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Post-fire survival and flushing in three Sierra Nevada conifers with high initial crown scorch

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Abstract. With growing debate over the impacts of post-fire salvage logging in conifer forests of the western USA, managers need accurate assessments of tree survival when significant proportions of the crown have been scorched. The accuracy of fire severity measurements will be affected if trees that initially appear to be fire-killed prove to be viable after longer observation. Our goal was to quantify the extent to which three common Sierra Nevada conifer species may 'flush' (produce new foliage in the year following a fire from scorched portions of the crown) and survive after fire, and to identify tree or burn characteristics associated with survival. We found that, among ponderosa pines (*Pinus ponderosa* Dougl. ex. Laws) and Jeffrey pines (*Pinus jeffreyi* Grev. & Balf) with 100% initial crown scorch (no green foliage following the fire), the majority of mature trees flushed, and survived. Red fir (*Abies magnifica* A. Murr.) with high crown scorch (mean = 90%) also flushed, and most large trees survived. Our results indicate that, if flushing is not taken into account, fire severity assessments will tend to overestimate mortality and post-fire salvage could remove many large trees that appear dead but are not.

Additional keywords: fire severity, Jeffrey pine, ponderosa pine, red fir.

Introduction

In recent years, controversy has grown over the effects of post-fire salvage logging in western USA conifer forests (Karr *et al*. 2004; Donato *et al*. 2006; Hutto 2006; Noss *et al*. 2006). Managers need accurate assessments of tree survival where high levels of crown scorch occur. If trees that initially appear to be dead prove to be viable after longer observation, the accuracy of fire severity estimates will be affected. This could lead managers to overestimate the amount of habitat available for wildlife species associated with high-severity fire effects (Smucker *et al*. 2005; Hutto 2006; Hanson and North 2008). Moreover, potential seed sources for natural post-fire conifer regeneration could be removed, affecting and impeding successional processes (Lindenmayer *et al*. 2004; Noss *et al*. 2006).

Following wildfire, rapid assessments of various fire effects are made by interagency Burned Area Emergency Rehabilitation (BAER) teams using remotely sensed data and field visits, often within several weeks of a fire (USDA 1995). Assessments that attempt to estimate conifer stand mortality may gather data immediately after fire or during the following year. Depending on timing, the assessment may occur before post-fire flushing from surviving terminal buds is complete in mid- or late summer of the year after the fire in montane forests (Thode 2005; Miller and Thode 2007). Many trees in high-intensity burns have extensive crown scorch, yet there are few studies that have followed these trees through several growing seasons, especially for large, mature conifers.

Rules for identifying post-fire dead or dying trees are largely based on datasets using smaller trees (generally ≤50 cm in diameter at breast height (DBH)) (see, e.g. Stephens and Finney 2002; Hull Sieg *et al*. 2006) and destructive cambial sampling (Hood *et al*. 2007). One recent study of post-fire survival among ponderosa pine (*Pinus ponderosa* Dougl. ex. Laws) in Arizona involved mature trees (McHugh and Kolb 2003), but there are few studies examining factors influencing post-fire survival among large conifers in the Sierra Nevada. The importance or frequency of post-fire flushing in the year following a fire has not been studied for conifers with high or complete initial crown scorch. Trees with complete crown scorch (no green foliage immediately after fire) are often excluded from post-fire conifer survival studies or assumed dead (Kobziar *et al*. 2006). However, a recent study in the Sierra Nevada found high survival in moderate- and high-intensity burn patches for one species, white fir (*Abies concolor* (Gord. & Glend.) Lindl.), when trees were >50 cm in diameter (Hanson and North 2006). Flushing was not apparent until the second or third growing season following fire, and was the result of epicormic branching. If flushing does occur, fire severity assessments will tend to overestimate mortality and post-fire salvage could remove large trees that appear dead but are not.

