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Damage and mortality patterns in young mixed conifer plantations following prescribed fires in the Sierra Nevada, California

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ABSTRACT

High-severity wildfires increasingly influence forests in the western United States. Extensive research has identified preventative practices including mechanical and prescribed fire treatments to reduce wildfire severity in mature stands. Yet limited research has investigated fuel management treatments in young stands which can be particularly vulnerable to even low intensity fire. To address this gap, we investigated how prescribed fire (conducted in both the spring and fall) and pre-treatment fuel modifications impacted individual tree damage (or injury) and mortality in nine 13–14 year old mixed conifer stands in the central Sierra Nevada, California, USA. Prior to burning, randomly selected trees were pruned to 1.8 m height above ground. Randomly selected trees were also raked to reduce surrounding surface fuel. Raking fuel from trees reduced the amount of crown volume scorched for all species, but not enough trees died to determine if raking influenced probability of survival. Pruning was associated with reductions in crown consumption height and percent crown volume consumed (5% of crown volume in pruned versus <1% of crown volume unpruned, $p = 0.02$) but was not a significant predictor of percent of crown volume scorched brown. Pruned trees had only 27% of the mortality of unpruned trees when less than half of the crown was scorched ($p = 0.046$). However the mortality of pruned trees showed no less sensitivity to fire damage at higher levels of crown scorch ($p = 0.0076$); in fact extremely scorched trees appeared more likely to die when pruned. Mortality differed strongly by species; giant sequoia (*Sequoiadendron giganteum*) showed 97% post-fire survival while nearly half of sugar pines (*Pinus lambertiana*) died. Fires occurring in spring months killed seven times as many trees as those in autumn months. While the results demonstrate that prescribed burns can be feasible in stands as young as 13 years old, the factors of post-fire damage and mortality are different compared to mature stands. Species composition, pre-fire fuel reduction treatments, and timing of prescribed burns are all important considerations for managers wanting to develop resilient young stands with prescribed fire.

1. Introduction

Forests face unprecedented threats from fire, drought, and pathogen invasion (Millar et al., 2007; Stephens et al., 2013). A century of fire exclusion has transformed conditions in many western United States forests towards high stem densities, heavy fuel loads, and community compositions dominated by species of low fire resistance (Miller et al., 2009). The altered fire regime has negatively affected large scale carbon storage (Gonzalez et al., 2015) and led to an increase in large high-severity wildfires (Fulé et al., 2014), which have created broad patches of severely burned areas. These patches may or may not develop into young forests (Goforth and Minnich, 2008; Crotteau et al., 2014), and post-fire regeneration processes and patterns can be highly variable (Shatford et al., 2007; Crotteau et al., 2013). Where young forests do establish from either planting or natural regeneration, developing stands can once again become vulnerable to fire within decades (Collins et al., 2007), making them a high priority for hazard reduction treatments.

Fuel treatment research has focused on reducing fire risk and impacts in mature stands while largely omitting young stand management (Agee and Skinner, 2005; Collins et al., 2014; Lyons-Tinsley and Peterson, 2012). For mature stands, a suite of decision-making tools are available to guide managers in deciding how, where, and when to conduct mechanical fuel treatments and prescribed fire (Stephens et al., 2013). However, large fires moving through landscapes inevitably encounter patches of young stands and small trees resulting from past disturbances or even-aged

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regeneration methods (Kobziar et al., 2009; Lyons-Tinsley and Peterson, 2012). Fires – even low intensity prescribed fires, – affect these young stands differently compared to mature stands due to their high stem density and high ladder fuel connectivity between the ground and canopy (Kobziar et al., 2009); influences of site preparation prior to cohort establishment (Lezberg et al., 2008; Weatherspoon and Skinner, 1995); persistence of logging slash as surface fuels (Lyons-Tinsley and Peterson, 2012; Thompson et al., 2007); and much lower crowning and torching indices compared to mature stands (Stephens and Moghaddas, 2005). Despite these differences, no studies have assessed prescribed fire in Sierra Nevada mixed conifer stands younger than 30 years old (Lyons-Tinsley and Peterson, 2012).

Various fuel alteration treatments have the potential to be effective in young stands. Prescribed burning can reduce the risk of future severe fires by consuming accumulated surface and ladder fuel and decreasing tree density (Collins et al., 2014; Keyes and O'Hara, 2002). Introducing prescribed fires early in stand development is appealing since it represents a low-cost alternative to other labor-intensive treatments such as pre-commercial thinning, herbicide use, and fuel removal. However, the capacity of young trees to survive even a low severity prescribed burn is questionable for some species and the age at which a young stand can withstand a prescribed fire without large-scale tree mortality has only been explored by a few studies (Lezberg et al., 2008; Engber and Varner, 2012).

Pruning trees prior to burning reduces young trees' high fuel connectivity from the ground to tree crowns by removing lower branches (Keyes and O'Hara, 2002). While pruning is often assumed to increase a tree's resistance to fire, it also remains largely untested. Mastication is a mechanical method of reducing non-merchantable tree density by chipping vegetation in place using a rotating head with teeth attached to an excavator boom (Harrod et al., 2009). This is a potentially effective pre-burn treatment since it can break up canopy continuity to desired levels, but the increased and novel (Kane et al., 2009; Kreye et al., 2012) surface fuel derived from mastication may result in increased mortality (Knapp et al., 2011; Reiner et al., 2012).

Understanding the impacts of fuel management treatments in young stands is essential to creating resilient forests at the landscape level. We explore the impacts of prescribed burning and pre-burn mechanical fuel alteration techniques in young conifer stands in the Sierra Nevada in California, USA. We draw on data from the on-going Treatment Alternatives for Young Stand Resilience (TAYSR) study. This study is exploring how fuel management treatments in 10–20 year old planted stands are affecting stand development and vulnerability to future wildfires. Specifically, we investigate the following: (1) the feasibility of prescribed burns in young conifer stands; (2) the potential reduction in prescribed fire-related mortality and damage (or injury) achieved by pre-burn pruning, raking, and masticating.

2. Methods

2.1. Site description

We conducted our research at Blodgett Forest Research Station (Blodgett Forest), California, USA, (38°54′45″N, 120°39′27″W), within the north-central Sierra Nevada mixed conifer forest. Blodgett Forest receives average annual precipitation of 157 cm, with roughly 1/3 of precipitation coming from snow. The forest is relatively productive for the region (Dunning Site Index I).

