USING BARK CHAR CODES TO PREDICT POST-FIRE CAMBIUM MORTALITY

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ABSTRACT

Cambium injury is an important factor in post-fire tree survival. Measurements that quantify the degree of bark charring on tree stems after fire are often used as surrogates for direct cambium injury because they are relatively easy to assign and are non-destructive. However, bark char codes based on these measurements have been inadequately tested to determine how well they relate to live or dead cambium. Methods for assessing cambium injury through direct sampling have also been questioned as a potential factor for increasing tree mortality. In this study we used data collected from 11 wildfires and 6 prescribed fires in California, Idaho, Montana, and Wyoming to develop a relationship between bark char codes and cambium status for 14 coniferous species. Burned trees were assessed at groundline for bark char severity on each bole quadrant and then sampled at the center of each quadrant to determine cambium status (live or dead). We found that the moderate and deep bark char codes were strongly associated with dead cambium for thin-bark species: lodgepole pine (*Pinus contorta*), whitebark pine (*P. albicaulis*), western white pine (*P. monticola*), western redcedar (*Thuja plicata*), Engelmann spruce (*Picea engelmannii*), western hemlock (*Tsuga heterophylla*), and subalpine fir (*Abies lasiocarpa*). However, bark char codes were somewhat inaccurate in predicting cambium status of the thicker-bark species of white fir (*Abies concolor*), incense cedar (*Calocedrus decurrens*), ponderosa pine (*Pinus ponderosa*), Jeffrey pine (*P. jeffreyi*), Douglas-fir (*Pseudotsuga menziesii*), western larch (*Larix occidentalis*), and sugar pine (*P. lambertiana*). We also evaluated the effect of direct cambium sampling on ponderosa pine tree mortality in eastern Montana. Mortality rates were equivalent for eastern Montana ponderosa pines with and without cambium sampling. Our results support using bark char codes as surrogates for cambium sampling in tree species with thin bark, but bark char codes for thick-bark species, especially the moderate char code, are often not accurate fire-injury variables, as they do not correlate well with cambium status.

Keywords: bark char, basal injury, cambium, tree mortality

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INTRODUCTION

A tree's ability to survive after fire largely depends on the level of injury sustained to the crown, bole, and roots (Ryan 1982, Filip *et al.* 2007). The level of fire-caused crown injury is relatively easy to determine by direct examination, while injuries to the bole and roots are much more difficult to quantify without destructive sampling (Ryan 1982). As a result, surrogate measures have been developed to assess the degree of post-fire cambium injury and, to a lesser extent, root injury. However, relationships between these easily-observed surrogates and actual injury remain speculative (Fowler and Sieg 2004).

A tree's susceptibility to cambium injury from heating is primarily influenced by heat duration and bark thickness (Ryan and Frandsen 1991), and secondarily by tree species morphology, due to varying bark thermal properties (van Mantgem and Schwartz 2003). The rate of cambium death also varies by species and season (Dickinson and Johnson 2004). The time required to cause cambium death from heat is proportional to the square of bark thickness (Martin 1963, Reifsnyder *et al.* 1967, Peterson and Ryan 1986, Rego and Rigolot 1990).

Various methods have been developed to estimate cambium injury from heating because direct sampling is invasive and time consuming, and because injury is difficult to predict from models (see Fowler and Sieg 2004 for a review). Jones *et al.* (2004) recently developed a stem heating model to predict cambium death from surface fires. However, the model requires duration of the heat pulse as an input, which is usually unknown. In addition, this model is still in the testing and developmental stages for many tree species. Other methods include estimating the percentage of the tree bole that was charred (Peterson and Arbaugh 1986, Beverly and Martell 2003, Keyser *et al.* 2006, Sieg *et al.* 2006), assessing the degree of charring around the tree bole (Ryan 1982, Harrington and Hawksworth 1990, McHugh and Kolb 2003, Thies *et al.* 2006), and assessing height of stem bark char (Regelbrugge and Conard 1993). Others have directly sampled a portion of the cambium (Mann and Gunter 1960, Hare 1965, Ryan *et al.* 1988, Peterson and Arbaugh 1989, Ryan 1990, Ryan and Steele 1990, Finney 1999, Ryan and Amman 1996, Hood and Bentz 2007, Hood *et al.* 2007), but this method still does not measure the total amount of cambium injury.

Ryan (1982) first developed categories (codes) of bark char severity to indicate stem injury resulting from fire, but he cautioned that these codes should only be used in conjunction with direct cambium sampling. However, these codes and others 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). While these studies reported that various measures of bark char were statistically significant variables for predicting delayed tree mortality, it is unknown how well bark char actually relates to cambium injury for many species (Fowler and Sieg 2004).

Few studies to date have tested the relationship between the Ryan (1982) codes and cambium status (Breece 2006, Hood and Bentz 2007, Hood *et al.* 2007). All reported an increase in cambium injury with increasing char severity, but noted that moderate charring is not clearly associated with either live or dead cambium. Our study is the first to examine the relationship of bark char to cambium injury for several species over a range of diameters at breast height (dbh) and fire types.