The goal of our research was to identify fire damage and tree characteristics useful for modeling post-fire flushing for three common species of Sierran conifers: ponderosa pine, Jeffrey pine, and red fir. We focussed on areas where crown scorch was complete (100% (no green foliage); pines) or nearly so (≥85%; red fir). We did not include trees in areas affected by crown fire (generally, trees that had most or all of their crown foliage consumed (i.e. incinerated by flames, as opposed to foliage

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being killed by radiant heat from high-intensity surface fire)) because there are no studies of which we are aware that have found survival when a tree crown is consumed. The objectives of our study were to evaluate the following: (1) of the trees presumed dead on initial post-fire evaluation (i.e. 100% crown scorch for pines, ≥85% crown scorch for red fir), what proportion flush and remain alive 3–4 years after fire? (2) Which tree or fire characteristics (diameter, bole char, crown scorch or kill, crown consumption) most effectively predict a tree's post-fire status (flushed and alive *v.* dead)? The accuracy of stand- and landscape-level fire severity assessments may be improved if crown and bole characteristics associated with post-fire conifer flushing and survival can be identified.

Methods

Study sites

We sampled trees in two study areas: the 2003 Tuolumne fire in Yosemite National Park (~1500 ha) in the central Sierra Nevada, and the 2002 McNally fire in Sequoia National Forest (60 750 ha) in the southern Sierra Nevada (Fig. 1). Both fires occurred during the summer, and were of mixed severity, with high-severity (high or complete tree mortality) patches in a mosaic of low- and moderate-severity effects.

The two study sites (one ponderosa pine site and one Jeffrey pine site) within the McNally fire were limited to a section of roadway along which initial crown scorch (before flushing) was assessed by the US Forest Service. Their assessment focussed on identifying roadside hazard trees using a criterion of 100% initial crown scorch (no green foliage) for trees located within ~50 m of the road. All such trees were marked for removal by agency staff. Along this section of road, all areas dominated by ponderosa pine or Jeffrey pine with 100% initial crown scorch (no green foliage) and trees >25 cm DBH were included in this study. The study sites, which totaled ~80 ha, experienced high-intensity surface fire. We included all trees >25 cm DBH with 100% crown scorch. No red fir sites were located in the McNally fire.

In the Tuolumne fire area, before the first post-fire growing season, we identified red fir with high (≥85%) to complete initial crown scorch. Matching our selection criteria in the McNally fire, we did not include areas with low- or moderate-intensity surface fire, which were dominated by trees with high levels of remaining green crown, or sites that experienced crown fire, which were dominated by trees with complete consumption of crown foliage. Within the site, which totaled ~45 ha, we included all trees >25 cm DBH with crown scorch of 85% or greater.

Measurements

We tagged trees in each study site and monitored them for 3 or 4 years after fire.

We measured the following variables as potential predictors of post-fire survival based on previous research in western USA conifer forests (Peterson and Ryan 1986; Ryan and Reinhardt 1988; Stephens and Finney 2002; McHugh and Kolb 2003; van Mantgem *et al*. 2003):

(1) Diameter at breast height (cm): DBH was measured (to the nearest 0.5 cm) for each tree. We analyzed DBH as a continuous variable in logistic regression.

(2) Percentage crown volume killed ('crown kill'): crown kill, as defined in this study, includes the portion of the pre-fire crown that is killed by fire (brown needles killed by radiant heat, with no surviving buds) and the portion consumed (black needles directly affected by flames). This variable is difficult to measure with precision, and usually is determined visually. Estimates must be made at least 1 year after fire to account for any flushing of foliage (from surviving terminal buds) occurring in the first growing season following the fire. In an effort to standardize estimates, our procedure was to visually estimate the number of times the remaining green crown volume would fit within the killed portion of the crown volume, then placing each tree into the appropriate crown kill category (e.g. 60–69.9, 70–79.9, 80–89.9, 90–94.9, 95–99.9, and 100% crown kill). For example, if the green crown volume would spatially 'fit' within the killed crown volume approximately three times, the tree had 70–79.9% crown kill, as the green crown was approximately one-fourth of the total crown volume. We made visual estimates on both sides of each tree to improve accuracy. We assigned trees on the boundary between two crown kill categories to the lower category.

