Best Predictors for Postfire Mortality of Ponderosa Pine Trees in the Intermountain West

Carolyn Hull Sieg, Joel D. McMillin, James F. Fowler, Kurt K. Allen, José F. Negron, Linda L. Wadleigh, John A. Anhold, and Ken E. Gibson

Abstract: Numerous wildfires in recent years have highlighted managers' needs for reliable tools to predict postfire mortality of ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) trees. General applicability of existing mortality models is uncertain, as researchers have used different sets of variables. We quantified tree attributes, crown and bole fire damage, ground fire severity, and insect presence from a total of 5,083 trees in four 2000 wildfires in four Intermountain states. Crown scorch (percentage) and consumption (percentage) volume collectively accounted for the majority of predictive capacity in all four individual models and in the pooled four-site model. The addition of tree diameter and presence of *Ips* beetles in the pooled model slightly improved predictive power. Four other statistically significant variables added little to the pooled model's predictive ability. The pooled model correctly classified 3-year postfire mortality of 89.9% of the trees and had a receiver operating characteristic (ROC) score of 0.96. In the external validation step, the model correctly classified 3-year postfire mortality of 96% of 1,361 trees in a 2001 wildfire. Our results and a number of previous studies suggest that a two-variable model using percentage crown scorch volume and crown consumed volume will have applicability beyond the Intermountain West. FOR. SCI. 52(6):718–728.

Key Words: *Pinus ponderosa*, logistic regression, Arizona, Colorado, South Dakota, Montana, wildfire, bark beetles or Scolytinae, modeling.

INCREASING NUMBERS OF LARGE WILDFIRES in ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) forests of the western United States in recent decades have generated a renewed interest in how best to predict which trees will survive following burning. Models that accurately predict tree survivability following wildland fire can assist managers in making postfire management decisions related to hazard tree removal, reforestation, salvage logging, wildlife habitat, and watershed quality (Brown et al. 2003). Many previous studies have addressed this issue, but consensus of which variables best predict mortality is confounded by the fact that researchers often measured different sets of variables and used different methods to measure their variables. These differences hamper our ability to assess whether postfire models might have general applicability across the extensive range of ponderosa pine.

Fire damage to the crown and bole influences a tree's probability of surviving fire. Previous studies have consistently ranked crown damage, usually crown scorch or consumption, or a combination, as important to predicting postfire mortality of ponderosa pine trees (Dieterich 1979, Wyant et al. 1986, Saveland and Neuenschwander 1990, Stephens and Finney 2002, Wallin et al. 2003, McHugh and Kolb 2003, McHugh et al. 2003). The percentage of the crown either consumed or scorched is frequently characterized relative to the total crown volume (Wyant et al. 1986, Saveland and Neuenschwander 1990, Stephens and Finney 2002, McHugh and Kolb 2003), but has also been estimated relative to total crown length (Harrington and Hawksworth 1990), or categorized by damage classes (e.g., Harrington 1987, 1993). Wyant et al. (1986) included a measure of crown consumption based on tree height in their Colorado study, and the inclusion of this variable added substantially to the predictive capacity of their discriminant models.

Tree size also influences the probability of mortality after burning. Larger-diameter and taller trees generally survive greater levels of fire damage (Wyant et al. 1986, Harrington 1993, Regelbrugge and Conard 1993, Stephens and Finney 2002, Thies et al. 2005). In Regelbrugge and Conard's (1993) model, increasing tree dbh and height were

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Carolyn Hull Sieg, USFS Rocky Mountain Research Station, 2500 S. Pine Knoll Drive, Flagstaff, AZ 86001—Fax: (928) 556-2151; csieg@fs.fed.us. Joel D. McMillin, USFS Region 3 Forest Health Protection, 2500 S. Pine Knoll Drive, Flagstaff, AZ 86001—jmcmillin@fs.fed.us. James F. Fowler, USFS Rocky Mountain Research Station, 2500 S. Pine Knoll Drive, Flagstaff, AZ 86001—jffowler@fs.fed.us. Kurt K. Allen, USFS Region 2 Forest Health Management, 1730 Samco Road, Rapid City, SD 57702—kallen@fs.fed.us. José F. Negron, USFS Rocky Mountain Research Station, 240 W. Prospect Street, Fort Collins, CO 80526—jnegron@fs.fed.us. Linda L. Wadleigh, USFS Region 3 Fire Management, 1824 S. Thompson Street, Flagstaff, AZ 86001—lwadleigh@fs.fed.us. John A. Anhold, USFS Region 3 Forest Health Protection, 2500 S. Pine Knoll Drive, Flagstaff, AZ 86001. Ken E. Gibson, USFS Region 1 Forest Health Protection, PO Box 7669, Missoula, MT 59807—kgibson@fs.fed.us.

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associated with decreasing probability of postfire mortality of ponderosa pine trees. In most of these studies, decreasing probability of mortality of ponderosa pine trees with increasing diameter was attributed to greater bark thickness with age (Ryan 1982). McHugh and Kolb's (2003) study suggests that especially large-diameter trees (>40 cm dbh) may be more susceptible to postfire mortality in some areas during severe droughts.

High levels of bole damage have been associated with increased postfire mortality of ponderosa pine trees. Actual cambial death, sampled in quadrants at 1.4 m height, was an important factor in determining mortality of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) (Ryan et al. 1988), but this technique has not been applied in published studies of ponderosa pine. Regelbrugge and Conard (1993) predicted mortality of ponderosa pine trees in central California using models that included either maximum or relative bole char height. McHugh and Kolb (2003) also used bole charring severity in their predictive model.

Ground fire severity has been linked with postfire mortality in a few studies (Swezy and Agee 1991, McHugh and Kolb 2003), but has been estimated in different ways. McHugh and Kolb (2003) categorized ground char severity using Ryan's (1982) and Ryan and Noste's (1985) four-class system (none, low, moderate, or high). Stephens and Finney (2002) quantified forest floor fuels before and after prescribed burns in California.