Nine stands were treated with prescribed burns and pre-burn pruning and raking treatments, which were applied to individual study trees with a corresponding number of untreated control trees. Stands were even-aged, 0.29–0.70 ha in size, and had treatment histories typical of plantations in the mixed conifer forest where the objective is to establish tree dominance quickly and to maintain high individual tree vigor. While smaller than industrial even-aged stands, mixed conifer stands of this size are similar to larger plantations at Blodgett Forest in terms of average growing environment and tree growth (York et al., 2004). Following clear-felling and site preparation, stands were planted in springs between 1999 and 2001 at 2.4 × 2.4 m spacing (1736 trees per hectare). Planting included approximately equal numbers of five native conifer species: sugar pine (*Pinus lambertiana*), ponderosa pine (*P. ponderosa*), incense-cedar (*Calocedrus decurrens*), white fir (*Abies concolor*), and coast Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*). Six of the nine stands were also planted with giant sequoia (*Sequoiadendron giganteum*). Six of the nine stands were pre-commercially thinned via mastication to approximately 320 trees per hectare 1 year prior to burning. The other three stands were not thinned prior to treatment.

2.2. Treatments

Study trees within the nine stands were treated with different combinations of fuel alteration techniques (Table 1). Pruning and raking treatments were applied on a tree-by-tree basis within each stand while mastication and prescribed burns were carried out across entire stands. Pruning and raking treatments were applied prior to burning to investigate the effectiveness of pre-burn mechanical treatments to reduce prescribed fire-caused mortality. Trees taller than 3.7 m were considered eligible for pruning and randomly assigned to either the pruned group or unpruned control group. Pruned trees had all branches removed flush with the stem up to 1.8 m high or 50% of live crown height, whichever was lower. Branches removed during pruning were scattered beyond driplines as a standard protocol for avoiding accumulations of fuel at tree bases. At trees randomly selected for raking, woody debris, mostly present as a result of the mastication thinning, were raked away from the tree to the dripline while leaving duff and litter layers intact. This was done one

Table 1
Mastication, pruning, raking, and prescribed burning treatments applied to nine young stands (0.2–1 ha) of mixed conifer forest at Blodgett Forest Research Station, CA. A full census of trees was measured in stands A-C, while a sample transect of trees was measured in stands D – I.

Stand	Treatment	Number of study trees	Pruned	Raked	Pruned & raked	Burn season
A	Masticate + burn	158	79	–	–	Fall
B	Masticate + burn	161	79	–	–	Spring
C	Masticate + burn	129	68	–	–	Spring
D	Masticate + burn	48	26	29	16	Fall
E	Masticate + burn	41	24	19	11	Fall
F	Masticate + burn	53	29	27	12	Fall
G	Burn only	20	10	–	–	Fall
H	Burn only	20	10	–	–	Fall
I	Burn only	30	15	–	–	Fall

month prior to burning, to assess the degree to which added surface fuel from mastication influences tree mortality. Once a tree was selected for raking, all neighboring trees were excluded from selection for the raking treatment to prevent fuel accumulation from raking adjacent trees.

Three different combinations of pruning and raking treatments were applied in the nine stands. Overall, both individual tree and stand-level treatments were applied consistently within various stands (see Table 1). Using a randomized design, in six stands (A-F), half of the trees were pruned. In three of these stands (D-F), a sample of all trees were then randomly selected for raking, resulting in each tree receiving treatments of pruning only, raking only, both raking and pruning, or neither raking nor pruning (no fuel structure modification). In the final three stands (G-I), two or three pairs of trees of each species with comparable size and vigor were identified. One tree of each pair was then randomly selected to be pruned. The remaining tree of the pair was designated a control and was not pruned or raked.

Blodgett Forest staff conducted prescribed burning under similar conditions and using identical ignition techniques in Fall 2012, Spring 2013, and Fall 2013. Stands were 13–14 years old when burned. The burning prescription was: 10-h time lag fuel moisture of 6–7%, relative humidity ranging between 30 and 37%, and winds less than eight kilometers per hour. Ignition strategy was primarily backing ignition with some strip headfires ignited to maintain the front of the fire progressing evenly across the burned area. In general, the fires were slow-moving with typical flame lengths of 0.3–0.9 m. Torching from surface fire up into tree crowns into crowns was infrequent but did occur in isolated trees.

The stands varied in the type of pre-burn treatments (Table 1). Three of the nine stands that were burned were not masticated prior to burning. All stands had paired pruned and non-pruned trees, while a subset of 3 stands had combinations of pruning and raking treatments around individual trees. Two stands were burned in the spring (April) and the rest were burned in the fall (October).

2.3. Data collection

In three stands (A, B, C in Table 1), all trees were tagged and measured prior to and following burning. Following an initial analysis that revealed this to be oversampling, the rest of the stands (D-I in Table 1) were sampled rather than conducting the 100% census. In sampled stands, all trees within a 7.3 m wide transect oriented from south to north across the center of the stand were measured. Pre-burn individual tree measurement included species identity, diameter at breast height (1.37 m; DBH), and height to crown base (HCB).

Tree damage from fire effects was measured approximately six months after burning. Scorched and consumed foliage was clearly evident on branches at this point, allowing for direct measurements of fire-related crown damage. At each tree, we recorded measurements of fire effects through the proxy of visible damage to individual trees. *Bole char height* was the height of blackened bark on the bole; *crown consumption height* was the height of blackened (i.e. enflamed) leaves on the crown; *crown scorch height* was the height of leaves that were scorched brown and killed from heating; *percent crown volume consumed* and *percent crown volume scorched* were the proportion of the crown that was consumed and scorched brown, respectively. Bark beetle incidence was also recorded shortly after a high prevalence of signs was noticed following the spring burns. Mortality surveys were conducted approximately 6 months following burns (M_1) and repeated 1 year (M_2) and 2–3 years (M_3) following burns to capture delayed mortality.

2.4. Data analysis

2.4.1. Tree damage and local fire characteristics

We analyzed tree damage measurements to investigate whether pruning and raking reduced fire-related tree damage. We created three categories of linear models of tree damage measurements: a null model, a full model with pruning covariates ("Full Model - Pruning"), and a model with raking covariates ("Full Model - Raking"). We separated the full model into two categories because the continuous explanatory variables were not available for trees in raking treatments. Categorical explanatory variables were stand, species, pruned or unpruned, raked or unraked, and interaction terms of pruning with species and raking. Continuous explanatory variables used only in Full Model - Pruning were DBH and height to crown base (HCB). All continuous response and explanatory variables were centered on their means before modeling. The null model attempted to build a linear relationship between tree damage based on stand alone. Full Model - Pruning fit tree damage as a factor of stand, species, pruning, interaction between pruning and raking, DBH, and HCB. Full Model - Raking full model fit tree damage as a function of stand, species, pruning, raking, and interactions between pruning and raking. Model fit was assessed with adjusted R^2, coefficient significance, model comparisons using a χ^2 test, and the Akaike Information Criterion (Woolley et al., 2012; Züur et al., 2010).

