

Delayed Tree Mortality following Fire in Western Conifers
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Field Locations:

Arizona- Apache-Sitgreaves, Coconino, and Kaibab National Forests

California- Sequoia, Plumas, Tahoe, Eldorado, and Lassen National Forests

Idaho- Idaho Panhandle National Forest

Montana- Glacier National Park, Northern Cheyenne Indian Reservation, Flathead, Lolo,
Beaverhead-Deerlodge, Lewis and Clark, and Custer National Forests

Wyoming- Yellowstone National Park, Bridger-Teton National Forest

See table 1 for more detail.

Brief Synopsis: We developed 3-year post-fire mortality models for 12 western conifer species by pooling data collected from multiple fire-injury studies. Models were developed for white fir, red fir, subalpine fir, incense cedar, western larch, lodgepole pine, whitebark pine, ponderosa pine, Jeffrey pine, sugar pine, Engelmann spruce, and Douglas-fir. Two sets of models were created, one for use in pre-fire planning where only crown injury and DBH were potential variables, and a second, optimal model for use in post-fire planning that used all significant variables. Predictive accuracy of all models was compared to the accuracy of the mortality model currently used in the First Order Fire Effects Model (FOFEM), BehavePlus, and the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS). These new models will be added to FOFEM version 5.7 and BehavePlus 4.5. The mortality options in FOFEM will also be expanded. We also examined the accuracy of bark char codes to predict cambium injury at the base of trees after fire and made management recommendations for when it is appropriate to use bark char codes in place of direct cambium sampling.

INTRODUCTION

Accurate prediction of post-fire tree mortality is critical for making sound land management decisions such as developing burning prescriptions and post-fire salvage marking guidelines. Numerous post-fire mortality models have been developed for western U.S. conifers. Ryan and Reinhardt (1988) developed the original logistic regression mortality model used in today's U.S. fire behavior and effects models, making it perhaps the most widely used post-fire mortality model in the U.S. This model is included in the First Order Fire Effects Model (FOFEM v. 5.0), BehavePlus (v. 3.0), and the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS, Suppose v. 1.19A) (Andrews et al. 2003; Reinhardt and Crookston 2003; Reinhardt et al. 1997).

Ryan and Amman (1994) updated the original model to the form currently used in FFE-FVS, FOFEM, and BehavePlus. The Ryan and Amman mortality model includes a bark thickness term based on species and diameter at breast height (DBH) and percent crown volume scorched, an easily and quickly determined fire-injury variable. While the Ryan and Amman model is now widely used as a silvicultural tool in the western U.S., it was developed from a relatively small sample of seven western coniferous species (n=2,356) and only from prescribed fires in the Pacific Northwest and Northern Rockies (see Ryan and Reinhardt 1988 for site descriptions). The predictive accuracy of the model has not been assessed for fires outside the original study's geographic area, for wildfires, or for other tree species except ponderosa pine (*Pinus ponderosa*) (Finney 1999; Weatherby et al. 1994).

Post-fire tree mortality models use a multitude of crown, bole, and root injury variables to predict mortality. This lack of standardized methods makes model comparison difficult and hard for managers to know what variables best predict mortality. Various methods have been developed to estimate cambium injury on the tree bole to avoid direct sampling. Ryan (1982) first developed categories of bark char severity to indicate stem injury resulting from fire. His codes et al. have since been used as a surrogate for stem injury in post-fire tree mortality models (Peterson and Arbaugh 1986, Peterson and Arbaugh 1989, Harrington and Hawksworth 1990, Regelbrugge and Conard 1993, Beverly and Martell 2003, Hély et al. 2003, McHugh and Kolb 2003, Kobziar et al. 2006, Sieg et al. 2006, Thies et al. 2006, Breece et al. 2007). While these studies have found various measures of bark char to be a statistically significant variable to predict delayed tree mortality, it is unknown how well bark char actually relates to cambium injury for many species (Fowler and Sieg 2004).

We pooled data amassed from numerous post-fire tree mortality studies across the western U.S. in order to:

- 1) Assess the predictive accuracy of the tree mortality models currently used in FOFEM, BehavePlus, and FFE-FVS both at the stand and individual tree level,
- 2) Assess the relationship between the Ryan (1982) bark char codes and cambium status (live/dead) to determine when it is appropriate to use bark char codes in place of direct sampling, and
- 3) Develop new 3-year post-fire mortality models to improve the predictive accuracy of FOFEM and BehavePlus.

We evaluated the FOFEM model using fire-injury data for white fir (*Abies concolor*), red fir (*A. magnifica*), subalpine fir (*A. lasiocarpa*), incense cedar (*Calocedrus decurrens*), lodgepole pine (*Pinus contorta*), whitebark pine (*P. albicaulis*), Jeffrey pine (*P. jeffreyi*), ponderosa pine, sugar pine (*P. lambertiana*), Douglas-fir (*Pseudotsuga menziesii*), western larch (*Larix occidentalis*), Engelmann spruce (*Picea engelmannii*), western red cedar (*Thuja plicata*), and western hemlock (*Tsuga heterophylla*).

We tested Ryan's (1982) bark char codes for lodgepole pine, whitebark pine, western white pine, western red cedar, Engelmann spruce, western hemlock, subalpine fir, white fir, incense cedar, ponderosa pine, Douglas-fir, western larch, and sugar pine.

We developed new mortality models with improved prediction capability for white fir, subalpine fir, red fir, incense cedar, western larch, lodgepole pine, whitebark pine, Engelmann spruce, sugar pine, Douglas-fir, ponderosa pine, and Jeffrey pine.

METHODS

Site Descriptions

We pooled data from previously published and unpublished fire-injury studies from 26 fires in Arizona, California, Idaho, Montana, and Wyoming. Data included 17,927 sample trees and 15 coniferous species (table 1). Three year post-fire tree mortality was used for all fires. Fires occurred between 1982 and 2004 and included both prescribed fires and wildfires. Sample trees covered a broad range of diameters and crown and cambium injury.

Post-fire Sampling

Field sampling methods were similar across studies; however, not all variables were collected for each fire. Species, DBH and percentage crown volume scorched and/or percentage crown length scorched were assessed for each tree within 1-year post-fire. Because of morphological similarities, the ponderosa and Jeffrey pines from fires in California were grouped into one yellow pine category during data collection. For the majority of trees, cambium kill rating (CKR), bark char, and bark beetle attacks were also assessed. All trees were monitored annually for three years post-fire for mortality. Trees were considered dead when no green foliage remained in the crown, regardless of beetle attack timing.

Both crown volume scorched and crown length scorched values were visually assessed based on the portions of the pre-fire crown that were either scorched or consumed. Crown volume scorched equals the percentage of the pre-fire crown volume where needles were either scorched or consumed and could include areas with live and dead buds. Total tree height, pre-fire crown base height, and the average height of crown scorch were measured to calculate percentage crown length scorched.

Crown needle scorch and crown bud kill are approximately equal for most species; however, the difference can be substantial for some species such as ponderosa pine, Jeffrey pine, and western larch (Dieterich 1979; Hood et al. 2007a; Ryan and Reinhardt 1988; Wagener 1961). Both crown bud kill and crown needle scorch were assessed on 5,635 ponderosa and Jeffrey pine trees. Crown bud kill equals the percentage of pre-fire crown volume where buds were killed either by heated air (scorched) or direct flame contact (consumed). Crown scorch equals the percentage of the pre-fire crown volume where needles were either scorched or consumed and could include areas with live and dead buds.

Trees measured for bark char and CKR were visually divided at the base into quadrants. Quadrants for most fires were oriented with the slope, one quadrant being on the uphill side, one on the downhill side, and two on the cross-slope. In flat areas and in the California fire sites, quadrants were oriented in the cardinal directions. Each quadrant was assigned one of the Ryan (1982) bark char codes based on its average level of charring near the groundline (non-California fires) or within 1 foot of groundline (California fires). In the center of each quadrant, cambium status at groundline was visually assessed as described in Ryan (1982) by removing a small portion of the bark to reveal the cambium. Live cambium is light in color, moist, and pliable. Dead cambium is darker in color and either sticky (resinosis) or hardened (Ryan 1982). Cambium kill rating (CKR) was calculated by summing the number of dead cambium samples per tree (0 - 4).

Delayed Tree Mortality in Western Conifers (05-2-1-105)

Table 1. Summary of fire data included in data analyses.

Fire Name	Location ¹	State	Fire Type	Fire Ignition Date	Species sampled ²	No. Trees ³	Used in analysis of:		
							FOFEM evaluation	Bark Char Codes evaluation	New mortality modeling
Dauber	Coconino NF	AZ	Prescribed	Sept. 1995	PP	222	X		X
Bridger-Knoll	Kaibab NF	AZ	Wild	June 1996	PP	833	X		X
Side	Coconino NF	AZ	Wild	May 1996	PP	313	X		X
Rodeo-Chediski	Apache-Sitgreaves NF	AZ	Wild	June 2002	PP	698	X		X
Barkley	Lassen NF	CA	Wild	Sept. 1994	SP	20	X		
Bucks	Plumas NF	CA	Wild	Aug. 1999	RF, WF, SP	236	X		X
Storrie	Plumas NF	CA	Wild	Aug. 2000	RF, WF	198	X		X
Star	Tahoe	CA	Wild	Aug. 2001	WF, SP	273	X		X
Cone	Lassen	CA	Wild	Sept. 2002	JP, PP	1065	X	X	X
McNally	Sequoia NF	CA	Wild	July 2002	WF, IC, JP, PP	3872	X	X	X
Power	Eldorado NF	CA	Wild	Oct. 2004	SP	719		X	X
Oops	Idaho Panhandle NF	ID	Wild	Oct. 1982	RC, WWP, WH, DF	151	X	X	
Danskin	Boise NF	ID	Prescribed	May 2002	PP, DF	385		X	
Lower Priest	Idaho Panhandle NF	ID	Prescribed	June 1984	RC, WWP, ES, WH, DF, WL	306		X	X
Upper Priest	Idaho Panhandle NF	ID	Prescribed	Sept. 1983	RC, WWP, ES, WH, DF, WL	180		X	X
Air Patrol	Northern Cheyenne IR	MT	Wild	Aug. 1988	PP	505	X	X	X
Brewer	Custer NF	MT	Wild	June 1988	PP	626	X	X	X
Early Bird	Northern Cheyenne IR	MT	Wild	June 1988	PP	615	X	X	X
Canyon Creek	Lolo NF	MT	Wild	Sept. 1988	WL	69	X	X	X
Mussigbrod	Beaverhead-Deerlodge NF	MT	Wild	Aug. 2000	LP, WP, ES, SF, DF	1102	X	X	X
Moose	Flathead NF; Glacier NP	MT	Wild	Aug. 2001	LP, WP, ES, SF, PP, DF, WL	1266	X	X	X
Lubrecht	Lolo NF	MT	Prescribed	April 2002	LP, PP, DF, WL	1696	X	X	X
Tenderfoot	Lewis and Clark NF	MT	Prescribed	Sept. 2002	LP, WP, ES, SF	1750	X	X	X
Slowey	Lolo NF	MT	Prescribed	March 1992	PP, DF	241		X	X
Green Knoll	Bridger-Teton NF	WY	Wild	Aug. 2001	LP, WP, ES, SF, DF	276	X	X	X
Yellowstone	Bridger-Teton NF; Yellowstone NP	WY	Wild	June 1988	SF, LP ES, DF	310	X		X

¹IR – Indian reservation; National Forest; NP – National Park

²Species: LP – lodgepole pine, WP – whitebark pine, WWP – western white pine, RC – western red cedar, ES – Engelmann spruce, RF – red fir, WH – western hemlock, SF – subalpine fir, WF – white fir, IC – incense cedar, JP - Jeffrey pine, PP – ponderosa pine, DF – Douglas-fir, WL – western larch, SP – sugar pine.

