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Development of post-fire crown damage mortality thresholds in ponderosa pine

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Abstract. Previous research has shown that crown scorch volume and crown consumption volume are the major predictors of post-fire mortality in ponderosa pine. In this study, we use piecewise logistic regression models of crown scorch data from 6633 trees in five wildfires from the Intermountain West to locate a mortality threshold at 88% scorch by volume for trees with no crown consumption. For trees with >40% crown consumption volume, linear regression indicates >85% mortality, but for trees with crown consumption volume <40%, there is a statistically significant, linear relationship between increasing crown scorch and increasing probability of mortality. Analysis of an independent 600+ tree dataset from Colorado produced similar results and supports the analysis approach. Crown scorch volume (>85%), crown consumption volume (>40%), and crown consumption between 5 and 40% combined with crown scorch volume >50% mortality thresholds could be incorporated into post-fire marking guidelines for forest management goals.

Additional keywords: crown consumption, crown scorch, logistic regression, marking guidelines, piecewise regression, *Pinus ponderosa*, statistical models, wildfire.

Michaletz and Johnson (2008) noted that post-fire tree mortality has traditionally been modelled by logistic regression, an empirical, statistical approach that may obscure the causal processes leading to tree death. Indeed, significant variables in logistic regression models may or may not be the direct cause of mortality. Biophysical models such as that presented by Michaletz and Johnson (2008) focussed on the direct physical and physiological causes of tissue necrosis and tree death. After a wildfire, however, land managers may be more interested in first-order fire effects and in being able to predict which trees will survive than in understanding causal processes. So although a biophysical model of tree mortality may lead to a greater understanding of tissue necrosis and tree mortality before prescribed fires and wildfires, statistical models may be of greater utility for predicting fire effects such as tree mortality after fire damage has occurred.

There is a general agreement within the research and management communities that ponderosa pine (*Pinus ponderosa* Douglas ex Lawson & C. Lawson) and Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco) can sustain up to 75% crown damage, but after that point mortality rates increase sharply. Many studies have contributed to that notion (see reviews in Fowler and Sieg 2004), but the most definitive are Peterson and Arbaugh (1986) and McHugh and Kolb (2003). However, no studies have explicitly looked for statistically significant mortality thresholds for crown scorch or crown consumption.

Piecewise regression models can be used to search for ecological thresholds and significant changes in rate (Ryan and Porth 2007). This modelling approach separates the range of values for an explanatory variable into two or more pieces and models them separately. Toms and Lesperance (2003) suggested that piecewise regression is an 'overlooked, objective technique for estimating ecological thresholds' (p. 2040). In a demonstration of the technique, they used a piecewise linear regression 'sharp breakpoint model' to locate an edge effect threshold for

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forest understorey plants at the continuity, the point at which the two regression lines join. Bernatchez and Wilson (1998) have shown that the two linear regression lines do not have to join to represent a threshold. They showed a discontinuous 'jump point' (Neter *et al.* 1990) at the adjacent ends of two linear regression lines. The above studies used piecewise linear regression models; only Bernatchez and Wilson (1999) used piecewise non-linear regression models in a re-analysis of a subset of their 1998 paper. In the present paper, we demonstrate the use of piecewise logistic regression models to locate a statistical mortality threshold in ponderosa pine following wildfire-caused crown damage.

Sieg *et al.* (2006) showed that crown scorch volume and crown consumption volume were the two best predictors of post-fire mortality for ponderosa pine out of a set 15 variables commonly used to predict post-fire mortality in that species. Their logistic regression model correctly classified (live or dead) almost 90% of the trees in a large post-fire dataset from four wildfires occurring in 2000 from the Intermountain West as well as almost 96% of the trees in an external 2001 wildfire dataset. However, field application of single-segment logistic regression models is not straightforward, in part owing to their multivariate nature and their tendency to produce smooth transitions and to obscure breakpoints if they exist. In this paper, we further investigate the utility of the top two predictors, crown scorch and crown consumption, because they represent direct loss of photosynthetic potential and they had almost as much predictive accuracy (85%) as the full set of eight statistically significant predictor variables from the same dataset (Sieg *et al.* 2006).

Methods

Study sites and field measurements

Four study sites were established following wildfires in 2000 and a fifth site following a 2001 wildfire to provide data for developing models to predict post-fire mortality. These five sites were located in forests strongly dominated by ponderosa pine in Arizona, Colorado, South Dakota, and Montana, USA. Site descriptions as well as pre- and post-fire measurement results are presented in Sieg *et al.* (2006).