Bark beetles (Coleoptera: Scolytinae) can cause pine mortality (Furniss and Carolin 1977) and may be attracted to fire-damaged trees (McCullough et al. 1998, Parker et al. 2006); however, only one prior study (McHugh et al. 2003) included bark beetle attacks in models of postfire mortality of ponderosa pine trees. Total crown damage (the sum of crown scorch and consumption) and bark beetle attack rating (none, partial, or mass attack) were significant variables in their logistic regression models for two wildfires and a prescribed burn in northern Arizona. The contribution of bark beetles in explaining variation in tree mortality relative to fire-caused crown damage was not presented. Although the western pine beetle (*Dendroctonus brevicomis* LeConte), red turpentine beetle (*D. valens* LeConte) and *Ips* species may be attracted to fire-damaged pine trees (Miller and Patterson 1927, Miller and Keen 1960, Smith 1971, Bradley and Tueller 2001, Ganz et al. 2003, McHugh et al. 2003), some species, such as the mountain pine beetle (*D. ponderosae* Hopkins), do not seem to be attracted to fire-damaged pine trees (Ryan and Amman 1996, Rasmussen et al. 1996, McHugh et al. 2003). Differences in species composition of bark beetle complexes throughout the geographic range of ponderosa pine, population levels of various species, plus other factors such as season of burn (Thomas and Agee 1986, Harrington 1987, 1993, Swezy and Agee 1991, Thies et al. 2005, 2006), stand density, and drought stress can confound extrapolation of results from one region to another (McHugh et al. 2003).

Identifying the best predictors of postfire mortality has also been hindered by the fact that most researchers have not provided an assessment of the relative contribution of individual variables to the predictive capacity of their models. Furthermore, a number of previously published studies do not provide internal or external validations of proposed models. However, Regelbrugge and Conard (1993) included an external validation test of a mortality model using data not included in the model development, and Weatherby et al. (1994) tested Ryan and Reinhardt's (1988) mixed species model developed from 43 prescribed fires in the Pacific Northwest with a new data set. External validation steps using data not used in the development of the model provide insights on the more general applicability of models designed to assess the probability of postfire mortality.

In this study, we developed standardized protocols and sampling methodology to characterize tree attributes, crown and bole fire damage, ground fire severity, and evidence of insect attacks on four 2000 wildfires in four states in the Intermountain West. Our objectives were to identify the set of independent variables that was most useful in predicting 3-year postfire tree mortality, provide a relative assessment of the contribution of individual variables to predicting tree mortality, and to test whether individual models for each of the four study sites differed from a single model that pooled data from all four sites. We then tested the validity of the four-site model using data collected from a 2001 wildfire that was independent of our original data set. We hypothesized that (1) total crown damage (a sum of crown scorch volume and crown consumed volume), plus tree diameter would be the best predictors of mortality; (2) the pooled model would correctly classify a lower percentage of trees than individual site models due to differences in site attributes such as bark beetle complexes; but (3) the pooled model would still be valid for predicting mortality of trees on the 2001 fire, because of the overriding importance of total crown damage and tree diameter.

Methods

Study Sites

We established four study sites following wildfires in 2000 to provide data for developing a model to predict postfire mortality. These four sites were located in forests strongly dominated by ponderosa pine in Arizona, Colorado, South Dakota, and Montana (Figure 1). The Pumpkin Fire, on the Kaibab National Forest in northern Arizona, started on May 25 and burned 5,972 ha by the time it was contained on July 15, 2000. Soils are basaltic, and elevations ranged from 2,256 to 3,048 m. The Bobcat Gulch Fire, on the Arapaho-Roosevelt National Forest in north-central Colorado, started on June 14 and burned 1,255 ha in 5 days. Soils are granitic and elevations ranged from 1,829 to 2,560 m. The Jasper Fire, in the Black Hills of western South Dakota, started on Aug. 24 and was contained on Sept. 8, 2000, after burning a total of 33,795 ha. Soil parent materials are limestone, and elevation ranged from 1,524 to 2,134 m. The fourth study site was on the Custer National Forest in Montana, on the Stag and Tobin Fires that started between July 23 and 26, 2000, and collectively burned 28,731 ha. Sandstone is the

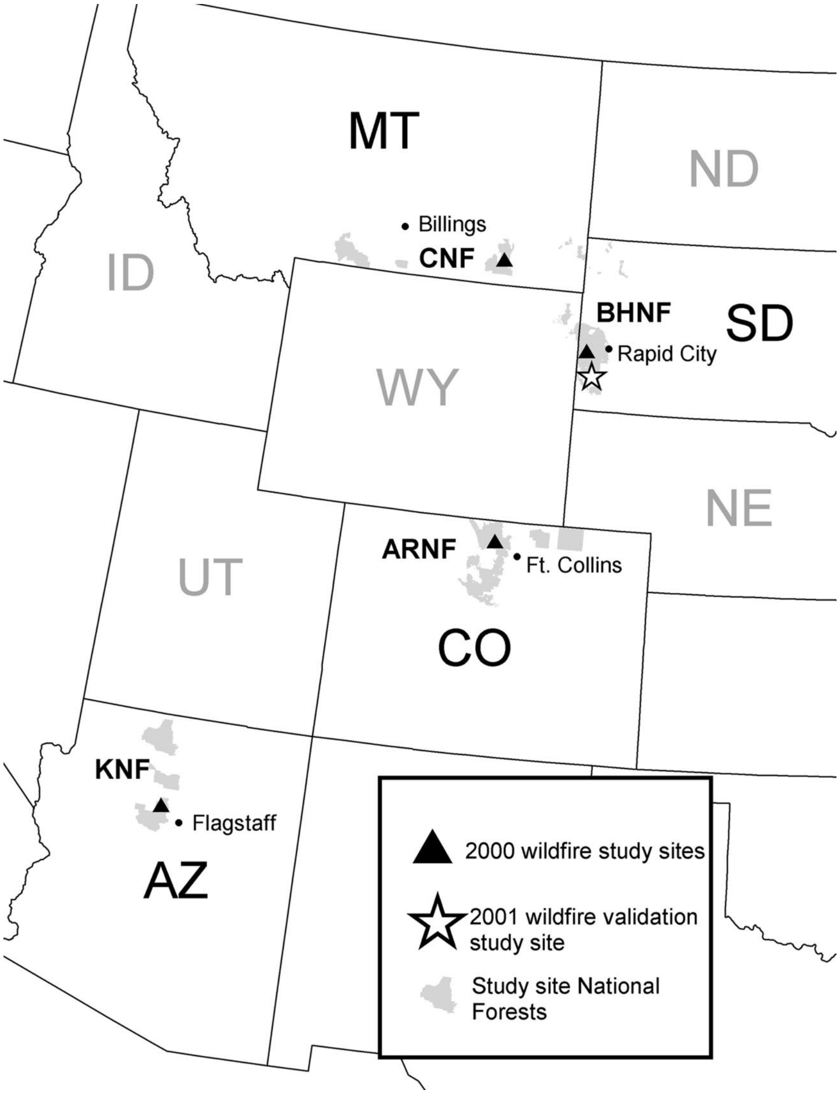

Figure 1. Study site locations of 2000 wildfires on the Kaibab National Forest (KNF) in northern Arizona, Arapaho-Roosevelt National Forest (ARNF) in north-central Colorado, Black Hills National Forest (BHNF) in western South Dakota, and Custer National Forest (CNF) in southeastern Montana, plus the 2001 wildfire on the Black Hills National Forest in South Dakota.