(3) Percentage crown volume scorch ('crown scorch'): We used the same method to estimate crown scorch as described above for crown kill. We measured crown scorch before the first season of foliage production after a fire to determine the difference in green crown volume between pre- and post-flushing. As defined in this study, crown scorch includes the portion of the crown in which foliage was killed (brown needles) but not terminal buds, the portion of the crown in which foliage and terminal buds were killed by radiant heat (brown needles), and the portion consumed (black needles, no surviving terminal buds) (Fig. 2). For the purposes of logistic regression analysis, we used the midpoint of each category (e.g. 75% for the category 70–79.9%).

(4) Crown consumption: this is defined by the percentage of total tree height with incinerated foliage (needles and small twigs consumed, blackened branches), and is expressed as the total tree height divided by the maximum height of complete foliage incineration (0–19, 20–39, 40–59, 60–79 or 80–100% of total tree height). For the purposes of logistic regression analysis, we used the midpoint of each category.

(5) Bole char: this is a composite of the amount and severity of bole char. Trees were categorized as having low bole char if they had <0.2-cm char depth (where char includes only blackened material, not discolored or 'cooked' bark or cambium underneath the char) completely around the tree circumference, or a mixture of <0.2-cm and 0.2–1.0-cm char depth around the tree circumference. Trees were defined as having medium bole char if they had 0.2–1.0-cm char depth completely around the tree circumference, or >1.0-cm char depth on >50% of tree circumference. Trees had high bole char if char depth was >1.0 cm around the entire tree circumference. We took bole char measurements in each of four quadrants on each tree at a height of ~1 m. We measured char depth by using a knife to scrape away the char, after which we measured the depth of the cut required to find no more char. For the purposes of logistic regression

