Delayed Conifer Tree Mortality Following Fire in California[1]

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Abstract

Fire injury was characterized and survival monitored for 5,246 trees from five wildfires in California that occurred between 1999 and 2002. Logistic regression models for predicting the probability of mortality were developed for incense-cedar, Jeffrey pine, ponderosa pine, red fir and white fir. Two-year post-fire preliminary models were developed for incense-cedar, Jeffrey pine, ponderosa pine and white fir. Three- and four-year post-fire models are presented for white fir and red fir, respectively. Mortality was predicted using percent crown length kill and cambium kill in all optimal models. Diameter at breast height was also a significant variable in all models except for red fir. A pre-bud break model for pine using crown length scorch was also developed. Additional models are provided for each species without the cambium injury variable to show the predictive capability lost when this variable is not assessed. A comparison between bark char classification and cambium condition status was also performed to determine the validity of using bark char classifications as a surrogate for cambium sampling. Light and deep bark char codes are relatively accurate in predicting live and dead cambium, respectively. However, the moderate bark char rating is not a good predictor of cambium status.

Introduction

The number of forested acres burned by high intensity wildfire in California has increased over the past several years. This increase is generally attributed to high stand densities of smaller diameter trees and the accumulation of dead fuels that have developed in response to management activities such as fire suppression. High intensity forest fires typically result in considerable tree mortality. This mortality can be immediate, due to the complete consumption of living tissue during the fire, or can be delayed, occurring over the course of a few years, as a result of fire injuries to the crown, bole, and roots and subsequent insect activity. The ability to accurately predict the probability of mortality of these fire-injured trees is critical when making most post-fire management decisions. Post-fire management activities, such as salvage logging, fuels treatments, and reforestation, are often based on economics and ecological considerations, both of which need to account for the current and expected levels of tree mortality.

Although there are numerous publications reporting findings with respect to fire injuries and conifer tree survival from many areas across the western United States

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(Lynch 1959, Bevins 1980, Peterson and Arbaugh 1986, Ryan and Reinhardt 1988, Ryan and Frandsen 1991), publications based on similar work completed in California are limited. Existing publications cover a limited number of species from single fires (Mutch and Parsons 1998, Borchert et al. 2002), provide a good description and method of application of the criteria for survival but present only generalizations as marking guidelines (Wagener 1961), or attempt to relate prescribed fire characteristics to mortality of mixed conifer species for use in achieving prescribed fire objectives, not to provide salvage marking guidelines from post-fire measurements (Stephens and Finney 2002).

Most researchers that have examined the effect of fire on conifers have concluded that crown injury is the most important predictive variable for mortality (see Fowler and Sieg 2004 for review). Crown injury is typically quantified by percentage of crown killed, described by either a length or height measurement (Herman 1954, Bevins 1980, Harrington 1993), or by percentage of crown volume killed (Reinhardt and Ryan 1989, Finney 1999, Weatherby et al. 2001, Borchert et al. 2002, McHugh and Kolb 2003).

In addition to crown injury, cambium death caused by lethal heating of the tree bole is another important predictive variable for mortality. Duff smoldering around the base of trees or extensive flame exposure to the bole can cause some level of cambium injury, which is dependent on bark thickness (Reinhardt and Ryan 1989). The fact that fire-killed cambium can contribute to subsequent tree mortality is rarely disputed. However, how much dead cambium causes tree mortality, either alone or in combination with crown kill, and how to accurately assess cambium condition while limiting direct cambium sampling, has not been determined for many species.

Various methods have been used to quantify cambium kill, from direct sampling of the cambial tissue (Bevins 1980, Ryan et al. 1988, Peterson and Arbaugh 1989, Ryan and Frandsen 1991) to indirect measures, such as amount or height of bark scorch or degree of bark char (Herman 1954, Peterson 1984, Wyant et al. 1986, Finney 1999, Borchert et al. 2002, McHugh and Kolb 2003). Limited studies exist that have analyzed bole char characteristics and compared them to actual cambium kill. Ryan (1982a) indicates that the depth of bark charring is not an adequate indicator of cambium kill without correlating cambium condition for each depth of char class. Ryan et al. (1988) found the number of dead cambium samples to be the most important predictor of mortality for Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco). They concluded that the ability to accurately predict mortality may be greatly limited if cambium kill is not considered. Wagener (1961), the only author prior to our study to assess cambium condition from work in California, concluded that, even in a single species, there are wide differences in bark thickness, depth of crevices, and size of bark ridges. For application in marking guidelines, he suggested using degree and location of bark char to determine where to sample for cambium injury.

The objective of our study was to develop mortality models for five conifer species in California that land managers can use to predict post-fire tree mortality. We used percent crown length kill, cambium kill, diameter at breast height (dbh), and insect attacks as potential variables for all models. We also compared the accuracy of established bole char classifications in predicting the degree of cambium injury.

Methods

Study Sites

A total of 5,246 fire-injured trees were characterized and monitored for survival in five wildland fires that occurred between 1999 and 2002 in California (*table 1*). The data set included a range of tree sizes and fire injuries for incense-cedar (*Calocedrus decurrens* [Torr.] Florin), Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.), ponderosa pine (*Pinus ponderosa* Laws), red fir (*Abies magnifica* A. Murr.) and white fir (*Abies concolor* [Gord. & Glend.] Lindl.). For the purposes of the analyses, Jeffrey pine and ponderosa pine were combined into one yellow pine group because of similar physical characteristics. Study sites comprised a wide geographical area in California extending from the southern end of the Cascade range to the southern end of the Sierra Nevada range (*fig. 1*). All fires were in the Sierra Nevada mixed conifer forest type (SAF Type 243), with the exception of the Cone fire, which occurred in the Interior ponderosa pine type (SAF Type 237) (Eyre 1980) (*table 2)*.

Table 1—*Number of trees by fire and by species. Yellow pine includes ponderosa and Jeffrey pine.*

Fire	Red Fir	White Fir	Incense-Cedar	Yellow Pine
Bucks	112	124	-	-
Cone	-	-	-	923
McNally	-	1866	781	1046
Star	-	199	-	-
Storrie	94	101	-	-
Total	206	2290	781	1969

Table 2—*Date of wildfire occurrence and general site characteristics.*

Fire	Month/year burned	Elevation (m)	Forest Type	MAP (cm)
Bucks	August, 1999	1400-1500	Sierra Nevada mixed conifer	152-178
Cone	September, 2002	1750-1800	Interior ponderosa pine	50-75
McNally	July, 2002	1700-2750	Sierra Nevada mixed conifer	50-75
Star	August, 2001	1550-1950	Sierra Nevada mixed conifer	152-178
Storrie	August, 2000	1650-1950	Sierra Nevada mixed conifer	152-178

Sampling

Personnel from local forest districts identified sites of mixed fire severity for inclusion in this project. For the Cone and McNally fire, individual fire-injured trees were selected from these areas in an attempt to fill a matrix of different crown and cambium injury levels, size classes, and species. Crews were instructed to fill each category with 30 trees from all the available trees in the area. In any given area, some trees may not have been sampled because they fit into a category that was already filled, or they may have been inadvertently missed as the crew worked the stand.

Although the target of 30 trees for every category was not met, this sampling gave us a broad range of fire injuries and size classes needed to test our objectives. For all other fires, crews selected trees with higher levels of crown kill, but were given no size or cambium injury selection criteria.

Initial assessments of tree condition were completed during the summer of the year following the fire for all fires with the exception of the Bucks Fire. Initial