Bark char has been used as a surrogate for cambium injury sampling because it is readily observed and non-destructive (Beverly and

Martell 2003*,* Thies *et al.* 2006). However, there is no empirical evidence that cambium sampling increases the probability of tree mortality. Van Mantgem and Stephenson (2004) found no difference in mortality between cored and uncored trees 12 years after they had been cored to determine age and growth rates. More injurious sampling of trees, however, may affect mortality rates. Heyerdahl and McKay (2001), for example, removed tree sections that averaged 8 % of the cross-sectional area and 7 cm thick to assess fire history and observed that mortality among the sectioned trees was low (8 %), but significantly higher than mortality for unsectioned trees.

In this study we used data collected from multiple wild and prescribed fires in the western US to: 1) assess the relationship between the Ryan (1982) bark char codes and cambium status (live/dead) for 14 conifer species over a range of tree sizes and fire types (prescribed fire and wildfire) and 2) evaluate the effect of direct cambium sampling on tree mortality rate. Combining fires allowed for a rigorous assessment of the validity of using bark char codes as a surrogate measure of cambium injury after fire. Species tested were lodgepole pine (*Pinus contorta*), whitebark pine (*P. albicaulis*), western white pine (*P. monticola*), western redcedar (*Thuja plicata*), Engelmann spruce (*Picea engelmannii*), western hemlock (*Tsuga heterophylla*), subalpine fir (*Abies lasiocarpa*), white fir (*A. concolor*)*,* incense cedar (*Calocedrus decurrens*), ponderosa pine (*P. ponderosa*), Jeffrey pine (*P. jeffreyi*), Douglas-fir (*Pseudotsuga menziesii*), western larch (*Larix occidentalis*), and sugar pine (*P. lambertiana*).

METHODS

Fire Descriptions

We collected fire-injury data from mixed-severity burned areas in 11 wildfires and 6 prescribed fires in California, Idaho, Montana, and Wyoming within one year of the fires (Table 1). All fires except the Power, Oops, Canyon Creek, Slowey, Air Patrol, Brewer, and Early Bird fires (Table 2) have been reported elsewhere and will not be described here.

The Power Fire began approximately 44 km east of Pioneer, California, in Amador County, and burned areas of private timberlands and the Eldorado National Forest, including a small portion of the Mokelumne Wilderness. It was primarily a moderate surface fire with some pockets of individual tree torching. Daytime temperatures at the nearby Beaver weather station were 24 ˚C to 25 ˚C with 10 hr fuel moisture between 6 % to 8 %.

The Canyon Creek Fire was ignited by lightning in Montana near the end of an unusually hot and dry fire season. The study site was near the North Fork of the Blackfoot River in an area burned by intense surface fire, essentially consuming all duff and completely scorching and killing Douglas-fir and lodgepole pine in the stand. Daytime temperatures at the nearby Lincoln ranger station were 31 ˚C to 34 ˚C with 10 hr fuel moisture between 3 % to 4 %.

The Early Bird, Air Patrol, and Brewer Fires in eastern Montana were ignited by lightning. Active surface fires burned the stands in the three study areas. The Early Bird Fire was east of Lame Deer, Montana, on the Northern Cheyenne Indian Reservation. Daytime temperatures were around 38 ˚C. The Air Patrol Fire was also on the Northern Cheyenne Indian Reservation approximately 16 km southeast of Lame Deer, Montana. Daytime temperatures were 30 ˚C to 36 ˚C with fine fuel moisture between 3 % to 5 %. The Brewer Fire began in the Long Pines Range of the Custer National Forest between Ekalaka, Montana, and Camp Crook, South Dakota. Daytime temperatures were between 37 ˚C to 44 ˚C accompanied by single digit fine fuel moisture.

The Slowey Fire was a prescribed burn set to reduce fuel hazards and restore wildlife

Table 1. Trees sampled for each fire included in the data analysis. Additional fire information is described in the noted references.

Fire name	State	Fire type	Fire ignition date	Species sampled[a]	n	Additional reference
Cone	California	Wild	9/2002	JP, PP	856	Hood *et al.* (2007)
McNally	California	Wild	7/2002	WF, IC, JP, PP	3268	Hood *et al.* (2007)
Power	California	Wild	10/2004	SP	707	D. Cluck, unpublished data[b]
Oops	Idaho	Wild	10/1982	RC, WWP, WH, DF	151	K. Ryan, unpublished data[b]
Danskin	Idaho	Prescribed	5/2002	PP, DF	385	Dumm (2003)
Lower Priest	Idaho	Prescribed	6/1984	RC, WWP, ES, WH, DF, WL	306	Ryan and Steele (1990)
Upper Priest	Idaho	Prescribed	9/1983	RC, WWP, ES, WH, DF, WL	180	Ryan and Steele (1990)
Air Patrol	Montana	Wild	8/1988	PP	86	Finney 1999; K. Ryan, unpublished data[b]
Brewer	Montana	Wild	6/1988	PP	104	Finney 1999; K. Ryan, unpublished data[b]
Early Bird	Montana	Wild	6/1988	PP	114	Finney 1999; K. Ryan, unpublished data[b]
Canyon Creek	Montana	Wild	9/1988	WL	10	K. Ryan, unpublished data[b]
Mussigbrod	Montana	Wild	8/2000	LP, WP, ES, SF, DF	878	Hood and Bentz (2007)
Moose	Montana	Wild	8/2001	LP, WP, ES, SF, PP, DF, WL	909	Hood and Bentz (2007)
Lubrecht	Montana	Prescribed	4/2002	LP, PP, DF, WL	1581	Gundale *et al.* (2005)
Tenderfoot	Montana	Prescribed	9/2002	LP, WP, ES, SF	1538	Hardy *et al.* (2006)
Slowey	Montana	Prescribed	3/1992	PP, DF	198	K. Ryan, unpublished data[b]
Green Knoll	Wyoming	Wild	8/2001	LP, WP, ES, SF, DF	214	Hood and Bentz (2007)