On each study site, our goal was to mark 1200–1500 trees in areas of varying fire severity, plus an additional 1200 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 belt transects 0.2 km long and 10.1 m wide. All trees >5.1 cm diameter at breast height (DBH) were permanently marked with numbered metal tags. The number of transects varied on each site, because fire severity, and tree size and density differed by site, and our goal was to encompass a range in tree diameters on both burned and unburned areas as well as representative levels of crown damage varying from 0 to 100% for both scorch and consumption in burned areas.

Fire damage to the crown of each tree was measured the first year post-fire in two ways: scorch and consumption (Dieterich 1979; Wyant *et al.* 1986; McHugh and Kolb 2003). Percentage crown scorch volume, the percentage of the prefire crown volume that was scorched but not consumed by the fire (Peterson 1985), was visually estimated to the nearest 5% by viewing the tree from all sides. 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. Presence of needle fascicles on small branches helped identify branches that supported foliage before the fire (McHugh and Kolb 2003). At 3 years post-fire, we revisited each study site and recorded the live or dead status of each of the marked trees in burned and unburned areas.

An independent dataset from the 2002 Hayman wildfire in Colorado was independently collected using the same protocols for crown scorch volume, crown consumption volume, and tree status variables (P. Fornwalt, US Forest Service Rocky Mountain Research Station, unpubl. data). We used this 3-year post-fire tree status (2005) for ponderosa pine trees to evaluate our investigative approach.

Statistical models

The dataset was divided into three categories for analysis: (1) trees with crown scorch (>2.5% by volume) but with no crown consumption (<2.5% by volume) ($n = 4549$); (2) trees with crown scorch and some crown consumption (>2.5% by volume) ($n = 1153$); and (3) trees with no crown damage (<2.5% by volume) ($n = 931$). For the first category, a single-segment, logistic regression model was developed with year 3 live or dead status as the dependent variable and crown scorch volume as the predictor variable using PROC NLMIXED, *SAS/STAT* software, version 9.1 of the SAS system for Windows 2000. Piecewise logistic regression (Bates and Watts 1988) was then used in PROC NLMIXED to identify the join point of two separate logistic regression lines, one each for lower amounts and higher amounts of crown scorch volume. Starting values for the two slopes and the first intercept were taken from PROC LOGISTIC models developed by subdividing the dataset into trees above and below the 70% crown scorch volume level: i.e. near and below the generally accepted 75% level. The join point identified in PROC NLMIXED is interpreted as a mortality threshold for crown scorch volume. Slope comparisons for the two segments of the piecewise regression model were performed with a contrast statement within PROC NLMIXED. Model fit comparison between single-segment and piecewise logistic regression models was by a likelihood ratio test and by a finite-sample corrected version of Akaike's information criterion (AICC) (Burnham and Anderson 1998) in which lower values indicate better model fit. Sample SAS code for this analysis approach is shown in the Accessory publication.

As piecewise regression models for crown consumption volume were not stable (did not converge), trees with some crown consumption (category 2) were grouped into 10% crown consumption classes in order to calculate within-class mortality rates. Linear regression techniques (PROC REG, *SAS/STAT 2002–2003*) were then used to model the relationship between these class mortality rates and crown scorch–crown consumption volumes. All graphs were prepared with PROC GPLOT, *SAS/GRAPH* software, version 9.1 of the SAS system for Windows 2000.

Results

For the 5702 trees in the dataset with either crown scorch or crown consumption, the overall 3-year mortality rate was 0.47.

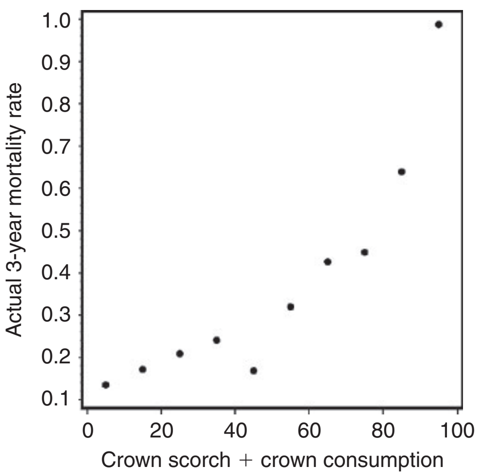

Fig. 1. Observed 3-year mortality rate by 10% crown damage classes for 5702 ponderosa pine trees with some crown damage.

