1). The influence of season in this data may be largely due to differences in fire behavior that are somewhat unique to this study. Norum (1975, 1976) reports that the spring of 1973 was unsea-

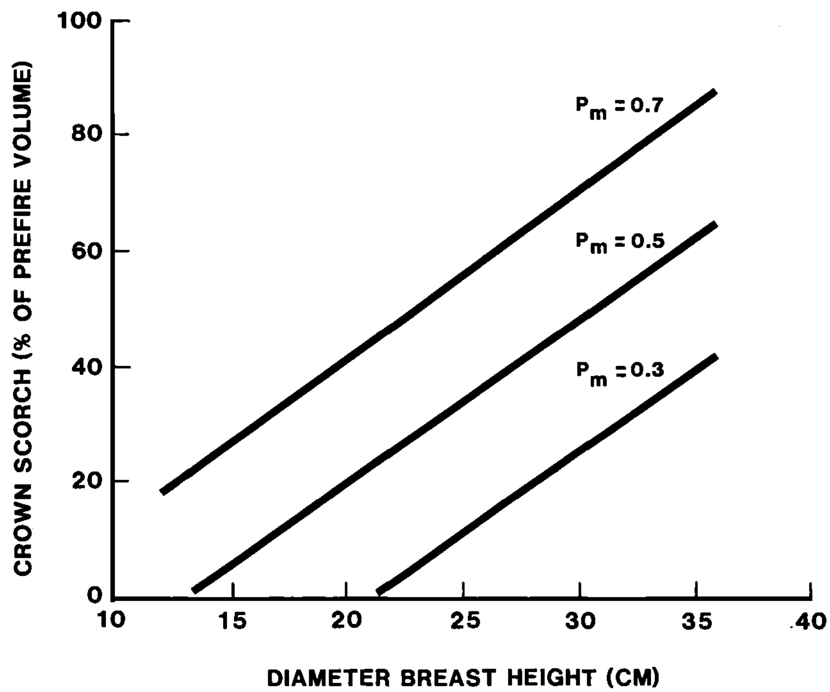

FIGURE 1. Linear combinations of diameter at breast height (cm) and crown scorch (percentage of prefire volume) resulting in 0.3, 0.5, and 0.7 predicted probability of mortality (P_m) from model 6.

sonably dry. Fire behavior of the spring fires was more intense than the fall fires. Wagener (1961), however, found trees are more susceptible to crown damage during the active spring growth period when new foliage and buds are more vulnerable to lethal heating. When Norum (1975, 1976) initiated his study, the primary objective was to describe plot differences in fuel consumption and fire behavior. Individual tree condition depends on localized fuel consumption and fire behavior, not plot averages. These data are not suitable for separating variation due to fire behavior from that due to tree susceptibility.

CONCLUSIONS

We determined that bole damage, expressed as the number of quadrants with dead cambium, was more valuable for predicting mortality than either scorch height or the percentage of crown volume scorched. The percentage of crown scorched was a better independent variable than scorch height. Tree size, expressed as DBH, was also an important indicator of resistance to damage and resulting mortality.

The logistic model predicts the probability of mortality continuously in the interval of 0 to 1. As such, logistic models are useful for predicting mortality on an area basis. When used in conjunction with a classification criterion, they can also be used to predict the status of individual trees. We used a $P_m \geqslant 0.5$ cutoff criterion because we had no *a priori* reason for selecting otherwise. If prior probabilities of mortality were available, or if different costs were associated with predicting mortality of a surviving tree than with predicting survival of a dying tree, other criteria could be used (cf. Johnson and Wichern 1982). The latter might be the case in a salvage operation. For example, if a manager wanted to be sure that only trees likely to die were salvaged, a 0.7 probability could be selected (Figure 1). In that case, a number of trees would be left in the stand but would eventually die. This might be desirable for modifying seedling microenvironment or providing wildlife habitat. When several logistic models are being compared, the classification criterion is useful for evaluating model performance and selecting the most suitable models.

A better understanding of cause and effect relationships is needed for modeling interactions between fire damage and conifer mortality. The relative contributions of crown, bole, and root damages to mortality are poorly understood. Historically, fire damage assessment has not quantified lower bole and root damage because of difficulty in obtaining nondestructive samples. Better quantification of these damages will help to separate site, physiological, or species-controlled responses from those due to fire.

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