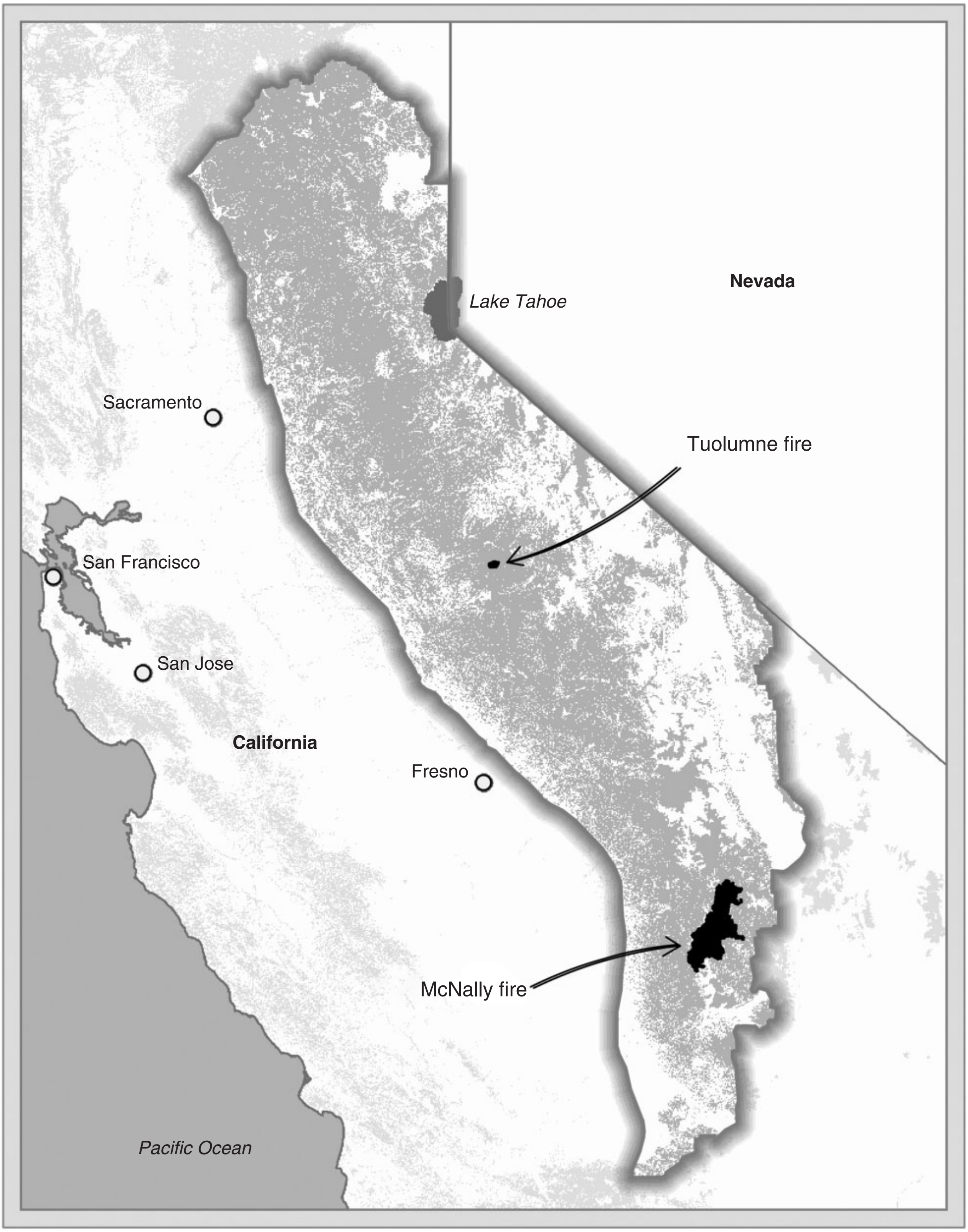

Fig. 1. The McNally fire and Tuolumne fire study areas.

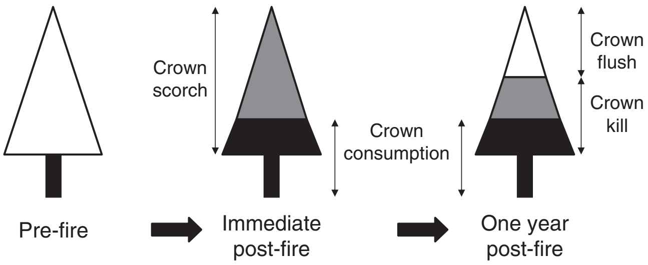

Fig. 2. Crown scorch, crown kill, and crown incineration.

analysis, we assigned the values 1, 2, and 3 to low, medium, and high bole char respectively.

Data analysis

To analyze whether DBH category was associated with survival of pines with 100% initial crown scorch, we used a Chi-square test of independence. We used logistic regression to analyze all other conifer survival data, with live or dead as the dependent variable. We used model selection and Akaike's Information Criteria (AIC) (Burnham and Anderson 2002) to identify predictor variables to include in the logistic regression analysis. All independent variables and their interactions were added to the model, and then terms were dropped if their C_p statistic (the likelihood version of AIC in *S-PLUS*) was lower than the C_p statistic for the null model. We used the Hosmer–Lemeshow goodness-of-fit test to assess the fit of final models to the data, where a good fit is indicated by non-significance ($P > 0.05$) (van Mantgem *et al*. 2003; Thies *et al*. 2006). We evaluated each model using a jackknife procedure to determine the percentage of correct live or dead classifications. We used *S-Plus* (S-Plus 2001) for all data analyses.

Ponderosa and Jeffrey pine

In the ponderosa and Jeffrey pine study sites within the McNally fire area, the US Forest Service had marked, adjacent to roads, all trees with 100% initial crown scorch a few months after the fire occurred, before the first post-fire growing season. Trees so marked were scheduled for removal as roadside hazard trees, but actual felling and removal did not occur until after the first post-fire growing season in the year after the fire. Trees that flushed, producing new green foliage, were unmarked before hazard tree operations, and were not felled. Our study site identification and data collection did not begin until several weeks after hazard tree felling. For felled trees, we estimated DBH by measuring stump diameter and subtracting 10%, based on our observations in the study area of the ratio of DBH and diameter at stump height, similar to common US Forest Service tree-marking protocols in the Sierra Nevada. We monitored trees for 4 years after fire (Table 1).