most common soil parent material, and elevation ranged from 981 to 1,274 m.

Annual average, as well as seasonal distribution, of precipitation is variable among the four study sites. The annual average precipitation on the Arizona study site is 54.6 cm, most of which is received in July and August, followed by February and March (Western Regional Climate Center, 2006. Available online at www.wrcc.dri.edu. Last access date Oct. 31, 2006). Average annual precipitation is 38.3 cm on the Colorado site (Western Regional Climate Center, 2006), 42.3 cm on the South Dakota site (High Plains Regional Climate Center, 2006. Available online at www.hprcc.unl.edu/index.html. Last access date Oct. 31, 2006), and 37.5 cm on the Montana site (Western Regional Climate Center, 2006); on all three of these sites precipitation is mostly received as rain in April, May, and June. All four sites recorded below-average precipitation totals in at least 3 years since 1999.

Measurements

On each study site, we marked >900 trees in areas of varying fire severity, plus an additional 1,000+ trees in unburned areas to provide information on background mortality rates in the absence of fire. Our sampling units in both burned and unburned areas consisted of permanently marked 10- × 200-m belt transects. All trees >5.1 cm dbh were permanently marked with numbered metal tags during the summer of 2001. The number of transects varied from 9 to 12 per site, because fire severity, tree size, and tree density differed by site, and our goal was to encompass a range in tree diameters on both burned and unburned areas plus varying levels of crown, bole, and ground fire severity in burned areas.

We selected 15 variables to measure or calculate, including variables shown in previous studies to reflect a tree's susceptibility to fire (Fowler and Sieg 2004), but were nondestructive and could be rapidly and accurately measured. Tree attributes included diameter (dbh; measured at 1.4 m height), tree height, and height to first prefire live branch. We calculated prefire live crown ratio from the latter two variables as the ratio of live crown to the total height of the tree. Fire damage to the crown of each tree was measured in four ways. Percentage crown scorch volume, or the percentage of the prefire crown volume that was scorched, but not consumed by the fire (Ryan 1982, Harrington 1987), was visually estimated to the nearest 5% by viewing the tree from all sides. Crown scorch included singed foliage but not that portion of foliage consumed by the fire (Dieterich 1979, Wyant et al. 1986, McHugh and Kolb 2003). Percentage crown consumption, the percentage of the prefire foliage volume that was consumed, was also visually estimated to the nearest 5% by viewing the tree from all sides. The presence of needle fascicles on small branches helped identify branches that supported foliage before the fire (McHugh and Kolb 2003). We also measured maximum crown scorch height and maximum crown consumption height.

We included four measures of fire damage to the bole: percentage of basal circumference that was scorched at 30 cm above the ground, maximum and minimum bole scorch height, and presence of resin flow as the result of the fire. No distinction was made between bole scorch and char (e.g., McHugh and Kolb 2003). We also measured ground fire severity used Ryan's (1982) rating classes (none, low, moderate, or high) based on changes in litter, duff, and soil characteristics due to burning.

In addition, we recorded evidence of bark beetle attacks. Bark beetle species included western pine beetle, roundheaded pine beetle (*D. adjunctus* Blandford), mountain pine beetle, red turpentine beetle, and pine engraver or *Ips* beetles (*Ips lecontei* Swaine, *I. pini* [Say], and *I. calligraphus* [Germar]). Evidence of bark beetle attack was determined by inspecting the lower bole of trees for pitch tubes, boring dust, and entrance and exit holes, and in the case of *Ips*, noting needle fading in the upper crowns while the lower crowns remained green. Tree status (dead or alive) was determined by the presence/absence of live needles. For dead trees, bark beetle species or genus were identified by removing portions of bark and exposing the phloem/cambium to examine egg gallery patterns (Ryan and Amman 1996). Finally, degree of dwarf mistletoe (*Arceuthobium vaginatum* [Willd.] Prel subsp. *cryptopodum* [Engelm.]) infestation of Arizona trees was rated using Hawksworth's (1977) rating system. Our intent was to eliminate trees with high levels of mistletoe infestation from the data set; however, very low levels of mistletoe infestation made this unnecessary. In 2002 and 2003, we revisited each study site and recorded the status of each of the marked trees in burned and unburned areas, as well as evidence and type of bark beetle attack.

Model Development

Individual Fire Models

We used logistic regression to develop models that best differentiated trees that died from those that survived using a binary response variable (dead/alive) using the 3-year postburn data set for each of the four sites. The logistic regression equation used to model mortality has the form

$$P = \frac{1}{1 + e^{-(\beta_1 + \beta_2 X_2 + \cdots + \beta_k X_k)}},$$

where P = probability of mortality, $X_2 - X_k$ are independent variables, and $\beta_1 - \beta_k$ are model coefficients estimated from mortality data. In addition to the independent variables described above, we calculated total crown volume damage as the sum of crown scorch volume + crown consumption volume. Categorical ground severity data (1 = low, 2 = moderate, 3 = high) were weighted for analyses: 1 = low, 2 = moderate, 4 = high as a continuous variable. Presence of resin, presence of *Dendroctonus* beetles, and presence of *Ips* beetles were coded as categorical variables: 1 ("yes") or 0 ("no").