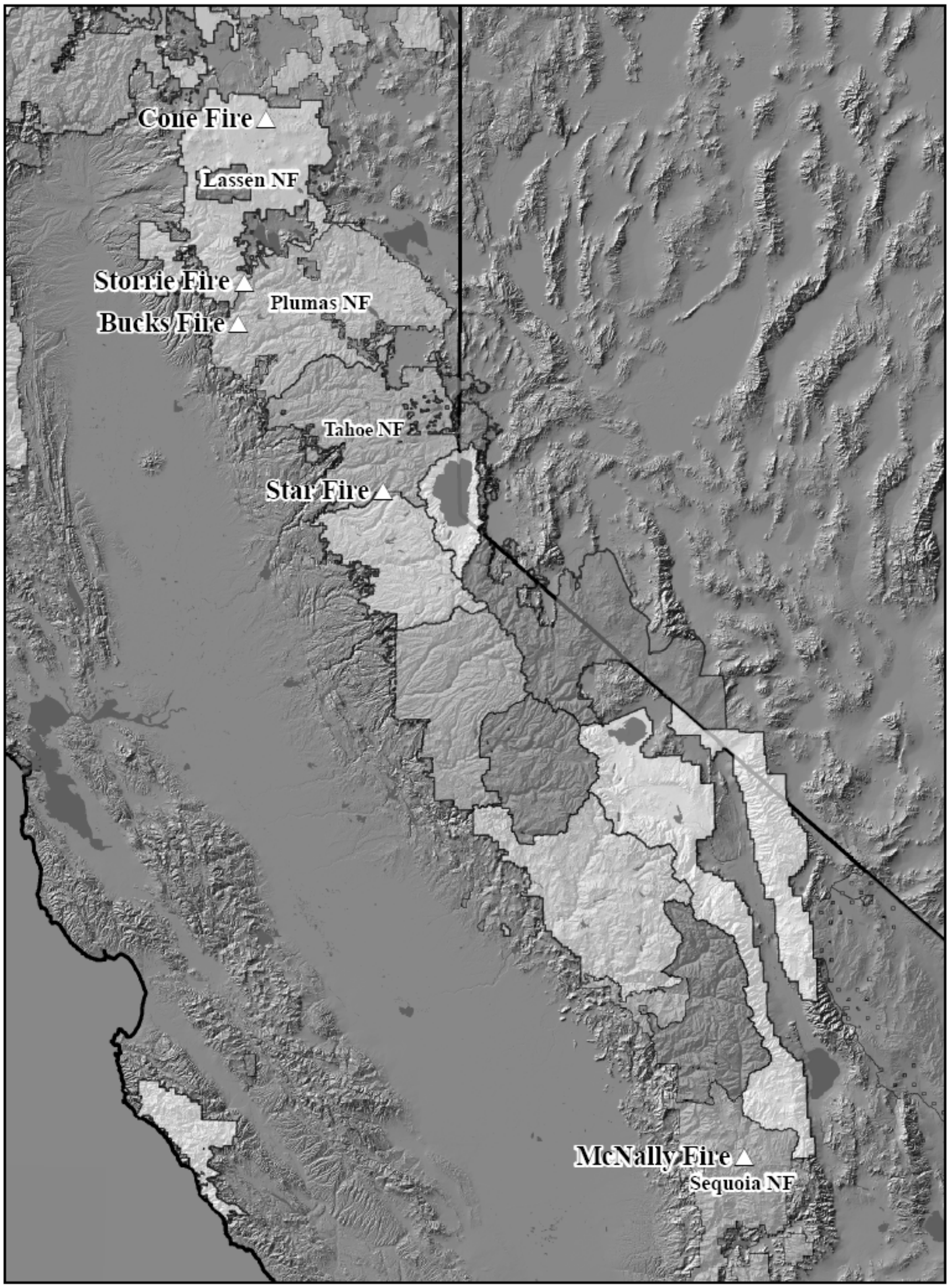

Figure 1--Map of fires included in analysis.

assessment for trees in the Bucks Fire occurred two years post-fire. For all Jeffrey and ponderosa pines, initial assessment occurred after bud break, as recommended by Wagener (1961). Tree status was reassessed annually for all fires. The last measurement year was 2004. A one-year post-fire status assessment was completed in the fall of the same year as the initial assessment for trees in the Cone, McNally, and Star fires. Trees were recorded as dead if no green foliage was visible, or if trees had either fallen or snapped off. Data collected included species, dbh, tree height, crown length killed, crown volume killed (McNally and Cone only), cambium kill rating (CKR), and post-fire insect activity. For pine trees in the McNally and Cone fires, length and volume estimates were also obtained for crown scorch. A bark char code (Ryan (1982a) was also determined by quadrant for each tree in the McNally and Cone fires to compare with cambium kill.

Crown kill refers to the portion of the crown that no longer has living tissue. It includes both tissue consumed by flames and tissue killed by convective heating during the fire. The linear measurement of crown kill was obtained by measuring the pre-fire crown length and the length of the remaining live crown to the nearest foot after estimating pre-fire crown base and height of crown kill. Pre-fire crown base was estimated by the presence of scorched needles or partially consumed needles and fine branches. Variations in crown kill pattern were averaged to obtain one crown kill length value. Lengths were measured using a clinometer or laser range finder. We calculated the percentage of pre-fire crown length killed (PCLK) by dividing the crown length killed by the original live crown length.

Percent crown volume killed (PCVK) was also determined for trees in the McNally and Cone fires. We visually estimated the volumetric proportion of crown killed compared to the space occupied by the pre-fire crown volume to the nearest five percent (Ryan 1982b). Obtaining both a length measurement and a volume estimate for crown kill enabled us to compare the predictive ability of the two variables. Also, collecting percent crown volume killed enabled us to compare our models with previously published probability models that use a volume estimate to predict mortality of fire-injured trees in California.

For ponderosa and Jeffrey pines on the McNally and Cone fire, we also assessed percent crown length scorched (PCLS) and percent crown volume scorched (PCVS). Crown scorch refers to the portion of the crown where needles are heat killed, but buds remain alive. The large buds of these species are more protected than those on true firs and incense-cedar and, consequently, often survive fire even when the surrounding needles are killed. A pine tree could feasibly have 100 percent crown scorch with little crown kill. For all other species in the study, crown kill is the equivalent of crown scorch.

Bole injury was assessed by first visually dividing the tree bole into four quadrants based on cardinal directions. The cambium was sampled in the center of each quadrant to obtain a cambium kill rating (CKR) for each tree. This was accomplished by drilling through the bark to the sapwood, within 7.5 cm of ground-line, using a power drill equipped with a 2.5 cm hole saw bit. Each sample was visually inspected in the field for color and condition of the tissue. Dead cambium is darker in color, often resin soaked and hard or gummy in texture. Live cambium is lighter in color, moist and rather pliable. Dead cells in the cambium zone also lose their plasticity which may allow the bark and wood to separate more easily (Ryan 1982a). A rating between zero and four was recorded for each tree by totaling the number of quadrants with dead cambium. In the McNally and Cone fires, a bark char code based on the charring that occurred in the majority of each quadrant within 30 cm of the ground line was also recorded following the methods in Ryan (1982a). Bark char was classified as unburned, light, moderate, or deep. Light charring has some blackened areas on the bark, but unburned portions also remain. With moderate charring, all bark is blackened, but the bark characteristics remain. When deep charring occurs, the bark characteristics are no longer discernable.

Insect activity was recorded for each tree. For white and red fir, the circumference of the bole with ambrosia beetle (*Trypodendron* and *Gnathotrichus* spp.) boring dust was recorded to the nearest ten percent. For ponderosa and Jeffrey pine, the number of red turpentine beetle (*Dendroctonus valens* LeConte) pitch tubes on the bole was recorded. Trees that showed signs of attack by primary bark beetles (*Dendroctonus jeffreyi, D. brevicomis, D. ponderosae,* and *Scolytus ventralis*) were not selected. Assessments of insect activity were limited to visual signs on the bole. No bark was removed to determine the success of the beetle attacks.

Statistical Analysis

Logistic regression was used to develop separate mortality models for red fir, white fir, incense-cedar, and yellow (ponderosa and Jeffrey) pine (SAS Institute v. 9.1). The predicted probability of mortality was estimated based on the dependent variable post-fire tree status, where dead trees were coded as one, and live trees as zero. An optimal model was developed for each species group from the following independent variables: percent crown length killed (PCLK), cambium kill rating (CKR), dbh (cm), and beetle presence (1) or absence (0). All models use the form:

$$P_m = 1/[1 + \exp(-(b_0 + b_1x_1 + b_2x_2 + \text{etc.}))]$$

Where:

P_m = predicted probability of mortality

b_0 = intercept

b_1, b_2, etc. = regression coefficient for x_1, x_2, etc.

x_1, x_2, etc. = value of fire injury variable (PCLK, CKR, dbh, AB, or RTB)

For ambrosia beetle (AB) and red turpentine beetle (RTB), only presence or absence of boring dust was used after determining that it performed equally well in the model compared to using the percent of the bole circumference with boring dust or number of pitch tubes, as initially assessed. The plot of the logit against CKR showed a linear increase. We therefore treated CKR as an ordinal variable and modeled it as a continuous variable (Hosmer and Lemeshow 2000).

PCLK was the common crown injury variable for all trees in the data set and is used in all models. It was a significant variable for determining the predicted probability of mortality for all species. We also tested the performance of the models when PCLK was squared or cubed and only report the model which contains the version of PCLK that performed the best. An optimal yellow pine model using percent crown length scorched (PCLS) is also presented for use when assessing crown injury prior to bud break. Models were also developed using percent crown volume killed (PCVK), or percent crown volume scorched (PCVS), to compare to those published by Mutch and Parsons (1998) and Stephens and Finney (2002). These comparisons are discussed, but the models are not reported in the paper.

The models predict probability of mortality for two, three or four years post-fire depending on the species. The majority of our data set includes only two-year post-fire mortality. Our two-year models should be considered preliminary, as additional mortality is expected. We chose the final models based on the combination of the lowest -2 log likelihood value (-2LogL) and the highest receiver operator characteristic curve value (ROC). The ROC reflects the accuracy of the model in classifying live and dead trees, with a value of 0.5 being no better than chance, and 1.0 indicating a perfect fit (Saveland and Neuenschwander 1990). After each optimal mortality model was developed from the potential variables, the CKR variable was dropped to create a second model. If the optimal model included a significant beetle attack variable, a third model was developed without the CKR or beetle variables. We created these second and third models to assess the importance of the CKR and beetle attack variables to predict tree mortality, and to give land managers the ability to compare probabilities of mortality when these specific fire injury criteria are not assessed.