[a] Species: LP – lodgepole pine, WP – whitebark pine, WWP – western white pine, RC – western redcedar, ES – Engelmann spruce, 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.
[b] See Table 2 and text for additional information about fire.

habitat in ponderosa pine on the Lolo National Forest, 12 km northwest of Superior, Montana. A helicopter ignited the unit by using plastic spherical ignition devices. Conditions at the time of the burn were sunny, temperatures were 10 ˚C to 18 ˚C, relative humidity was 34 % to 50 %, and surface litter and upper duff moisture contents were 14 % and 12 %, respectively. Lower duff and mineral soil were moist. The resultant fire was an actively spreading surface fire with a light depth of burn (Ryan 2002).

The Oops Fire was a small wildfire that escaped from a nearby site preparation fire and burned a mixed conifer forest on the Priest River

Table 2. General location and physical features of sampled trees in fires that have not been previously described in literature.

Fire description	Fire name						
	Power	**Canyon Creek**	**Early Bird**	**Air Patrol**	**Brewer**	**Slowey**	**Oops**
County, state	Amador, CA	Powell, MT	Rosebud, MT	Rosebud, MT	Carter, MT	Mineral, MT	Bonner, ID
UTM coordinates (NAD27)	239416E 4265749N	350894E 5218593N	380911E 5055714N	378878E 5046561N	567336E 5050241N	650524E 5235366N	517705E 5356112N
UTM Zone	10	12	13	13	13	11	11
Fire size (ha)	6880	98 428	8400	1640	23 600	512	1.5
Dominant forest type[a]	Sierra Nevada mixed conifer (SAF 243)	Western larch (SAF 212)	Interior ponderosa pine (SAF 237)	Interior ponderosa pine (SAF 237)	Interior ponderosa pine (SAF 237)	Interior and Pacific ponderosa pine (SAF 237 and 245)	Western hemlock (SAF 224)
Aspect	South	East	South-southeast	Southwest	Northwest	South-southeast	Southwest
Elevation (m)	1500-1850	1420-1500	1316	1231	1185-1282	997-1230	1524

[a] Eyre 1980

Experimental Forest in the Selkirk Mountains on the Idaho Panhandle National Forest, Idaho. The site was a mixed conifer forest dominated by western hemlock, with a heavy coarse woody debris component of rust-killed western white pine. The fire burned around 1.5 ha at night in mid-October 1983. No significant rain had fallen for a month, and fuels were very dry for that time of year. The fire consumed all of the duff and resulted in extensive basal injury. The burn was classified as an active surface, moderate depth of burn fire (Ryan 2002).

Field Sampling

We sampled randomly selected trees to represent a wide range of fire injuries and diameters (Table 3). We selected sample locations that burned under mixed-severity conditions, with either no plans for post-fire salvage or where only dead trees (i.e., no green needles) would be cut. Trees sampled from non-California fires were clustered into randomly chosen plots. For the California fires, individual fire-injured trees were selected over a range of fire severity levels in an attempt to fill a matrix of injury levels, size classes, and species. At each tree, we measured dbh at 1.4 m above the ground on the uphill side of the tree and recorded tree species. No distinction was made between ponderosa pine and Jeffrey pine for the McNally and Cone Fires due to similar morphological characteristics, so we will only refer to ponderosa pine hereafter. We visually divided the base of each tree into quadrants and assessed bark char and cambium condition in each quadrant. 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 California fire sites, quadrants were oriented in the cardinal directions. We assigned each quadrant as unburned, light, moderate, or deep bark char (Ryan 1982) (see Table 4 for descriptions) based on its average level of charring near the groundline (non-California

Table 3. Tree characteristics of species sampled in study and included in data analysis. Species are arranged in ascending order of bark thickness using bark thickness equations in FFE-FVS.