2.4.2. Mortality

We analyzed prescribed burn impacts on tree survival by modeling mortality as a function of species, stand, pruning, and tree characteristics of DBH and HCB. We used percent crown volume scorched (PCVS) as the sole covariate representing tree damage because this measurement is widely utilized in fire modeling literature (Woolley et al., 2012), and it was not collinear with pruning in these stands (see Results Section 4.2). Although it was a treatment of interest, raking was not used as an explanatory variable for tree mortality since only two raking study trees died (one raked, one not raked).

Four models were used to predict tree mortality for each set of mortality data, at 6 months, 1 year, and 2 years post-burn. First, we predicted mortality based only on stand modeled as a random effect in the null model. This random effect accounted for spatial variability across stands and avoided pseudoreplication from non-independence of measurements within each stand (Züur et al., 2010). Full models predicted mortality based on species, pruning, crown scorch, an interaction term between pruning and crown scorch, DBH, HCB and stand. We used several full models in order to investigate the impact of a geographical effect on tree mortality. In the first full model ("Full Model – Random Effect") we use stand as a random effect. In the second full model, ("Full Model – Fixed Effect") treated stand is a categorical fixed effect. In the third full model, ("Full Model - No HCB"), we treated stand as a random effect and also we omitted DBH and HCB as they had not been highly significant predictors in the earlier models. The third full model was used to build mortality visualizations in Figs. 3 and 4. In all models tested, we assessed fit using coefficient significance, model comparisons using a χ^2 test, and the Akaike Information Criterion (Woolley et al., 2012; Züur et al., 2010). For interpretation, coefficients were transformed from logit units to odds ratios.

For all analyses, data were compiled and analyzed using R version 2.15.1. Functions glm() and glmer() from R package lme4 with a logit link function were chosen for generalized linear model with fixed effects and generalized linear mixed model for mixed effects (Züur et al., 2010).

3. Results

There was high variability among and within stands in the extent of tree-level fire damage. Damage to individual trees ranged from no visible damage to 100% crown scorch (Tables 2–4). Post fire mortality averaged 21% at the stand level, with high between-stand variation and mortality effects delayed over a year posts-burn (Figs. 1 and 2, Tables 5 and 6). Despite inherent difficulty in classifying highly damaged and discolored trees as either "dead" or "live", only one tree was recorded as "dead" at one measurement and "live" at a subsequent measurement. The majority of mortality was concentrated in the stands burned in the spring. These two stands contained almost 90% of all mortality, or 170 of the 200 dead trees. A considerable amount of mortality was delayed to between six months to 3 years post burn with only half of the mortality (98 of 200 dead trees) occurring in the first six months of the fires.

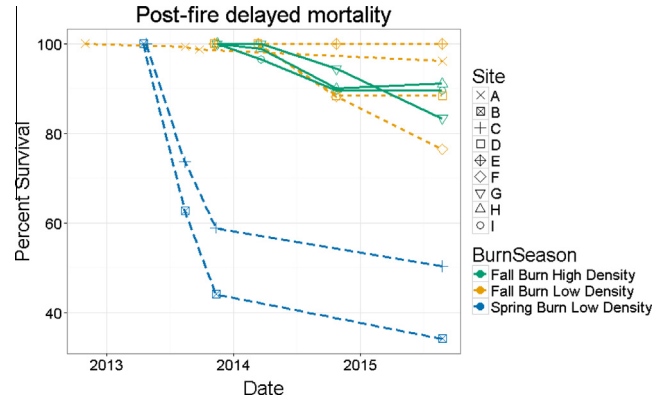

Fig. 1. Survival for several years post-burn showing extensive delayed mortality and high variability between the nine study sites.

Table 2
Descriptive statistics showing the range of fire damage as percent crown volume scorched (PCVS) at each site.

Stand	Burn season	Treatment	Min PCVS	Mean PCVS	Max PCVS
A	Fall	Masticate + burn	0	15	85
B	Spring	Masticate + burn	0	69	100
C	Spring	Masticate + burn	0	58	100
D	Fall	Masticate + burn	0	13	70
E	Fall	Masticate + burn	0	25	45
F	Fall	Masticate + burn	0	23	90
G	Fall	Burn only	0	9	45
H	Fall	Burn only	0	31	90
I	Fall	Burn only	0	26	100
All sites			0	40	100

Table 3
Descriptive statistics showing the range of fire damage as percent crown volume scorched (PCVS) of each species.

Species	Low density (masticated) PCVS			High density (burn only) PCVS		
	Min	Mean	Max	Min	Mean	Max
Douglas-fir	0	40	100	0	23	70
Giant sequoia	0	49	100	–	–	–
Incense-cedar	0	36	100	0	24	70
Ponderosa pine	0	42	100	0	33	100
Sugar pine	0	43	100	5	11	35
White fir	0	58	100	0	21	85
All	0	4	100	0	27	100

Table 4
Descriptive statistics of tree damage measurements across all nine burned stands. Bole char height is the height of blackened consumption on the bole; foliage consumption height is the height of blackened (consumed) leaves on the crown; foliage scorch height is the height of leaves that were scorched brown and killed but not consumed on the crown; percent crown volume consumed and percent crown volume scorched are the proportion of the crown consumed and scorched brown, respectively; percent crown damage is the sum of percent consumed volume and percent scorch volume.

Tree damage measurement	Portion of trees damaged (%)	Mean	Max	Std. deviation
Bole consumption height (m)	81	0.9	8.8	1.1
Crown scorch height (m)	89	0.3	1.7	0.2
Percent crown volume scorched	83	38.6	100	34.2
Crown consumption height (m)	18	0.04	0.9	0.1
Percent crown volume consumed	16	3.00	95.0	11.4

3.1. Species and delayed mortality

Mortality in the years following prescribed burns varied distinctly by species (see Table 5). Half of the mortality occurred six months or more following fires. Giant sequoias had much higher survival than all other species. By the third mortality measurement, only six percent of giant sequoias died, six trees across all sites. This high species survival rate was observed despite the fact that giant sequoias exhibited a great deal of delayed mortality. Over eighty percent of the giant sequoias that ultimately died were still alive six months post-burn. Incense-cedar showed the next lowest mortality of 25%. Incense-cedar also had the second-highest delayed mortality, with a two-thirds of the dead trees dying more than six months post-burn. Ponderosa pine, Douglas-fir, and white fir, had similar mortality rates of 51%, 54%, and 48%, respectively. Each of these species had moderate amounts of delayed mortality of 21%, 31%, and 32% (respectively) of dead trees still alive after six months. Sugar pines had the highest rate of mortality, with 59% of sugar pines dying (58 trees total). Dead sugar pines showed the lowest portion of delayed mortality, with 40% of the dying sugar pines already clearly dead by the first mortality survey six months post-burn.