We used the independent variables in logistic regression models to predict tree mortality using SAS/STAT software, Version 9.1 of the SAS system for Windows 2000 (2002–2003). Exploratory models were developed with PROC LOGISTIC using score and backward selection options. Final models were developed with generalized estimating equations (GEE) in PROC GENMOD to account for autocorrelated data within each transect. This formulation permitted us to mimic the fact that tree mortality data were compiled on a transect-by-transect basis and that trees near each other within a transect were subject to similar fire behavior. Multicollinearity between model variables was checked during model development to ensure that variables had tolerance values greater than 0.4 (Allison 1999). Selection of final variables was based on generalized score statistics (type 3, $P < 0.05$) for GEE models. Assessment of model fit and selection of the final model was based on the lowest deviance value among competing models. Deviance compares the model of interest to a saturated model (Allison 1999). We then used the final model in PROC LOGISTIC to generate statistics on the model's goodness-of-fit, predictive power, and discriminative power; classification accuracy was assessed by the likelihood χ^2 statistic, max-rescaled R^2 values, receiver operating characteristic (ROC) scores, and percentage of correctly classified trees, respectively. Max-rescaled R^2 (Negelkerke 1991) measures predictive power and divides the generalized R^2 for logistic regression by its upper limit since it is less than 1.0 (Allison 1999). ROC values range from 0 to 1, and provide a measure of the model's ability to discriminate between dead and alive trees. ROC values ≥ 0.7 are acceptable; values ≥ 0.9 are indicative of outstanding discrimination (Hosmer and Lemeshow 2000). Percentage of correctly classified trees was estimated using internal model cross-validation procedures based on the leave-one-out principle (PROC LOGISTIC ctable option). We also used standardized parameter estimates (PROC LOGISTIC stb option) to rank significant variables in the model (Allison 1999), and then ran a series of models adding one variable at a time in rank order to measure increased correctly classified percentage with each addition.

Four-Site Model

We next pooled all the data from the four individual sites and developed a combined model following the procedures described above. We added a categorical "site" variable to assign data to one of the four sites and test whether this variable added significantly to the ability of the model to predict tree mortality. If "site" was significant, this indicated that pooling the data from all four sites may not be appropriate. Using the coefficient ranking provided by standardized parameter estimates, we then ran a series of rank-order models to provide model fit statistics (max-rescaled R^2, ROC scores, AIC (Akaike's information criterion), and percentage correct classification) at each increment of the combined model. AIC in PROC LOGISTIC is very similar to deviance in PROC GENMOD in comparing relative fit of different models for the same data set (Allison 1999). Lower AIC values indicate better relative fit. Finally, we developed a combined model using total crown damage in place of both crown scorch volume and crown consumption volume to compare model fit statistics with the model using crown scorch and consumption volume as two separate variables.

External Model Validation

We established an additional study site in 2001 on the Roger's Shack Fire, part of the Elk Mountain wildfire complex, in the Black Hills National Forest, South Dakota. The fire complex started on July 30 and was declared contained on Aug. 4, 2001 after burning approximately 10,846 ha. We followed the same protocols and methods as described above to establish transects, permanently mark trees, and collect data on tree and fire damage attributes in 2001. Postfire data on the status of the trees (alive or dead) and evidence of *Dendroctonus* or *Ips* beetles were collected in 2002, 2003, and 2004. We then used the equation developed from the four-site combined model to compare the model's predictions to the observed status of trees 3 years postburn on the Roger's Shack Fire. Agreement between the combined model prediction and observed status was measured by the Kappa statistic (Cohen 1960) with zero indicating chance agreement and the strength of positive agreement ranging up to positive one.

Results

We measured a total of 5,083 trees from the four study sites in burned areas, of which 36.5, 63.6, 47.9, and 62.7% were dead in 2003 in Arizona, Colorado, South Dakota, and Montana, respectively. In contrast, mortality in unburned transects on the four study sites averaged <2% over the 3 years. The prefire average basal area ranged from 18.2 to 29.4 m^2/ha; average tree density ranged from 519 to 989 trees/ha on the four sites. Our sampling was successful in capturing a range of tree diameters from 5.1 to 106.9 cm across all four sites, as well as a range in the degree of crown and bole fire damage, and varying levels of ground fire severity (Table 1). By the third year postburn, the percentage of trees with evidence of *Ips* beetles ranged from 6% to 26%, and the percentage of trees with evidence of *Dendroctonus* bark beetles ranged from approximately 5% to nearly 19%. Two species of *Ips* beetles (*I. pini* and *I. calligraphus*), plus red turpentine beetles, were common on all study sites. Western pine beetle, roundheaded pine beetle, and one species of *Ips* beetle (*I. lecontei*) were unique to the Arizona site. Mountain pine beetle was present at all sites except for Arizona.

Individual Site Models

Between four and seven variables were significant ($P < 0.0001$) in the individual models (Table 2). In all four models, crown scorch and crown consumption volume offered the greatest explanatory value (Figure 2), followed by either tree diameter or presence of *Ips* beetles. Other significant variables in at least one of the four individual models included minimum bole scorch, presence of *Dendroctonus* beetles, basal circumference scorch, ground fire severity, and prefire live crown ratio. ROC scores for each of the four study sites ranged from 0.94 to 0.97, and max-rescaled R^2 values were between 69 and 83% for 3-year postburn ponderosa pine tree mortality. The likelihood ratio χ^2 was highly significant ($P < 0.0001$) for all models, and the models correctly classified between 85 and 93% of the trees as dead or alive.

Four-Site Model

Eight variables were significant ($P < 0.0001$) in the pooled model (Table 3). The first two variables in the model, crown scorch and crown consumption volume, accounted for most of the predictive power in the model (max-rescaled $R^2 = 67\%$, ROC score of 0.92) and collectively correctly classified 84.8% of the trees as either alive or dead. Crown scorch volume for dead trees averaged 69.4%, compared to 32.1% for trees that survived, and crown consumption averaged 18.2% for dead trees compared to <1% for trees that survived 3 years postburn (Figure 3a and b).

Six variables in addition to the percentage volume of crown consumption and scorch were significant in the pooled model: dbh, presence of *Ips* beetles, minimum bole scorch height, ground fire severity, maximum bole scorch height, and prefire live crown ratio. The addition of tree diameter increased the max-rescaled R^2 by 3% and correct classification by approximately 1%. The addition of *Ips* beetle presence increased the max-rescaled R^2 by 7% and increased the correct classification by nearly 4%. Trees that had died by 3 years postburn had smaller average diameters (16.0 cm) than trees that survived (average dbh 25.0 cm) (Figure 3c), and nearly 89% of the dead trees in the pooled data set had evidence of *Ips* beetles compared to 11% of trees that were alive (Figure 3d).