Species	n[a]	Mean dbh (cm)	Range	Distribution of bark char samples (% of total)				Cambium samples (%)	
				Unburned	Light	Moderate	Deep	Live	Dead
Lodgepole pine	1866	20.7	10.2-54.9	54	10	25	11	60	40
Whitebark pine	125	24.0	12.4-100.8	49	13	29	9	54	46
Western white pine	108	43.1	19.1-84.1	28	21	43	8	48	52
Western redcedar	44	28.6	17.8-52.8	33	10	37	20	39	61
Engelmann spruce	239	32.8	10.2-85.1	24	9	31	36	37	63
Western hemlock	226	33.0	13.5-69.6	23	18	57	2	35	65
Subalpine fir	475	19.7	10.2-75.2	41	12	27	19	44	56
White fir	1894	60.2	25.4-152.7	6	8	59	27	48	52
Incense cedar	790	51.6	25.4-166.4	4	10	59	26	47	53
Ponderosa pine	4084	47.9	10.2-178.1	6	12	70	12	62	38
Douglas-fir	1464	35.5	10.2-126.7	26	8	59	7	78	22
Western larch	391	39.2	10.2-98.8	16	9	70	5	86	14
Sugar pine	707	73.8	25.7-188.0	5	13	43	38	45	55

[a] Four cambium samples were collected per tree.

fires) or within 0.3 m (1 ft) of groundline (California fires). In the center of each quadrant, we directly sampled cambium at groundline by removing a small portion of the bark to reveal the cambium. We visually assessed each direct sample for cambium status as described in Ryan (1982) for all fires except those in eastern Montana. These samples were treated with a vital stain (Ryan 1982) to determine cambium status. Live cambium is light in color, moist, and pliable. Dead cambium is darker in color and either resinous or hardened (Ryan 1982).

Ponderosa pine trees from the Air Patrol, Brewer, and Early Bird Fires in eastern Montana were part of a larger post-fire tree mortality study. We randomly selected approximately 20 % of the study trees 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. We did not sample cambium on the other trees. We also assessed percent crown volume scorched for each tree. We revisited all trees in this study annually for four years post-fire to assess tree mortality.

Data Analysis

We used logistic regression to evaluate the relationship between direct measurement of cambium status and external bole char ratings for each species. This included all visually

Table 4. Bark char codes and description of bark appearance (adapted from Ryan 1982).

Bark char code	Bark appearance
Unburned	No char
Light	Evidence of light scorching; can still identify species based on bark characteristics; bark is not completely blackened; edges of bark plates charred
Moderate	Bark is uniformly black except possibly some inner fissures; species bark characteristics still discernable
Deep	Bark has been burned into, but not necessarily to the wood; outer bark species characteristics are lost

assessed and stained cambium samples. Because four samples were taken per tree, we used estimates from generalized estimating equations to account for within tree correlation (Liang and Zeger 1986). We only included trees that were alive at the time of initial assessment in the analysis because we assumed cambium was dead for dead trees. We included tree dbh in the model to evaluate whether the predictive accuracy of the bole char codes varied with tree size. We evaluated fire type (wild or prescribed) for model inclusion for those species where sufficient data existed: lodgepole pine, Engelmann spruce, subalpine fir, ponderosa pine, and Douglas-fir. We retained all variables with p-values <0.05 in the full model. If dbh was significant in the model, we developed a second model without dbh in order to compare the added value of using dbh to predict cambium status from bark char. We performed all analyses in SAS (PROC GENMOD, SAS Institute, v. 9.1) using the following model form:

$$P_{DeadCambium} = 1/[1 + \exp(-(B_0 + B_1 X_1 + \ldots B_k X_k))]$$

where $P_{DeadCambium}$ is the probability of dead cambium, B_0, B_1, and B_k are regression coefficients, and X_1 and X_k are independent variables (bark char code, dbh, and fire type).

All whitebark pine, western white pine, and western hemlock quadrants with deep bark char had dead cambium. Logistic regression models cannot converge when 100 % of categorical variable samples have the same response (Hosmer and Lemeshow 2000). Therefore, we did not include quadrants with deep char when developing the equations for whitebark pine, western white pine, and western hemlock.

All tables and figures list species in ascending order of bark thickness based on the bark thickness equations in the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) (Reinhardt and Crookston 2003). In this model, western white pine and western redcedar have the same bark thickness, as do ponderosa pine, Douglas-fir, and western larch. We did not measure bark thickness directly because this variable would be impractical for managers to measure due to the time required. Also, sampling occurred post-fire when a portion of bark on many trees had burned away and pre-fire bark thickness could not be determined.

We tested 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 using a general linear mixed model (Littell *et al.* 1996). We included fire name and plot number within fire as random effects.

RESULTS

For all species, the percentage of quadrants with dead cambium increased with increasing bark char severity (Figure 1), and bark char codes were significantly correlated with cambium status (Table 5). Over 80 % 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 redcedar, Engelmann spruce, western hemlock, and subalpine fir