3.2. Tree damage models

Pruning and raking showed opposite associations with tree damage. Pruned trees had five times lower percent crown volume consumed, but were similar in terms of percent crown volume scorched compared to unpruned trees. Even with unpruned trees, however, crown consumption was minimal (5% on average). In general, damage from direct consumption was much lower compared to damage from scorching (i.e. heating). Raking had a different effect as compared to pruning. Raking was not associated with reduced consumption, but was associated with reduced scorch (Fig. 2, Panels C & D; Table 7).

3.3. Mortality models

Post-fire mortality models attempted to determine if species, site, tree damage measurements, DBH, HCB, and pruning treatments were good predictors of tree mortality. We selected percent crown volume scorch (PCVS) as the sole measure of tree damage since it is widely used in fire literature (Woolley et al., 2012) and because the linear model of tree damage found that PCVS was not correlated with pruning and thus avoided collinearity in the mortality model. Full models showed that mortality was

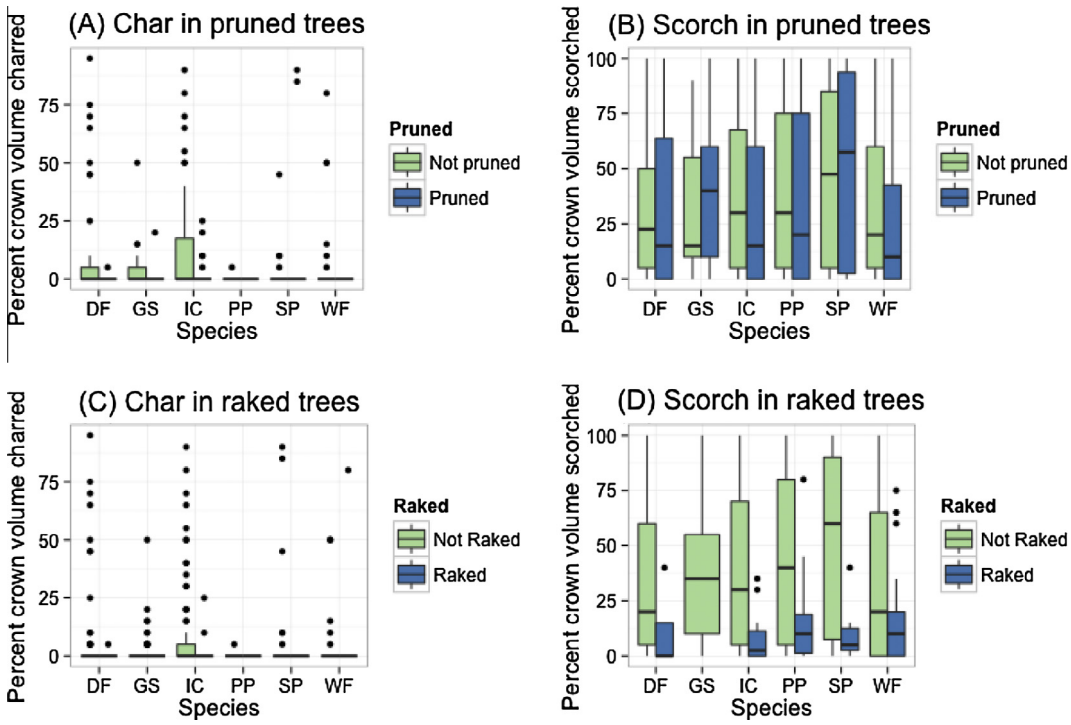

Fig. 2. Boxplots of consumed and scorched foliage as a percent of crown volume by species and pruning and raking treatments. Pruning had a statistically significant but small impact on consumption volume but not scorch volume (A). Raking showed opposite results: a significant associate with scorch volume, but not consumption volume (D). The absence of blue boxplots for pruned and raked trees in panels B and E reflects the low prevalence of consumed foliage among pruned and raked trees. Species: DF = Douglas-fir, GS = giant sequoia, IC = incense-cedar, PP = ponderosa pine, SP = sugar pine, and WF = white fir.

Table 5
Mortality by species approximately six months (M_1) one year (M_2), and 2–3 years (M_3) following prescribed burns.

Species	Total trees	Dead trees			Mortality		
		6 months	1 year	2–3 years	Total	Delayed >6 months	Delayed >1 year
Douglas-fir	77	11	21	24	0.31	0.54	0.13
Giant sequoia	98	1	3	6	0.06	0.83	0.50
Incense-cedar	120	10	21	30	0.25	0.67	0.30
Ponderosa pine	208	30	56	61	0.29	0.51	0.08
Sugar pine	98	35	49	58	0.59	0.40	0.16
White fir	65	11	16	21	0.32	0.48	0.24
All	666	98	166	200	0.30	0.51	0.17

Table 6
Mortality by stand approximately six months (M_1) one year (M_2), and 2–3 years (M_3) following prescribed burns. Only two stands (B & C) were burned in the spring. These two stands contained 85% of the dead trees by the third measurement.

Stand	Treatment	Burn season	Total trees	Number of dead trees			
				6 months	1 year	2–3 years	% mortality
A	Masticate + burn	Fall	157	1	2	6	0.04
B	Masticate + burn	Spring	161	60	90	106	0.66
C	Masticate + burn	Spring	129	34	53	64	0.50
D	Masticate + burn	Fall	26	0	3	3	0.12
E	Masticate + burn	Fall	10	0	0	0	0.00
F	Masticate + burn	Fall	17	0	2	4	0.24
G	Burn + only	Fall	18	0	1	3	0.17
H	Burn + only	Fall	90	1	9	8	0.09
I	Burn + only	Fall	58	2	6	6	0.10
Average			74	11	18	22	0.21

significantly associated with species, stand, PCVS, pruning, and an interaction term of pruning and PCVS (see Tables A2–A6). The same covariates were statistically significant in the two full models for each mortality measurement date whether stand was treated as a fixed effect or a random effect. However, pruning was significant only in models using the first 6–12 months of mortality data or omitting DBH and HCB for the most recent mortality survey 2–3 years post-burn.