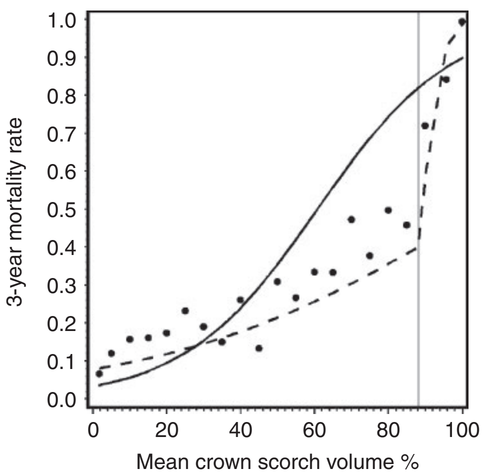

Fig. 2. The 3-year mortality rates for 4549 ponderosa pine with crown scorch and no observable ($<$2.5%) crown consumption: mortality proportion by mean crown scorch volume classes. Dots represent actual mortality rate. Solid line represents single-segment logistic regression equation model predictions. Dashed line represents predictions from a two-segment piecewise logistic regression model with a join point of 88.1% (vertical line for reference) indicating a mortality threshold.

To examine the general mortality pattern, mortality rates were calculated by 10% crown damage classes (scorch + consumption). The resulting mortality plot (Fig. 1) shows a sharp increase in mortality after the 70–80% damage class and suggests the possibility of a mortality threshold.

The overall 3-year mortality rate was 0.42 for trees with crown scorch but no crown consumption. Using piecewise logistic regression, we found a crown scorch volume mortality threshold at 88.1% (s.e. $\pm$0.6, 95% confidence limits 86.9–89.2%) where the two logistic regression lines of the piecewise model join. This is shown graphically (Fig. 2) using 5% crown scorch volume class means. The slope coefficient for the first regression is 0.024 (s.e. $\pm$0.002) but sharply steepens on the second regression at 0.388 (s.e. $\pm$0.029). This is a significant change in slope ($F_{1,4549} = 153.13$, $P < 0.0001$). The model fit for piecewise regression is much better than for the single-segment logistic regression model also shown in Fig. 2 (log-likelihood ratio test $\chi^2 = 573.2$, d.f. = 2, $P < 0.001$, AICC = 3284 *v.* 3853 respectively). It also visually tracks the distribution of the grouped mean data points better (Fig. 2). These data points represent the mortality rates for 5% crown scorch volume classes for trees in category 1. Predicted mortality rate for 85% crown scorch volume is 0.49 for the piecewise model, much closer to the dataset mean of 0.46 than the 0.79 prediction from the single-segment logistic regression model (Fig. 2). Mean crown scorch volume for these 4549 trees was 67% (Table 1).

In the second category, the 1153 trees with crown scorch and some crown consumption had an overall 3-year mortality rate of 0.96. A linear regression model of mortality for these trees by 10% crown consumption classes (Fig. 3) indicated high mortality at low crown consumption volumes and had good explanatory power ($r^2 = 0.71$). Crown consumption volumes above 40% indicated a probability of mortality of $>$0.9 (Fig. 3) but probability of mortality was more variable below 40%. For the 259 trees in category 2 with less than 40% crown consumption, there is a significant linear relationship between increasing crown scorch classes and increasing probability of mortality (Fig. 4).

The 931 trees in category 3 with no observable crown damage had an overall 3-year mortality rate of 0.008. This is very similar to the 3-year mortality rate of 0.006 for 4752 trees in the unburned plots near the wildfires in Arizona, South Dakota and Montana.