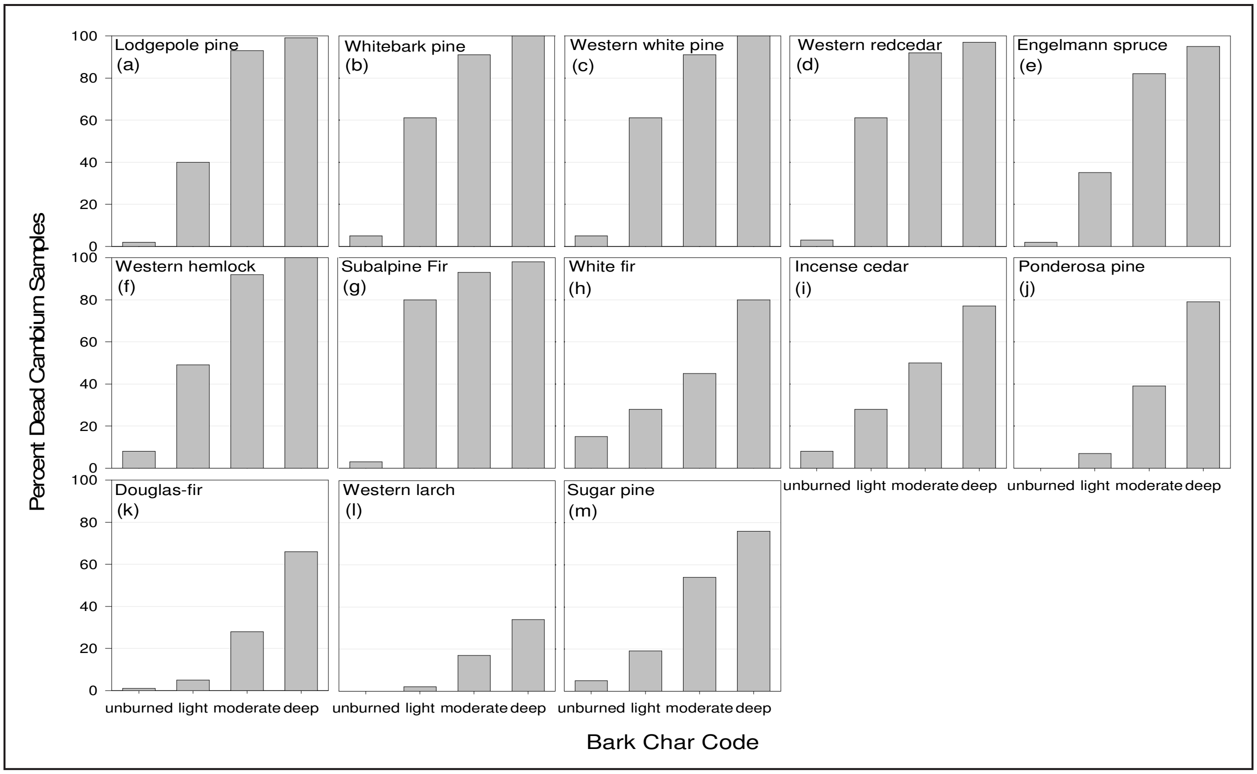

Figure 1. Percent of bark char quadrants with dead cambium by bark char code. Species are arranged in ascending order of bark thickness using bark thickness equations in FFE-FVS.

(Figure 1a-g). Even light bark char indicated dead cambium for the majority of these thin-barked species. In contrast, cambium was dead for only 17 % to 54 % of the samples with moderate charring on species with thicker bark: white fir, incense cedar, ponderosa pine, Douglas-fir, western larch, and sugar pine (Figure 1h-m). Except for western larch, deep char on thick-barked species usually indicated dead cambium as well. 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 redcedar, Engelmann spruce, western hemlock, and subalpine fir—all species with relatively thin bark (Table 6).

A small percentage of unburned quadrants had dead cambium for all species. These quadrants either were dead before the fire, or a small portion of the quadrant may have been charred and that was where the cambium happened to be sampled, or we sampled uncharred bark directly adjacent to charred bark. The bark char codes were assigned based on the average level of charring in each quadrant and the cambium was only sampled at the center of each quadrant. Therefore, the codes did not always match where the cambium was sampled.

Diameter 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 5). For species where dbh was significant, the predicted probability of dead cambium decreased as dbh increased except for ponderosa pine, where the relationship was reversed (Figures 2 and 3). The predicted probability of dead cambium changed less than 20 % across the range of diameters for all species except western white pine, western hemlock, and western larch. The decrease in the predicted probability of dead cambium

Table 5. 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 using bark thickness equations in FFE-FVS. N.S. indicates regression coefficient is not significant; all other coefficients are significant (p-value < 0.05). Empirical standard error estimates are in parentheses.

Species	Regression coefficients					
	Unburned	**Light**	**Moderate**	**Deep**	**dbh (cm)**	**Fire type[b]**
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[a]	-2.5654 (0.36)	2.8636 (0.49)	4.1890 (0.50)	N/A	N.S.	---
Western white pine[a]	-1.6112 (0.70)	2.4877 (0.53)	4.2776 (0.50)	N/A	-0.0299 (0.12)	---
Western redcedar	-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[a]	0.2731 (0.50)	2.1288 (0.33)	4.2023 (0.34)	N/A	-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.	---
Ponderosa pine	-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)	---

[a] N/A: not applicable. All deep bark char samples had dead cambium and therefore could not be included in the regression analysis.
[b] Class levels for fire type: prescribed fire = 1; wildfire = -1. Dash (---) indicates data were insufficient to include fire type in model.

was particularly sharp for western larch as dbh increased, with little difference between bark codes for trees greater than 55 cm dbh (Figure 2e).