Table 7
Covariates that showed statistically significant association with six measurements of tree damage under Full Model – Pruning and Full Model - Raking, including adjusted R-squared as a measure of model fit. Pruning was statistically significant for percent crown volume consumed, but not percent crown volume scorched. Raking treatment was statistically significant for percent crown volume scorched, but not percent crown volume consumed. DBH = diameter at breast height (1.37 above ground); HCB = Height to Crown Base from ground.

Response	Pruning model significant covariates	Adjusted R-squared
% Crown scorch	Stand, species, HCB	0.43
% Crown consumed	Stand, species, HCB, pruning, pruning:species	0.16
Response	**Raking model significant covariates**	**Adjusted R-squared**
% Crown scorch	Stand, species, raking	0.50
% Crown consumed	Stand, species, pruning, pruning:species	0.14

Pruning was associated with reduced mortality, but only when the fire burned with relatively low intensity and with a diminishing impact as time passed following burns. Although regressions using response variables from the first and second mortality surveys showed statistically significant association with mortality in all full models, the statistical significance of these coefficients held for mortality data 2–3 years post-burn only for the full model which omitted DBH and HCB. In general, pruned trees that had less than ~80% crown scorch damage were less likely to die than unpruned trees (Fig. 3). When less than half of the crown was scorched, the odds ratio of mortality probability between pruned and unpruned trees was in the range of 0.2–0.46 (Tables A2–A6). In other words, pruned trees had three times greater chance of survival immediately following fire. Note, however, that for most species probability of mortality was still relatively low (less than ~20%) for both pruned and unpruned trees when crown scorch was low. Unpruned ponderosa and sugar pine had the highest probability of mortality, even when crown scorch was low (Tables A2–A6). At higher scorch volume (greater than 80%), pruning was not associated with reduced mortality. Somewhat surprisingly, DBH and HCB were not significant predictors of mortality. Since much of the mortality occurred in stands B and C, both full models were heavily influenced by data from these two stands.

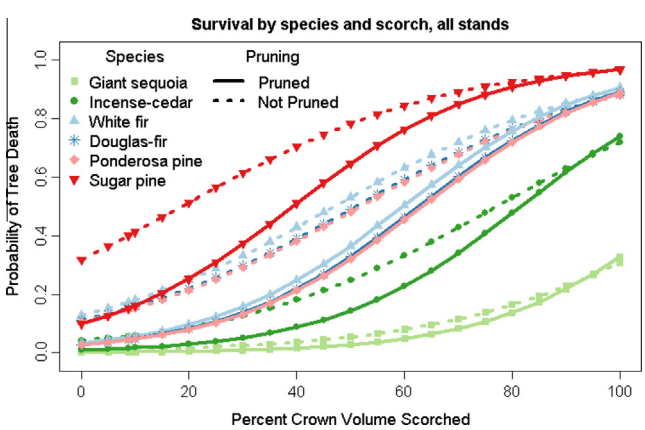

Fig. 3. Visualization of post-fire mortality across all stands by species, pruning treatment, and percent of crown volume scorched. Post-burn mortality in a sample stand is associated with species and an interaction of pruning with percent crown volume scorched (PCVS). Sugar pine had especially high mortality, and giant sequoia showed especially high survival. Pruning impact depends on percent of foliage scorched. Under low- intensity burn conditions scorching <50% of the crown, pruning was associated with reduced mortality for all species. The effect of pruning decreased under medium-intensity burn conditions scorching 50–80% of the crown. In situations of highest scorch and burn intensity, pruning was associated with increased mortality.

4. Discussion

For numerous reasons, there is a widespread reluctance to use prescribed fire as a tool for building resilience across many forest types (Ryan et al., 2013a, 2013b). In young stands perceived to be vulnerable to even low intensity fire, this reluctance is even more common. Our study demonstrates that it is feasible to conduct prescribed burns in young Sierra Nevada mixed-conifer plantations without high levels of mortality, but factors of mortality are likely different compared to mature stands. While mortality is not always an undesirable outcome, especially in high density stands where fire may be used as an alternative to pre-commercial thinning, it is often of concern where the long-long term objective is to promote large and fire resistant trees as quickly as possible. As the application of prescribed fires is expanded to landscape levels, it may not be necessary to exclude young stands from low intensity prescribed fires depending on their age and size. Introducing fire early is also consistent with the pre-suppression fire regime of the mixed conifer forest. In the forest surrounding our study area, for example, median point fire return interval is 9–15 years. At least some, if not most, young stands likely experienced fire prior to the era of fires suppression. While our study demonstrated the feasibility of burning in young stands (especially if burned during the fall), a high degree of variability in burn effects on damage and mortality should be expected, potentially to an even greater extent compared to mature stands.

4.1. Tree damage and local fire characteristics

We found that fuel modification surrounding individual trees influenced fire effects on tree damage. High scorch and consumption heights imply that the fire burned at higher intensity (Alexander, 1982; Alexander and Cruz, 2012; van Wagner, 1973; Woolley et al., 2012), although tree physiology also affects tree damage (Ryan et al., 2010). Our results for young stands concur to some degree with findings from mature forests that localized treatments to reduce fuel continuity (i.e. pruning) can decrease fire intensity (Keyes and O'Hara, 2002) and that modifying surface fuel structure can affect fire behavior and mortality (Collins et al., 2014; Nesmith et al., 2010). However, in these young stands unusually small increases in fire intensity resulted in relatively large impacts on trees. The ignition pattern was used to encourage a slow-moving, low intensity prescribed fire with a reduced probability of crowning. Despite this ignition pattern and flame lengths generally less than 1 m, the local effects on individual trees was highly variable. Injury of greater than half of tree crowns were common because crown base heights of small trees are low.

