Modeling Postfire Mortality of Ponderosa Pine following a Mixed-Severity Wildfire in the Black Hills: The Role of Tree Morphology and Direct Fire Effects

Tara L. Keyser, Frederick W. Smith, Leigh B. Lentile, and Wayne D. Shepperd

Abstract: We examined the relationship among tree size, crown and stem damage, and 5 years of postfire mortality of ponderosa pine (*Pinus ponderosa* Dougl. ex. P. & C. Laws.) in the Black Hills following a large, mixed-severity wildfire. We measured tree morphology and direct fire effects on 963 trees and assessed individual tree mortality annually from 2001 to 2005. We used logistic regression to model tree mortality as a function of tree morphology (dbh) and bark thickness (BARK) and direct fire effects [percentage of the live crown scorched (PSCOR) and basal char measured as the percentage of the bole charred below 30 cm (CHAR)]. Models using dbh and BARK were modeled separately due to correlation between the variables. In all models, mortality decreased with increasing dbh and BARK and increased with increasing PSCOR and CHAR. Basal char contributed to the mortality of trees less than 40 cm but became less influential as dbh and BARK increased. Overall, probability of mortality modeled as a function of dbh, PSCOR, and CHAR correctly predicted the status of 78% of trees, whereas the model predicting mortality as a function of BARK, PSCOR, and CHAR had an increase in prediction accuracy of only 1%. FOR. SCI. 52(5):530–539.

Key Words: Logistic regression, *Pinus ponderosa*, South Dakota, crown scorch, stem/bole damage.

T HE ABILITY TO ACCURATELY PREDICT individual tree mortality following fire has important management implications. Whether a tree will live or die influences timber salvage operations that focus on removing trees immediately killed by fire or those trees that can be expected to die within a period of a few years following fire. The ability to predict postfire mortality provides managers insight into postfire forest structure and function and its relation to future timber production, changes in wildlife habitat, and long-term planning objectives. Decision-making criteria regarding postfire management operations need to be based on accurate and efficient postfire assessments. Of particular importance is information regarding delayed tree mortality as fire-killed trees are subject to insect and disease infestations (McHugh et al. 2003), rendering the timber unsalvageable. The issues and concerns over the potential ecological effects that postfire salvage operations have on forest recovery processes and future forest stand development (Lindenmayer et al. 2004, Purdon et al. 2004, Donato et al. 2006) along with the increased loss of timber from forests' timber base due to the increase in large-scale wildfires (Keegan et al. 2004), have emphasized the need to base postfire management decisions on accurate models of predicted postfire mortality. In this article we develop accurate and efficient models to predict the 5-year mortality of ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Laws.) based on tree morphology, in particular tree size and bark thickness, and observed fire effects following a large, mixed-severity wildfire in the Black Hills of South Dakota.

Individual tree mortality caused by fire is the result of direct heat or flame damage to the foliage (i.e., scorch and consumption), cambium, and root system, which disrupts tree physiological processes such as water transport, nutrient uptake, and photosynthesis (Ryan and Reinhardt 1988, Ryan et al. 1988, Swezy and Agee 1991). Tree morphology, in particular tree diameter, bark thickness, crown base height, and foliage density (Ryan and Reinhardt 1988) and prefire tree vigor (van Mantgem et al. 2003) all play a significant role in estimating the resistance of individual trees and tree species to fire-related injury and death. Dbh and bark thickness have an impact on the resistance of a tree to cambial injury and girdling (Vines 1968), whereas crown base height and foliage density influence the severity and degree of crown injury that directly affect bud survival and new shoot production, as well as postfire photosynthetic capacity (Wyant et al. 1983).

The most important factor influencing postfire tree mortality is crown injury. Recent mortality studies have focused on the percentage of crown volume killed either by scorch and (or) consumption as an indicator of crown damage (Ryan and Reinhardt 1988, Stephens and Finney 2002,

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McHugh and Kolb 2003). Many species are able to withstand moderate to extreme levels of crown damage without experiencing increased mortality rates. McHugh and Kolb (2003) found following wildfire in northern Arizona, mortality for ponderosa pine did not begin until 70% of the total crown volume was damaged; whereas Stephens and Finney (2002) report giant sequoia (*Seqoiadendron giganteun* [Lindley] Buchholz) was able to withstand 90% total crown volume damage before mortality occurred following prescribed fire in central California. These results suggest the amount of crown damage an individual tree can withstand is species-specific. Regardless of species, however, there are no studies that report high rates of mortality at levels of crown damage below 10% (Stephens and Finney 2002).

Stem damage has also been shown to be an important predictor of postfire mortality (Peterson and Arbaugh 1986, 1989, McHugh and Kolb 2003). Ryan et al. (1988) found that the amount of dead cambium at 1.4 m was the most important predictor of postfire mortality for Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) following light surface fire in Montana, while numerous other studies report that cambial damage describes a significant amount of variability in mortality models second in importance, however, to crown damage (e.g., Peterson and Arbaugh 1986, 1989, Wyant et al. 1986). Tree mortality is often lower for trees with larger dbh and greater bark thickness compared to smaller trees (Ryan and Reinhardt 1988, Regelbrugge and Conard 1993, Borchert et al. 2002, Hély et al. 2003). Increased dbh and subsequently increased bark thickness (van Mantgem and Schwartz 2003) insulate cambial tissue from the heat flux from fire. Bark scorch/char measurements taken as bark char ratio (depth of char/bark thickness) (Peterson and Arbaugh 1986, 1989) and height of bole scorch/char (Wyant et al. 1986) are often used as a surrogate for stem and cambial damage in many models. No single predictor provides an accurate estimate of postfire mortality; rather, a combination of crown and stem damage and morphology most accurately predict mortality. Current published tree mortality models often seek to explain the underlying physiological processes of postfire mortality rather than use variables that can be easily or efficiently applied to the field and salvage marking operations.