Fire type (wild vs. prescribed) was significant in predicting lodgepole pine, subalpine fir, ponderosa pine, and Douglas-fir dead cambium (Table 5). It was not significant for Engelmann spruce. Predicted probability of dead cambium by bark char code was lower for prescribed fires than wildfires (Table 6, Figure 3). The predicted probability of dead ponderosa pine cambium from prescribed fires was low for all char codes and tree sizes (Figure 3).

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, $P = 0.7667$). The two groups did not have significantly different crown scorch

Table 6. 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 using bark thickness equations in FFE-FVS.

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[a]	0.07	0.57	0.84	1.00
Western white pine[a]	0.06	0.40	0.79	1.00
Western redcedar	0.05	0.55	0.92	0.97
Engelmann spruce	0.03	0.40	0.81	0.94
Western hemlock[a]	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
Ponderosa pine				
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

[a] All deep bark char samples had dead cambium.

(54 % scorch for both groups, DF = 1743, *P* = 0.8078) or dbh (29.2 cm for cambium sampled trees and 28.2 cm for trees without cambium sampling, DF = 1743, *P* = 0.0646).

DISCUSSION

Many studies have found various measures of bark char to significantly predict delayed tree mortality after fire (see Fowler and Sieg 2004). This study shows that bark char severity is related to cambium death. The probability of dead cambium increased with increasing bark char severity for all species tested, but moderate char was not clearly associated with either live or dead cambium for thicker-bark species (Figure 1). Breece (2006) found an ambiguous relationship between Ryan's (1982) bark char codes, actual cambium injury, and ponderosa pine tree mortality and reported that only 42 % of cambium samples with moderate char were dead. Breece *et al.* (2008) concluded that the codes should not be used for post-fire ponderosa pine mortality models. Moderate char was the most commonly assigned category for most of the species included in this study. Therefore, the use of moderate bark char as a surrogate for cambium status on thick-bark species could lead to large errors when estimating post-fire tree injury, thus limiting the utility of bark char codes.