The remaining four significant variables did not greatly

Table 1. Mean ± standard error, plus ranges, of tree and fire damage variables measured on four 2000 wildfires and a 2001 validation wildfire

Variable	Arizona ($n = 1257$)	Colorado ($n = 947$)	South Dakota ($n = 1244$)	Montana ($n = 1635$)	Total ($n = 5083$)	Validation Fire ($n = 1361$)
	(Mean ± SE and Range)					
Diameter breast height (cm) (dbh)	24.2 ± 0.3 5.1–106.9	17.0 ± 0.3 5.1–61.0	24.3 ± 0.2 5.1–51.1	16.0 ± 0.3 5.1–61.5	20.2 ± 0.1 5.1–106.9	17.1 ± 0.2 5.1–43.9
Tree height (m) (THT)	12.2 ± 0.1 2.7–28.7	9.0 ± 0.1 2.4–24.1	14.7 ± 0.1 3.7–25.3	10.4 ± 0.1 1.5–27.4	11.6 ± 0.1 1.5–28.7	13.3 ± 0.1 2.4–21.6
Pre-fire live crown ratio (%) (LCR)	58.7 ± 0.5 3–93	63.0 ± 0.5 7–94	60.6 ± 0.4 9–94	60.8 ± 0.4 5–95	60.6 ± 0.2 3–95	56.4 ± 0.4 5–92
Crown scorch volume (%) (CSV)	45.8 ± 1.1 0–100	58.3 ± 1.2 0–100	49.2 ± 1.0 0–100	54.6 ± 1.1 0–100	51.8 ± 0.5 0–100	54.2 ± 1.2 0–100
Crown consumption volume (%) (CCV)	9.7 ± 0.8 0–100	8.7 ± 0.8 0–100	12.5 ± 0.9 0–100	8.5 ± 0.6 0–100	9.8 ± 0.4 0–100	24.7 ± 1.1 0–100
Total crown damage (TCD = CSV + CCV)	55.2 ± 1.1 0–100	67.0 ± 1.1 0–100	61.8 ± 1.0 0–100	62.9 ± 1.0 0–100	61.5 ± 0.5 0–100	78.8 ± 1.0 0–100
Basal circumference scorch (%) (BSC)	92.4 ± 0.6 0–100	96.5 ± 0.4 0–100	96.9 ± 0.3 5–100	95.7 ± 0.4 0–100	95.3 ± 0.2 0–100	93.7 ± 0.5 0–100
Height to first live branch (m) (LBH)	5.1 ± 0.1 0.3–15.2	3.3 ± 0.1 0.3–13.7	5.8 ± 0.1 0.6–16.5	4.1 ± 0.1 0.3–20.7	4.6 ± 0.04 0.3–20.7	5.9 ± 0.1 0.8–16
Crown scorch height (m) (CSH)	6.8 ± 0.1 0–20.7	5.8 ± 0.1 0–16.8	9.9 ± 0.1 0–24.4	6.4 ± 0.1 0–25.9	7.3 ± 0.1 0–25.9	9.6 ± 0.2 0–22
Crown consumption height (m) (CCH)	1.3 ± 0.1 0–18.6	0.9 ± 0.1 0–14.9	2.3 ± 0.1 0–22.3	1.0 ± 0.1 0–23.5	1.4 ± 0.1 0–23.5	3.6 ± 0.2 0–19
Max. bole scorch height (m) (BSH)	5.3 ± 0.1 0–19.2	4.0 ± 0.1 0–15.2	6.4 ± 0.1 0.1–23.5	4.0 ± 0.1 0–23.5	4.9 ± 0.1 0–23.5	7.9 ± 0.1 0–20
Min. bole scorch height (m) (BSL)	2.9 ± 0.1 0–18.6	1.5 ± 0.1 0–14.9	3.7 ± 0.1 0–21.3	2.0 ± 0.1 0–23.5	2.6 ± 0.1 0–23.5	5.3 ± 0.1 0–20
Ground fire severity rating (GSV)	1.8 ± 0.03 0–4	2.0 ± 0.03 1–4	2.1 ± 0.03 1–4	1.7 ± 0.02 1–4	1.9 ± 0.01 0–4	1.9 ± 0.01 1–4
Ips spp. (% trees) (IPS)	6.4	10.2	26.1	24.0	17.6	62.7
Dendroctonus spp. (% trees) (DEN)	18.9	16.4	29.3	5.4	16.6	28.0

Table 2. Significant ($P < 0.0001$) variables in four separate ponderosa pine mortality models for 3 year postfire status of trees sampled on 2000 wildfires in Arizona (AZ), Colorado (CO), South Dakota (SD), and Montana (MT)

Model	Predictor variables							ROC	R^2	% correct
AZ	CSV	CCV	−dbh	BSL	DEN	GSV		0.96	0.77	91.0
CO	CSV	CCV	−dbh	IPS				0.94	0.69	84.8
SD	CCV	CSV	IPS	GSV	BSL	−dbh	BSC	0.97	0.82	91.5
MT	CCV	CSV	IPS	−dbh	BSC	−LCR		0.97	0.83	92.5

Significant variables include crown scorch volume (CSV), crown consumed volume (CCV), diameter at breast height (dbh), presence of *Ips* beetles (IPS), minimum bole scorch (BSL), ground scorch severity (GSV), presence of *Dendroctonus* beetles (DEN), basal circumference scorch (BSC), and pre-fire live crown ratio (LCR). The probability of mortality increased with increasing levels of each variable, except those indicated with a negative sign. Also shown are ROC scores, max-rescaled R^2, and percentage of correctly classified trees. Variables are ranked (left to right) from greatest explanatory value to least significant.

The logistic regression equation for the AZ model is $P(\text{mortality}) = 1/\{1 \exp[-(-1.32985 - 0.00069(\text{CSV2}) + 0.00001(\text{CSV3}) + 0.04687(\text{CCV}) - 2.19528(\log \text{dbh}) + 0.4214(\sqrt{\text{BSL}}) - 2.04983(\text{DEN}) + 1.591(\sqrt{\text{GSV}}))]\}$.