Results and Discussion

Bark Char Classification versus Cambium Kill Rating

The bark char classification was compared to the cambium status for each quadrant per tree by species for all trees in the Cone and McNally fires. Bark charring is often used as a surrogate for direct cambium sampling because it can be obtained quickly. It is unknown how well the bark char classification system predicts cambium status. The following comparisons between bark char classification and cambium condition were similar across all dbh classes. We assessed very few unburned and light bark char ratings in our fires, and, with the exception of light bark char for yellow pine, few had dead cambium (*fig. 2*). While light charring on yellow pine equated to a dead cambium sample 45 percent of the time, only three percent of the pine samples were classified as light (*fig. 2,* pie chart inset). Because our sample size is so large (n=18,464 quadrants), we believe that light bark charring on white fir, incense-cedar, and yellow pine is relatively uncommon in wildfires and, therefore, would have little impact on the post-fire management decisions, if all light charring were assumed to have live cambium.

For our trees, the moderate bark char class described by Ryan (1982a) did not accurately predict cambium status (*fig. 2*). Fifty percent of the quadrants classified as moderate bark char had dead cambium samples. The majority of total recordings for bark char by quadrant were classified as moderate across all species, with 59 percent for incense-cedar, 60 percent for white fir, and 78 percent for yellow pine. Based on these results, reaching the conclusion that quadrants with moderate bark char equate to those with dead cambium would result in an incorrect determination 50 percent of time. Dead cambium was associated with deep bark charring for approximately 80 percent of the samples across all species.

When salvage marking guidelines include a measure of cambium condition, additional time is required to assess each tree. Based on our results, direct cambium sampling could be reduced by 20-40 percent by using unburned, light and deep bark char classes as a substitute. Moderately charred quadrants would still require direct sampling. Based on the inconsistency of the moderate bark char classification and the fact that most of the quadrants in our data set were classified as moderate, we did not use bark char as a variable in the logistic models.

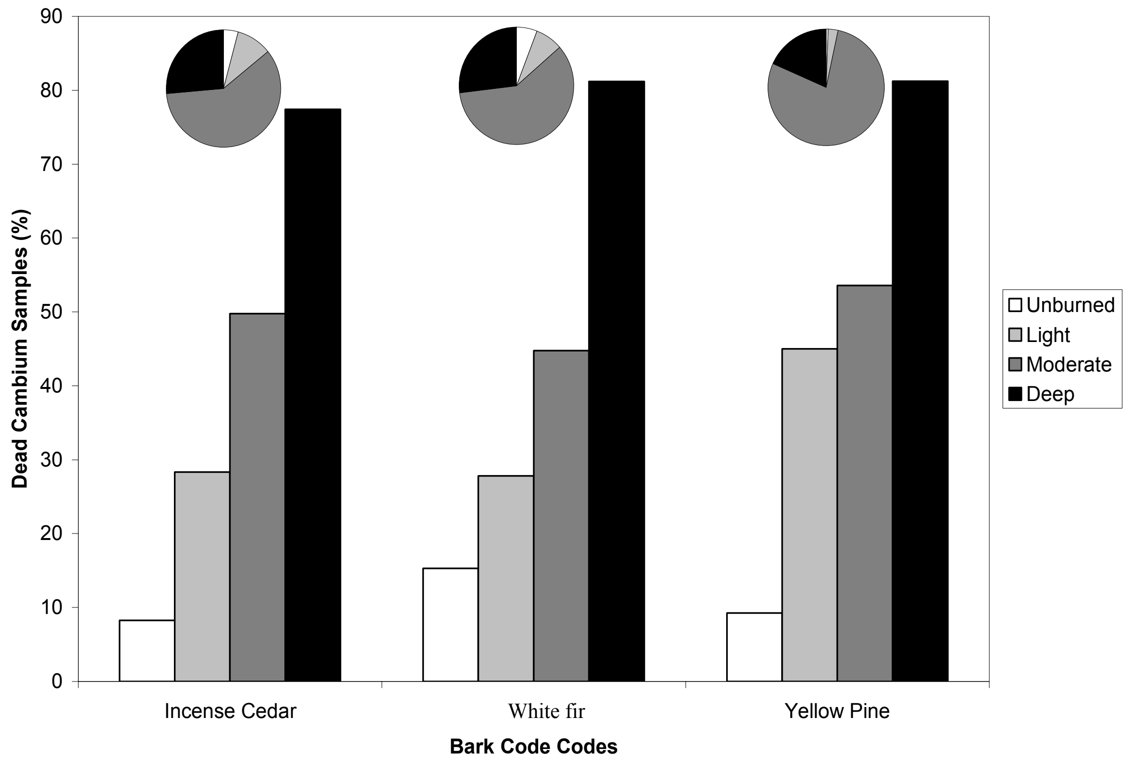

Figure 2--Percent of dead samples by bark char code for incense-cedar, white fir and yellow (ponderosa and Jeffrey) pine. Pie charts show distributions of bark char codes by species. Cambium status was determined by taking a 2.5 cm diameter sample within 7.5 cm of ground line in the middle of each quadrant. Bark char was assessed for each quadrant within 30 cm of ground line based on the classification that best fit the majority of the charring.

Mortality Models

Red Fir

The data set for red fir includes trees in the Bucks Fire and the Storrie Fire. Tree status four years post-fire was used for model development. All variables were significantly different between live and dead trees except for dbh (*table 3*). The total mortality over the four-year period following the fires was 22 percent.

The optimal model for predicting red fir mortality includes percent crown length kill (PCLK), cambium kill rating (CKR), and ambrosia beetle attacks (AB) (*table 4*). Modeled probability of mortality increased as PCLK increased for all ratings of cambium kill (*figs. 3, 4*). When the CKR is excluded from the optimal model, the ROC value drops from 0.83 to 0.72 (grey line in *figs. 3, 4*, model 2). Contrary to the CKR curves displayed for all models, we would expect every tree with a crown length kill equal to 100 percent to die, regardless of the CKR. The maximum PCLK for our study trees was 89 percent.

Table 3--*Mean characteristics of variables for red fir. P-values test differences between live and dead values.*

Variable[1]	Mean (n=206)	SE	Range	Live Mean (n=160)	Dead Mean (n=46)	p-value
Dbh	42.2	1.2	15-105	42.4	41.7	0.8221
PCLK	42	1.8	0-89	38	52	0.0009
CKR	1.6	0.1	0-4	1.3	2.3	<0.0001
AB	13	1.5	0-100	10	25	0.0017

[1] Dbh – diameter at breast height (cm); PCLK – percent crown length killed; CKR – cambium kill rating; AB – percent of bole circumference with boring dust.

Table 4--*Red fir mortality models four years post-fire. Model 1 is the statistically best, optimal model. The class effect ambrosia beetle (AB) is modeled as 1 when present and -1 when absent.*

Model	Intercept	PCLK	CKR	AB	-2LogL	ROC
1	-4.2066	0.0330	0.8702	0.4619	165.18	0.83
2	-2.1342	0.0221	-	0.6218	195.06	0.72
3	-2.3431	0.0240	-	-	207.35	0.67

Ambrosia beetles attack weakened, recently dead, freshly felled, or other unseasoned or moist wood (Furniss and Carolin 1977). They penetrate the bark, sapwood, and sometimes heartwood, thus providing an entry court for fungi and other organisms to begin the decomposition process. Their piles of white boring dust on tree boles often provide a good external indicator that a tree is not healthy. A tree with AB present has a higher predicted probability of mortality than a tree with similar PCLK and CKR but no AB (*figs. 3, 4*, model 1).

We found CKR to be the most important predictor of red fir mortality (ROC =0.74 for CKR alone). Wagener (1961) found that cambium killing involving more than 25 percent of the bole circumference would greatly affect survival for several conifer species, including red fir. Ryan et al. (1988) reported the number of dead samples to be the most important predictor of mortality for fire-injured Douglas-fir. When CKR is not used in the models, mortality predictions would be slightly overestimated at low levels of cambium kill and greatly underestimated at higher levels of cambium kill (*figs. 3, 4*, models 2 and 3).

Dbh was not a statistically significant variable in our red fir model. This differs from most other tree mortality equations, although there is no other published model for red fir mortality to which to directly compare. Tree size is widely recognized as an important factor in resistance to fire injury due to an increase in basal crown height and bark thickness as tree height and diameter increase (Ryan et al. 1988). The difference in mean dbh for our red fir trees was not statistically significant between live and dead trees (*table 3*). It is unclear why dbh was not correlated with mortality for red fir, as it is for all other species. A significant relationship might develop with an increase in the sample size.