Ponderosa pine is the dominant tree species in the Black Hills of South Dakota and occupies an estimated 85% of the landscape (Deblander 2002). Ponderosa pine is also the single most valuable timber species in the Black Hills. In recent years more frequent, large-scale fires have occurred, resulting in substantial losses of standing timber. Between 2000 and 2004, seven fires have burned ~60,000 ha of ponderosa pine-dominated forests in the Black Hills (Lentile 2004). Mortality models that can accurately predict the future status of fire-injured trees by measuring fire effects on the crown and stem helps to ensure that only those trees likely to die within the years following wildfire are salvaged and any potentially live trees will be reserved and left to influence postfire recovery processes, such as postfire regeneration. The Jasper fire and the subsequent long-term monitoring of postfire recovery processes has provided a unique opportunity to observe how wildfire impacts postfire mortality of ponderosa pine in the Black Hills. The objective of this study was to develop an accurate model of postfire mortality for ponderosa pine in the Black Hills. Specifically, we used long-term monitoring data to (1) evaluate the role crown and bole damage has in conjunction with tree size and bark thickness in predicting postfire mortality, (2) identify the potential physiological relationships between mortality and the predictive variables, and (3) provide an efficient, predictive mortality model that can be used in postfire management decision-making processes regarding ponderosa pine in the Black Hills.

Methods

Study Area

This study was conducted within the Black Hills National Forest, South Dakota. The Black Hills are an isolated, forested uplift on the Missouri Plateau of the Great Plains Province (Hoffman and Alexander 1987) and form the easternmost extent of the Rocky Mountains (Froiland 1990). In late Aug. 2000, the Jasper fire was ignited near Custer, SD in the southwestern Black Hills. The Jasper fire burned ~34,000 ha of the Limestone Plateau area of the Black Hills (Shepperd and Battaglia 2002, USDA Forest Service http://www.fs.fed.us/r2/blackhills/fire/history/jasper/00_11_09_JRAT_Report.PDF. Oct. 15, 2005). Elevations within the burn area range from ~1,500 to 2,100 m. The fire was a mixed-severity fire producing a combination of surface fire (low fire behavior), surface fire with torching (moderate fire behavior), and active crown fire (extreme fire behavior) that burned through predominantly ponderosa pine forest leaving behind a mosaic of low-, moderate-, and high-severity fire effects across the landscape (USDA Forest Service http://www.fs.fed.us/r2/blackhills/fire/history/jasper/00_11_09_JRAT_Report.PDF. Oct. 15, 2005, Lentile et al. 2005). Dominant soil types are similar within the fire perimeter and consist of Alfisols, Mollisols, and Inceptisols (Shepperd and Battaglia 2002). Annual precipitation averages from 45 to 48 cm with between 60 and 73% of the annual precipitation falling from Apr. to Sept. (Hoffman and Alexander 1987). Mean daily minimum and maximum temperatures are -3.3 and $13.2°C$.

Methods

In June 2001, before the fall of fire-scorched needles, we established 18 ~0.3-ha permanent study sites in ponderosa pine stands within the Jasper fire perimeter. Within these burned stands, nine sites were located in areas exhibiting evidence of surface fire behavior with low initial postfire tree mortality, and nine sites were located in ponderosa pine stands exhibiting moderate fire behavior consisting of surface fire with individual tree torching, resulting in moderate initial postfire tree mortality. Each site consisted of three 0.03-ha plots. Plots were located at bearings 0°, 135°, and 225° azimuth 20 m from site center. Study sites were similar in respect to species composition, aspect, slope (5–13%), elevation, and soil type.

Within each plot, we tagged every tree ≥1.4 m in height, recorded species, and assessed tree mortality annually from 2001 to 2005. Trees with no green foliage were considered dead. We measured tree morphology, including bole diameter taken at 1.4 m above the soil surface (dbh) and bark thickness. Bark thickness was sampled at dbh at two different locations on the bole so an average bark thickness per tree could be computed (BARK). In addition, we measured total tree height (HT) and prefire crown base height (CBH). Crown base height was measured at the point of branch-bole attachment of the lowest prefire live whorl. We identified prefire crown base height from the position of scorched needles in the case where no foliage consumption occurred and fine branch structure in the case where consumption of needles occurred. Scorched needles were easily distinguishable from nonscorched needles as they were brown or orange in color. Crown injury was measured on individual trees and included maximum height of crown scorch (MAXSCOR), which was measured as the maximum height on the crown where necrotic foliage occurred. Foliage necrosis due to crown scorch is caused when the foliage experiences lethal temperatures as a direct result of radiant heat or direct flame produced by the flaming front of the fire (Johnson and Miyanishi 2001). We measured the percentage of the bole circumference charred below 30 cm (CHAR) to the nearest 5% as an indicator of stem and cambial damage. Charred bark was distinguished from scorched bark as it was metallic black in color (similar to the color and texture of charcoal) and was eroded to the point where the bark no longer contained grooves or furrows, whereas scorched bark was completely intact and black or gray in color (Lentile 2004). We calculated an additional fire effects variable, percentage of live crown length scorched (PSCOR), which was calculated as $[(MAXSCOR - CBH)/(HT - CBH)] * 100$.