We first analyzed 4-year survival of all ponderosa and Jeffrey pine with 100% initial crown scorch ($n = 354$). As this included trees that did not flush, and that were therefore felled and removed before data collection, the only variable that could be used was DBH. We used a Chi-square test of independence to determine whether DBH was a significant factor in determining survival of trees with 100% crown scorch, using DBH categories

Table 1. Characteristics of study trees in the McNally and Tuolumne fire areas (values in parentheses are standard deviations)
PIPO, ponderosa pine; PIJE, Jeffrey pine; ABMA, red fir; DBH, diameter at breast height

Species	DBH category (cm)	*n*	Number flushed[A]	Number survived[B]	Mean DBH (cm)	Mean crown scorch	Mean crown kill[C]	Mean crown consumption	Mean bole char
PIPO ($n = 310$)	25–49	190	54	41	40.9 (5.8)	100 (0)	80.1 (17.4)	24.4 (15.7)	2.6 (0.5)
	50–75	95	50	44	61.0 (5.7)	100 (0)	67.2 (19.1)	21.6 (11.5)	2.7 (0.5)
	>75	25	16	15	86.4 (8.8)	100 (0)	56.3 (24.5)	22.5 (12.4)	2.4 (0.7)
PIJE ($n = 44$)	25–49	25	11	6	40.1 (6.2)	100 (0)	94.1 (2.3)	20.9 (10.4)	2.3 (0.5)
	50–75	13	8	7	58.6 (6.7)	100 (0)	85.3 (7.3)	17.5 (10.4)	2.1 (0.4)
	>75	6	3	3	100.3 (12.1)	100 (0)	75.0 (10.0)	10.0 (0)	2.0 (0)
ABMA ($n = 57$)	25–49	18	2	3	40.7 (6.0)	90.4 (5.6)	67.5 (21.7)	15.6 (9.2)	2.3 (0.8)
	50–75	17	7	8	61.9 (6.8)	89.4 (5.3)	63.8 (16.4)	12.4 (6.6)	2.4 (0.8)
	>75	22	13	14	97.8 (17.2)	89.8 (4.9)	67.1 (15.3)	19.1 (18.2)	2.5 (0.7)

[A] For red fir, we gathered pre-flush data in 2004 and post-flush data in 2006, but were unable to gather data in 2005. Thus, the total number of red fir that flushed is unknown, because some may have flushed in the summer of 2004 (after our initial data collection) but could have died in 2005.
[B] For red fir, in each of the three DBH categories, all of the surviving trees flushed except one.
[C] For red fir, crown kill data pertains only to trees alive as of 2006, as no data were gathered in 2005 for this species.

Table 2. Logistic regression summary for survival of ponderosa and Jeffrey pines >25-cm diameter at breast height (DBH) that flushed after having 100% initial crown scorch, McNally fire ($n = 142$)

Variable	Coefficient	s.e.	*P* value
Crown kill	−0.166	0.044	$P < 0.001$
Bole char	−2.239	0.773	$P = 0.004$
Crown consumption	−0.061	0.023	$P = 0.008$
Intercept	23.082	5.035	$P < 0.001$

that track existing ones used by land managers in the Sierra Nevada for post-fire salvage marking guidelines (25–49, 50–75, and >75 cm DBH).

We next analyzed 4-year survival of the ponderosa and Jeffrey pine that not only had 100% initial crown scorch, but that also flushed in the year after the fire ($n = 142$). We analyzed the following independent variables: DBH, crown kill, crown consumption, and bole char. Three pines flushed, and were therefore not felled, but died in the brief period between felling and data collection, precluding an estimate of the extent of flushing. We excluded these trees from this analysis.

Red fir

All red fir ($n = 57$) were located within the Tuolumne fire (Table 1). Initial data were gathered in the year following the fire, but before flushing. We analyzed 3-year survival of red fir, using the following independent variables: DBH, crown scorch, crown consumption, and bole char. We were able to analyze crown scorch for red fir because, unlike our data for ponderosa and Jeffrey pine, there was variance in crown scorch for red fir (all ponderosa and Jeffrey pine had 100% crown scorch).

Results

Ponderosa and Jeffrey pine

The C_p statistic for species, between ponderosa pine ($n = 310$) and Jeffrey pine ($n = 44$) with 100% initial crown scorch, was lower than the C_p statistic for the null model, and a Chi-square test found no significant difference in survival between the two species ($\chi^2_1 = 0.12$, $P = 0.722$). Accordingly, we analyzed these species together. In the McNally fire area, 4-year post-fire survival of ponderosa and Jeffrey pines with 100% initial crown scorch ($n = 354$) was 22% (47 of 215), 47% (51 of 108), and 58% (18 of 31) for trees 25–49, 50–75, and >75 cm DBH respectively. Diameter at breast height was a significant predictor of survival ($\chi^2_2 = 32.41$, $P < 0.001$), with the larger trees surviving at higher rates.