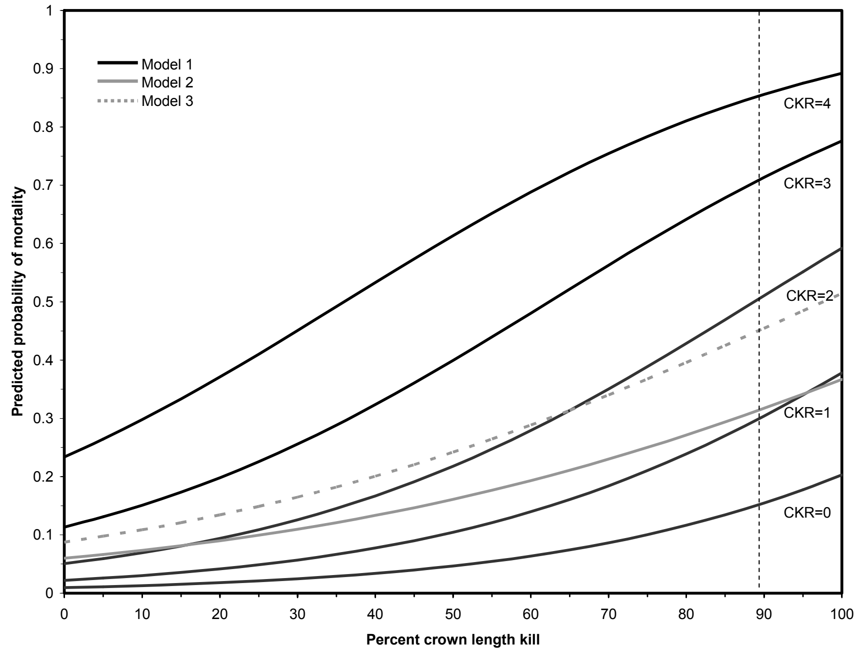

Figure 3–Year 4 red fir mortality curves for trees with no signs of ambrosia beetle attack. Solid black lines indicate optimal mortality model (model 1). Grey line is model 2 mortality curve. Dashed line is model 3 mortality curve. The vertical dashed line shows the upper limit of the data set (maximum PCLK = 89%).

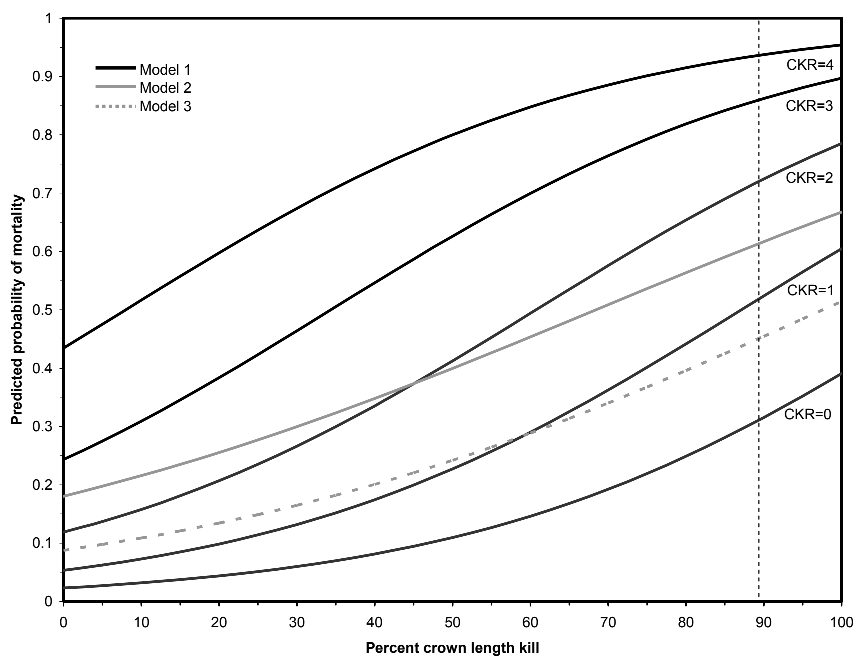

Figure 4–Year 4 red fir mortality curves for trees with signs of ambrosia beetle attack. Solid black lines indicate optimal mortality model (model 1). Grey line is model 2 mortality curve. Dashed line is model 3 mortality curve. The vertical dashed line shows the upper limit of the data set (maximum PCLK = 89%).

When developing post-fire salvage marking guidelines for red fir based on these models, both the desired level of predicted probability of mortality and the intensity of individual tree sampling need to be determined. Models 2 and 3 are displayed to facilitate a comparison in the predicted probabilities of mortality when statistically significant variables are excluded. Based on comparing our models, if only PCLK and AB are used and AB is present, the highest predicted probability of mortality possible is 0.66 (*fig. 4*). In model 3, where only PCLK is used, the highest predicted probability of mortality possible is 0.52. Of the variables included in the optimal model, percent crown length kill and the presence or absence of AB are both easily obtained by a quick observation of the crown and bole. Obtaining a cambium kill rating involves direct cambium sampling in each quadrant, which requires additional time to assess each tree. Land managers should be aware that not assessing for cambium injury can greatly decrease their ability to accurately predict the mortality of fire-injured red fir. We do not have data on bark char classifications compared to cambium condition for red fir, however, based on our results with other species, we can presume that the classifications of unburned, light, and deep bark char would be appropriate to use in place of direct cambium sampling. Moderately charred quadrants would still need a direct assessment.

Incense-cedar

All incense-cedar data was collected on the McNally fire and the status of trees two years post-fire was used in model development. All variables were significantly different between live and dead trees (*table 5*). Through 2004, the second year post-fire, twelve percent of our sample trees had died.

Table 5--*Mean characteristics of variables for incense-cedar. P-values test differences between live and dead values.*

Variable[1]	Mean (n=781)	SE	Range	Live Mean (n=688)	Dead Mean (n=93)	p-value
Dbh	51.5	0.9	25.4-166.4	52.2	46.3	0.0137
PCLK	40	1.1	0-98	34	79	<0.0001
PCVK	44	1.2	0-95	38	85	<0.0001
CKR	2.1	0.0	0-4	2.0	2.8	<0.0001

[1] Dbh – diameter at breast height (cm); PCLK – percent crown length killed; PCVK – percent crown volume killed; CKR – cambium kill rating.

The preliminary optimal model for predicting incense-cedar mortality within two years post-fire includes percent crown length kill cubed ($PCLK^3$), cambium kill rating (CKR) and dbh (*table 6*). PCLK is the most important predictor of mortality. Mortality equations developed from our incense-cedar data predict a low probability of mortality (less than 25 percent) until PCLK reaches approximately 70 percent when CKR equals four and 90 percent when CKR equals zero. As PCLK increases above these levels, the predicted mortality increases considerably. In this study, 85 percent of the observed incense-cedar mortality occurred in trees with greater than 65 percent PCLK.

CKR is also a significant variable accounting for slight increases in the predicted mortality with increasing cambium kill ratings (*fig. 5*). When CKR is dropped from the model, for PCLK greater than 50 percent, mortality of trees with a CKR of four would be slightly under predicted while mortality of trees with a CKR less than

Table 6–*Incense-cedar mortality models two years post-fire. Model 1 is the statistically best, optimal model.*

Model	Intercept	PCLK^3 (%)	CKR	Dbh	-2LogL	ROC
1	-4.9639	0.0000068	0.5398	-0.0143	325.20	0.92
2	-4.2505	0.0000068	-	N.S.	348.68	0.90

three would be slightly over predicted (*fig. 5,* model 2). Contrary to the CKR curves displayed in model 1 (*fig. 5*), where the predicted mortality never reaches 1.0, we would not expect any tree to survive with 100 percent crown kill. Also, there were no trees in our data set with PCLK > 95 percent and CKR < 2, which helps explain why the curves do not approach 1 when PCLK equals 100 percent for low CKR's. The maximum crown length kill for our study trees was 98 percent. Dbh is significant in the model, however, it does not greatly affect the predicted mortality for trees with similar percent crown length kill and cambium kill rating.

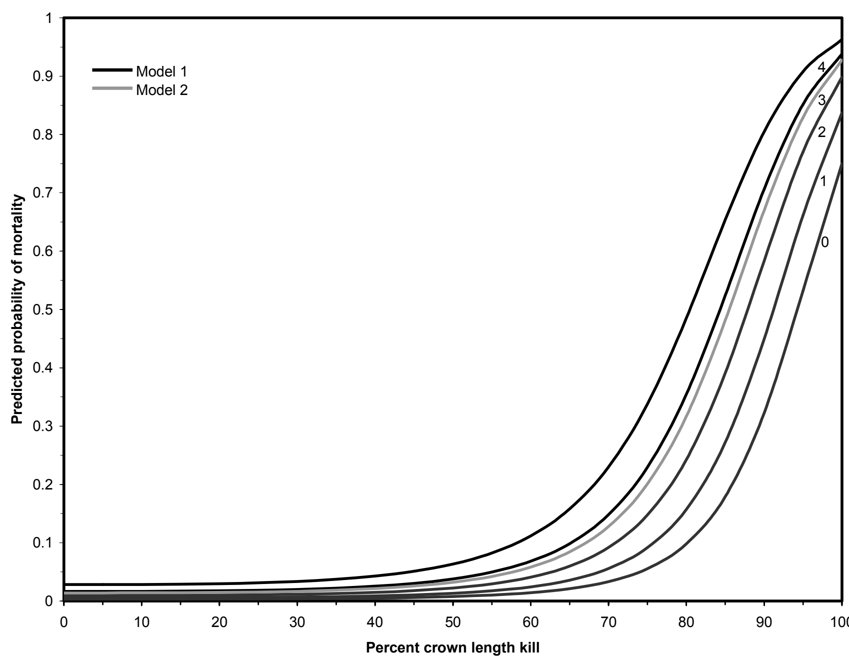

Figure 5–Year 2 incense-cedar mortality curves by cambium kill rating and dbh of 51.5 cm. Solid black lines indicate optimal mortality model (model 1). Grey line following CKR=3 line is model 2 mortality curve.