³Tree numbers vary slightly between analyses based on available data.

For ponderosa pine trees from the Air Patrol, Brewer, and Early Bird fires in eastern Montana, a die was thrown to randomly select approximately every sixth tree for direct sampling to determine cambium status (307 of 1748 trees) by removing a sample of cambium at groundline from each quadrant using an increment borer and then treating it with a vital stain (Ryan 1982). All trees in this study were revisited annually for four years post-fire to assess tree mortality.

Beetle assessment varied by tree species and fire-injury study. For the current analyses, all trees were coded as either attacked or unattacked based on the more detailed attack data collected in the original study. For more detailed beetle attack collection methods refer to Hood and Bentz (2007), Hood et al. (2007a), McHugh and Kolb (2003), Ryan and Amman (1994). Trees were monitored annually for three years post-fire for additional beetle attacks, with the exception of the California fires. Attacks were only noted one year following the fire for these trees.

Data Analyses

Evaluation of FOFEM tree mortality model

We used general linear mixed models (GLMM) to test for differences in crown volume scorched and DBH between live and dead trees, including fire as a random effect when sample trees were distributed across multiple fires (Littell et al. 1996). When sample trees came from only one fire, we used Wilcoxon-Mann-Whitney tests to test for differences between live and dead trees. P-values less than or equal to 0.05 in the GLMM and Wilcoxon-Mann-Whitney tests were considered statistically significant.

We calculated the predicted probability of mortality (P_m) for all trees ($n=14,803$) using the Ryan and Amman (1994) mortality model. Predictive accuracy of the model by species was then assessed at the individual tree level and stand level. We evaluated individual tree accuracy using classification tables and Receiver Operating Characteristic (ROC) curves. Stand level mortality was assessed by comparing actual versus predicted mortality across 0.1 P_m classes.

Classification tables allow the user to determine classification accuracy of a model based on the selected P_m . Trees with values above the selected cutoff probability are classified as dead, whereas trees below the cutoff probability are classified as live. The selected cutoff level determines the model accuracy. Studies have typically reported model accuracy based on either P_m equal to 0.5 or 0.6 (Keyser et al. 2006; Regelbrugge and Conard 1993; Ryan and Reinhardt 1988; Thies et al. 2006). The classification data presented for this study display the percent of trees that were correctly predicted as live and dead (total correct), the percent of trees the model predicted to die and were observed dead (correctly predicted mortality), and the percent of trees the model predicted to live and were observed live (correctly predicted survival) from P_m 0.1 to 0.9.

The ROC curve is a plot of the probability of a true positive prediction (tree classified and observed dead) versus the probability of a false positive prediction (tree classified as dead when it is alive) across the continuous P_m cutoff ranges from 0 to 1 (Bradley 1996; Saveland and Neuenschwander 1990). 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.

When using the model to predict stand level mortality, the calculated P_m equals the percentage of the trees in a stand that are predicted to die by tree species and size class. To test stand level model accuracy, we grouped trees into 0.1 P_m classes by species after calculating the P_m for each tree. Predicted mortality equaled the respective P_m class (e.g. P_m class 0.8 equaled 80% predicted mortality). We then calculated the actual percentage of trees in each P_m group that died (observed mortality). We compared actual versus predicted group mortality by subtracting the

predicted mortality from the observed mortality. Positive differences reveal where the Ryan and Amman model over-predicts stand level post-fire mortality, whereas negative differences indicate where stand level post-fire mortality is under-predicted. We calculated overall stand level accuracy by summing the predicted mortality of each group and subtracting the summed value from the total observed mortality.

We used this process for all species except Engelmann spruce. FFE-FVS, FOFEM, and BehavePlus predict 80% post-fire spruce mortality, regardless of injury or size class. Therefore, we compared observed mortality versus the predicted 80% mortality for Engelmann spruce.

See Hood et al. (2007b) for more detailed information regarding the evaluation of the tree mortality model used in FOFEM.

Evaluation of Bark Char Codes to Predict Cambium Status

We used logistic regression to evaluate the relationship between direct measurement of cambium status and the external bole char ratings for each species. Because four samples were taken per tree, estimates from generalized estimating equations were used to account for within tree correlation. Only trees that were alive at the time of initial assessment were included in the analysis because cambium was assumed dead for dead trees. Tree DBH was included in the model to evaluate whether the predictive accuracy of the bole char codes varied with tree size. Fire type (wild or prescribed) was also evaluated for model inclusion for those species where sufficient data existed— lodgepole pine, Engelmann spruce, subalpine fir, yellow pine (ponderosa and Jeffrey pine), and Douglas-fir. Variables with p-values < 0.05 were retained in the full model. If DBH was significant in the model, a second model without DBH was also developed in order to compare the added value of using DBH to predict cambium status from bark char. All analyses were performed in SAS (PROC GENMOD, SAS Institute, v. 9.1)

Differences in four year post-fire mortality, crown volume scorched (%), and DBH between ponderosa pines with and without cambium sampling from the Air Patrol, Brewer, and Early Bird fires were tested using a general linear mixed model (Littell et al. 1996). Fire name and plot number within fire were included as random effects.

Tree Mortality Modeling

All trees were coded as either 0 (live) or 1 (dead) based on post-fire year 3 status. The probability of tree death within three years post-fire was modeled using GLM with a binomial error distribution, logit link function specified, and the model form:

$$P_m = 1/[1 + \exp(-(B_0 + B_1 X_1 + \dots B_k X_k))],$$

where P_m is the probability of mortality, B_0 , B_1 , and B_k are regression coefficients, and X_1 and X_k are independent variables. Model variable screening was performed in SAS using PROC LOGISTIC (SAS Institute, v. 9.1). All final models were developed using either PROC GENMOD or PROC LOGISTIC. Within-subject correlation was accounted for using the REPEATED statement where trees were grouped into plots (PROC GENMOD). If trees were not grouped into plots (i.e. California fires), PROC LOGISTIC was used. Only variables with p-values ≤ 0.5 and non-significant Hosmer-Lemeshow goodness-of-fit tests were retained in the full model.

We first attempted to develop one mortality model for all species, similar to the current model in FOFEM. However, this model lacked sufficient predictive accuracy for all species and this effort was stopped in favor of species specific models.

Pre-fire and post-fire models were developed for each species, with two exceptions. Lodgepole pine and whitebark pine were grouped because of the small size of whitebark pine ($n=147$) and no statistical differences between DBH, crown volume scorched, and CKR between the two species. Because of morphological similarities, the ponderosa and Jeffrey pines from fires in California were grouped into one yellow pine category during data collection and therefore were modeled together. The pre-fire model is designed for planning prescribed burns and used a limited set of variables to predict tree mortality. Candidate variables for the pre-fire mortality model included DBH and crown scorch. The post-fire model is the most accurate model for predicting tree mortality. It is more useful in post-fire planning, such as creating salvage guidelines. Candidate variables for the post-fire model included DBH, crown scorch, CKR, and beetle attack. Based on plots of the logits, CKR was included as a continuous rather than class variable (Hosmer and Lemeshow 2000).

We cross-validated each final model to obtain a weighted classification table to determine prediction accuracy. Each species dataset was divided into 10 approximately equal groups for the cross-validation exercise. Groups were assigned based on fires so that each group contained either all the observations from a given fire or a randomly chosen subset of observations from the same fire. Therefore, each group contained observations from one fire only. We did this in order to compare accuracies both between and within fires. We then ran the logistic regression model 10 times, leaving one group out at a time. Trees with predicted probabilities of mortality ≥ 0.5 were then classified as dead and trees with probabilities < 0.5 were classified as alive for each model run. We used these classifications to calculate the weighted percentage of trees that were correctly predicted to live and die.

RESULTS

Evaluation of FOFEM tree mortality model

Please see Hood et al. (2007b) for the complete results from the mortality model evaluation exercise.

Individual Tree Mortality

The model most accurately classified subalpine fir (ROC = 0.91), followed closely by incense cedar (ROC = 0.88) (table 2). Red fir (ROC = 0.65) and Engelmann spruce (ROC = 0.69) were the least accurately classified. Comparisons of ROC values for individual fires showed large fluctuations in accuracy. In the yellow pine group, ROC values ranged from a high of 0.93 for the Bridger Knoll fire to a low of 0.68 for the McNally fire. Douglas-fir ROC values ranged from a high of 0.88 for the Lubrecht fire to a low of 0.64 for the Green Knoll fire.

Individual tree survival was most accurately predicted for red fir, incense cedar, and western larch, while individual tree mortality accuracy was the lowest (figure 1d, h, and k). Mortality was very low ($<17\%$) for these species (table 2). When observed post-fire mortality was very low, the model over-predicted mortality, but predicted survival very accurately. Large fluctuations in correctly predicted survival for lodgepole and whitebark pine were due to the model predicting very few trees to survive (figure 1a and b). In this situation, a few misclassified trees caused large differences in the percent of correctly classified trees.