Data Analysis

Only trees ≥5 cm dbh were included in the data analysis. We conducted Wilcoxon rank sum tests to determine whether prefire stand structure differed between areas of low and moderate postfire mortality ($\alpha = 0.05$). We also tested whether tree size and bark thickness as well as the severity of direct fire effects differed among live trees and trees that died within a given year and at the end of 5 years. We used logistic regression to model the probability of tree mortality five years postfire. Numerous studies (e.g., Ryan and Reinhardt 1988, Regelbrugge and Conard 1993, Stephens and Finney 2002) have used logistic regression to effectively model postfire tree mortality. The logistic model has the form:

$$P_m = \frac{1}{1 + \exp[-(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n)]}$$

where P_m is the probability of mortality, β_0 through β_n are the model coefficients, and X_1 through X_n are the explanatory variables. Mortality data are categorical with a binary outcome (Peng et al. 2002); 0 = live or 1 = dead. The logistic function provides a continuous estimate of the probability of mortality between 0 and 1. We used the standard cutoff of 0.5 to signal mortality (Saveland and Neuenschwander 1990). Therefore, when $P_m < 0.5$, the tree is predicted live; when $P_m > 0.5$, the tree is predicted dead.

We used dbh, BARK, PSCOR, and CHAR, as well as the appropriate interactions, as independent variables to predict the 5-year mortality of ponderosa pine. Unless specified, interactions among independent variables were not significant ($P > 0.05$) and therefore not included in the final models. Due to the high correlation between dbh and bark thickness ($r = 0.70$), separate models were created using these two variables. All other variables were uncorrelated with one another ($r < 0.50$). Similar to Regelbrugge and Conard (1993), models were built using a random sample of ~75% of the full data set [calibration data set ($n = 722$ for models using dbh and $n = 721$ for models using BARK)]. To test the predictability of the model, we ran validation runs on the remaining ~25% of the full data set [validation data set ($n = 241$)]. All analyses were performed using SAS version 9.1. We used a maximum likelihood fitting procedure (Cook and Weisberg 1999) using SAS LOGISTIC to estimate model coefficients (SAS Institute 1989). We used the generalized Wald statistic with a χ^2 distribution to test if model coefficients were different from 0 ($\alpha = 0.05$). Asymptotic confidence intervals based on the profile likelihood procedure were calculated for all regression coefficients and provide an understanding of how precisely the coefficients were estimated. Model goodness-of-fit was assessed using the Hosmer-Lemeshow goodness-of-fit statistic ($\alpha = 0.05$; Hosmer and Lemeshow 2000) and receiver operations characteristic (ROC) curve analysis (Saveland and Neuenschwander 1990, Hosmer and Lemeshow 2000). The ROC curve is a plot of the sensitivity versus (1-specificity) of the model where sensitivity is equal to the probability of detecting a true event and (1-specificity) is equal to the probability a predicting a false event over the entire range (0 to 1) of cutoff points (Hosmer and Lemeshow 2000). Models with ROC values ≥0.7 are considered to have an acceptable discrimination between live and dead trees, ROC values ≥0.8 have excellent discrimination, and ROC values ≥0.9 are considered to have outstanding discrimination (Hosmer and Lemeshow 2000). Nested models were compared against each other based on the likelihood ratio test where the $\Pr(\chi^2 > G) = -2$ log-likelihood value ($-2LL$) of the full model $- -2LL$ value of the reduced model with $df = df_{\text{full model}} - df_{\text{reduced model}}$.

Results

Prefire stand structure, including density and average stand diameter, was similar between areas that experienced low and moderate levels of fire behavior, suggesting that sites were similar enough in stand structure to be modeled together ($P > 0.05$). Study sites had an average ponderosa pine density of 594 trees ha^{-1}, with an average stand diameter of ~23 cm.

Postfire ponderosa pine mortality differed among all 5

years of the study, although most mortality occurred between 2001 and 2003 (Fig. 1). The number of trees dying in a single year peaked in 2002, with 93 trees ha^{-1} dying within the year. Mortality declined slightly in 2003 and was negligible by 2005 when the equivalent of only 7 trees ha^{-1} were identified as having died from the previous year. Eighty-nine percent of the mortality in low and moderate severities occurred by the end of 2003, with the remaining 11% mortality occurring the following 2 years.

Five years postfire, tree morphology differed between live and dead trees (Fig. 2). Trees that died in years 2001–2003 were smaller in dbh than live trees ($P < 0.05$); however, differences in dbh between surviving trees and trees that died in 2004 and 2005 were indistinguishable ($P > 0.05$). Throughout all five years, dead trees had significantly thinner bark than surviving trees ($P < 0.05$). Fire effects were also different between live and dead trees, with dead trees possessing a significantly greater percentage of crown and stem damage throughout all 5 years of the study ($P < 0.05$). Crown damage was greatest in trees that died between 2000 and 2001, when PSCOR of a dead tree averaged 100%. In contrast, stem damage was greatest in trees that died between 2001 and 2002 when CHAR averaged 38%.

Using the model calibration data set, a total of eight univariate and multivariate logistic regression models were created (Table 1). Models 1 through 4 describe postfire mortality as a function of dbh, while models 5 through 8 describe postfire mortality as a function of BARK. We included site as a variable in all models during the initial analysis to determine whether differences among sites accounted for any significant variability in the ability to predict postfire mortality. In all eight models, site was not a significant variable ($P > 0.05$), suggesting that mortality was independent of site location.