The mean dbh for incense-cedar was significantly lower for dead versus live trees (*table 5*). This is similar to the results reported in Stephens and Finney (2002), where their incense-cedar model also showed a lower predicted probability of mortality with increasing dbh. These similar results are likely due to both incense-cedar data sets being heavily weighted towards smaller diameter trees.

Model 2 (gray dashed line in *fig. 5*) was developed to compare the probabilities of mortality when CKR is excluded. Note that dbh becomes insignificant in the model when CKR is dropped (*table 6*). When CKR is dropped, there is little effect on the performance of the model (ROC = 0.92 vs. 0.90) revealing the relative importance of PCLK over CKR for incense-cedar. Since CKR only accounts for minimal differences in the predicted mortality and requires additional time for sampling, land managers may choose to disregard cambium sampling without losing much predictive accuracy.

White Fir

The data set for white fir trees from the Bucks, Storrie, and Star fires were combined and the status of trees three years post-fire was used for model development. The model for white fir on the McNally fire is presented separately as a preliminary two-year status model. There was a significant difference between live and dead trees for all variables collected for both the three-year and two-year data sets (*table 7*). Mean dbh was higher for dead trees than for live trees in both data sets. Total mortality observed over the three-year post-fire period was 43 percent compared to 50 percent after only two years on the McNally fire.

Table 7--*Mean characteristics of variables for white fir. The McNally fire was analyzed separate from other fires. P-values test differences between live and dead values.*

Variable[1]	Mean	SE	Range	Live Mean	Dead Mean	p-value
			Bucks, Star, and Storrie Fires (3 years post-fire)			
	(n=424)			(n=242)	(n=182)	
Dbh	54.5	1.0	15.2-134.4	47.3	63.9	<0.0001
PCLK	57	1.4	0-100	45	74	<0.0001
CKR	1.8	0.1	0-4	1.4	2.3	<0.0001
AB	14	1.1	0-100	6	25	<0.0001
			McNally Fire (2 years post-fire)			
	(n=1866)			(n=929)	(n=937)	
Dbh	60.2	0.5	25.4-152.7	56.4	64.0	<0.0001
PCLK	69	0.6	0-100	53	83	<0.0001
PCVK	71	0.6	0-95	55	83	<0.0001
CKR	2.1	0.0	0-4	1.8	2.1	<0.0001

[1]Dbh – diameter at breast height (cm); PCLK – percent crown length killed; PCVK – percent crown volume killed; CKR – cambium kill rating; AB – percent of bole circumference with boring dust.

The optimal three-year model for predicting white fir mortality includes percent crown length kill cubed ($PCLK^3$), cambium kill rating (CKR), dbh, and ambrosia beetle attacks (AB) (*table 8*). *Figure 6* shows the predicted probability of mortality by CKR when AB is assessed but not present. *Figure 7* shows the predicted probability of mortality by CKR when AB is assessed and present. Trees with AB have a higher predicted probability of mortality with the same levels of injury compared to trees without AB (*figs. 6, 7*).

The ROC value is reduced by 0.02 when CKR is not used in the model. Model accuracy further declines when neither CKR nor AB is included. Using the average dbh of 54.5 cm as an example, for a tree with 70 PCLK, if a land manager chose to not evaluate the cambium condition but did assess for AB, and it was not present, the predicted mortality is underestimated by 0.1 to 0.4 when CKR is greater than one (*fig. 6*). For the same tree, predicted mortality would be overestimated by as much as 0.2 when there is no cambium kill. When AB boring dust is present and cambium condition is not assessed, the predicted mortality follows a curve similar to when

CKR equals two (*fig. 7*). If a land manager chose to only evaluate PCLK, mortality of trees with higher amounts of cambium kill would be under predicted.

Table 8--*White fir mortality models three years post-fire. Model 1 is the statistically best, optimal model. The class effect ambrosia beetle (AB) is modeled as 1 when present and -1 when absent.*

Model	Intercept	$PCLK^3$ (%)	CKR	Dbh	AB	-2LogL	ROC
1	-5.3456	0.000006	0.6584	0.0367	0.5308	319.37	0.91
2	-3.5603	0.000005	-	0.0296	0.7338	351.85	0.89
3	-4.2829	0.000006	-	0.0397	-	381.284	0.87

The preliminary optimal model for white fir using two-year data from the McNally fire includes the same variables as the three-year white fir model with the exception of ambrosia beetle (*table 9*). Ambrosia beetle was only observed on a few trees in the McNally fire and there was no significance difference between live and dead trees for this variable. Excluding the CKR from the model does not change the ROC value, which is evidence that crown kill is a more important criterion for predicting mortality within two years.

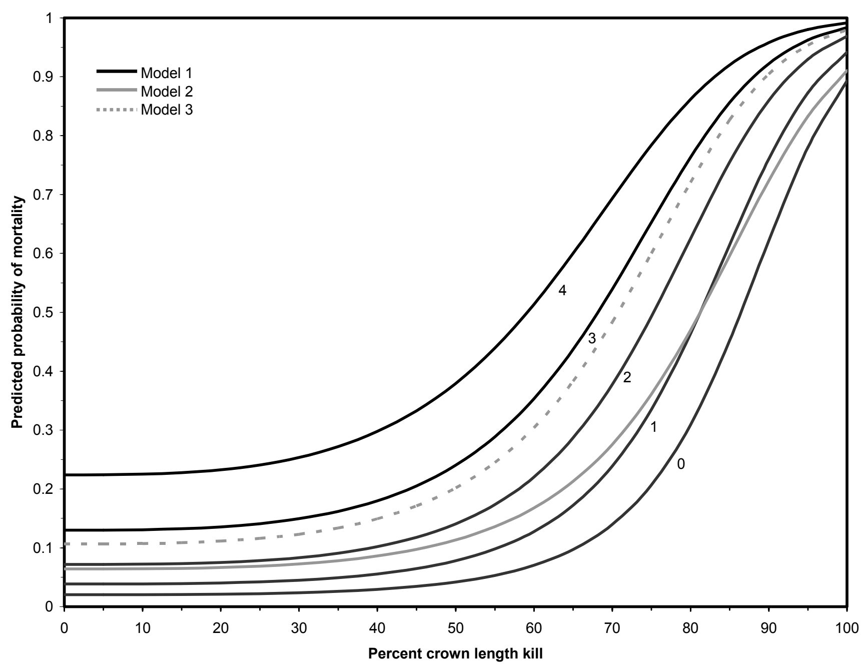

Figure 6--Year 3 white fir mortality curves for trees with no signs of ambrosia beetle attack and a dbh of 54.5 cm. Solid black lines indicate optimal mortality model (model 1). Grey line is model 2 mortality curve. Dashed line is model 3 mortality curve.

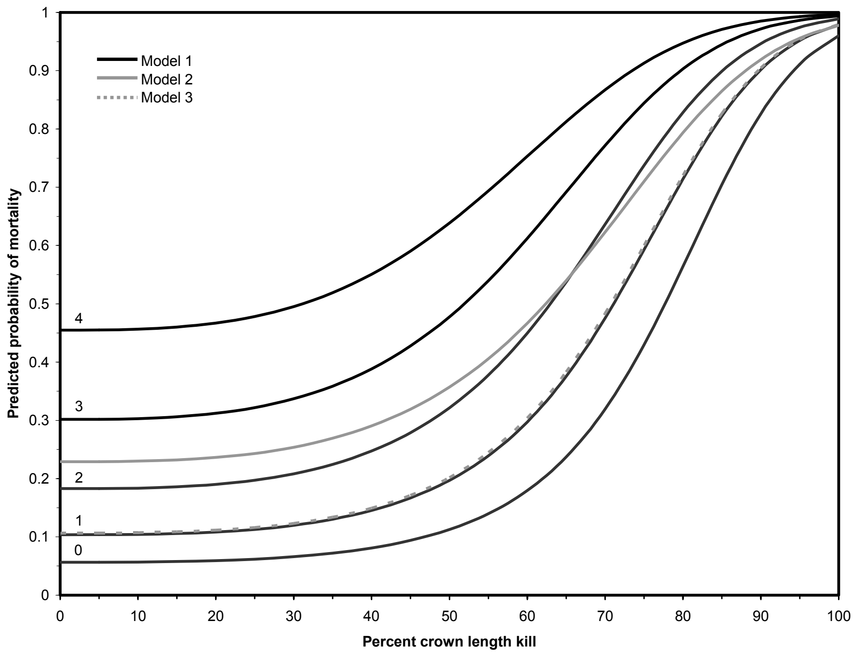

Figure 7–Year 3 white fir mortality curves for trees with signs of ambrosia beetle attack and a dbh of 54.5 cm. Solid black lines indicate optimal mortality model (model 1). Grey line is model 2 mortality curve. Dashed line is model 3 mortality curve.