Delayed Tree Mortality in Western Conifers (05-2-1-105)

Table 2. Summary statistics of trees by species and fire used to evaluate the Ryan and Amman (R-A) mortality model and predictive accuracy of the R-A mortality model. Statistics are only reported for individual fires if more than 100 trees were sampled. Species are listed in order of increasing bark thickness using bark thickness equations in FFE-FVS. Reprinted from Hood et al. 2007b.

Species	No. Trees	Average DBH (cm)			Average Crown Scorch (%)			Observed Dead (%)	R-A Predicted Dead (%)	Predicted – Observed (%)	ROC
		Live	Dead	P-value	Live	Dead	P-value				
Lodgepole pine	1550	24.7	22.4	<0.001	12	41	<0.001	62	69	+7	0.74
Mussigbrod	527	21.9	18.9	<0.001	5	14	0.002	53	65	+11	0.68
Tenderfoot	767	22.7	20.2	<0.001	13	57	<0.001	67	73	+6	0.79
Yellowstone	151	24.4	25.3	0.615	1	30	<0.001	58	62	+4	0.67
Whitebark pine	154	24.0	22.0	0.087	30	58	<0.001	49	66	+17	0.75
Engelmann spruce	266	32.1	31.8	0.920	25	55	<0.001	74	80	+6	0.69
Moose	118	44.3	30.8	0.051	8	40	0.002	88	80	-8	0.79
Mussigbrod	105	31.0	36.6	0.147	11	36	<0.001	54	80	+26	0.62
Red fir	209	43.5	37.9	0.090	56	76	0.008	17	66	+48	0.65
Western hemlock	147	32.8	25.2	<0.001	10	27	0.001	71	47	-24	0.79
Subalpine fir	905	21.7	21.3	0.550	16	77	<0.001	82	79	-3	0.91
Moose	453	23.8	20.1	0.043	36	83	<0.001	95	84	-11	0.90
Mussigbrod	205	20.0	20.4	0.580	14	59	<0.001	67	71	+4	0.83
Tenderfoot	172	16.9	16.4	0.833	5	86	<0.001	60	74	+14	0.92
White fir	1880	56.3	63.3	<0.001	54	84	<0.001	57	59	+2	0.79
Incense cedar	788	52.2	47.6	0.077	37	86	<0.001	13	35	+22	0.88
Yellow pine ^A	7004	39.1	36.6	<0.001	42	78	<0.001	43	53	+10	0.82
Air Patrol	505	28.8	27.9	0.102	42	71	<0.001	58	59	+1	0.74
Brewer	627	24.7	21.9	<0.001	49	75	<0.001	29	62	+33	0.75
Bridger Knoll	833	51.7	51.6	0.920	22	90	<0.001	14	23	+9	0.93
Cone	1064	46.1	40.7	<0.001	75	98	<0.001	56	77	+21	0.85
Dauber	222	25.1	20.3	<0.001	37	85	<0.001	18	55	+37	0.92
Early Bird	616	32.7	27.3	<0.001	29	72	<0.001	33	42	+10	0.85
Lubrecht	1041	26.0	20.0	<0.001	13	66	<0.001	11	35	+25	0.85
McNally	1086	73.1	81.9	<0.001	70	87	<0.001	84	57	-27	0.68
Rodeo-Chediski	698	36.3	31.3	<0.001	45	92	<0.001	65	69	+4	0.86
Side	312	41.8	36.4	0.007	52	93	<0.001	32	57	+24	0.85

Delayed Tree Mortality in Western Conifers (05-2-1-105)

Species		Average DBH (cm)			Average Crown Scorch (%)							
Douglas-fir	1482	39.0	34.5	<0.001	15	60	<0.001	39	39	0	0.74	
Green Knoll	218	39.5	47.0	0.005	9	46	<0.001	68	32	-36	0.64	
Lubrecht	549	24.8	20.3	<0.001	16	70	<0.001	21	43	+21	0.88	
Moose	468	42.5	33.1	<0.001	24	69	<0.001	47	40	-7	0.83	
Mussigbrod	118	32.1	25.5	0.012	10	36	<0.001	28	33	+5	0.75	
Yellowstone	125	40.5	37.8	0.053	22	67	<0.001	52	40	-12	0.76	
Western larch	309	33.9	25.1	0.001	37	67	<0.001	12	37	+25	0.77	
Sugar pine	109	57.9	65.2	0.195	51	68	0.018	62	44	-18	0.79	

^A Includes ponderosa and Jeffrey pine.

Delayed Tree Mortality in Western Conifers (05-2-1-105)

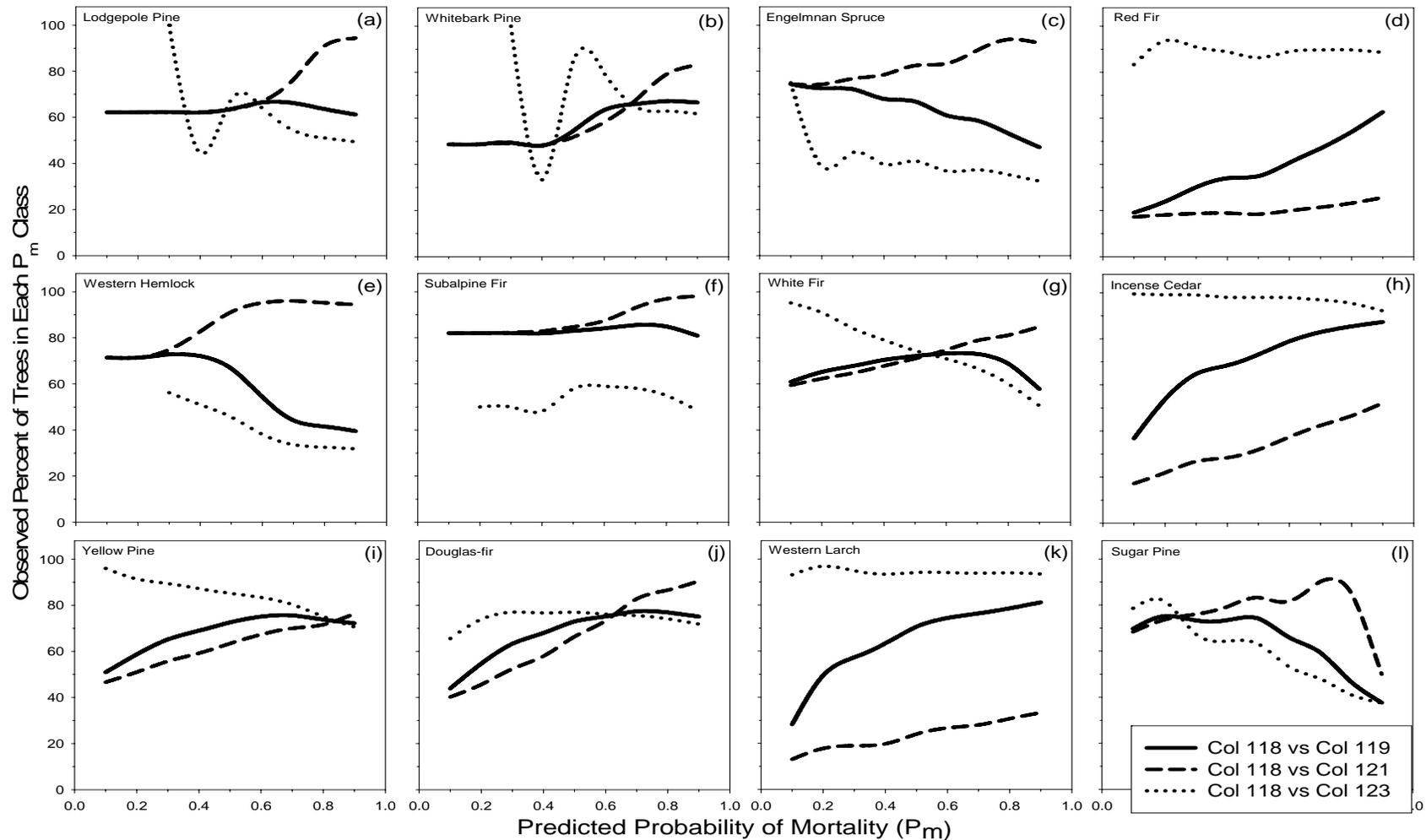


Figure 1. Classification accuracy of (a) lodgepole pine, (b) whitebark pine, (c) Engelmann spruce, (d) red fir, (e) western hemlock, (f) subalpine fir, (g) white fir, (h) incense cedar, (i) yellow pine (ponderosa and Jeffrey pine), (j) Douglas-fir, (k) western larch, and (l) sugar pine using the Ryan and Amman (R-A) mortality model to predict individual tree mortality. Species are arranged in order of increasing bark thickness using bark thickness equations in FFE-FVS. Large fluctuations in accuracy can result when few trees are predicted to either live or die (a, b, c, and l). For example, when lodgepole pine $P_m = 0.3$, two trees were predicted to live and both lived. At $P_m = 0.4$, nine lodgepole trees were predicted to live, but five died. When sugar pine $P_m = 0.9$, two trees were predicted to die, but one lived. Reprinted from Hood et al. 2007b.

Accuracy of predicted individual tree mortality generally increased with increasing P_m (figure 1). The exception was sugar pine. This again was due to the model predicting very few trees to die. At $P_m = 0.9$, only two trees were predicted to die and of these, one survived. At the upper P_m levels, the model predicted individual tree mortality with greater than 80% accuracy for all species except red fir, incense cedar, and western larch (figure 1).

With the exception of red fir, those species with thinner bark – lodgepole pine, whitebark pine, Engelmann spruce, western hemlock, and subalpine fir, tended to have low correctly predicted survival rates (figure 1). When correctly predicted survival is low, many of the trees the model predicts to live actually die and individual tree mortality is under-predicted. This was especially true for Engelmann spruce, western hemlock, and subalpine fir. For these three species, observed mortality 3 years post-fire was greater than 70%. The majority of western hemlock trees (72%) and Engelmann spruce trees (86%) with scorch greater than 5% died.

The model correctly predicted surviving yellow pine trees with greater than 80% accuracy for all fires, except Air Patrol and McNally, across all P_m cutoffs. Survival accuracy was very poor (<40% across all cutoffs) for the McNally fire. Yellow pine mortality was predicted more accurately at the upper P_m cutoffs for all fires. At a P_m cutoff of 0.9, the model correctly predicted mortality within 80% accuracy for all fires except Brewer, Dauber, and Side.