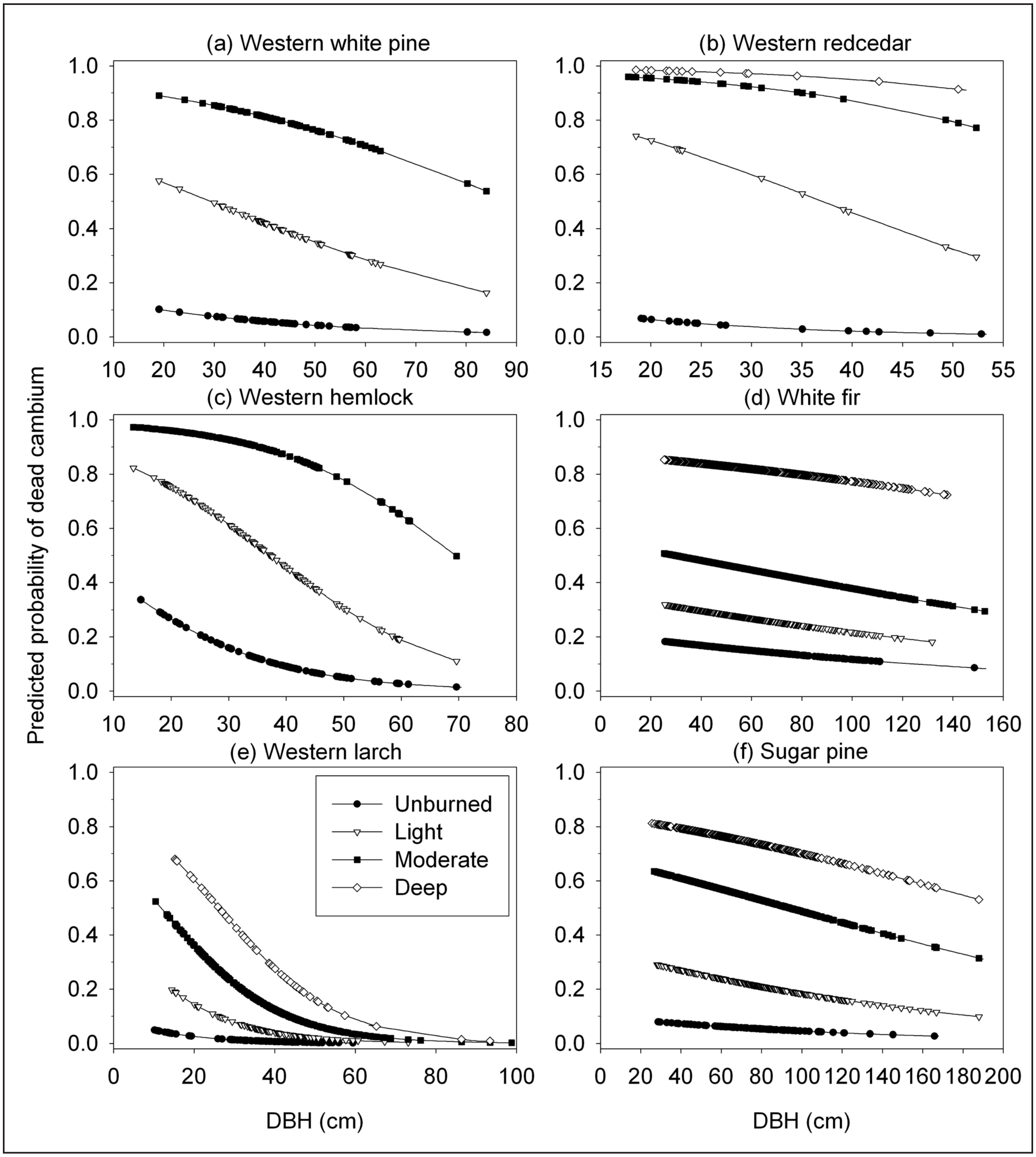

Figure 2. Predicted probability of dead cambium by bark char code for species where dbh is significant in the model. All western white pine and western hemlock quadrants with deep bark char were dead and could not be included in the regression analysis. Lodgepole pine, ponderosa pine, and Douglas-fir are shown in Figure 3 because fire type is significant in the model. Species are arranged in ascending order of bark thickness using bark thickness equations in FFE-FVS.

Given the same dbh and bark char code, wildfires resulted in higher rates of dead cambium compared to those in prescribed fires for lodgepole pine, subalpine fir, ponderosa pine, and Douglas-fir. However, the actual differences in probabilities between wildfires and prescribed fires were only large for ponderosa pine (Figure 3). The reason for

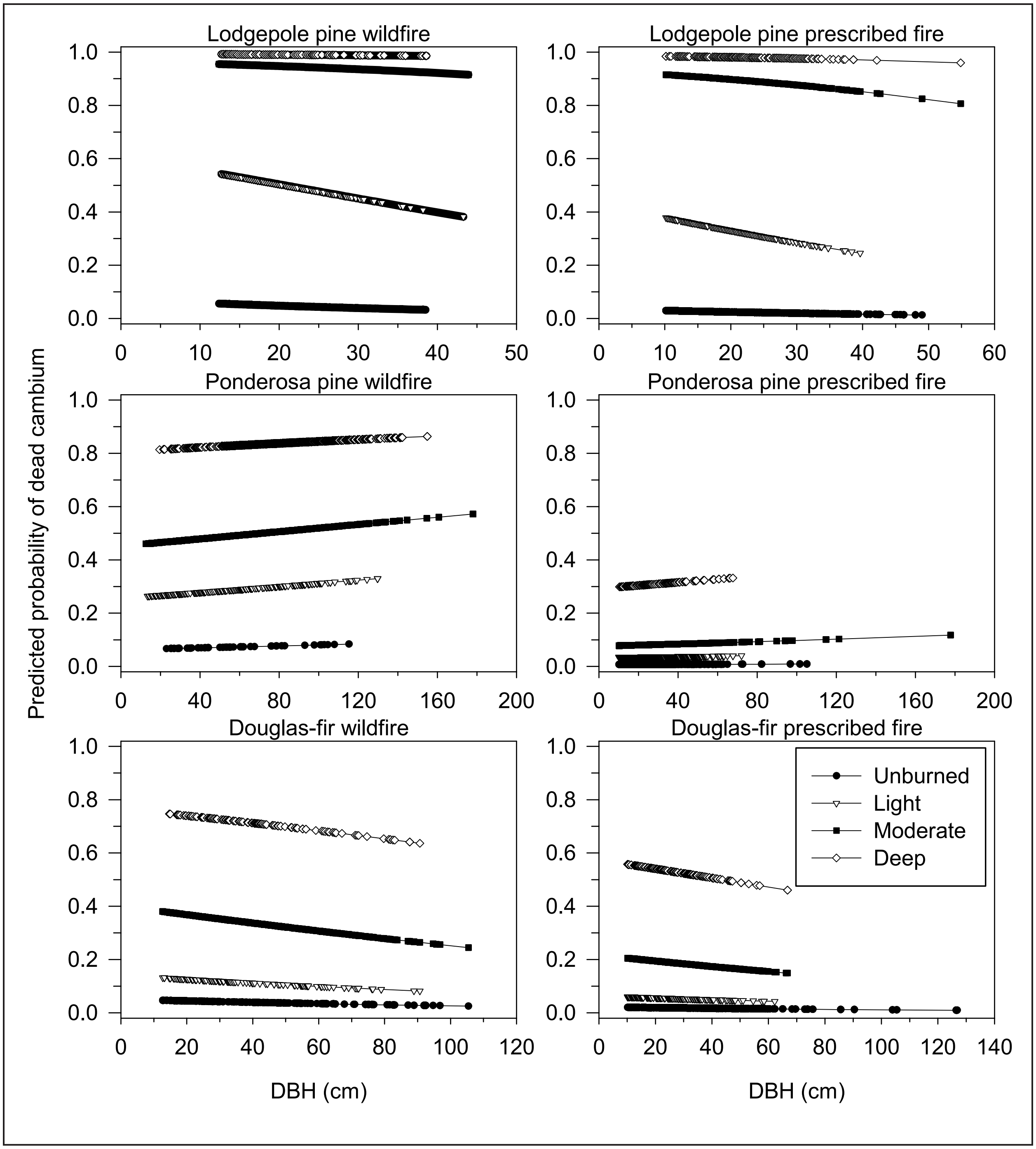

Figure 3. Predicted probability of dead cambium by bark char code and fire type for species where dbh and fire type are significant in the model. Species are arranged in ascending order of bark thickness using bark thickness equations in FFE-FVS.