Table 9--*White fir mortality models two years post-fire. Model 1 is the statistically best, optimal model.*

Model	Intercept	$PCLK^3$ (%)	CKR	Dbh	-2LogL	ROC
1	-4.2913	0.000006	0.2185	0.0174	1669.23	0.87
2	-3.7578	0.000006	-	0.0162	1689.69	0.87

Cambium kill becomes more important in white fir models in the third year post-fire. When comparing the predicted mortality between the two- and three-year white fir models, the probability of mortality is much higher in year three for trees with a CKR equal to three or four (*fig. 8*). The difference in predicted mortality between CKR's of three and four also widens in the year three model (*fig. 8*). As PCLK increases above 70 percent, the differences between the year two and year three three lines decrease. As crown kill approaches 100 percent, trees do not have enough photosynthetic capacity remaining to sustain life, regardless of the amount of cambium kill. If enough photosynthetic capacity remains, trees with terminal levels of cambium injury may take a longer period of time to die. Foliage may remain green for several years due to water being conducted upward through the uninjured xylem. However, the inability of the dead phloem to transport carbohydrates to the roots results in a slow starvation and eventual death.

The mean dbh for dead trees was higher than live trees in both the two- and three-year data sets. Our white fir models have higher predicted probabilities of

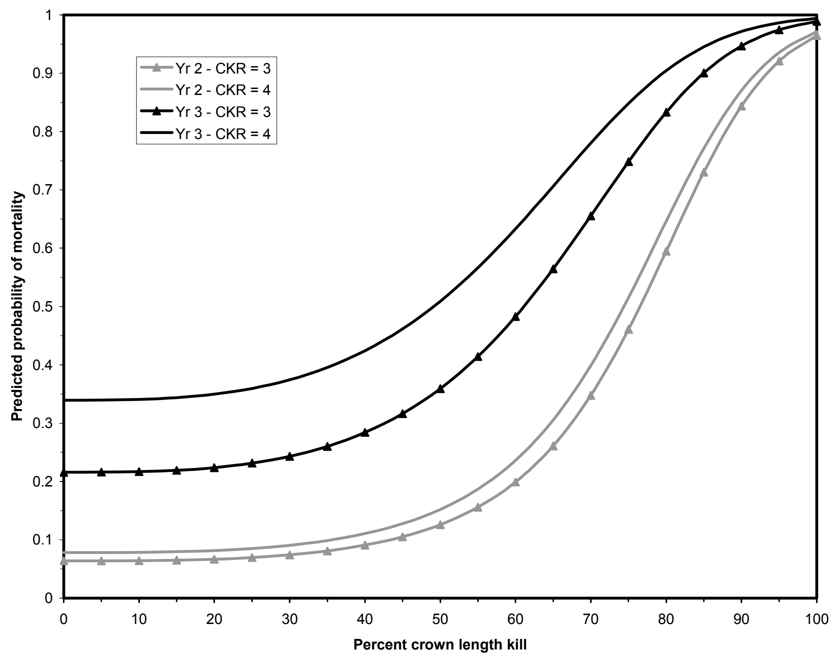

Figure 8--Comparison of years 2 (grey) and 3 (black) white fir mortality curves where dbh equals 54.5 cm. Year 3 curves include both attacked and unattacked trees. Only cambium kill ratings of three and four are shown.

mortality with increasing dbh when comparing trees with similar crown and cambium kill. Our results are contrary to those reported by Stephens and Finney (2002) and Mutch and Parsons (1998) for white fir. Their models show a decrease in predicted mortality as dbh increases, which may be due to the small number of large trees in their data sets. An increase in the predicted mortality as dbh increases has only previously been reported for ponderosa pine (Ryan and Frandsen 1991, McHugh and Kolb 2003). We also report similar findings for Jeffrey and ponderosa pine in this paper.

Mutch and Parsons (1998) developed a model for white fir based on the status of trees five years after a prescribed fire. The majority of white fir trees in their study were less than 50 cm dbh. When modeling only percent crown volume killed (PCVK) and dbh, for trees with dbh less than 50 cm, their model predicts higher mortality than our model. The predicted mortality for trees smaller than 50 cm dbh with 70 percent crown kill is 0.28 in our model compared to 0.84 in theirs. This large difference in the probabilities of mortality between models begins to decrease as trees get larger. However, the predictive capability of their model for trees larger than 50 cm dbh is questionable because their data range is limited.

Stephens and Finney (2002) developed a model for white fir based on the status of trees three years post-fire. Their data set included a minimum of five trees per five cm diameter class for white fir between 5-65 cm dbh. Their mean dbh for white fir was 20.3 cm compared to a mean of 60.2 cm for our trees. For trees less than 50 cm dbh, the predicted probabilities of mortality are very similar for all levels of crown injury between models when using only PCVK and dbh. As trees get larger than 50 cm dbh, the Stephens and Finney model dramatically underestimates tree mortality. For example, our predicted mortality for trees greater than 75 cm dbh with 70 percent crown volume kill is 55 percent compared to less than 10 percent for theirs. It should be noted that the Stephens and Finney model is intended for use by forest managers planning prescribed fires. Their data were collected before and after a prescribed fire and the majority of their mortality was in the smaller size classes, as would be expected burning under prescribed fire conditions. Their lack of data for trees greater than 65 cm dbh and the dramatic differences in the predicted probabilities of mortality for larger trees between our model and theirs illustrates the concern of using models beyond the authors' intent and extrapolating beyond the data used for model development.

Yellow Pine

The data set for yellow pine includes Jeffrey and ponderosa pine trees in the Cone and McNally fires. Tree status two years post-fire was used for model development. There was a significant difference between live and dead trees for all variables collected (*table 10*). Average dbh was higher for dead trees than live trees. Sixty-five percent of the trees died in the first two years post-fire.

Table 10--*Mean characteristics of variables for yellow pine. P-values test differences between live and dead values.*

Variable[1]	Mean (n=1974)	SE	Range	Live Mean (n=682)	Dead Mean (n=1292)	p-value
Dbh	62.6	0.6	25.4-160.8	56.7	65.8	<0.0001
PCLK	64	0.5	0-100	42	76	<0.0001
PCLS	85	0.4	0-100	73	91	<0.0001
PCVK	71	0.5	0-95	52	81	<0.0001
PCVS	87	0.4	0-100	76	92	<0.0001
CKR	2.4	0.0	0-4	1.5	2.8	<0.0001
RTB	3	0.1	0-31	1	4	<0.0001

[1] Dbh – diameter at breast height (cm); PCLK – percent crown length killed; PCLS – percent crown length scorched; PCVK – percent crown volume killed; PCVS – percent crown volume scorched; CKR – cambium kill rating; RTB – number of red turpentine beetle pitch tubes on bole.

The preliminary optimal model to predict mortality within two years post-fire includes crown length kill squared ($PCLK^2$), cambium kill rating (CKR), dbh, and red turpentine beetle (RTB) as variables (*table 11*, model 1). While leaving CKR out of the model only reduced the ROC slightly, the graphs of the mortality curves illustrate the reduced accuracy when cambium condition is not assessed (*figs. 9, 10,* model 2). Excluding RTB and CKR reduce model accuracy even further. The predicted probability of mortality for trees that were attacked by RTB would be underestimated if RTB and CKR were not assessed (*fig. 10*, model 3). Conversely, if RTB and CKR were not assessed for individual trees that were not attacked by RTB, the predicted probability of mortality would be overestimated (*fig. 9,* model 3).