Douglas-fir survival was predicted most accurately on the Lubrecht fire (>90% across all cutoffs) and least accurately on the Green Knoll fire (~40% across all cutoffs). The model was most accurate in predicting both survival and mortality at the upper cutoffs. The model predicted lodgepole pine, Engelmann spruce, and subalpine fir mortality with greater accuracy than survival for all individual fires tested. Survival prediction accuracy was less than 30% for spruce on the Moose fire.

Model accuracy increased slightly when crown bud kill values were used instead of crown scorch to calculate yellow pine probability of mortality (ROC=0.81 vs. 0.79). When kill was used in the model, no surviving trees over 75 cm DBH were predicted to die. Rather, mortality was under-predicted for the larger trees. Mortality was over-predicted for trees less than 75 cm, especially for trees between 13 and 50 cm DBH with crown kill levels between 30 and 70% and scorch levels greater than 75%.

Stand Level Mortality

Overall stand level mortality was most over-predicted for red fir, incense cedar, and western larch (table 2). Observed mortality was also the lowest for these three species, and the majority of dead trees had greater than 95% scorch. Western hemlock and sugar pine mortality were most under-predicted. Overall stand level mortality was predicted extremely accurately for subalpine fir, white fir, and Douglas-fir (table 2).

The model over-predicted stand level mortality across nearly all P_m levels for all species except western hemlock, subalpine fir, white fir, and sugar pine (figure 2). White fir stand level mortality was predicted within 10% for all P_m levels (figure 2g). There was no clear trend in over- or under-prediction for subalpine fir across all P_m levels (figure 2f). Western hemlock and sugar pine mortality were under-predicted (figure 2e and 2i). Douglas-fir mortality was also under-predicted when P_m values were less than 0.2 (figure 2j).

When differences in individual fires were examined, the model over-predicted yellow pine mortality across all P_m levels for all fires except the McNally and Air Patrol fires. Mortality on the Air Patrol fire was under-predicted for P_m levels less than 0.4 and was over-predicted above this level. Mortality on the McNally fire was under-predicted across all P_m levels. The

Delayed Tree Mortality in Western Conifers (05-2-1-105)

Lubrecht fire was the only fire where Douglas-fir mortality was over-predicted across all P_m levels. Douglas-fir mortality was most under-predicted on the Green Knoll and Yellowstone fires (table 2). Lodgepole pine, Engelmann spruce, and subalpine fir mortality was over-predicted for all fires except the Moose fire. For this fire, Engelmann spruce and subalpine fir were under-predicted and lodgepole pine was not sampled (table 2).

Delayed Tree Mortality in Western Conifers (05-2-1-105)

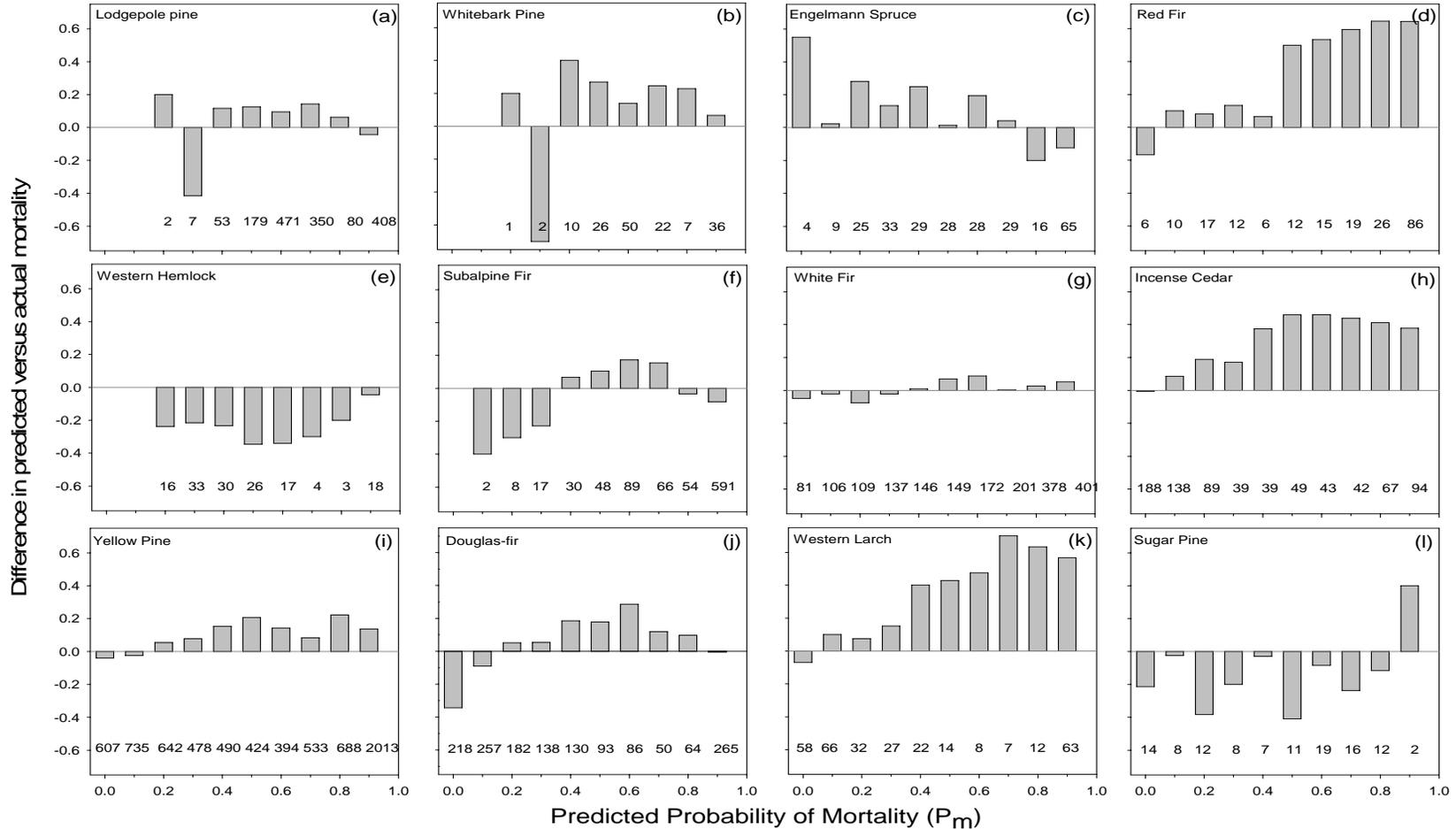


Figure 2. Difference between predicted and observed stand level predicted mortality for 10 predicted probability of mortality classes for (a) lodgepole pine, (b) whitebark pine, (c) Engelmann spruce, (d) red fir, (e) western hemlock, (f) subalpine fir, (g) white fir, (h) incense cedar, (i) yellow pine (ponderosa and Jeffrey pine), (j) Douglas-fir, (k) western larch, and (l) sugar pine using the Ryan and Amman (R-A) mortality model. Species are arranged in order of increasing bark thickness using bark thickness equations in FFE-FVS. Numbers at bottom of figures are numbers of trees per probability of mortality (P_m) class. Values greater than zero reflect an over-prediction in stand level mortality for that P_m class. Values less than zero reflect an under-prediction. Reprinted from Hood et al. 2007b.

Evaluation of Bark Char Codes to Predict Cambium Status

Full details of the evaluation of bark char codes are in press:

Hood, S. M.; Ryan, K. C.; Smith, S. L.; Cluck, D. In Press. Using bark char codes to predict post-fire cambium status. *Fire Ecology*.

For all species, the percentage of quadrants with dead cambium increased with increasing bark char severity (Figure 3) and bark char codes were significantly correlated with cambium status (Table 3). Over 80 percent of the quadrants with moderate and deep bark char had dead cambium for species with thinner bark— lodgepole pine, whitebark pine, western white pine, western red cedar, Engelmann spruce, western hemlock, and subalpine fir (Figure 3a-g). Even light bark char indicated dead cambium for the majority of these thinned barked species. Except for western larch, deep char on thicker barked species usually indicated dead cambium as well. However, the relationship between moderate bark char and cambium status was not as strong for species with thicker bark— white fir, incense cedar, yellow pine, Douglas-fir, western larch, and sugar pine (Figure 3h-m). Fewer than 50% of cambium samples coded as moderate char were dead on these thicker bark species. Regression models also predicted a high probability (>0.8) of dead cambium when quadrants had moderate or deep bark char for lodgepole pine, whitebark pine, western white pine, western red cedar, Engelmann spruce, western hemlock, and subalpine fir— all species with relatively thin bark (Table 4).

DBH was a statistically significant variable for predicting the probability of dead cambium for all species except whitebark pine, Engelmann spruce, subalpine fir, and incense cedar (Table 3). For species where DBH was significant, the predicted probability of dead cambium decreased as DBH increased except for yellow pine, in which case the probability of dead cambium increased slightly as DBH increased. The decrease in the predicted probability of dead cambium was particularly sharp for western larch as DBH increased, with little difference between bark codes for trees greater than 55 cm DBH.

Fire type (wild vs. prescribed) was significant in predicting lodgepole pine, subalpine fire, yellow pine, and Douglas-fir dead cambium (Table 3). It was not significant for Engelmann spruce. Predicted probability of dead cambium by bark char code was lower for prescribed fires than wildfires (Table 4). The predicted probability of dead yellow pine cambium from prescribed fires was low for all char codes and tree sizes.

There was no difference in the amount of ponderosa pine mortality four years post-fire between trees with cambium sampling and those that were not sampled for cambium injury (40% trees died with cambium sampling compared to 39% without cambium sampling, $DF = 1746$, $p\text{-value} = 0.7667$). The two groups did not have significantly different crown scorch (54% scorch for both groups, $DF = 1743$, $p\text{-value} = 0.8078$) or DBH (29.2 cm for cambium sampled trees and 28.2 cm for trees without cambium sampling, $DF = 1743$, $p\text{-value} = 0.0646$).