Scorch and consumption are indicative of the different ways fire can damage a tree: direct combustion and heat exposure without combustion (Ryan et al., 2010). Further, height and percent of crown damage show different aspects of tree damage. Height of scorch and char are indicative of local fire behavior at the tree, while percent of crown scorched or consumed more closely measures the extent of injury a tree sustained as reduction in photosynthetic capacity (Fowler and Sieg, 2004; Ryan et al., 2010). Crown scorch was the primary class of crown damage observed in this study, and pruning had little effect on this injury. Any mitigating effect that pruning had on crown damage was through reducing the amount of crown consumed, suggesting that the lower branches that were removed in pruning would have otherwise been consumed by the fire. Therefore, the net impact of pruning on injury appears to be minimal. Further, the results from the raking

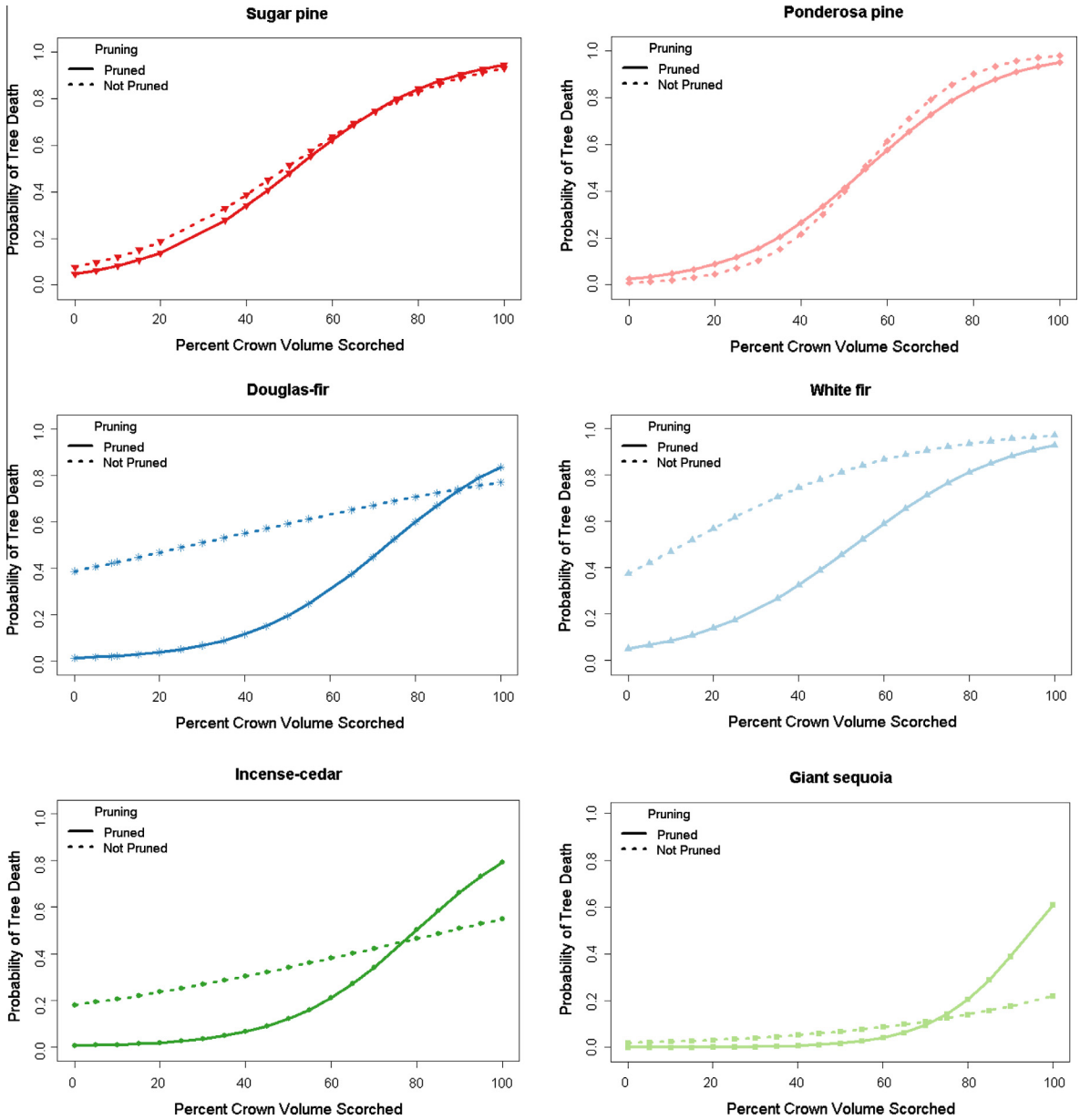

Fig. 4. Visualization of post-fire mortality for each species, across all stands. When modeled separately for each species, only incense-cedar showed a statistically significant association between pruning and mortality.

treatment suggest that crown scorch may have been increased if the pruned branches had been left beneath tree crowns.

4.2. Fire mortality in young stands

4.2.1. Species effects

It is well known that species-specific traits and functional ecology affect post-fire mortality, both immediately during a burn and in the following months or years. Physiological differences may contribute to variation in vulnerability among these species. For example, thicker bark protects cambium from heat damage (Martin, 1963) with Fahnestock and Hare (1964) finding that bark thicker than 0.5 in. protected longleaf pine cambium during prescribed fires and Wade and Johansen (1986) finding that bark less than 0.5 in. protect young loblolly pine from low-intensity fire. In addition, different needle shapes and volatile compounds in foliage and bark may spread flame differently (Ryan et al., 2010). At the community level, the impacts of beetles and pathogens may differentially affect fire-weakened trees of particular species (Stark et al., 2013). Taken together these different species characteristics can influence the degree to which a species is injured by a fire as well as the capability of a species to survive that injury.

Our study suggests that, similar to mature trees, young giant sequoia also have a relatively high resistance to fire. The fire-adaptive traits of large giant sequoia may be similar in young giant sequoia. Mature giant sequoias have a distinct ability to suffer great loss of leaf area yet still survive intense fire (Stephens and Finney, 2002). Similarly, young giant sequoias in our study demonstrated higher survival than other species despite comparable levels of foliage scorch. Thick bark protects large giant sequoia cambium from fire and reduces damage due to prolonged heat (Weatherspoon, 1990). While the characteristic thick bark of large giant sequoias has not yet developed in these young trees, the relative degree of bark insulation may be high in giant sequoia compared to other species.

Our findings of high post-fire survival in incense cedar is consistent with existing literature for more mature trees (Stephens and Finney, 2002). This occurs despite apparent differences, such as

the thick, fibrous, fire resistant bark of mature incense-cedar trees have in comparison with the thin, flaky bark of young incense-cedars (Powers and Oliver, 1990). Mature trees of shade-intolerant species in this forest type, ponderosa pine and giant sequoia, tend to retain fewer live branches close to the ground compared to the shade-tolerant species of white fir and incense-cedar. The young trees in these stands, however, have yet to substantially differentiate crowns according to species groups. All species still have foliage close to the ground and therefore vulnerable to heating effects of even a low intensity fire.