The logistic regression equation for the CO model is $P(\text{mortality}) = 1/\{1 \exp[-(4.2779 + 0.084956(\text{CSV}) - 0.0019(\text{CSV2}) + 0.0000156(\text{CSV3}) + 0.06676(\text{CCV}) - 2.0244(\log \text{dbh}) - 2.5674(\text{IPS}))]\}$.

The logistic regression equation for the SD model is: $P(\text{mortality}) = 1/\{1 \exp[-(1.46072 + 0.072461(\text{CCV}) + 0.00000454(\text{CSV3}) - 2.93438(\text{IPS}) + 3.533568(\sqrt{\text{GSV}}) + 0.48483(\sqrt{\text{BSL}}) - 2.41617(\log \text{dbh}) - 0.016(\text{BSC}))]\}$.

The logistic regression equation for the MT model is $P(\text{mortality}) = 1/\{1 \exp[-(1.184817 + 0.10403(\text{CCV}) + 0.000005404(\text{CSV3}) - 3.0373(\text{IPS}) - 1.76628(\log \text{dbh}) - 0.03897(\text{BSC}) - 0.0002625(\text{LCR}))]\}$.

enhance the model's ability to predict mortality. Trees that were dead had greater minimum bole scorch height (4.0 m) than those that were live (0.95 m) (Figure 3e). Weighted ground fire severity ratings averaged 2.1 for dead trees and 1.6 for trees that survived (Figure 3f), maximum bole scorch averaged 6.2 m for dead trees compared to 3.5 m for live trees, and dead trees had a prefire live crown ratio of 58% in contrast to 63% for trees that survived the wildfires.

The final model, including eight variables, had a highly significant likelihood ratio χ^2 ($P < 0.0001$), an AIC score of 2,447, a max-rescaled R^2 of 79%, an ROC score of 0.96, and correctly classified 89.9% of the trees (Table 3). When we ran the seven-variable model using total crown damage in place of crown scorch volume and crown consumed volume, the max-rescaled R^2 decreased to 77%, and the model correctly classified a slightly lower percentage of the trees (89.5%; Table 4). Nonsignificant variables included site ($P = 0.0951$ when run with the eight-variable model) as

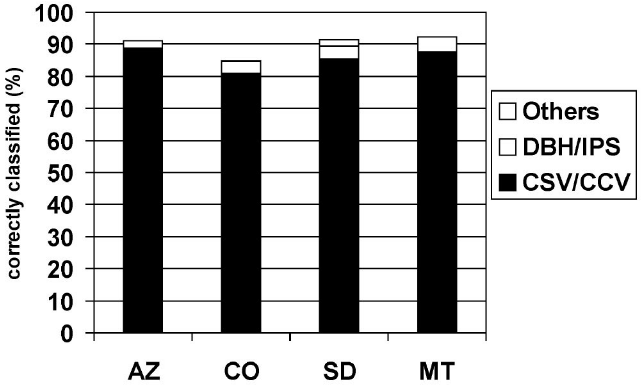

Figure 2. Relative contribution (percentage correctly classified by internal cross-validation) of major variables to individual fire models for Arizona (AZ), Colorado (CO), South Dakota (SD), and Montana (MT) wildfires. Variables include crown consumed volume (CCV), crown scorch volume (CSV), dbh, and presence of *Ips* beetles (IPS). "Other" variables include DEN (presence of *Dendroctonus* beetles), BSL (minimum bole scorch height), and GSV (ground fire severity) for AZ; BSL, GSV, and LCR (prefire live crown ratio) for SD; and LCR and BSL for MT.

well as tree height, crown scorch height, crown consumed height, basal circumference scorch, presence of resin, presence of *Dendroctonus*, and height of first live branch, which were eliminated during GENMOD/GEE analysis.

External Model Validation Test

We measured 1,361 trees on the Roger's Shack Fire on the Black Hills National Forest in western South Dakota in 2001, of which 83.4% were dead 3 years postburn. Attributes of the trees fell within the range observed on the trees sampled on the four 2000 fires, with dbh averaging 17.1 cm, tree height 13.3 m, and an average prefire live crown ratio of 56.4% (Table 1). Fire damage was variable, as well, with crown scorch and consumption ranging from 0 to 100%.

The four-site model correctly classified the status of 95.7% of the trees on the Roger's Shack Fire; misclassification rates were slightly higher for trees that were alive that were predicted to be dead (3.7%) than for dead trees predicted to be alive (1.7%; Table 5). The Kappa statistic (0.83) indicated a strong positive agreement between predicted and observed, and that agreement was not due to chance ($P < 0.0001$).

Discussion

Our results from both individual site models and the pooled four-site model indicate that crown scorch and consumption volume were the two most useful variables in discriminating between trees that survived and those that died following wildfires. In contrast to McHugh and Kolb (2003) and McHugh et al. (2003), who determined that total crown damage had the greatest discriminative power, we found that including both individual variables resulted in greater predictive power and better fit for resulting models. Based on lower deviance and AIC scores, our eight-variable model using crown scorch volume and crown consumed volume as separate variables, was superior to the seven-variable model using total crown damage in place of crown scorch volume and crown consumed volume.

There is a sound biological basis for including measures of both crown consumption and scorch volume when assessing damage from fires. Ponderosa pine is able to tolerate consumption or scorching damage of especially the lower portions of the crown, because needles in the upper third of the crown have greater photosynthetic capacity than lower portions of the crown (Helms 1970). Damage to only the lower two-thirds of the crowns would reduce transpiration demand, but maintain the most efficient photosynthetic tissues (Stephens and Finney 2002). However, the physiological effects of scorching and consumption are not equal, as scorching may damage foliage but not kill buds (Dieterich 1979), while consumption would be more likely to cause some, if not the majority, of the bud mortality (Wyant et al. 1986). Total crown damage, the sum of crown scorch and crown consumption, was a poorer predictor of mortality because it did not account for the varying proportion of the total damage that was consumed. For example, the model predicts that a tree with 20% crown consumption + 20% crown scorch has a probability of >40% of dying (Figure 4). If that 40% crown damage was 40% scorch and no consumption, the probability of dying is <30%; if the damage was 40% consumption and no scorch, the model predicts a >65% chance of mortality.