Model 1, which is the univariate model using dbh as a predictor of mortality, was a significant predictor of postfire mortality (ROC = 0.70). Univariate models were produced because they are the simplest and most time-efficient models to use; however, they often do not explain enough variability in postfire mortality to provide an accurate esti-

mate of the probability of mortality. While model 1 accounts for significant variability, the ROC value was at the threshold of the acceptable level of discrimination preferred in logistic regression analysis. Multivariate models that incorporated variables describing fire damage to the crown and stem significantly improved the model. Model 2 was initially tested as a two-variable model predicting mortality as a function of dbh and PSCOR. However, further analysis indicated a significant interaction between these two variables. Therefore, model 2 was produced as a three-variable model using dbh and included PSCOR and the significant interaction between dbh and PSCOR as predictors of mortality. The inclusion of PSCOR and the interaction between dbh and PSCOR explained significantly more variation in postfire mortality than did model 1, and had an acceptable level of discrimination between live and dead trees ($G = 141.1$, $df = 2$, $P < 0.0001$, ROC = 0.82). Although a significant improvement over model 1, model 3, which calculates mortality as a function of dbh, and CHAR did not explain as much variability in postfire mortality as did model 2, suggesting that CHAR in conjunction with dbh is not as strong a predictor of mortality as PSCOR and the interaction between PSCOR and dbh. Based on $-2LL$ and ROC values, the best logistic equation modeling postfire mortality as a function of dbh was model 4. Model 4 was the three-variable model using the combination of dbh, PSCOR, and CHAR as significant predictors of mortality. In conjunction with CHAR, the interaction between dbh and PSCOR that existed in model 2 was no longer significant ($P > 0.05$). The addition of CHAR to the mortality model explained significantly more variability in the ability to predict postfire mortality than model 2 [$-2LL = 724.0$, ROC = 0.83 for (4) versus $-2LL = 757.9$, ROC = 0.82 for (2)].

Overall, the models using BARK as the morphological predictor of mortality explained substantially more variation in postfire mortality than did the models that used dbh based on the ROC values. Model 5, which is the univariate model using BARK as a predictor of mortality, explained significantly more variation in postfire mortality than did model 1 [ROC = 0.80 for (5) versus ROC = 0.70 for (1)]; however, the Hosmer-Lemeshow test showed a significant lack-of-fit of model 5 to the calibration data ($P = 0.036$). As with the multivariate models containing dbh, significant improvement in model fit and predictability occurred when fire effects variables were incorporated into the model. Model 6 was the best two-variable model using BARK and included PSCOR as a predictor of mortality. Model 6 was a better model and predictor of mortality than BARK alone, producing a lower $-2LL$ value and greater ROC value ($G = 72.8$, $df = 1$, $P < 0.0001$, ROC = 0.84). The best model using BARK as a predictor of mortality, however, was model 8, which was the three-variable model predicting postfire mortality as a function of BARK, PSCOR, and CHAR. The addition of CHAR to model 6, which was the best two-variable model, resulted in a significant increase in model performance and ability to predict mortality ($G = 27.7$, $df = 1$, $P < 0.0001$, ROC = 0.86).
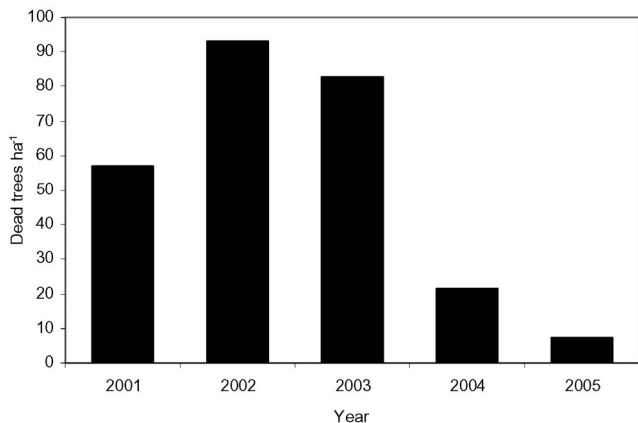
In all models the coefficient for dbh and BARK was