Among ponderosa and Jeffrey pine with 100% initial crown scorch and that flushed in the year following the fire (142 of the 354 analyzed above), 82% survived and were alive 4 years after fire. The average extent of flushing among surviving pines was 30 percentage points (i.e. 0% green foliage initially to 30% green crown volume after flushing). The final model to predict survival of these trees included crown kill, crown consumption, and bole char (Table 2) (Hosmer–Lemeshow test, $\chi^2 = 7.42$, $P = 0.386$ (P values >0.05 indicate good model fit)). The C_p statistic for DBH was lower than the C_p statistic for the null model, so we did not include DBH in the logistic regression analysis. The final model had a max-rescaled R^2 value of 0.549. The model correctly predicted 88% of observed mortality.

Red fir

For red fir ($n = 57$), mean crown scorch was 90%, and overall survival was 44% at 3 years after fire. Trees >50 cm DBH had a mean crown scorch of 90%, and survival rate of 56% (22 of 39) at 3 years post-fire. The average extent of flushing among surviving trees was 23% (Fig. 3). The final model to predict survival included DBH and bole char (Table 3) (Hosmer–Lemeshow test, $\chi^2 = 6.70$, $P = 0.461$). The C_p statistic for crown scorch was lower than the C_p statistic for the null model, so we did not include crown scorch in the logistic regression analysis. Crown consumption was included in the logistic regression analysis, but was not significant ($P = 0.998$). The final model had a max-rescaled R^2 value of 0.618. The model correctly predicted 83% of observed mortality.

Discussion

Post-fire flushing was widespread among ponderosa pine, Jeffrey pine, and red fir, and survival was high, especially among larger trees. The majority of the large pines that had no green foliage after fire and that appeared dead nevertheless flushed and survived. Our results have important implications for post-fire salvage logging. If land managers do not wait to determine the extent of post-fire flushing in mid- or late summer of the year following the fire, intermediate and large trees that might otherwise survive could be felled because they appear to be dead. Moreover, if post-fire flushing is not taken into account, the accuracy of fire severity estimates (both field-based and remote-sensing) will be diminished. Assessments made before flushing will tend to overestimate the extent of high-severity effects.

Our findings are consistent with another study pertaining to flushing and survival of ponderosa pines with 100% crown scorch in Colorado (Harrington 1987). They are also consistent with survival estimates (∼42%) for ponderosa pine ∼50 cm DBH with 100% crown scorch in the Sierra Nevada (Stephens and Finney 2002). Neither of these studies, however, included large trees.

Hood *et al*. (2007) predicted far lower rates of survival for ponderosa and Jeffrey pine with 100% initial crown scorch; overall predicted survival of such trees was ∼12%, and the range was ∼5% to approximately ∼37%, depending on the level of cambial damage. This discrepancy could be in part due to destructive cambial sampling used by Hood *et al*. (2007), which may have influenced mortality. Although we found higher survival than Hood *et al*. (2007), there are several limitations to our design that may influence our results. We had a relatively small sample size from only two locations and sampling was restricted to a narrow subset of trees (e.g. ponderosa and Jeffrey pine with 100% scorch and red fir with 85% or greater scorch). We also did not sample in high-severity crown-fire areas where foliage consumption is high. Future investigations with larger samples in other locations will facilitate more precise estimates of flushing and survival. Nevertheless, our results represent the first data on

Fig. 3. Red fir (Tuolumne fire) pre-flush (*a*) and post-flush (*b*).

Table 3. Logistic regression summary for survival of red fir >25-cm diameter at breast height (DBH) with ≥85% crown scorch (mean crown scorch = 90%), Tuolumne fire ($n = 57$)

Variable	Coefficient	s.e.	*P* value
Bole char	−2.869	0.779	$P < 0.001$
DBH	0.056	0.018	$P = 0.002$
Intercept	2.744	1.648	$P = 0.096$

post-fire flushing and survival of the large ponderosa and Jeffrey pines that can dominate overstorey structure, and the first data on post-fire flushing of red fir of any size.