the higher proportions of dead cambium in wildfires is likely due to higher levels of fuel and duff consumption caused by burning under drier, more extreme weather conditions than those of prescribed fires. In addition, because duration of heating is longer in areas of deep duff combustion, greater charring and cambium injury would be expected (Ryan and Frandsen

1991). The Slowey, Danskin, and Lubrecht Fires—the prescribed fires from which ponderosa pine data were collected—were early season, low intensity surface fires with modest amounts of duff at the tree bases (K.C. Ryan and S.M. Hood, personal observation). While the pre-wildfire duff depths are unknown, differences in basal duff depths may be another reason why predicted probability of dead cambium was lower for prescribed fires than wildfires. In contrast, Ryan and Frandsen (1991) found that even in a relatively moist summer, extensive basal injury occurred in a late August prescribed burn which consumed deep duff mounds around large diameter, old ponderosa pine in Glacier National Park. Prescribed fires in areas with deep, dry duff mounds will likely result in cambium injury similar to that observed in our wildfires.

Although dbh was a significant explanatory variable for cambium mortality in many species, predicted probability of dead cambium changed little across the range of diameters observed except for western hemlock and western larch. This suggests that, for management purposes, the models that exclude dbh are probably sufficient for all examined species except western larch and western hemlock (Table 6). Keyser *et al.* (2006) reported that bark char measurements greatly improved prediction of ponderosa pine tree mortality for trees smaller than 40 cm dbh, but had a reduced value for predicting mortality of trees larger than 40 cm dbh. Bark thickness generally increases with increasing dbh for a given species. Therefore, equivalent bark char ratings on smaller diameter, and thus thinner-barked, trees should be associated with higher levels of cambium injury than in larger diameter, thicker-barked trees.

The ponderosa pines in our study were much larger than those in Keyser *et al.* (2006), and ponderosa pine was the only species in which predicted mortality of cambium increased as dbh increased. Ryan and Frandsen (1991) found a similar relationship for ponderosa pines in a prescribed fire in northwestern Montana. Other studies have found higher post-fire mortality rates for larger and smaller diameter trees than mid-diameter trees (McHugh and Kolb 2003, Hood *et al.* 2007) and attributed the relationship to higher levels of cambium injury resulting from consumption of deep duff mounds, which are common at the base of larger diameter trees. Complete consumption of deep duff at the bases of large diameter trees may be the reason for increased cambium injury in these large trees (Ryan and Frandsen 1991, Swezy and Agee 1991, Kaufmann and Covington 2001).

Sample size varied greatly between species (Table 3), and it is difficult to control for these differences (Rudy King, USDA Forest Service, personal communication). Models developed from small sample sizes may have less precision than those developed from larger samples, and it may only be possible to detect strong associations between the independent and dependent variables with small samples (Whittemore 1981). The significant relationship of bark char codes to cambium status indicate that it is a strong association for all species tested here. The differences in significance for dbh and fire type among species may be partially explained by the variation in sample sizes and indicate that these variables have a weaker association with cambium status than bark char codes.

CONCLUSIONS

Bark char codes are a good indicator of cambium status for the thin-bark species included in this analysis and can be used to save sampling time for many species when determining post-fire tree injury (Table 7). However, moderate bark char was not strongly associated with dead cambium for thicker-bark species. For these species (white fir, incense cedar, ponderosa pine, Douglas-fir, and sugar pine), cambium should be sampled directly to

Table 7. 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 redcedar Engelmann spruce Subalpine fir	Light, moderate, or deep	Dead
White fir Incense cedar Ponderosa pine Douglas-fir Sugar pine	Light	Alive
White fir Incense cedar Ponderosa pine (wildfire) Douglas-fir (wildfire) Sugar pine	Deep	Dead
Ponderosa pine (prescribed fire)[a]	Moderate or deep	Alive
Douglas-fir (prescribed fire)[a]	Moderate	Alive
Western larch	Light, moderate, or deep	Alive

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

determine injury when bark char is moderate. Western larch cambium is most likely alive regardless of the degree of bark charring.

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 using an increment borer does not contribute to additional post-fire ponderosa pine tree mortality. We expect a similar response from other tree species or from sampling with a hatchet due to similar wound response mechanisms among species and wound sizes (Shigo and Marx 1977). This research indicates that direct cambium sampling is a better variable than bark char codes for use in post-fire tree injury assessments for species with thick bark and that direct sampling can be performed without causing additional tree mortality.

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