Intermediate post-fire survival of white firs differs somewhat from existing findings for mature trees, which found relatively low white fir survival (Safford et al., 2012; Stephens and Finney, 2002). Like incense-cedar, young white firs may have higher survival relative to other species than mature white fir since crown architecture has not yet differentiated between species in young trees. In addition, mature white firs may be more vulnerable to damage associated with fire consumption of the forest floor (Stephens and Finney, 2002). In the young forests studied, fuel loads may not have accumulated sufficiently.

Moderate post-fire survival of young Douglas-fir trees was consistent with previous studies of in mature trees and more recently in studies of smaller trees (Engber and Varner, 2012). They found that crown injury was a significant factor affecting post-fire survival with 20% crown scorch being a threshold for survival. While we did not observe a threshold, we definitely observed a relationship between percent crown scorch and survival. Mature Douglas-fir has middling bark thickness and intermediate fire survival relative to other trees. Similarly, young trees demonstrated an intermediate survival. Small Douglas-firs may not possess the particular characteristics that make young giant sequoias particularly resistant to fire damage, but neither do they appear to be particularly vulnerable.

The intermediate post-fire survival observed in ponderosa pine was surprising, considering this species is thought to relatively high resistance to low intensity prescribed fire when mature (Safford et al., 2012; Stephens and Finney, 2002). The divergent responses to fire in young and mature pine trees may be due to physiological differences. Different bark thickness and root sensitivity may both be important factors, and young trees with small root systems may be more vulnerable during drought years. Red turpentine beetles (*Dendroctonus valens*) were noted on nearly all sampled ponderosa pines following spring burns. However, this species does not generally cause tree death but rather attacks already weakened trees (Smith, 2015).

High mortality of young sugar pines was also surprising, as mature sugar pines have been found to have intermediate-to-high resistance to low-intensity fire. As with ponderosa pines, young sugar pine roots may have been more vulnerable to heat damage (Stephens and Finney, 2002). Alternatively, a species-specific pathogen may have interacted with pine survival in this study. Pines are host to several native bark beetles (Stark et al., 2013), and sugar pine is vulnerable to mortality from white pine blister rust (*Cronartium ribicola).* It is possible that both ponderosa pine and sugar pine mortality was exacerbated here by a complex combination of fire, drought, insects, and disease (Knapp et al., 2009).

4.2.2. Delayed mortality

Although delayed mortality was observed in all species, it had a disproportionate effect on several species. Interestingly, there was an inverse relationship between the overall survival rate of the species and the portion of the mortality that occurred more than six months post-burn. Giant sequoia had extremely high survival, yet over 80% the mortality it experienced was delayed a year or more after burns. At the other end of the spectrum, sugar pine showed high immediate mortality and high overall mortality, but over half of that had already occurred by the first mortality measurements. The high incidence of delayed mortality is consistent with existing literature demonstrating mortality extending well beyond the end of a fire (Thies et al., 2006; Knapp et al., 2009; Reiner et al., 2012). Fire damage, individual species characteristics, and other factors such as beetles and drought may have contributed further to mortality in the years following the burns (Knapp et al., 2009). In particular, giant sequoia is generally considered a moisture sensitive species (Weatherspoon, 1990), so dry years following the burns may have made this species particularly vulnerable.

4.2.3. Pruning effects on mortality

Pruning and percent crown volume scorched had a complex association with young tree mortality: pruned trees were less likely to die, but only when less than half of the tree was scorched. This 50% transition point between beneficial and ambiguous pruning impact is notably parallel to the point at which pruning alone can reduce tree growth. Pruning is known to negatively affect tree vigor when greater than 50% of the live crown is removed (Kozlowski et al., 1991; O'Hara et al., 2010). This suggests that 50% of crown volume may be a critical point for tree survival, regardless of the mechanism of crown reduction (pruning or fire). In other words, removing more than half of a tree's crown can reduce vigor, whether the mechanism is fire or mechanical. As with pruning, reduced fire impacts on lower crowns may be linked to the relatively low photosynthetic efficiency and high respiration demands of lower or lowermost branches (Kozlowski et al., 1991). This suggests that following a higher-intensity fire pruning likely would have not affected mortality.

4.2.4. Burn season effects

Exceptionally high mortality following low-intensity spring burns was an unexpected outcome of this study. Even though burning prescriptions were identical, the spring burns killed seven times as many trees as fall burns. Over half of this mortality was delayed more than six months post-burn. Although we were not able to analyze burn season statistically because there were only two stands with spring burns, the concentration of mortality in stands burned in the spring was noteworthy. The reason for the seasonal effect is unclear, but we speculate that it is likely related to a window of spring time vulnerability. Cambial growth is active in the spring, but young trees lack the thick bark to protect what may be seasonally sensitive tissue. However, it is also possible, which is consistent with other studies that have looked at seasonal effects on post-fire mortality in larger size classes (Thies et al., 2005, 2006, 2013; Knapp et al., 2009) that seasonal difference in fire intensity may explain the seasonal differences in mortality. While flame lengths were comparable across seasons, fire damage (Table 2) was higher during spring brings indicating that the two spring fires may have been more intense. Overall, further investigation into the seasonal effects of prescribed burns in young stands is needed. If the high rates of mortality that we observed during the spring season hold true elsewhere, this could lead to an avoidance of spring burns when mortality is not desirable and thus greatly reduce burning windows for young stands. Alternatively, high mortality in especially dense stands may be more acceptable. It may be feasible to plan spring burns in high density stands where a pre-burn thinning treatment was not possible.

4.3. Management applications

Management practices during the establishment phase will have an influence on the feasibility of burning in young stands and resulting levels of mortality. Site preparation practices can

greatly reduce the amount of surface fuel during young stand burns. This is likely to be of significant importance since large diameter fuel can increase local fire intensity and therefore increase mortality. For example, Lezberg et al. (2008) found that sampling burn severity was higher in unscarified treatments, though they did not observe any differences between shelterwood and seedtree prescriptions for ponderosa pine. Prescribed fire may be delayed until pine dominated stands are more mature and develop fire-resistant characteristics, or may be used intentionally as a thinning treatment based upon anticipated mortality. Mechanical treatments as a surrogate for fire in young pine stands may also be a reasonable alternative (Knapp et al., 2012; Kreye et al., 2014).