Table 3. Significant variables ($P < 0.001$), in rank order, in the four-site model, using pooled data based on 3-year postfire status (dead or alive) of 5,083 trees in four states

Variable	Model Step	Max-rescaled R^2	ROC score	Correct classification (%)	AIC
Crown scorch volume (CSV)	1	0.43	0.78	74.3	5,053
Crown consumed volume (CCV)	2	0.67	0.92	84.8	3,465
Tree diameter (dbh)	3	0.70	0.93	85.7	3,250
Presence of *Ips* beetles (IPS)	4	0.77	0.96	89.3	2,670
Min. bole scorch height (BSL)	5	0.78	0.96	89.7	2,549
Ground fire severity (GSV)	6	0.79	0.96	89.6	2,497
Max. bole scorch height (BSH)	7	0.79	0.96	89.7	2,482
Live crown ratio (LCR)	8	0.79	0.96	89.9	2,447

Also given are cumulative max-rescaled R^2, ROC score, percentage of correctly classified trees, and AIC score at each step of the model. The resulting logistic regression equation is $P(\text{mortality}) = 1/\{1 \exp[-(0.0734 - 2.4678(\log \text{dbh}) + 0.0942(\text{CSV}) - 0.0024(\text{CSV}^2) + 0.000019(\text{CSV}^3) + 0.0521(\text{CCV}) - 0.0002(\text{LCR}) + 0.1588(\log \text{BSH}) + 0.3698(\sqrt{\text{BSL}}) + 1.4257(\sqrt{\text{GSV}}) + 2.9478(\text{IPS}))]\}$.

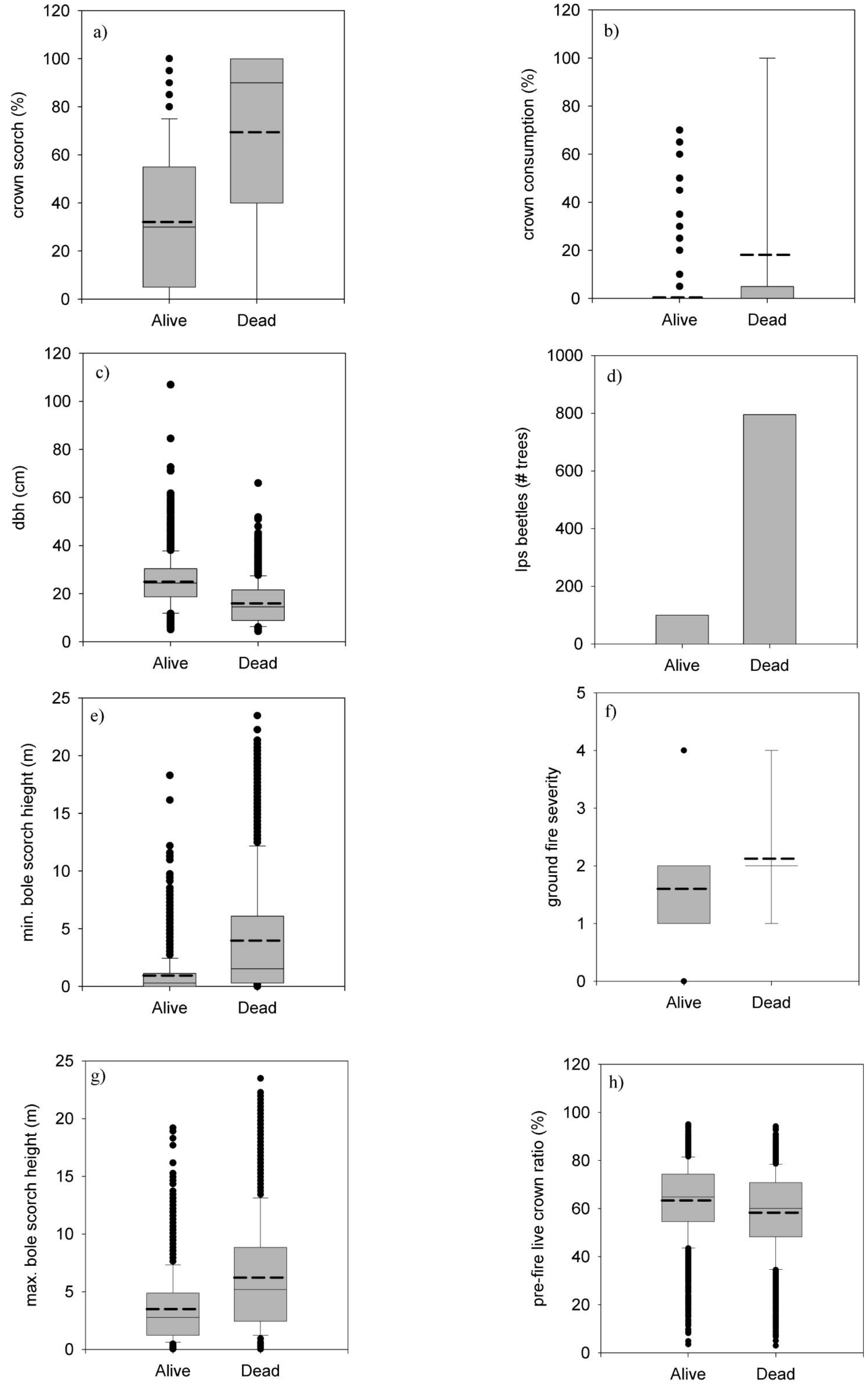

Figure 3. Average percentage crown volume scorched (a) and consumed (b), dbh (c), number of trees with *Ips* beetles (d), minimum bole scorch height (e), average weighted ground severity rating (f), maximum bole scorch height (g), and prefire live crown ratio (h) by tree status (dead or alive), for pooled data from four fires and 5,083 trees, 3 years postburn. The boundary of the box closest to zero indicates the 25th percentile, the solid line within the box marks the median, the dashed line marks the mean, and the boundary of the box farthest from zero indicates the 75th percentile. Whiskers above and below the box indicate the 90th and 10th percentiles, and the dots are outliers.