Delayed Tree Mortality in Western Conifers (05-2-1-105)

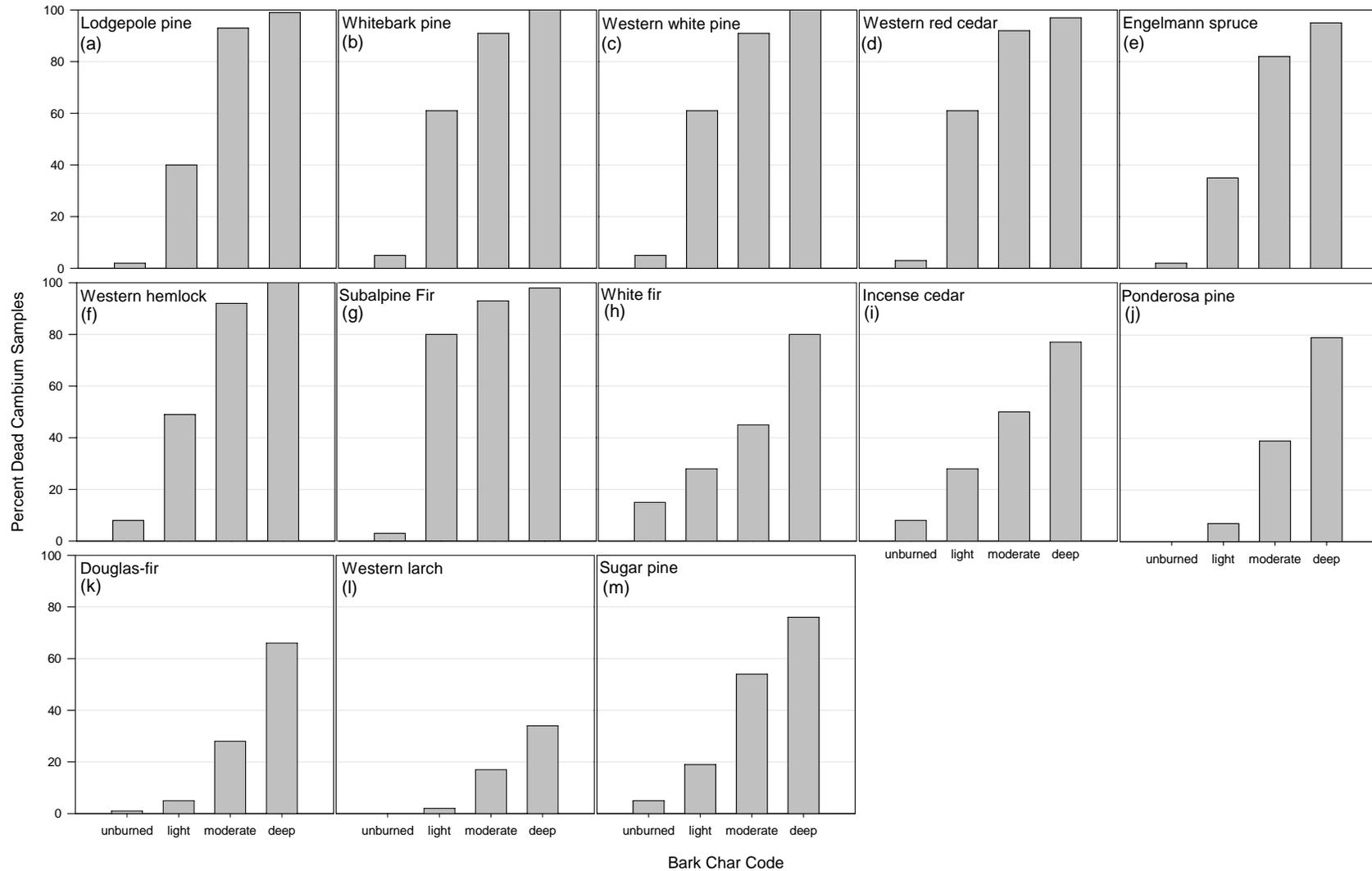


Figure 3. Percent of bark char quadrants with dead cambium by bark char code. Species are arranged in ascending order of bark thickness. (j) Includes Jeffrey pine.

Delayed Tree Mortality in Western Conifers (05-2-1-105)

Table 3. Full regression model coefficients by species to predict probability of dead cambium from bark char codes. Species are arranged in ascending order of bark thickness. N.S. indicates regression coefficient is not significant at $\alpha = 0.05$. Empirical standard error estimates are in parenthesis.

Species	Regression coefficients					
	Unburned (B_0)	Light	Moderate	Deep	DBH (cm)	Fire Type ²
Lodgepole pine	-2.9241 (0.22)	3.0063 (0.16)	5.8827 (0.17)	7.6328 (0.27)	-0.0214 (0.01)	-0.3605 (0.07)
Whitebark pine ¹	-2.5654 (0.36)	2.8636 (0.49)	4.1890 (0.50)	---	N.S.	---
Western white pine ¹	-1.6112 (0.70)	2.4877 (0.53)	4.2776 (0.50)	---	-0.0299 (0.12)	---
Western red cedar	-1.5430 (1.38)	3.6535 (1.18)	5.7411 (1.27)	6.7834 (1.74)	-0.0569 (0.03)	---
Engelmann spruce	-3.6534 (0.47)	3.2280 (0.52)	5.0967 (0.51)	6.4749 (0.54)	N.S.	N.S.
Western hemlock ¹	0.2731 (0.50)	2.1288 (0.33)	4.2023 (0.34)	---	-0.0645 (0.01)	---
Subalpine fir	-2.7920 (0.20)	3.7472 (0.30)	4.9345 (0.30)	5.8406 (0.35)	N.S.	-0.5522 (0.11)
White fir	-1.3171 (0.16)	0.7437 (0.17)	1.5257 (0.15)	3.2526 (0.16)	-0.0071 (0.01)	---
Incense cedar	-2.2271 (0.28)	1.2907 (0.29)	2.2325 (0.27)	3.4036 (0.29)	N.S.	---
Yellow pine ³	-3.8583 (0.31)	1.6447 (0.31)	2.5123 (0.31)	4.1280 (0.32)	0.0027 (0.01)	-1.1520 (0.05)
Douglas-fir	-3.3762 (0.24)	1.1384 (0.24)	2.5326 (0.21)	4.1168 (0.24)	-0.0069 (0.01)	-0.4412 (0.05)
Western larch	-2.2604 (0.60)	1.8632 (0.53)	3.0776 (0.57)	4.0688 (0.64)	-0.0691 (0.01)	---
Sugar pine	-2.2186 (0.38)	1.5593 (0.38)	2.9937 (0.36)	3.8950 (0.36)	-0.0083 (0.01)	---

¹ All deep bark char samples had dead cambium and therefore could not be included in the regression analysis.

² Class levels for fire type: prescribed fire = 1; wildfire = -1. Dash (---) indicates data were insufficient to include fire type in model.

³ Includes ponderosa and Jeffrey pine.

Delayed Tree Mortality in Western Conifers (05-2-1-105)

Table 4. Predicted probability of dead cambium by bark char code and fire type when DBH is excluded from the model. Species are arranged in ascending order of bark thickness.

Species	Predicted Probability of Dead Cambium			
	Unburned	Light	Moderate	Deep
Lodgepole pine				
Prescribed fire	0.02	0.33	0.89	0.97
Wildfire	0.05	0.50	0.94	0.99
Whitebark pine ¹	0.07	0.57	0.84	1.00
Western white pine ¹	0.06	0.40	0.79	1.00
Western red cedar	0.05	0.55	0.92	0.97
Engelmann spruce	0.03	0.40	0.81	0.94
Western hemlock ¹	0.15	0.54	0.9	1.00
Subalpine fir				
Prescribed fire	0.03	0.60	0.83	0.92
Wildfire	0.10	0.82	0.94	0.97
White fir	0.15	0.28	0.45	0.82
Incense cedar	0.10	0.28	0.50	0.76
Yellow pine ²				
Prescribed fire	0.01	0.04	0.08	0.32
Wildfire	0.07	0.29	0.50	0.83
Douglas-fir				
Prescribed fire	0.02	0.05	0.18	0.50
Wildfire	0.04	0.11	0.34	0.71
Western larch	0.02	0.07	0.15	0.30
Sugar pine	0.05	0.22	0.54	0.74

¹All deep bark char samples had dead cambium.

²Includes ponderosa and Jeffrey pine.

Tree Mortality Modeling

Pre-fire Models

We developed models for 12 species from 16,838 trees. Yellow pine (43%), white fir (14%), lodgepole pine (13%), and Douglas-fir (9%) comprised the majority of the total dataset (table 5).

Crown scorch was a significant variable in all tree mortality models; however, the scale of crown scorch varied from species to species (table 6). The P_m increased with increasing crown scorch. DBH was only included in the western larch, whitebark pine and lodgepole pine mortality models. The P_m decreased with increasing DBH. DBH was a significant variable in many of the models; however, the Hosmer-Lemeshow (H-L) goodness of fit test was significant, indicating a poor model fit. In these cases, DBH was dropped from the model and the H-L test became non-significant.

All pre-fire models were more accurate than the mortality model currently in FOFEM (figure 4). Improvement over the current model was primarily because of better prediction of trees that died. Little improvement was made in predicting trees that survived, and in many cases there was a decrease in accuracy with the new models. Over all species, the new models offer an 11% improvement over the current model (15% in mortality; 0% in survival).

The models correctly predicted mortality and survival for over 90% of incense cedar, subalpine fir, and western larch using a cutpoint of 0.5 (table 7). Prediction of spruce survival was poor, with no trees predicted to survive three years post-fire.

Delayed Tree Mortality in Western Conifers (05-2-1-105)

Table 5. Mean, standard error, median, and range of crown scorch and DBH by species of trees used to develop pre-fire mortality models. Species are listed in order of increasing bark thickness using bark thickness equations in FFE-FVS.

Species	No. Trees	Type ^B	Crown Scorch (%)			DBH (cm)		
			Mean ± se	Median	Range	Mean ± se	Median	Range
Lodgepole pine	2196	V	19 ± 0.7	0	0-100	20.8 ± 0.1	19.6	10.2-56.4
Whitebark pine	148	V	24 ± 2.9	2	0-100	22.9 ± 0.6	22.5	12.4-58.9
Engelmann spruce	223	V	30 ± 2.2	20	0-100	33.2 ± 1.1	30.2	12.7-85.1
Red fir	209	L	42 ± 1.8	46	0-89	42.1 ± 1.2	38.9	15.2-104.6
Subalpine fir	947	V	65 ± 1.3	85	0-100	19.4 ± 0.2	17.5	10.2-75.2
White fir	2304	L	67 ± 0.5	74	0-100	59.2 ± 0.4	56.9	15.2-152.7
Incense cedar	783	L	40 ± 1.1	38	0-98	51.6 ± 0.9	43.7	25.4-166.4
Yellow pine ^A	7309	V	58 ± 0.4	70	0-100	41.8 ± 0.3	35.1	6.3-178.1
Douglas-fir	1539	V	34 ± 0.9	20	0-100	33.7 ± 0.4	30.5	10.2-105.4
Western larch	461	V	26 ± 1.7	5	0-100	38.1 ± 0.6	38.1	10.2-98.8
Sugar pine	719	L	40 ± 1.1	41	0-98	73.3 ± 1.0	70.4	25.6-188.0

^A Includes ponderosa and Jeffrey pine.