Figure 1. Ponderosa pine mortality (ha^{-1}) within an individual year 1, 2, 3, 4, and 5 years postfire.
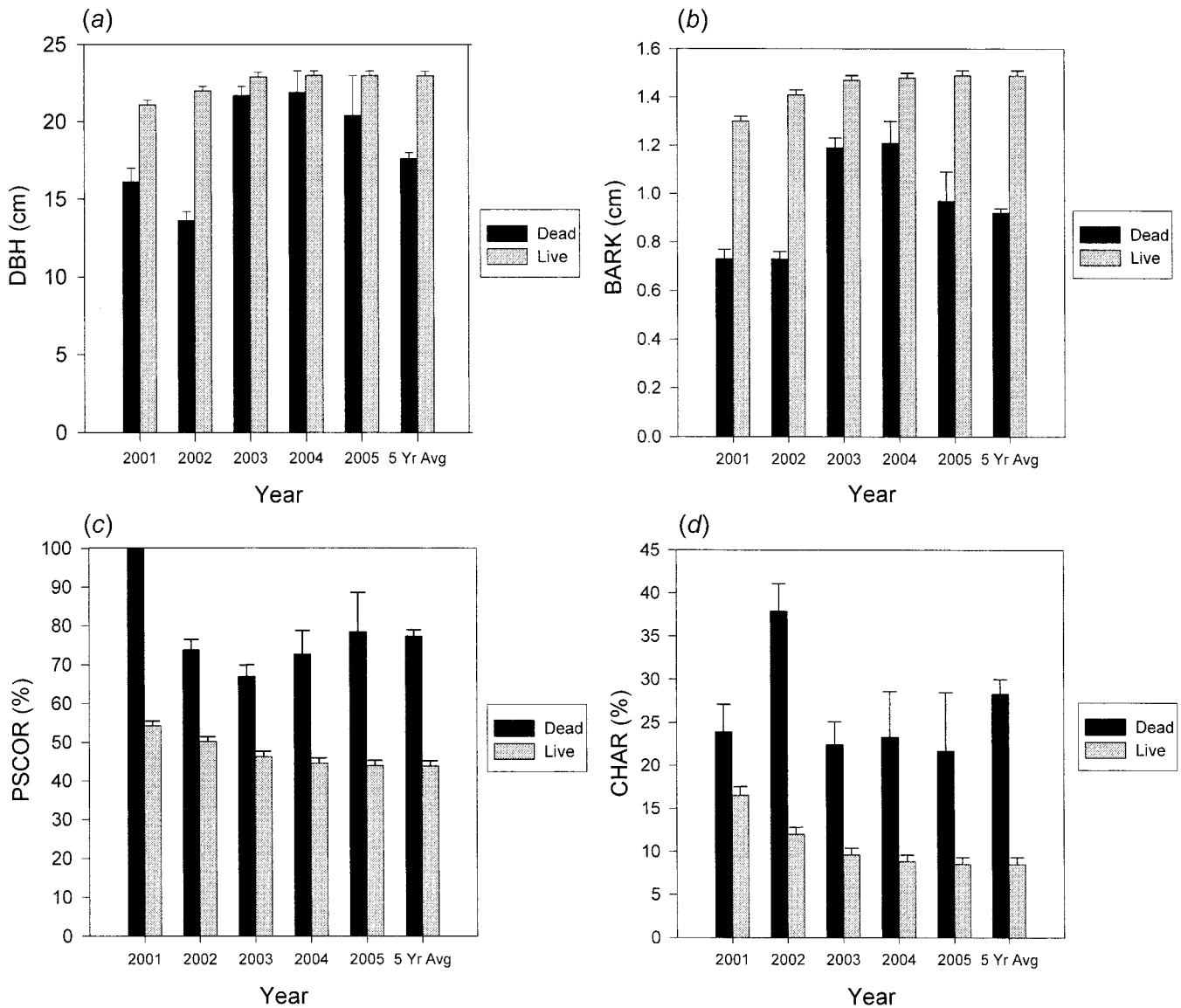
Figure 2. Average (a) dbh (cm), (b) BARK (cm), (c) PSCOR, and (d) CHAR for live and dead trees within a given year 1, 2, 3, 4, and 5 years postfire as well as the 5-year cumulative average. Error bars represent ±1 SE.

negative, suggesting that an increase in dbh or BARK results in a significant decrease in the predicted probability of mortality. In contrast, coefficients for PSCOR and CHAR in all eight models were positive, suggesting that any increase in PSCOR and (or) CHAR results in a significant increase in the probability of mortality. At similar levels of CHAR, larger trees and trees with thicker bark were less susceptible to fire-induced mortality than smaller trees and trees with thinner bark at comparable levels of PSCOR (Fig. 3). Increased predicted mortality associated with increasing levels of CHAR was most visible on small trees less than 30 cm dbh. These trees possessed a substantially higher predicted probability of mortality with CHAR levels of 75% versus only 25% (Fig. 3). In contrast, when CHAR was used in combination with bark thickness at comparable levels of PSCOR, the predicted probability of mortality was less sensitive to increases in CHAR. Trees with bark thickness of 2 cm and greater did not experi-

ence large increases in the predicted probability of mortality with increases in CHAR (Fig. 3).

Model Validation

Model validation was performed using the model coefficients from the best model containing dbh (model 4, Table 2) and the best model containing BARK (model 8; Table 2). Model 4 accurately predicted the status of 189 observations, producing an overall accuracy rate of 78%. Model 4 was better at predicting survival rather than mortality, correctly predicting the status of 84% of the live trees versus only 71% of the dead trees. Model 4, therefore, failed to detect 29% of the observed mortality in the test data and misclassified 16% of the observed live trees as dead. Model 8, which had better statistical properties than model 4, accurately predicted the status of 79% of the observations.

Table 1. Five-year postfire mortality models for ponderosa pine following the Jasper fire in the Black Hills, South Dakota

Model	β_0	β_1	β_2	β_3	β_4	−2LL	H-L	ROC
Models using dbh (N = 722)								
1. dbh	1.659† (1.209, 2.126)	−0.094† (−0.116, −0.074)				899.0	0.076	0.70
2. dbh, PSCOR, dbh*PSCOR	1.104* (0.044, 2.185)	−0.156† (−0.213, −0.103)	0.013 (−0.002,0.027)		0.001* (0.0001–0.0015)	757.9	0.072	0.82
3. dbh, CHAR	1.222† (0.745, 1.712)	−0.092† (−0.115, −0.070)		0.027† (0.019, 0.034)		835.5	0.633	0.75
4. dbh, PSCOR, CHAR	−0.237 (−0.825, 0.350)	−0.098† (−0.123, −0.074)	0.027† (0.021, 0.032)	0.022† (0.015, 0.030)		724.0	0.558	0.83
Models using BARK (N = 721)								
5. BARK	2.556† (2.092, 3.046)	−2.389† (−2.791, −2.012)				772.0	0.036*	0.80
6. BARK, PSCOR	0.915† (0.317, 1.522)	−2.153† (−2.571, −1.759)	0.022† (0.017, 0.027)			699.2	0.599	0.84
7. BARK, CHAR	2.059† (1.574, 2.567)	−2.256† (−2.664, −1.873)		0.022† (0.015, 0.030)		732.8	0.341	0.82
8. BARK, PSCOR, CHAR	0.538 (−0.086, 1.169)	−2.038† (−2.460, −1.640)	0.021† (0.016, 0.026)	0.019† (0.012, 0.027)		671.5	0.567	0.86