Consistent with our hypothesis, tree diameter was significant in all the models, and increased the percentage of correctly classified trees by about 1% in the pooled four-site model. Yet, despite differences in bark beetle complexes,

Table 4. Model fit statistics (deviance, AIC, max-rescaled R^2, ROC score, and percentage correct classification) comparing the full eight-variable model (Table 3) that includes crown consumption and scorch as separate variables; a seven-variable model that incorporates total crown damage in place of separate measures of consumption and scorch; a four-variable model with crown scorch and crown consumption volume, dbh, and *Ips*; and a two-variable model using just crown scorch and crown consumption volume

Model	Deviance	AIC	Max-rescaled R^2	ROC score	Correct classification (%)
Eight-variable model with both CCV and CSV	2,425	2,447	0.79	0.963	89.9
Seven-variable model with TCD instead of CCV and CSV[1]	2,623	2,640	0.77	0.958	89.5
Four-variable model (CCV, CSV, dbh, IPS) [2]	2,656	2,760	0.77	0.955	89.3
Two-variable model (CCV and CSV) [3]	3,455	3,465	0.67	0.915	84.8

[1] The logistic regression equation for the seven-variable model is $P(\text{mortality}) = 1/\{1\ \exp[-(-0.3553 - 2.5859(\log \text{dbh}) + 0.5102(\text{RES}) - 0.00021(\text{LCR}) + 0.4725(\sqrt{\text{BSL}}) + 1.6858(\sqrt{\text{GSV}}) + 3.0823(\text{IPS}) + 0.0393\ (\text{TCD}))]\}$.

[2] The logistic regression equation for the four-variable model is $P(\text{mortality}) = 1/\{1\ \exp[-(-0.12 - 1.6238(\log \text{dbh}) + 0.078(\text{CCV}) + 0.1084(\text{CSV}) - 0.0025(\text{CSV2}) + 0.00002(\text{CSV3}) + 2.9235(\text{IPS}))]\}$.

[3] The logistic regression equation for the two-variable model is $P(\text{mortality}) = 1/\{1\ \exp[-(-2.6513 + 0.1132(\text{CSV}) - 0.0029(\text{CSV2}) + 0.00002(\text{CSV3}) + 0.0808(\text{CCV}))]\}$.

Table 5. A comparison of predicted versus actual tree status (alive or dead) of 1,361 trees (number and percentage) on the Roger's Shack Fire

	Predicted	
Actual	Alive	Dead
Alive (n = 258)	208 (15.28%)	50 (3.67%)
Dead (n = 1103)	23 (1.69%)	1080 (79.35%)

Predictions were made using the 3 years postburn four-fire model, compared to the actual status of trees 3 years postburn. Shaded cells are trees misclassified by the model.

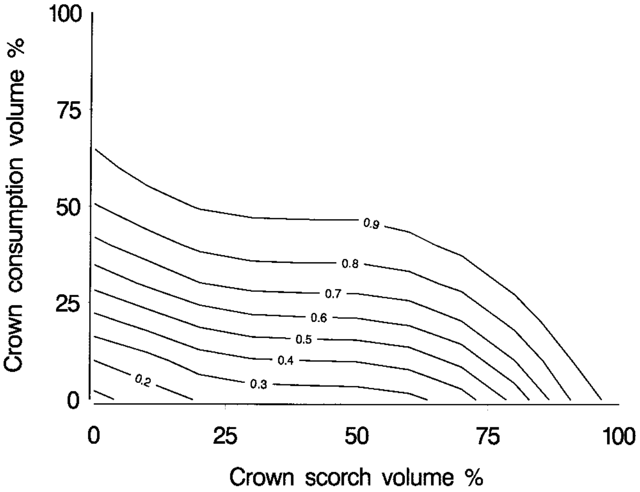

Figure 4. Contour graph showing the relationship between model predicted probability of tree death for the entire data set (n = 5,083) and the two major predictive variables for postfire mortality: crown consumption volume and crown scorch volume. Contour lines are probability of mortality.

the presence of *Ips* beetles increased predicted probability of mortality in all but the Arizona fire model, and the addition of this variable increased the percentage of correctly classified trees by approximately 4% in the pooled four-site model. In the Arizona model, the presence of *Dendroctonus* beetles was a significant variable, accounting for a small percentage of variation in tree mortality. The remaining variables that were significant in the various models each added little to the predictive capacity of any of the individual or pooled four-site model. Minimum and maximum bole scorch height, bole scorch circumference, ground fire severity, and prefire live crown ratio can be considered "tailoring" variables, as their addition resulted in the correct classification of a few trees whose survival was not predictable based solely on crown scorch and consumption volume.

The percentage of correctly classified trees was higher on the Colorado site using the pooled four-site model, but was only 1.1 to 2.4% lower on the three other sites compared to using the individual models. This comparable level of accuracy of the pooled model lends support to its use on all four sites. The pooled model also correctly classified the majority of trees on the Roger's Shack fire, which occurred in 2001. These results indicate that seasonality (and other differences among sites) did not strongly influence the probability of mortality. Other studies have shown that seasonal differences in mortality rates are most pronounced when comparing "growing season" fires with "dormant season" fires (Harrington 1987, 1993, Thomas and Agee 1986, Swezy and Agee 1991). However, Thies et al. (2006) showed that after accounting for varying fire damage attributes, the probability of a tree dying following spring versus fall burning in eastern Oregon was similar. If differences in mortality rates between "growing season" and "dormant" fires are largely due to differences in fire intensity, our pooled model may be applicable to nongrowing season fires as well. Our fires all occurred during the growing season during dry periods, when most historical fires occurred and when most species of bark beetles were dispersing; the phenological stage of the trees did not differ widely among the four sites, and droughty conditions persisted on all four sites in subsequent years.

Our study has implications for managers and for researchers. The strength of crown scorch and crown consumed volume in predicting mortality of ponderosa pine trees suggests that managers could measure these two variables and correctly classify 3-year postmortality of nearly 85% of the trees on these four sites. Adding dbh and the presence of *Ips* beetles would increase the percentage of correctly classified trees on these sites to just over 89% (Table 4). For even finer precision, managers could use the eight-variable model. These models are most applicable to growing season burns in ponderosa pine stands in the Intermountain West with stand attributes similar to our sites. The question for researchers is whether crown scorch volume and crown consumed volume are the two best predictors of ponderosa pine mortality in other regions, regardless of differences in timing of fires, bark beetle complexes, and other stand attributes such as duff accumulation. Our results and a number of previous studies suggest that a two-variable model using percentage crown scorch volume and crown consumed volume will likely have applicability beyond the Intermountain West.

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