^B L = crown length; V = crown volume.

Delayed Tree Mortality in Western Conifers (05-2-1-105)

Table 6. Predicted probability of mortality equations for use in pre-fire planning (i.e. only crown scorch and dbh are potential variables). CLS = crown length scorched (%); CVS = crown volume scorched (%); DBH = diameter at breast height (cm).

Species	Predicted probability of mortality equation
White fir	$P_m = 1/[1 + \exp(-(-3.5083 + (CLS * 0.0956) - (CLS^2 * 0.00184) + (CLS^3 * 0.000017)))]$
Subalpine fir	$P_m = 1/[1 + \exp(-(-1.6950 + (CVS * 0.2071) - (CVS^2 * 0.0047) + (CVS^3 * 0.000035)))]$
Red fir	$P_m = 1/[1 + \exp(-(-2.3085 + (CLS^3 * 0.000004059)))]$
Incense cedar	$P_m = 1/[1 + \exp(-(-4.2466 + (CLS^3 * 0.000007172)))]$
Western larch	$P_m = 1/[1 + \exp(-(-1.6594 + (CVS * 0.0327) - (dbh * 0.0489)))]$
Whitebark pine / Lodgepole pine	$P_m = 1/[1 + \exp(-(-0.3268 + (CVS * 0.1387) - (CVS^2 * 0.0033) + (CVS^3 * 0.000025) - (dbh * 0.0266)))]$
Engelmann spruce	$P_m = 1/[1 + \exp(-(-0.0845 + (CVS * 0.0445)))]$
Sugar pine	$P_m = 1/[1 + \exp(-(-2.0588 + (CLS^2 * 0.000814)))]$
Ponderosa pine / Jeffrey pine	$P_m = 1/[1 + \exp(-(-2.7103 + (CVS^3 * 0.000004093)))]$
Douglas-fir	$P_m = 1/[1 + \exp(-(-2.0346 + (CVS * 0.0906) - (CVS^2 * 0.0022) + (CVS^3 * 0.000019)))]$

Delayed Tree Mortality in Western Conifers (05-2-1-105)

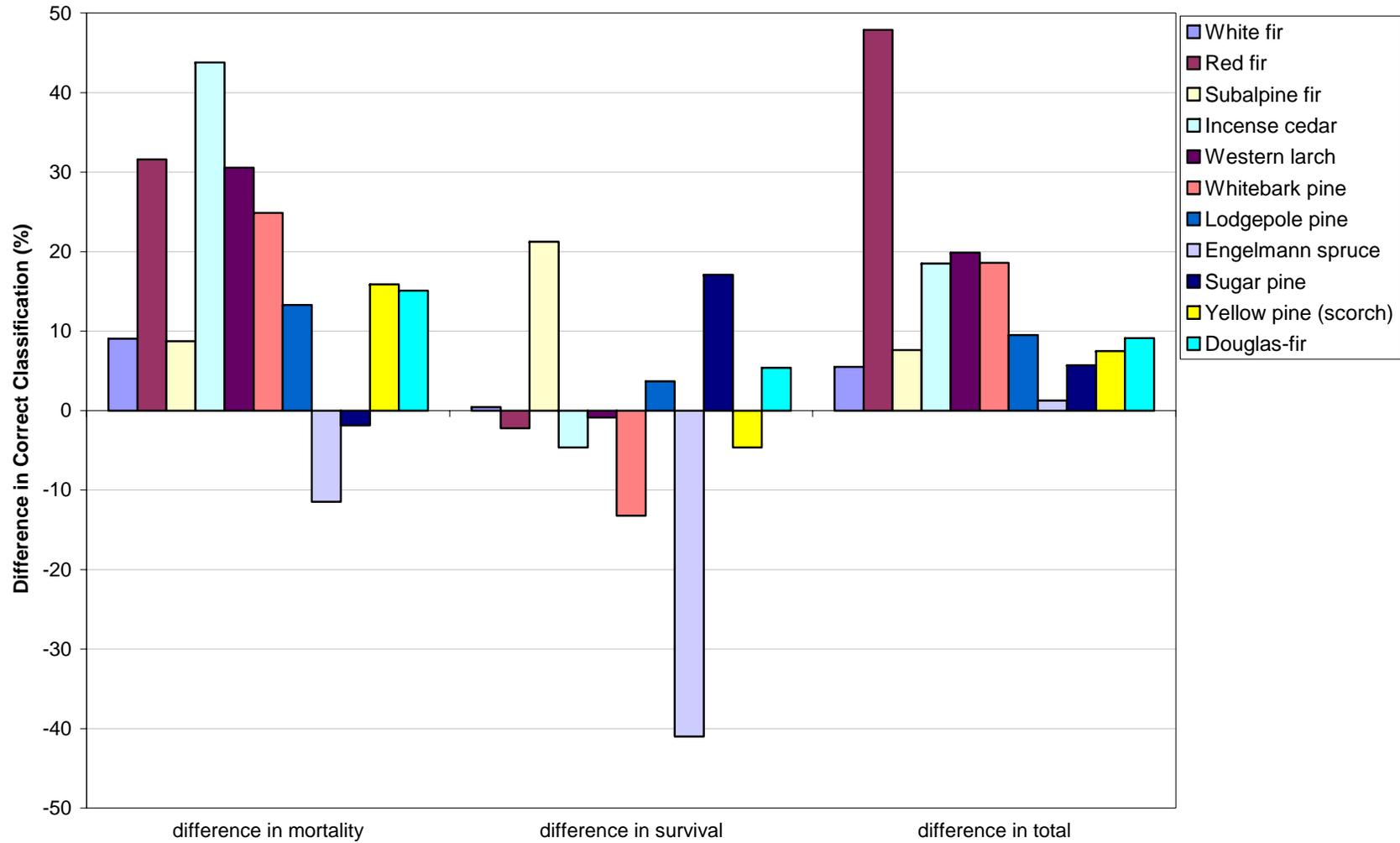


Figure 4. Percent change in mortality model accuracies by species between the current FOFEM model and new pre-fire mortality models. Positive numbers reflect an increase in accuracy over FOFEM, negative numbers reflect a decrease in accuracy. For evaluating how well the model classified trees as either live or dead, we assumed a tree with a predicted value greater than or equal to 0.5 was dead and less than 0.5 was alive.

Delayed Tree Mortality in Western Conifers (05-2-1-105)

Table 7. Classification accuracy by species of pre-fire and post-fire mortality models. Cutpoint = 0.5.

Species	PRE-FIRE MODEL ACCURACY			POST-FIRE MODEL ACCURACY			DIFFERENCE		
	Correctly predicted mortality (%)	Correctly predicted survival (%)	Total correct (%)	Correctly predicted mortality (%)	Correctly predicted survival (%)	Total correct (%)	Mortality difference	Survival difference	Total difference
Lodgepole pine / Whitebark pine	76.7	71.4	73.1	88.9	88.6	88.7	+12.2	+17.2	+15.6
Engelmann spruce	71.0	0	68.2	88.7	78.2	86.1	+17.7	+78.2	+17.9
Red fir	50.0	84.1	82.8	63.2	87.4	85.2	+13.2	+3.3	+2.4
Subalpine fir	93.4	79.1	90.6	96.3	89.5	95.0	+2.9	+10.4	+4.4
White fir	80.0	74.8	77.6	81.2	77.1	79.3	+1.2	+2.3	+1.7
Incense cedar	75.7	93.4	91.7	67.5	92.8	90.3	-8.2	-0.6	-1.4
Ponderosa pine / Jeffrey pine - scorch	79.3	80.5	80.1	84.8	79.8	81.8	+5.5	-0.7	+1.7
Ponderosa pine / Jeffrey pine - kill	n/a	n/a	n/a	87.1	85.3	86.0	n/a	n/a	n/a
Douglas-fir	85.8	76.9	78.9	81.5	82.4	82.1	-4.3	+5.5	+3.2
Western larch	54.5	93.2	90.5	68.4	93.8	92.5	+13.9	+0.6	+2
Sugar pine	81.4	80.4	80.8	84.2	85.8	85.1	+2.8	+5.4	+4.3

Post-fire Models

We developed models for 12 species from 13,284 trees. As in the pre-fire model development, yellow pine (31%), white fir (17%), lodgepole pine (15%), and Douglas-fir (11%) comprised the majority of the total dataset (table 8).

Crown scorch and CKR were significant variables in all tree mortality models; however, the scale varied from species to species (table 9). The P_m increased with increasing crown scorch and CKR. DBH was only significant for explaining white fir, whitebark pine, lodgepole pine, and Douglas-fir mortality ($p \leq 0.5$). The P_m decreased with increasing DBH for whitebark and lodgepole pine. For white fir however, the P_m increased with increasing DBH. For Douglas-fir, P_m decreased with increasing DBH for unattacked trees, but increased for attacked trees. DBH was a significant variable in many of the other models; however, the Hosmer-Lemeshow (H-L) goodness of fit test was significant, indicating a poor model fit. In these cases, DBH was dropped from the model and the H-L test became non-significant.

All post-fire models were more accurate than the mortality model currently in FOFEM (figure 5). Improvement over the current model was primarily because of better prediction of trees that died, over 40% for some species. As in the pre-fire models, mortality prediction was improved more than survival prediction. Over all species, the new models offer a 15% improvement over the current model (22% in mortality; 4% in survival).

The models correctly predicted mortality and survival for over 90% of incense cedar, subalpine fir, and western larch using a cutpoint of 0.5 (table 7). Including CKR in the models improved prediction, especially for spruce (+18%) and lodgepole/whitebark pine (+16%). The additional model variables offered a 2-4% increase in accuracy for the other species, except incense cedar. The incense cedar pre-fire model was slightly more accurate (1%) than the post-fire model at classifying live and dead trees using the cutpoint 0.5 (table 7).