β_0 through β_4 are model coefficients corresponding to the intercept, dbh (models 1–4), or BARK (models 5–8), PSCOR, CHAR, and dbh * PSCOR (95% log-likelihood asymptotic confidence intervals). −2LL represents the −2 log-likelihood value, H-L is the Hosmer-Lemeshow goodness-of-fit test $[P(\chi) > \chi^2]$, and ROC is the value associated with the receiver operations characteristic (ROC) curve analysis. Regression coefficients and H-L tests are significant at *α = 0.05 and †α = 0.01.

Model 8 was better at predicting survival rather than mortality, correctly predicting 86% of the live trees versus 71% of the dead trees. Model 8 failed to detect 29% of observed mortality in the test data and misclassified 14% of the live trees in the test data as dead.

Discussion

Mortality Models

The goal of this study was to model long-term postfire mortality of ponderosa pine following a large, mixed-severity wildfire in the Black Hills. We focused on direct measurements of crown damage (PSCOR) and indirect measurements of cambial damage (CHAR) along with tree morphological characteristics that have been shown to influence postfire survival (dbh and BARK) as predictors of postfire mortality. Tree size is important because it influences a tree's susceptibility, resistance, and ability to survive both wildfire and prescribed fire, while direct fire effects have an impact on postfire physiological processes. We found that ponderosa pine mortality occurred throughout all 5 years of the study, with the majority of postfire mortality occurring between 2001 and 2003 (Fig. 1). Data from this study relating tree mortality to time since fire are consistent with numerous other long-term studies (Ryan et al. 1988, Mutch and Parson 1998, Agee 2003) that report high mortality within the first 2 to 4 years postfire followed by a dramatic decrease in mortality in the later postfire years.

Tree size was found to be an important variable for predicting postfire mortality. In model 4, we found that the predicted probability of mortality decreased with increases in dbh, confirming other studies (Regelbrugge and Conard 1993, Borchert et al. 2002, Stephens and Finney 2002, Hély et al. 2003) that suggest that as tree diameter increases, the probability of mortality decreases. Tree diameter is positively related to bark thickness (van Mantgem and Schwartz 2003). Therefore, dbh should provide a reliable estimate of resistance to cambium injury from fire as the corky bark often found in ponderosa pine insulates the cambium from the heat flux of a surface fire, preventing full or partial girdling (Hare 1965). In addition to resistance to stem damage, tree size has an effect on the severity of crown damage a tree sustains in a wildfire. Smaller trees have lower crown base heights than larger trees. Low crown base height often facilitates the transition of fire from the surface into the canopy.

In model 4, which predicted mortality as a function of dbh, crown, and stem damage, PSCOR was a significant variable for predicting postfire mortality. We measured crown damage using PSCOR that included the percentage of the live crown length consumed as well as scorched. Needle scorch occurs when either direct or indirect heat kills crown foliage (Harrington 1987). Depending on scorch height and crown length, this can have significant impacts on postfire photosynthetic production and recovery. Needles in the middle and lower third of ponderosa pine crowns produce significantly less photosynthate than is produced in
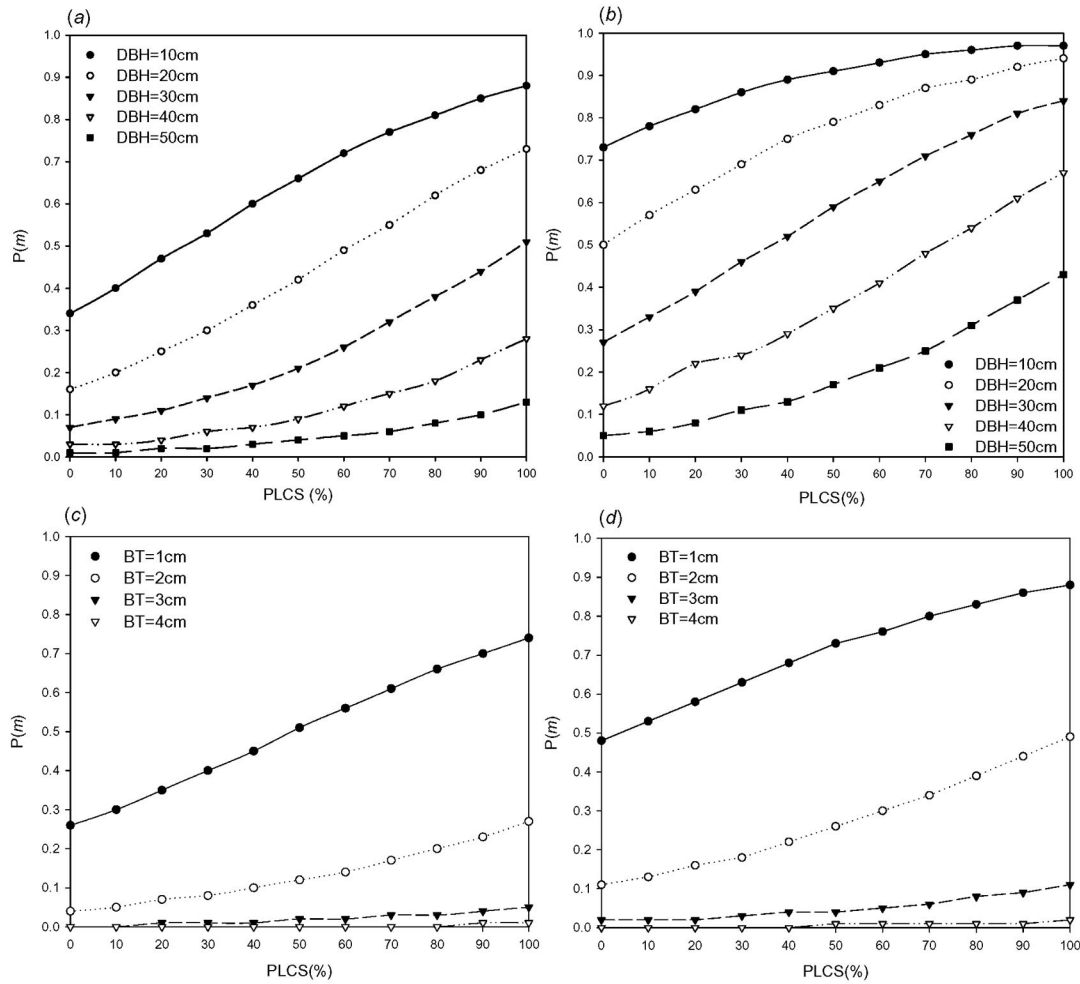
Figure 3. Probability of mortality (P_{m}) of ponderosa pine as predicted by (a) model 4, CHAR = 25%; (b) model 4, CHAR = 75%; (c) model 8, CHAR = 25%; and (d) model 8, CHAR = 75% 5 years postfire.