Table 1. Tree size and crown damage variables

Tree diameter, height, and crown scorch volume means $\pm$ standard errors and range for trees with crown scorch but no crown consumption in the main five fire dataset (AZ, CO, MT, SD) and the independent dataset (Hayman Fire)

Dataset	*n*	Diameter at breast height, DBH (cm)	Height (m)	Crown scorch (%)
Main	4549	19.4 ± 0.1	11.8 ± 0.7	67 ± 1
		5.0 – 6.5	1.5 – 28.0	2.5–100
Independent	325	19.6 ± 0.7	9.7 ± 0.3	45 ± 2
		1.0 – 59.7	1.4 – 26.5	5–100

Independent data set model

Analysis of the Hayman Fire dataset using the same analysis approach produced similar results. For category 1 trees (with crown scorch but no crown consumption), piecewise logistic regression indicated a crown scorch volume mortality threshold at 86.3% (s.e. $\pm$3.6, 95% confidence limits 79.3–93.4%, $n = 325$) where the two regression lines join, graphically shown (Fig. 5) using 5% crown scorch volume class means. The regression slope coefficients are significantly different ($F_{1,325} = 12.89$, $P = 0.0004$) and model fit for the piecewise regression model is better than the single-segment logistic regression model (log-likelihood ratio test $\chi^2 = 33.4$, d.f. = 2, $P < 0.001$, AICC = 118 *v.* 147 respectively). Mean crown scorch volume for these trees was 45% (Table 1). For the 276 trees in this dataset that had crown scorch and some crown consumption, a linear regression model

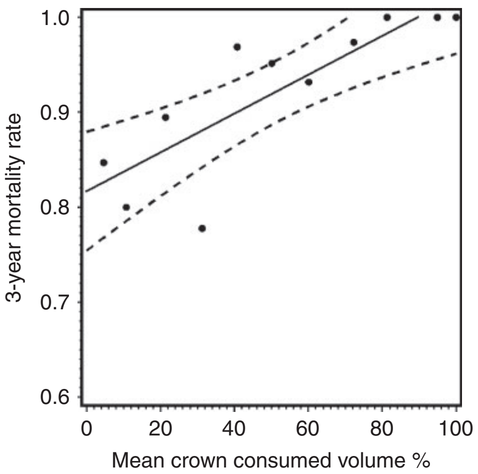

Fig. 3. The 3-year mortality rates for 1153 ponderosa pine with observable crown consumption (>2.5%): mortality proportion by crown consumption volume classes. Linear regression model: 3-year mortality rate = 0.8115 + 0.0021 × mean crown consumption volume ($r^2 = 0.710$). Dashed lines are 95% confidence bands. Slope is significantly different from 0 ($P = 0.0011$).

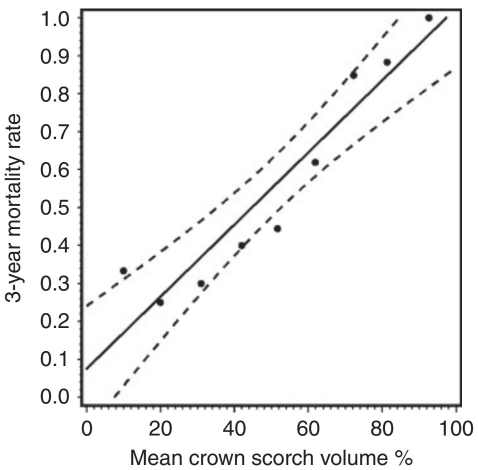

Fig. 4. The 3-year mortality rates for 259 ponderosa pine with crown consumption volumes between 2.5 and 40%: mortality proportion by crown scorch volume classes. Linear regression model: 3-year mortality rate = 0.07533 + 0.00951 × mean crown scorch volume ($r^2 = 0.899$). Dashed lines are 95% confidence bands. Slope is significantly different from 0 ($P = 0.0001$).

showed a probability of mortality >0.85 with crown consumption volumes >40%, with more variable mortality below 40% (Fig. 6). Similarly to the main dataset, a separate crown scorch model for trees with less than 40% crown consumption showed a significant linear relationship between increasing crown scorch volume classes and increasing probability of mortality (Fig. 7).

Discussion

Several previous ponderosa pine post-fire mortality studies have separated crown damage into crown scorch and crown consumption variables (Dieterich 1979; Wyant *et al.* 1986; McHugh