Delayed Tree Mortality in Western Conifers (05-2-1-105)

Table 8. Mean, standard error, median, and range of crown scorch and DBH by species of trees used to develop post-fire (i.e. optimal) mortality models. Species are listed in order of increasing bark thickness using bark thickness equations in FFE-FVS.

Species	No. Trees	Type ^B	Crown Scorch (%)			DBH (cm)		
			Mean ± se	Median	Range	Mean ± se	Median	Range
Lodgepole pine	2038	V	19 ± 0.7	0	0-100	20.5 ± 0.1	19.3	10.2-54.9
Whitebark pine	148	V	24 ± 2.9	2	0-100	22.9 ± 0.6	22.5	12.4-58.9
Engelmann spruce	223	V	30 ± 2.2	20	0-100	33.2 ± 1.1	30.2	12.7-85.1
Red fir	209	L	42 ± 1.8	46	0-89	42.1 ± 1.2	38.9	15.2-104.6
Subalpine fir	947	V	65 ± 1.3	85	0-100	19.4 ± 0.2	17.5	10.2-75.2
White fir	2304	L	67 ± 0.5	74	0-100	59.2 ± 0.4	56.9	15.2-152.7
Incense cedar	783	L	40 ± 1.1	38	0-98	51.6 ± 0.9	43.7	25.4-166.4
Yellow pine ^A	4115	V	62 ± 0.6	80	0-100	47.1 ± 0.4	40.1	9.7-178.1
Douglas-fir	1409	V	33 ± 0.9	20	0-100	33.2 ± 0.5	30.0	10.2-105.4
Western larch	389	V	15 ± 1.3	0	0-100	38.8 ± 0.7	39.4	10.2-98.8
Sugar pine	719	L	40 ± 1.1	41	0-98	73.3 ± 1.0	70.4	25.6-188.0

^A Includes ponderosa and Jeffrey pine.

^B L = crown length; V = crown volume.

Delayed Tree Mortality in Western Conifers (05-2-1-105)

Table 9. Post-fire predicted probability of mortality equations (i.e. all significant variables included, $p \leq 0.5$). CLS = crown length scorched (%); CVS = crown volume scorched (%); CVK = crown volume killed (%); DBH = diameter at breast height (cm); CKR = cambium kill rating; beetle presence/absence: white fir, sugar pine, Jeffrey/ponderosa pine: 1 = attacked, -1 = unattacked. Douglas-fir: 1 = attacked, 0 = unattacked.¹

Species	Predicted probability of mortality equation
White fir	$P_m = 1/[1 + \exp(-(-3.5964 + (CLS^3 * 0.00000628) + (CKR * 0.3019) + (DBH * 0.019) + (beetles * 0.5209)))]$
Subalpine fir	$P_m = 1/[1 + \exp(-(-2.6036 + (CVS^3 * 0.000004587) + (CKR * 1.3554)))]$
Red fir	$P_m = 1/[1 + \exp(-(-4.7515 + (CLS^3 * 0.000005989) + (CKR * 1.0668)))]$
Incense cedar	$P_m = 1/[1 + \exp(-(-5.6465 + (CLS^3 * 0.000007274) + (CKR * 0.5428)))]$
Western larch	$P_m = 1/[1 + \exp(-(-3.8458 + (CVS^2 * 0.0004) + (CKR * 0.6266)))]$
Whitebark pine / Lodgepole pine	$P_m = 1/[1 + \exp(-(-1.4059 + (CVS^3 * 0.000004459) + (CKR^2 * 0.2843) - (DBH * 0.0485)))]$
Engelmann spruce	$P_m = 1/[1 + \exp(-(-2.9791 + (CVS * 0.0405) + (CKR * 1.1596)))]$
Sugar pine	$P_m = 1/[1 + \exp(-(-2.7598 + (CLS^2 * 0.000642) + (CKR^3 * 0.0386) + (beetles * 0.8485)))]$
Ponderosa pine / Jeffrey pine	$P_m = 1/[1 + \exp(-(-4.1914 + (CVS^2 * 0.000376) + (CKR * 0.5130) + (beetles * 1.5873)))]$
	$P_m = 1/[1 + \exp(-(-3.5729 + (CVK^2 * 0.000567) + (CKR * 0.4573) + (beetles * 1.6075)))]$
Douglas-fir	$P_m = 1/[1 + \exp(-(-1.8912 + (CVS * 0.07) - (CVS^2 * 0.0019) + (CVS^3 * 0.000018) + (CKR * 0.5840) - (DBH * 0.031) - (beetles * 0.7959) + (DBH * beetles * 0.0492)))]$

¹ Beetle species in presence/absence data: White fir: attacked by ambrosia beetle. Sugar pine: attacked by red turpentine or mountain pine beetle. Jeffrey pine / Ponderosa pine: attacked by mountain pine beetle, red turpentine beetle, or ips beetle. Douglas-fir: attacked by Douglas-fir beetle.

Delayed Tree Mortality in Western Conifers (05-2-1-105)

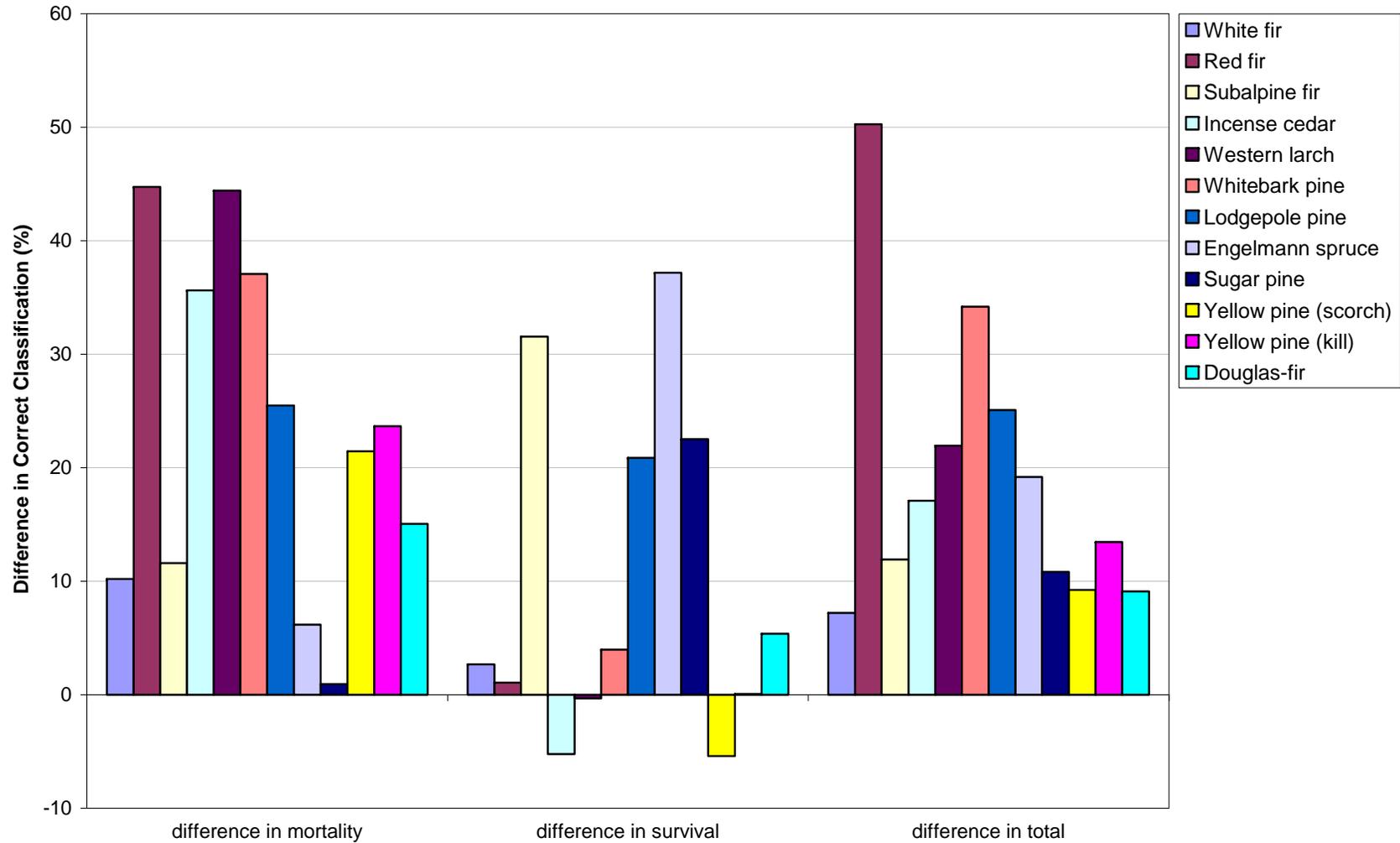


Figure 5. Percent change in mortality model accuracies by species between the current FOFEM model and new post-fire mortality models. Positive numbers reflect an increase in accuracy over FOFEM, negative numbers reflect a decrease in accuracy. For evaluating how well the model classified trees as either live or dead, we assumed a tree with a predicted value greater than or equal to 0.5 was dead and less than 0.5 was alive.

CONCLUSIONS

Evaluation of FOFEM tree mortality model

For this study, we examined the accuracy of a widely used U.S. tree mortality model on numerous western U.S. coniferous species over much wider geographic ranges and fire types (wildfire and prescribed fire). We evaluated the efficacy of the model in predicting mortality of several species not included in the development of the original model. Few independent evaluations of this commonly used post-fire tree mortality model have been completed prior to this study (but see Finney 1999; Weatherby et al. 1994). This evaluation provides managers in the U.S. with an assessment of the model's accuracy when predicting tree mortality and survival after fire in order to better understand the strengths and weaknesses of the model. It also established a baseline accuracy level to determine if new models were more accurate than the current Ryan and Amman model.

The Ryan and Amman mortality model is widely accessible to managers in the U.S. through several fire behavior and effects software packages. It is easily applied to any species as long as crown scorch and DBH are known. For prescribed burn planning purposes, the model proved to be a useful and relatively accurate method for predicting stand level post-fire tree mortality. It correctly predicted overall mortality within $\pm 20\%$ of the observed mortality for the majority of species tested. These species were lodgepole pine, whitebark pine, Engelmann spruce, subalpine fir, white fir, ponderosa pine, Jeffrey pine, Douglas-fir, and sugar pine. However, correctly predicted mortality was quite variable when individual fires were examined and model accuracy may be lower for some fires, as indicated by the data. Red fir, incense cedar, and western larch stand level mortality was over-predicted. Western hemlock was the only species tested where stand level mortality was greatly under-predicted.