Table 2. Classification table displaying the results of the model validation for postfire mortality as a function of (a) model 4, which had an overall accuracy of 78.4%, and (b) model 8, which had an overall accuracy of 79.3%

(a)	Observed dead	Observed live	Total	(b)	Observed dead	Observed live	Total
Predicted dead	33.2% ($N = 80$)	8.3% ($N = 20$)	41.5% ($N = 100$)	Predicted dead	33.2% ($N = 80$)	7.5% ($N = 18$)	40.7% ($N = 98$)
Predicted live	13.3% ($N = 32$)	45.2% ($N = 109$)	58.4% ($N = 141$)	Predicted live	13.3% ($N = 32$)	46.1% ($N = 111$)	59.4% ($N = 143$)
Total	46.5% ($N = 112$)	53.5% ($N = 129$)	100% ($N = 241$)	Total	46.5% ($N = 112$)	53.6% ($N = 129$)	100% ($N = 241$)

The sum of the percentages from those trees observed dead and predicted dead and those trees observed live and predicted live results in the overall percentage of trees whose status was accurately predicted by each of the models.

the upper third of the crown (Assman 1970, Ryan 1998). Consequently, low mortality is associated with low values of PSCOR as the inefficient portions of the canopy are removed; however, as PSCOR increases, especially as scorch height approaches the most phytosynthetically active and productive upper third of the canopy, increased mortality is observed.

We found that the predicted probability of mortality increased as PSCOR increased, especially in trees less than 30 cm dbh (Fig. 3). Regardless of CHAR levels, model 4 predicted survival of large trees even with 100% PSCOR. This is likely due to the fact that we used the percentage of

the crown length scorched, whereas other studies have used the proportion of the total crown scorched and (or) consumed (Wyant et al. 1986, Saveland and Neuenschwander 1990, McHugh and Kolb 2003), which is a more accurate but more time-consuming measurement of crown damage taking into consideration the volume of needles and buds killed, not just the crown length killed. At low levels of CHAR (25%), we found that trees with a dbh of 10 cm can sustain only ~20% PSCOR before mortality occurs, whereas trees with a dbh of 20 cm can withstand a maximum of ~70% PSCOR before mortality occurs (Fig. 3).

This is consistent with results from Harrington (1987), who found crown scorch thresholds upward of 90% for larger ponderosa pine in western Montana. In contrast, mortality of trees greater than 30 cm dbh was not affected by PSCOR in combination with low levels of CHAR.