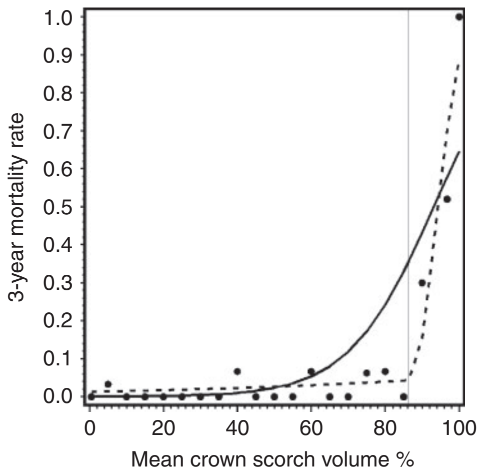

Fig. 5. Hayman Fire 3-year mortality rates for 325 ponderosa pine trees with crown scorch and no observable (<2.5%) crown consumption: mortality proportion by mean crown scorch volume classes. Dots represent actual mortality rate. Solid line represents single-segment logistic regression equation model predictions. Dashed line represents predictions from a two-segment piecewise logistic regression model with a join point of 86.3% (vertical line for reference) indicating a mortality threshold.

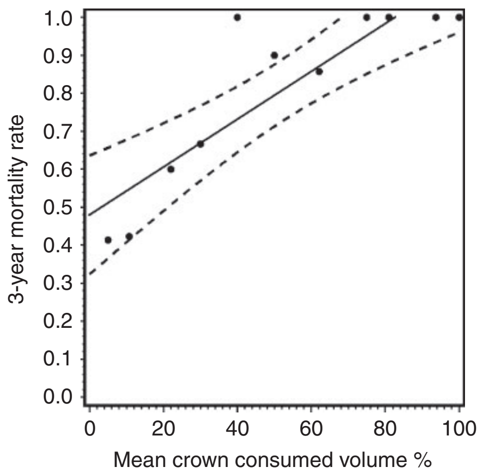

Fig. 6. Hayman Fire 3-year mortality rates for 276 ponderosa pine with observable crown consumption (>2.5%): mortality proportion by crown consumption volume classes. Linear regression model: 3-year mortality rate = 0.47962 + 0.00629 × mean crown consumption volume ($r^2 = 0.772$). Dashed lines are 95% confidence bands. Slope is significantly different from 0 ($P = 0.0004$).

and Kolb 2003; Sieg *et al.* 2006; Breece *et al.* 2008), but, in a review, Fowler and Sieg (2004) noted that most studies do not. Plant cell necrosis has been shown to occur near 60°C (Methven 1971; Dickinson and Johnson 2004) and most fire mortality studies assume a 60°C cell necrosis threshold (e.g. Van Wagner 1973; Michaletz and Johnson 2006). However, combustion initiates at 300–365°C (Butler *et al.* 2004; Michaletz and Johnson 2006) and measured maximum flame temperatures in wildfires fall between 700° and 1000°C (Hare 1961; Butler *et al.* 2004). This temperature difference provides an explanation for

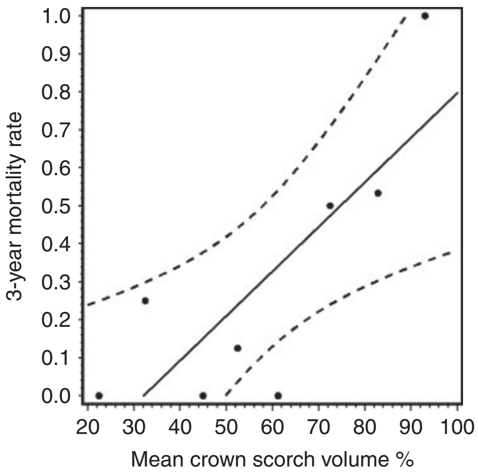

Fig. 7. Hayman Fire 3-year mortality rates for 76 ponderosa pine with crown consumption volumes between 2.5 and 40%: mortality proportion by crown consumption volume classes. Linear regression model: 3-year mortality rate $= -0.37729 + 0.01174 \times$ mean crown consumption volume ($r^2 = 0.649$). Dashed lines are 95% confidence bands. Slope is significantly different from 0 ($P = 0.0158$).

the different mortality effects of crown scorch (Fig. 2) and crown consumption (Figs 3, 4) in ponderosa pine, i.e. due to greatly increased convective and radiant heat in the crown once the combustion point has been reached. By the time foliage temperatures reach the point of combustion, there would be enough heat in the crown to cause needle scorch on a surrounding portion of the canopy.