When using the Ryan and Amman model, managers can expect less mortality than the model predicts when burning in incense cedar, western larch, and red fir forests. Managers can also expect higher mortality than the model predicts when planning prescribed burns in stands of western hemlock if tree boles are charred.

The Ryan and Amman model was less accurate for predicting individual tree mortality. Individual tree mortality predictions are used to develop post-fire salvage marking guidelines. For this purpose, other species specific mortality models developed from individual geographic areas may be more accurate. Species specific models often include other variables, such as stem injury and insect attacks, that can increase predictive accuracy. The species we tested that provided excellent discrimination ($ROC \geq 0.8$) were subalpine fir, incense cedar, and yellow pine. The Ryan and Amman model was especially poor at classifying Engelmann spruce, red fir, and very large diameter yellow pine.

The classification figures we developed allow managers to see correctly predicted mortality and survival based on a range of P_m values. These figures can help managers determine if accuracy is acceptable and choose a P_m level for development of marking guidelines. Poor predictions of mortality will lead to cutting many trees that may have lived, but poor predictions of survival will leave many trees that may die. Managers can predict future forest stand structure by examining the accuracy of the chosen P_m level.

Evaluation of Bark Char Codes to Predict Cambium Status

Bark char codes were relatively accurate for predicting cambium status after fire for many species (table 10). However, moderate bark char was not clearly associated with either live or dead cambium for thicker bark species. For these species (white fir, incense cedar, yellow pine, Douglas-fir, and sugar pine), cambium should be sampled directly to determine injury when bark char is moderate.

It may be possible to improve the accuracy of predicting cambium status by initially comparing bark char codes to sampled cambium and developing an understanding of the association between bark char and the underlying cambium condition. Splitting the moderate char rating into two codes may also improve accuracy. Future research to test these ideas for improving the accuracy of bark char codes is needed.

Results from this study show that tree injury from direct sampling of the cambium does not contribute to additional post-fire ponderosa pine tree mortality. We expect that other tree species would have a similar response. This research indicates that direct cambium sampling is a better variable than bark char codes for use in post-fire tree mortality modeling for species with thick bark and that direct sampling can be performed without causing additional tree mortality.

Tree Mortality Modeling

The species specific models developed for this project offer improved prediction over the current mortality model in FOFEM. Crown scorch was the most important variable in predicting mortality. CKR and beetle attacks also were consistently significant in the models. However, tree size was not significant in predicting mortality for most species.

For most species, the optimal post-fire model increased accuracy by approximately 2-4%. This is likely not enough to justify the extra time needed to assess these additional variables. Assessing cambium injury for Engelmann spruce, whitebark pine, and lodgepole pine however, greatly increases model accuracy. This is most likely because these three species all have very thin bark and fire around the tree bases will kill most trees even with little to no crown scorch.

Delayed Tree Mortality in Western Conifers (05-2-1-105)

Table 10. Recommended management guidelines for using Ryan (1982) bark char codes as a surrogate for direct cambium sampling after fire. Species/code combinations not listed are not clearly associated with either live or dead cambium and should be sampled directly to determine injury.

Species	Bark Char Code	Probable Cambium Status
Lodgepole pine Whitebark pine Western white pine Western red cedar Engelmann spruce Western hemlock Subalpine fir	Light, moderate, or deep	Dead
White fir Incense cedar Ponderosa pine Jeffrey pine Douglas-fir Sugar pine	Light	Alive
White fir Incense cedar Ponderosa pine (wildfire) Jeffrey pine (wildfire) Douglas-fir (wildfire) Sugar pine	Deep	Dead
Ponderosa pine Jeffrey pine (prescribed fire) ¹	Moderate or deep	Alive
Douglas-fir (prescribed fire) ¹	Moderate	Alive
Western larch	Light, moderate, or deep	Alive

¹If pre-fire duff mound depths are high and most of duff is consumed in fire, then the probability of cambium mortality is higher.

MANAGEMENT IMPLICATIONS

- When using the Ryan and Amman model (FOFEM prior to version 5.7), managers can expect less mortality than the model predicts when burning in incense cedar, western larch, and red fir forests.
- When using the Ryan and Amman model (FOFEM prior to version 5.7), managers can expect higher mortality than the model predicts when planning prescribed burns in stands of western hemlock if tree boles are charred.
- Moderate bark char was not clearly associated with either live or dead cambium for thicker bark species (white fir, incense cedar, ponderosa pine, Jeffrey pine, Douglas-fir, and sugar pine). Cambium should be sampled directly to determine injury when bark char is moderate for these species (see Table 10 for additional recommendations on bark char use).
- Tree injury from direct sampling of the cambium does not contribute to additional post-fire ponderosa pine tree mortality.
- FOFEM 5.7 offers improved accuracy in predicting 3-year post-fire tree mortality for white fir, subalpine fir, red fir, incense cedar, western larch, lodgepole pine, whitebark pine, Engelmann spruce, sugar pine, Douglas-fir, ponderosa pine, and Jeffrey pine.
- FOFEM 5.7 now allows users to directly enter crown scorch, cambium injury, and beetle attacks to improve model accuracy.

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Delayed Tree Mortality in Western Conifers (05-2-1-105)

Appendix 1. Crosswalk between proposed and delivered outreach activities for JFSP #05-2-1-05.

Proposed	Delivered	Status
Publication	Hood, S. M.; Bentz, B.; Gibson, K.; Ryan, K. C.; DeNitto, G. 2007. Assessing post-fire Douglas-fir mortality and Douglas-fir beetle attacks in the northern Rocky Mountains. Gen. Tech. Rep. RMRS-GTR-199, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO. 31 p.	completed
Publication	Hood, S. M.; McHugh, C.; Ryan, K. C.; Reinhardt, E.; Smith, S. L. 2007. Evaluation of a post-fire tree mortality model for western US conifers. International Journal of Wildland Fire. 16: 679-689.	completed
Publication	Hood, S. M.; Ryan, K. C.; Smith, S. L.; Cluck, D. In Press. Using bark char codes to predict cambium status after fire. Fire Ecology.	In Press
Publication	Delayed tree mortality following fire in western conifers.	In prep. Planned for submission in 2008
Website	http://www.firelab.org/index.php?option=com_content&task=view&id=690&Itemid=350	Ongoing
Software	FOFEM 5.7. Replaces mortality model for species included in the analysis and expands the mortality options to include variables known post-fire such as cambium injury and beetle attacks. Available for download at: www.fire.org	completed
Software	BehavePlus 4.5. Replaces mortality model for species included in analysis using the 'pre-fire' mortality equations	Planned release within 1 year
Presentation	"Delayed tree mortality following fire in western conifers." Presentation to be given at the IAWF conference in Yellowstone.	Planned for Sept. 2008
Presentation	"Fire-Injury" Region 5 Forest Insect and Disease Training, San Bernardino NF. 4/2008.	Completed
Presentation	"Fire-Injury" Region 5 Forest Insect and Disease Training, Lassen NF. 6/2008	Completed
Presentation	"Delayed Conifer Mortality Following Fire in California" The Association for Fire Ecology, Regional Conference, Tucson, AZ. 1/2008	Completed
Presentation	"Understanding the Smith and Cluck 2007 fire salvage marking guidelines." Audience: R5 RO appeals/FOIA team, Vallejo, CA. 11/2007	Completed
Presentation	"Update on the development and use of fire salvage marking guidelines in R5." R5 Silviculturists Meeting, Regional Office, Vallejo, CA. 7/17/07	Completed
Presentation	"Delayed Conifer Mortality Following Fire in California"	Completed

Delayed Tree Mortality in Western Conifers (05-2-1-105)

Proposed	Delivered	Status
	Western Forest Insect Work Conference, Boise, ID. 4/2007	
Presentation	"Delayed Conifer Mortality Following Fire in California" SAF Chapter Meeting, Placerville, CA. 8/2007	Completed
Presentation	"Predicting Post-Fire Douglas-fir Beetle Attacks and Tree Mortality." Delayed tree mortality workshop, Sisters, OR, July 25-26, 2006	Completed
Presentation	"Fire salvage marking guidelines in CA - where we were, where we are and where we're going." Forest Health Protection Fair - San Bernardino NF - Audience was 4 National Forests in So Cal, reps. from CAL FIRE and members of the public. 9/2006	Completed
Presentation	"Delayed Conifer Mortality Following Fire in California" California Forest Pest Council, Woodland, CA. 11/2006	Completed
Presentation	"Delayed Conifer Mortality Following Fire in California" Lassen/Plumas County Forest Forum, Westwood, CA. 10/2006	Completed
Poster	Delayed tree mortality following fire in western conifers. Poster for the JFSP board visit. Missoula, MT Sept. 14, 2006.	Completed
Workshops/Personal communications with managers	Trained crew in NE Utah about how to assess post-fire tree injuries. 6/4-6/08	Completed
Workshops/Personal communications with managers	Moonlight Fire Salvage Project: Eagle Lake RD, Lassen NF. Meeting 2008	Completed
Workshops/Personal communications with managers	Moonlight Fire Salvage Projects (3 projects): Mt. Hough RD, Plumas NF. Meeting 2008	Completed
Workshops/Personal communications with managers	Moonlight Fire Salvage Projects (3 projects): Mt. Hough RD, Plumas NF, 2007	Completed
Workshops/Personal communications with managers	Antelope Fire Salvage Project: Mt. Hough and Beckwourth RD, Plumas NF, 2007	Completed
Workshops/Personal communications with managers	Bear Fire Salvage Project: McCloud RD, Shasta-Trinity NF, 2007	Completed
Workshops/Personal communications with managers	Hungry Fire Salvage Project: Mt. Hough RD, Plumas NF, 2007	Completed
Workshops/Personal communications with managers	Day Fire, Los Padres NF: Deputy Regional Forester, RO Appeals team and LP NF reps	Completed
Workshops/Personal communications	Boulder Fire Salvage Project: Mt. Hough RD, Plumas NF, 2006	Completed

Proposed	Delivered	Status
with managers		
Workshops/Personal communications with managers	Creek Fire Salvage Project: Private lands, Beaty and Associates, Susanville, CA, 2006	Completed

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