Similar to Peterson and Arbaugh (1986), who found that the proportion of the basal circumference charred was significant in predicting postfire mortality of lodgepole pine (*Pinus contorta* Dougl.), we found that including CHAR as a predictor of mortality for ponderosa pine greatly improved model fit and discrimination (Table 1). Cambium damage is greater and more damaging at the base of the tree than at breast height or above (Ryan 1990). Variables such as bark char ratio for Douglas-fir and lodgepole pine (Peterson and Arbaugh 1986, 1989), maximum height of stem-blackening in white pine (*Pinus strobus* L.) (Beverly and Martell 2003), and maximum height of bole char in ponderosa pine (Regelbrugge and Conard 1993) have all been used as surrogate measurements for fire-related cambium injury and have been shown to be important predictors in postfire mortality. Other studies (e.g., Ryan et al. 1988) have directly sampled the cambium to determine damage; however, this measurement, due to time constraints in postfire management decisions, is not a practical nor is it a time-efficient measurement of stem damage. While not greatly influencing mortality of larger trees, CHAR did contribute to mortality in trees less than 40 cm dbh (Fig. 3). As trees exceeded 40 cm dbh, even CHAR measurements of 75 to 100% contributed to only a ~20% increase in the probability of mortality. Without crown scorch, therefore, potential girdling as measured by CHAR does not significantly contribute to tree death and survival; however, in combination with crown scorch, increased CHAR significantly decreased postfire survival especially in trees less than 40 cm dbh. While large diameter trees (>40 cm) can be found throughout the Black Hills, they are rare on the landscape. The average size of a tree in the Black Hills is significantly smaller than 40 cm, with the majority of the total live tree volume occurring in trees between ~23 and 28 cm dbh (Deblander 2002). Given the data presented from this study, CHAR, therefore, should be expected to significantly influence postfire mortality of the majority of ponderosa pine in the Black Hills. The importance of stem damage as a predictor of mortality in small diameter ponderosa pine trees, in particular, has been demonstrated through experimental manipulation of bark defenses and fuel loading around individual trees by van Mantgem and Schwartz (2004) in central California. van Mantgem and Schwartz (2004) suggest that, similar to mortality in the absence of fire, postfire mortality is an additive effect of damage to different tree structures and organs and (or) interruption of important physiological functions, which impact photosynthesis and water/nutrient transport.

In model 8, which predicted mortality as a function of the BARK, crown, and stem damage, BARK significantly influenced mortality (Table 1; Figure 3). All models using BARK were statistically better models than those using dbh based on ROC values. The increase in model significance implies that resistance to cambium damage is more accu-rately measured by BARK rather than dbh. Studies using bark thickness as a function of dbh to predict mortality are not often based on actual field measurements of bark thickness on burned trees; rather, predictions of bark thickness are often based on species-specific dbh and BARK relationships (Ryan and Reinhardt 1988) or off-site, unburned trees (Harmon 1984). This method of determining BARK, however, does not take into consideration variation in bark thickness due to factors such as age-related differences (Regelbrugge and Conard 1993, van Mantgem and Schwartz 2003). We took direct measurements of BARK and found that mortality was more responsive to small changes in BARK rather than dbh, with only slight increases in BARK resulting in a greatly reduced predicted probability of mortality even in combination with high levels of PSCOR and CHAR (Fig. 3). For example, trees with a BARK of 1 cm were able to withstand 70% PSCOR and 75% CHAR before mortality occurred, whereas trees with a BARK of 2 cm were able to survive following both 100% PSCOR and CHAR.

Management Implications

The use of bark thickness instead of dbh produced a model with better statistical properties; however, the resultant increase in the overall estimated model accuracy was only 1%, which was the direct result of accurately predicting the status of live trees versus actual mortality within the test data set. Bark thickness is a time-consuming measurement to take, especially in the context of postfire salvage-marking operations. The relatively small increase in the accuracy of discriminating between live and dead trees, therefore, does not warrant taking BARK measurements or including BARK as a variable in marking guidelines.

We have shown that model 4, which uses dbh in conjunction with PSCOR and CHAR, can predict 5-year postfire mortality of ponderosa pine in the Black Hills with an overall estimated accuracy of 78%. This model did not detect observed mortality within the test data set as reliably as it predicted survival; however, misclassifications of tree status may be due to factors such as extreme measurements within the data set or long-term delayed mortality. Many of the trees that were misclassified in the validation run possessed high levels of PSCOR in combination with low levels of CHAR. In addition, many of the trees that were misclassified as live by the end of the 5-year period did not die until the third or fourth year postfire, suggesting that our explanatory variables may be, less sensitive to long-term causes of mortality. More detailed measurements of crown damage, such as percentage of crown volume scorched in lieu of PSCOR, may account for the misclassification of tree status due to extreme values associated with high PSCOR and low CHAR. Similarly, additional explanatory variables such as ground char severity or other variables that could potentially explain root damage could aid in the long-term predictive ability of the model (Swezy and Agee 1991). The addition of explanatory variables may produce a model with better statistical properties and improve the predictive

power of the model. However, additional variables associated with more time-consuming measurements in the field could result in the model being more difficult to implement during postfire management planning processes, with only a potentially slight improvement in the ability to discriminate between the future status of fire-affected trees.

The goal of model calibration was to produce the simplest yet most accurate postfire mortality model for ponderosa pine in the Black Hills given easily and efficiently measured morphological and first-order fire effects variables. We found that three-variable equations (models 4 and 8) resulted in significant improvements in predictive power over two-variable mortality equations (models 3, 6, and 7), suggesting the stem damage as measured by CHAR has an important role in determining whether a tree lives or dies, especially in trees of smaller size. The incorporation of stem damage into postfire mortality models increases a land manager's ability to discriminate between those trees that will die and those trees that will survive throughout the immediate years following fire. This increased predictive power will aid managers in making more science-based postfire management decisions and designing more ecologically sound postfire management operations. The assurance that postfire management operations are implemented based on the best available science and most recent models, including measures of tree size, crown damage, and stem damage, helps to ensure that salvage operations remove only trees with a high probability of dying postfire while leaving those trees predicted to survive. Minimizing the removal of postfire survivors would increase the retention of live trees and minimize the ecological impacts that have been proposed to be associated with salvage operations (e.g., Donato et al. 2006), and assures natural postfire recovery processes (i.e., postfire regeneration) occur while still allowing for the recuperation of resources following large-scale wildfires.

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