All three models predict increasing probabilities of mortality with increasing dbh. This is similar to results in McHugh and Kolb (2003) for ponderosa pine models developed using wildfire alone and prescribed and wildfire combined data sets, but contrary to the prescribed fir models reported in Stephen and Finney (2002) and McHugh and Kolb (2003). Most often, the objective of a prescribed fire is to limit mortality of the overstory while reducing fuel loadings and ingrowth of smaller trees. Therefore, a data set from a prescribed burn likely does not contain many

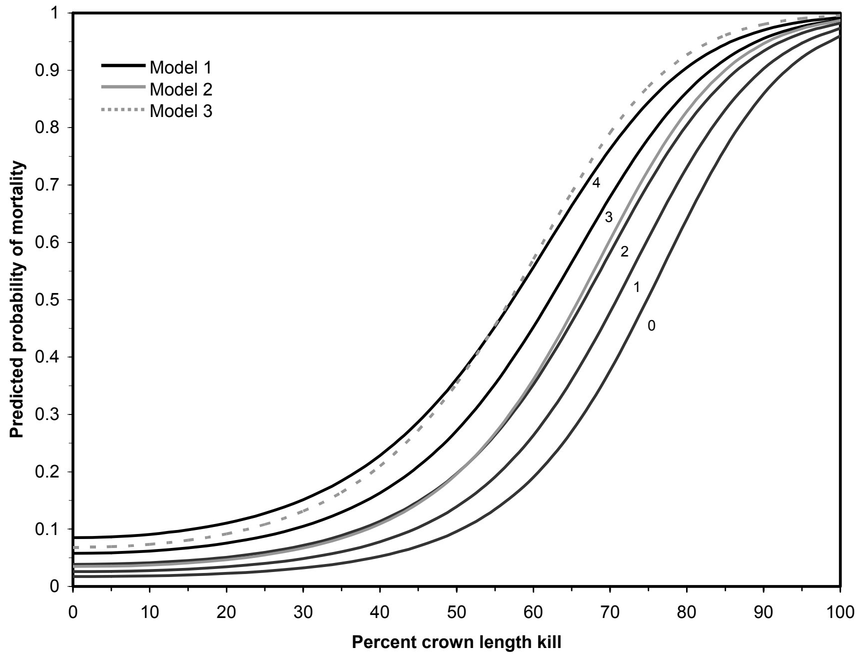

Figure 9--Year 2 yellow pine mortality curves for trees without red turpentine beetle pitch tubes and a dbh of 62.6 cm. Solid black lines indicate optimal mortality model (model 1). Grey line is model 2 mortality curve. Dashed line is model 3 mortality curve.

Table 11–*Yellow pine mortality models two years post-fire for use after bud break. Model 1 is the statistically best, optimal model. The class effect red turpentine beetle (RTB) is modeled as 1 when present and -1 when absent.*

Model	Intercept	$PCLK^2$	CKR	Dbh	RTB	-2LogL	ROC
1	-4.3202	0.000723	0.4185	0.0188	0.9048	1294.79	0.92
2	-3.7431	0.000765	-	0.0219	0.9515	1355.70	0.92
3	-3.1647	0.000805	-	0.0088	-	1530.79	0.89

larger, overstory trees with high levels of crown and cambium kill. The differences in tree size and fire type could account for the different effects of dbh when predicting mortality.

In ponderosa and Jeffrey pines, extensive heat killing of foliage may occur with only light injury to buds and twigs (Wagener 1961). Delaying the evaluation of fire-injured pines until after bud break results in a more accurate determination of the residual amount of live crown. However, the ability to predict mortality of pine trees prior to bud break may be useful for land managers that want to expedite tree removal to limit wood deterioration. Our optimal model for use in Jeffrey and ponderosa pine trees prior to bud break includes percent crown length scorch squared ($PCLS^2C$), cambium kill rating (CRK), and dbh (*table 12,* model 1). The models using PCLS do not predict mortality as accurately as the percent crown length kill (PCLK) models (Model 1 ROC = 0.92 vs. 0.87). We did not include red turpentine beetle in the model, as few beetles would fly prior to bud break the year after the fire.

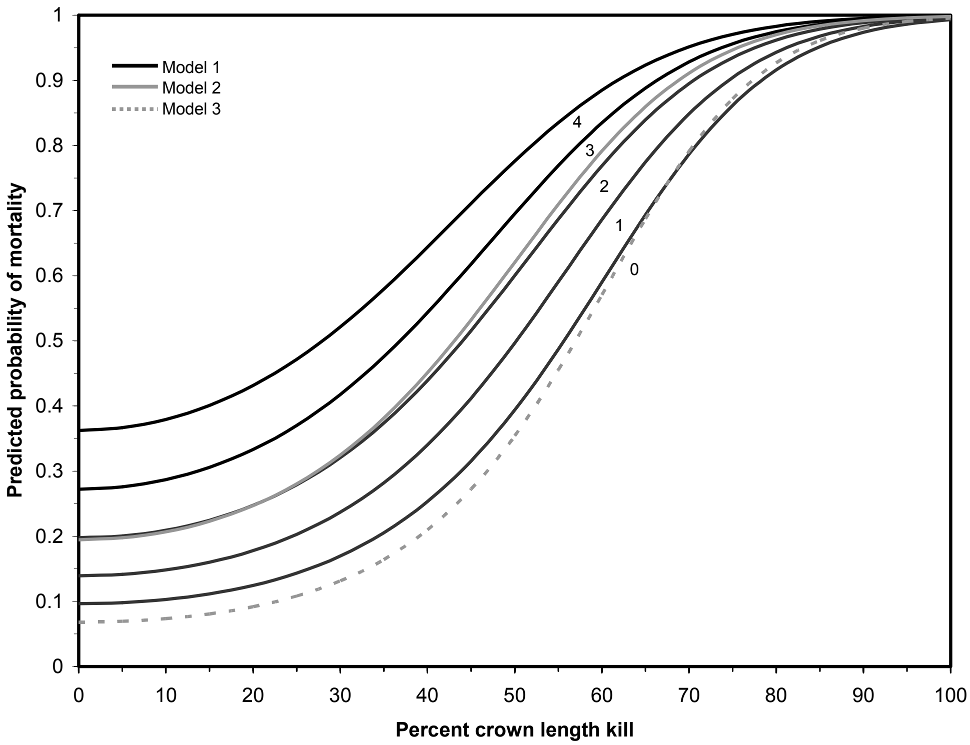

Figure 10–Year 2 yellow pine mortality curves for trees with red turpentine beetle pitch tubes and a dbh of 62.6 cm. Solid black lines indicate optimal mortality model (model 1). Grey line is model 2 mortality curve. Dashed line is model 3 mortality curve.

Table 12–*Yellow pine mortality models two years post-fire for use prior to bud break. Model 1 is the statistically best, optimal model.*

Model	Intercept	$PCLS^2$	CKR	Dbh	-2LogL	ROC
1	-6.8243	0.000568	0.6688	0.0285	1675.73	0.87
2	-5.5637	0.000578	-	0.0308	1903.87	0.81

Once bud break has occurred, the models using percent crown length kill are preferable.

Our model using PCVS and dbh for trees equal to 50 cm dbh was very similar when comparing with the model by Stephens and Finney (2002). Above 75 percent PCVS, our model predicted slightly higher probabilities of mortality. This discrepancy between predicted probabilities of mortality increases greatly as trees get larger. The lower predicted probabilities in their models compared to ours may be attributed to the small overlap between the data sets. Our data set contains much larger trees (average of 62.6 cm dbh versus 26.3 cm dbh). Their lack of data for trees greater than 60 cm dbh and the dramatic differences in the probabilities of mortality for larger trees between our model and theirs again illustrate the concern of using models beyond the authors' intent and extrapolating beyond the data used for model development.

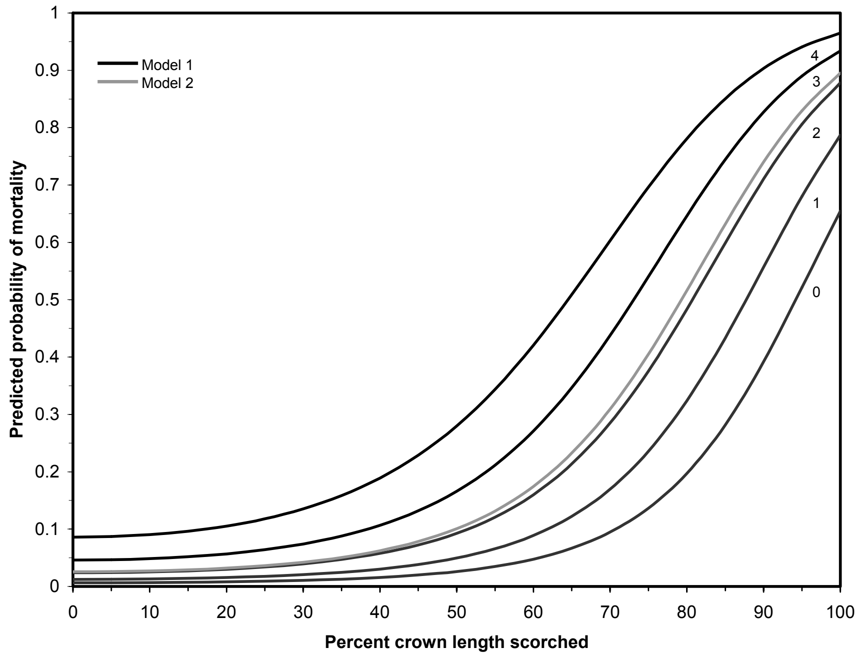

Figure 11–Year 2 yellow pine mortality curves percent crown length scorched (model 1) by cambium rating for a dbh of 62.6 cm. Solid black lines indicate optimal mortality model (model 1). Grey line is model 2 mortality curve. Models are intended for use before bud break occurs within one year following fire.