In our results, post-fire flushing was not limited to ponderosa and Jeffrey pine. Red fir with high crown scorch also flushed, and survival of such trees was high in the largest size class. We have not found any previous reports of post-fire flushing in red fir with high levels of crown scorch in the scientific literature. In the Sierra Nevada, post-fire crown reiteration through epicormic branching on the scorched portion of the bole has been found in white fir (Hanson and North 2006), though there are no reports of post-fire flushing (i.e. new growth from surviving terminal buds in the scorched portion of the crown) among white fir. Conversely, although there are no reports of epicormic branching in red fir, the red fir in the present study did exhibit flushing, reflecting different physiological responses to fire by these two fir species.

Diameter and bole char were generally significant factors associated with the survival of trees with high or complete crown scorch. Other studies, sampling trees with <100% initial crown scorch, have also found these factors to be significantly associated with post-fire conifer survival (Stephens and Finney 2002; McHugh and Kolb 2003; Hull Sieg *et al*. 2006). Larger-diameter trees have thicker, more fire-resistant bark, making them more resistant to cambial damage, which may minimize post-fire stress (Peterson and Ryan 1986; Wyant *et al*. 1986). Larger diameter is also correlated with taller tree height, often providing a greater separation between surface fire and live crown base. A small tree would experience a greater proportion of crown loss compared with a large tree with a larger and longer prefire crown for an equivalent scorch height (Wyant *et al*. 1983, 1986).

Tree diameter, however, was not associated with ponderosa and Jeffrey pine survival once trees flushed. Following flushing, percentage crown kill, bole char, and crown consumption were significant predictive variables. These variables, or very similar ones, have been found to be important in other post-fire conifer survival studies, with crown damage affecting a tree's capacity to produce photosynthate, and bole char potentially affecting the living cambial tissue needed to transport nutrients to support root structure (Peterson and Ryan 1986; Stephens and Finney 2002; McHugh and Kolb 2003). The significance of crown consumption may result from the effects of radiant or convection heating, where greater levels of heat reach the upper crown, killing not only needles but also terminal buds and increasing crown incineration (Peterson and Ryan 1986). We can only speculate as to why tree diameter was not a significant factor following flushing. We hypothesize that higher levels of stored photosynthate in larger trees may confer greater vigor, allowing more large trees to flush. Flushed tree survival, however, may be influenced by the future amount of photosynthate that can be produced from the remaining crown foliage and transported to the roots.

Management implications

Many of the pines in our study that initially appeared to be dead (0% green foliage) flushed and survived. This may occur because foliage succumbs to radiant heat more readily than do protected terminal buds (Methven 1971; Peterson and Ryan 1986). Moreover, photosynthate production per unit area of crown foliage in the uppermost portion of the crown is approximately twice that of the lower crown (Helms 1970). This suggests pines can survive and flush even if all of the crown foliage is killed, as long as the terminal buds in the upper crown remain viable. In such an event, water demand will be reduced owing to loss of lower and middle crown structure, while photosynthate production will see relatively smaller declines owing to the survival of the most productive tissues (Wyant 1981; Stephens and Finney 2002).

The ability of large red fir, and ponderosa and Jeffrey pines to flush and survive high or complete levels of crown scorch implies a need for caution in making early estimates of fire effects in large-diameter stands. To avoid overestimating high-severity effects, our study suggests remote-sensing and field-based assessments of fire severity should be conducted after flushing is completed in the late summer of the year following the fire. Similarly, where managers seek to remove roadside hazard trees along popular recreation roads, as was the case in our McNally fire study sites, early severity estimates (i.e. before completion of the following year's growing season) may lead to needless felling of many large, old trees based on the erroneous assumption that they are dead. Our data strongly suggest assessments of post-fire mortality be postponed until the passage of one post-fire growing season. Additional study is needed to more completely determine the degree of flushing and survival in a variety of site conditions for ponderosa and Jeffrey pines, and red fir.

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