Visible crown scorch may encompass more crown damage than just dead foliage. Michaletz and Johnson (2008) use the term crown scorch to represent vegetative bud mortality in their biophysical model: that is, death of the apical meristem. Although this assumption may be acceptable for conifer species with small buds, such as Douglas-fir (Ryan and Reinhardt 1988), it may not be true for ponderosa pine (Mitchell 1914; Wagener 1961; Ryan 1982*a*, 1982*b*). Fire-scorched foliage in ponderosa pine may simply represent dead foliage attached to live stems (Wyant *et al.* 1986) with an intact apical meristem. Michaletz and Johnson (2006) present model predictions that show foliage necrosis at 60°C for white spruce (*Picea glauca* (Moench) Voss) and Scots pine (*Pinus sylvestris* L.) and bud necrosis from 87 to 143°C for white spruce and lodgepole pine (*Pinus contorta* Dougl.). Clearly bud necrosis can occur between foliage necrosis (60°C) and foliage consumption (~300°C). If foliage consumption has occurred, the buds are probably dead, but without consumption, dead foliage may or may not indicate bud mortality. Undetectable amounts of stem tip and bud necrosis in ponderosa pine trees with high crown scorch volume may be a strong contributing factor to tree death and to a crown scorch mortality threshold of 85–90%.

Dead foliage is easier to assess than vegetative bud condition. Field assessment of bud condition may need to wait until the first post-fire growing season when live buds break dormancy (Ryan 1982*a*; Thies *et al.* 2006), although Ryan (1982*b*) indicates that live buds will drop dead foliage soon after the fire whereas dead buds will not. This may provide an opportunity to assess bud condition before bud break.

Defoliator insects may have impacts similar to fire-induced crown scorch with dead foliage and live buds. Impacts of biotic-caused defoliation to conifers depend on defoliation type, intensity of damage, health of host tree, and age of trees and foliage being defoliated (Kulman 1971; Gottschalk 1993; Lyytikäinen-Saarenmaa 1999). Tree mortality caused by single or repeated biotic defoliation events in the absence of secondary mortality agents is likely due to the depletion of carbohydrate reserves to a level that does not support respiration or growth (Kulman 1971). Mortality of Scots pine resulting from a single-year pine looper moth (*Bupauls piniaria* L.) defoliation event was found to occur at a threshold of $>90\%$ defoliation (Cedervind and Långström 2003), which is similar to the 85–90% crown scorch volume mortality threshold we found for ponderosa pine. In both cases, loss of carbohydrate reserves and loss of photosynthetic potential may be reduced to the level needed to support cell respiration in the living tissues of the tree.

At least two previous studies have noted possible mortality thresholds for conifer crown damage. Peterson and Arbaugh (1986) graphically indicated a mortality increase at 90% crown scorch for Douglas-fir 2 years post-fire. Similarly, McHugh and Kolb (2003) showed that total crown damage above 70–80% results in a sharp increase in mortality rate for ponderosa pine 3 years post-fire. Our results concur and use a much larger, more extensive dataset to demonstrate via statistical models the existence of a mortality threshold between 85 and 90% crown scorch volume in the absence of crown consumption. This threshold should be suitable for use as a general guideline to anticipate ponderosa pine mortality after wildfire.

Crown scorch volume as we measured it may have included an unknown amount of bud kill. However, note that for trees without crown consumption, crown scorch drives the post-fire mortality function, but for trees with crown consumption, their interaction is more complicated. Our data and models showed that crown consumption at the 40% by volume level indicates an 85–90% probability of tree death but that for crown consumption less than 40%, crown scorch is still a significant factor in determining mortality rates. The differing statistical functions for crown scorch and crown consumption also suggest that they are not simply additive as in a total crown damage predictor variable. This difference also explains why logistic regression models with separate scorch and consumption variables perform better than models with total crown damage (Sieg *et al.* 2006).

The above results can be incorporated into marking guidelines for post-fire evaluation of probable tree death for salvage logging, and wildlife habitat, biodiversity, or ecosystem process management decisions. For wildfires in ponderosa pine stands of the Intermountain West with a mix of surface and crown fire and where no bark beetle outbreak is nearby, post-fire prediction of tree death can be based on the following criteria: (1) if no crown consumption is present, then crown scorch greater than 85% indicates probable tree death (Fig. 2); (2) if crown consumption is greater than 40% (Fig. 3), then tree death is very likely; and (3) if crown consumption is between 5 and 40%, a crown scorch volume $>50\%$ would indicate a $>50\%$ chance of tree death (Fig. 4).

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