Conclusion

We found that percent crown length killed and the number of quadrants with dead cambium samples to be the most important variables for predicting post-fire mortality for mixed conifer species in California. The size of the tree, in terms of diameter at breast height, was also important in the models for all species except red fir. For white fir, ponderosa and Jeffrey pines, larger trees were more likely to die than smaller trees given the same level of crown and cambium injury. This could be due to larger trees having greater duff accumulations, leading to increased smoldering times and the potential for more root injury. Larger trees may also be less vigorous than smaller trees, reducing their capability to recover from fire caused injuries (McHugh and Kolb 2003). The opposite was true for incense-cedar, where smaller trees succumbed more often, given the same level of crown and cambium injury. The variables indicating the presence of ambrosia beetle boring dust on red and white fir and red turpentine beetle pitch tubes on Jeffrey and ponderosa pines increased model accuracy in all equations.

Land managers need the ability to predict mortality following wildfires to plan tree removal and regeneration projects. The logistic models presented in this paper were specifically developed for use in predicting post-fire mortality for salvage marking, but may also be useful in determining future stocking levels and planning fuels treatments. These models enable managers to select a desired level of predicted probability of mortality based on land management objectives. The logistic curves for additional models are also provided to demonstrate the decrease in accuracy when significant variables are removed. Each variable in a model requires additional time for assessment in the field. Estimating crown injury takes the least amount of time, followed by assessing for insect activity and measuring dbh. Sampling the cambium in each quadrant is the most time consuming, but based on the significance of CKR in all our models, not sampling for it may result in great inaccuracies in model predictability, with the possible exception of incense-cedar. Compared to using the optimal models for developing marking guidelines, using less accurate models will likely result in leaving more dead trees than desired on the landscape or removing more trees that would have survived. The implementation of a bark char classification system that equates to unburned and light char as no cambium kill and deep char as dead cambium could be used as an reasonably accurate alternative to cambium sampling. Bole quadrants with moderate char, which was the most common char rating in our study, would still require direct sampling due to the poor correlation with cambium status.

Crown injury can be assessed using a variety of methods. We chose to use percent crown length killed in all of our models because it was a common variable between data sets. Unlike conclusions drawn by other authors suggesting that a volume estimate is more accurate (Peterson 1985, Stephens and Finney 2002), we did not find great differences in predictive accuracy between models developed with percent crown length killed versus models developed with percent crown volume killed. The selection of one method of crown injury assessment over another can therefore be based on the assessor's preferred method. However, volume versus length killed estimates are not interchangeable in the models and only percent crown length killed should be used with the models in this paper.

The logistic models in this paper for incense-cedar, Jeffrey pine, ponderosa pine and white fir are based on tree status two years post-fire. Mortality of study trees is still occurring in all fire areas and incorporating additional annual assessments into model development should improve accuracy. For fires where assessments have been made over a longer period of time, the majority of the mortality occurred within three years post-fire. Delayed mortality, in terms of crown death, may take several years to occur for trees with fatal levels of cambium kill. For white fir, cambium kill was a more important variable in the three-year model compared to the two-year model. We anticipate similar results for our remaining species.

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References

Bevins, C.D. 1980. **Estimating survival and salvage potential of fire-scarred Douglas-fir.** Res. Note 287, U. S. Dept. of Agriculture Forest Service Intermountain Forest and Range Experiment Station, Ogden, Utah. 8 p.

Borchert, M.; Schreiner, D.; Knowd, T.; and Plumb, T. 2002. **Predicting postfire survival in Coulter pine (*Pinus coulteri*) and gray pine (*Pinus sabiniana*) after wildfire in central California.** Western Journal of Applied Forestry. 17: 134-138.

Eyre, F.H. 1980. Forest cover types of the United States and Canada. Society of American Foresters. 148 p.

Finney, M. 1999. **Fire-related mortality of ponderosa pine in eastern Montana.** Unpublished Report INT-93800-RJVA, USDA Forest Service, RMRS Fire Sciences Laboratory, Missoula. 14 p.

Fowler, J.F. and Sieg, C.H. 2004. **Postfire mortality of ponderosa pine and Douglas-fir: a review of methods to predict tree death.** Gen. Tech. Rep. RMRS-GTR-132, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO. 25 p.

Furniss, R.L. and Carolin, V.M. 1977. **Western forest insects.** Misc. Pub. 1339, United States Dept. of Agriculture, Forest Service, Washington, D.C. 654 p.

Harrington, M.G. 1993. **Predicting *Pinus ponderosa* mortality from dormant season and growing season fire injury.** International Journal of Wildland Fire. 3(2): 65-72.

Herman, F.R. 1954. **A guide for marking fire-damaged ponderosa pine in the southwest.** Research Note 13, U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO. 4 p.

Hosmer, D.W. and Lemeshow, S. 2000. Applied logistic regression, 2nd Edition. John Wiley and Sons, New York. 375 p.

Lynch, D.W. 1959. **Effects of a wildfire on mortality and growth of young ponderosa pine trees.** Res. Note 66, U. S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah. 8 p.

McHugh, C. and Kolb, T.E. 2003. **Ponderosa pine mortality following fire in northern Arizona.** International Journal of Wildland Fire. 12: 7-22.

Mutch, L.S. and Parsons, D.J. 1998. **Mixed conifer forest mortality and establishment before and after prescribed fire in Sequoia National Park, California.** Forest Science. 44: 341-355.

Peterson, D.L. 1984. **Predicting fire-caused mortality in four Northern Rocky Mountain conifers.** *In:* Proceedings of the 1983 Convention of the Society of American Foresters, New Forests for Changing World; 1983 October 16-20, Portland, OR. Society of American Foresters, Bethesda, MD: 276-280.

Peterson, D.L. 1985. **Crown scorch volume and scorch height: estimates of postfire tree condition.** Canadian Journal of Forest Research. 15: 596-598.

Peterson, D.L. and Arbaugh, M.J. 1986. **Postfire survival in Douglas-fir and lodgepole pine: comparing the effects of crown and bole damage.** Canadian Journal of Forest Resources. 19: 1175-1179.

Peterson, D.L. and Arbaugh, M.J. 1989. **Estimating postfire survival of Douglas-fir in the Cascade Range.** Canadian Journal of Forest Research. 19: 530-533.

Reinhardt, E.D. and Ryan, K.C. 1989. **Estimating tree mortality resulting from prescribed fire.** *In:* Prescribed fire in the Intermountain Region: forest site preparation and range improvement: symposium proceedings. Pullman, WA: Washington State University Cooperative Extension: 41-44.

Ryan, K.C. 1982a. **Techniques for assessing fire damage to trees.** *In:* J. Lotan, ed. Fire, its field effects: proceedings of the symposium, a symposium sponsored jointly by the Intermountain Fire Council and the Rocky Mountain Fire Council; 1982 October 19-21; Jackson, Wyoming. Intermountain Fire Council: 1-11.

Ryan, K.C. 1982b. **Evaluating potential tree mortality from prescribed burning.** *In:* Site preparation and fuels management on steep terrain: proceedings of a symposium; 1982 February 15-17, Spokane, WA. Pullman WA: Washington State University Cooperative Extension: 167-179.

Ryan, K.C.; Peterson, D.L.; and Reinhardt, E.D. 1988. **Modeling long-term fire-caused mortality of Douglas-fir.** Forest science. 34(1): 190-199.

Ryan, K.C. and Reinhardt, E.D. 1988. **Predicting postfire mortality of seven western conifers.** Canadian Journal of Forest Research. 18(10): 1291-1297.

Ryan, K.C. and Frandsen, W.H. 1991. **Basal injury from smoldering fires in mature *Pinus ponderosa***. International Journal of Wildland Fire. 1(2): 107-118.

Saveland, J.M. and Neuenschwander, L.F. 1990. **A signal detection framework to evaluate models of tree mortality following fire damage.** Forest Science. 36(1): 66-76.

Stephens, S.L. and Finney, M.A. 2002. **Prescribed fire mortality of Sierra Nevada mixed conifer tree species: effects of crown damage and forest floor combustion.** Forest Ecology and Management. 162: 261-271.

Wagener, W.W. 1961. **Guidelines for estimating the survival of fire-damaged trees in California.** Miscellaneous paper-60, Pacific Southwest Forest and Range Experiment Station, Berkeley, CA. 11 p.

Weatherby, J.C.; Progar, R.A.; and Mocettini, P.J. 2001. **Evaluation of tree survival on the Payette National Forest 1995-1999.** FHP Report R4-01-01, U.S. Department of Agriculture, Forest Service, Forest Health Protection. 29 p.

Wyant, J.G.; Omi, P.N.; and Laven, R.D. 1986. **Fire induced tree mortality in a Colorado ponderosa pine/Douglas-fir stand.** Forest Science. 32: 49-59.