Pruning trees in young stands prior to burning can decrease mortality, but the cost of pruning is high relative to the modest mortality reductions found here. Pruning may be worthwhile only when managers have a strong impetus to avoid fire-related mortality, or where pruning provides additional benefits. For example, pruning can help to protect all trees from prescribed fire that is administered in stands already at a precise target level of density and spacing. Besides resistance to fire, pruning can fulfill other management objectives such as clearwood production, taper reduction, epicormic sprout reduction, and disease resistance (Keyes and O'Hara, 2002; O'Hara et al., 2010, 2008). For example, in areas of high white pine blister rust incidence, it may be worthwhile to prune sugar pines prior to burning given the modest benefits of pruning on resistance to both fire and white pine blister rust (O'Hara et al., 2010). For giant sequoia, however, pruning would not benefit giant sequoia survival following fire because of the lack of mortality in general. Pruning giant sequoia could, however, meet timber objectives by reducing taper and producing clear wood.

Although avoiding fire mortality during burns in young stands is often a primary goal, the opposite objective of removing some trees may also be desirable. In high density stands, for example, it may be effective to use prescribed fires with relatively high mortality as a tool for thinning and reducing stand density (Wade and Lundsford, 1990). While this can be a cost-effective alternative to mechanical thinning, our results suggest that managers need to be willing to accept high degrees of variability in outcomes following young stand burning when compared to mechanical thinning.

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Appendix A. Regression results tables

See Tables A1–A6.

Table A1
Linear model results fitting percent crown volume consumed with pruning full model. Note that pruning significantly reduced consumed volume. * indicates $p = 0.01–0.05$; ** indicates $p = 0.001–0.01$; *** indicates $p < 0.001$.

Model results: Percent crown volume consumed as predicted by pruning, and DBH					
	Estimate	Std.	Error	t-Value	Pr(>|t|)
(Intercept)	5.22408	2.47891	2.107	0.035643	*
Prune	−8.03489	3.50143	−2.295	0.022214	*
Giant Sequoia	−9.57912	2.59409	−3.693	0.00025	***
Incense-cedar	−0.33424	2.53647	−0.132	0.895225	
Ponderosa pine	−10.12005	2.63898	−3.835	0.000144	***
Sugar pine	−10.65213	2.50138	−4.259	2.51E−05	***
White fir	−7.70245	3.53715	−2.178	0.029964	*
DBH	−0.08118	0.12679	−0.64	0.522324	
HCB	−0.74477	0.37935	−1.963	0.05024	
Stand B	5.32848	1.33289	3.998	7.49E−05	***
Stand C	2.38768	1.42317	1.678	0.094107	
Stand D	0.72704	2.3494	0.309	0.757121	
Stand E	−0.2189	3.53866	−0.062	0.950702	
Stand F	1.29021	2.77995	0.464	0.642795	
Prune × sequoia	8.88123	3.66734	2.422	0.015848	*
Prune × cedar	−0.1501	3.71471	−0.04	0.967786	
Prune × pon. pine	9.73485	3.6837	2.643	0.008517	**
Prune × sug. pine	11.90665	3.74689	3.178	0.001588	**
Prune × white fir	6.10196	4.7706	1.279	0.20154	

Table A2
Young conifer post-burn mortality model results for Full Model with stand as a random effect, 2–3 years following prescription burns. Not statistical significance of pruning associated with increased survival of odds ratio <1, high survival likelihood for giant sequoia, (odds ratio much <1), and low survival for sugar pine (odds ratio >1). This was the regression model used to construct the survival visualization curves. * indicates $p = 0.01–0.05$; *** indicates $p < 0.001$.

	Estimate	Std. error	z value	Pr(>|z|)	Significance	Odds ratio
(Intercept)	−0.69037	0.563094	−1.226	0.2202		
Prune	−0.77556	0.365314	−2.123	0.0338	*	0.460445
PCVS	0.040927	0.006769	6.046	1.49E−09	***	1.041776
Giant sequoia	−2.8169	0.662047	−4.255	2.09E−05	***	0.059791
Incense-cedar	−1.06672	0.540409	−1.974	0.0484	*	0.344137
Ponderosa pine	−0.03354	0.513656	−0.065	0.9479		
Sugar pine	1.323005	0.543369	2.435	0.0149	*	3.754687
White fir	0.165353	0.642673	0.257	0.797		
Prune: PCVS	0.015428	0.010606	1.455	0.1458		
AIC	310.7					

Table A3
Young conifer plantation post-burn mortality model results for full model with DBH and HCB as well as stand as a random effect, one year following prescription burns. Note statistical significance of both pruning and the interaction of pruning with PCVS. * indicates $p = 0.01–0.05$; ** indicates $p = 0.001–0.01$; *** indicates $p < 0.001$.

Mortality full model with stand as a random effect
glmer(bin.mort2 ~ bin.pr * cent.cvb_pct + Spp + cent.dbh + cent.hcb + (1|CompGap), family = binomial, data = dat3)

	Estimate	Std. error	z value	Pr(>|z|)	Significance	Odds ratio
(Intercept)	−1.60	0.74	−2.15	0.0313	*	0.20
Prune	−1.30	0.65	−2.00	0.0460	*	0.27
PCVS	0.03	0.01	5.07	3.96E−0.7	***	1.03
Prune × PCVS	0.04	0.01	2.67	0.0076	**	1.04
Sequoia	−3.90	1.15	−3.40	0.0007	***	0.02
Incense-cedar	−1.03	0.57	−1.82	0.0686		0.36
Ponderosa pine	0.68	0.61	1.11	0.2679		
Sugar pine	1.21	0.57	2.10	0.0356	*	3.34
White fir	−0.32	0.71	−0.45	0.6559		
DBH	0.01	0.03	0.33	0.7449		
HCB	0.03	0.11	0.32	0.7517		
AIC	279					

Table A4
Young conifer plantation post-burn mortality model results for full model with DBH and HCB as well as stand treated as fixed effects, one year post-burn. Note statistical significance of both pruning and the interaction of pruning with PCVS. * indicates $p = 0.01–0.05$; ** indicates $p = 0.001–0.01$; *** indicates $p < 0.001$.

Mortality model with stands as fixed effects
glm(formula = bin.mort2 ~ bin.pr * cent.cvb_pct + cent.dbh + cent.hcb + Spp + CompGap, family = binomial, data = dat3)

	Estimate	Std. Error	z value	Pr(>|z|)	Significance	Odds ratio
(Intercept)	−3.52E+00	9.76E−01	−3.605	0.000313	***	
Prune	−1.27E+00	6.55E−01	−1.937	0.052707		0.28
PCVS	3.19E−02	6.78E−03	4.702	2.58E−06	***	1.03
DBH	1.16E−02	3.52E−02	0.328	0.742881		
HCB	1.42E−02	1.09E−01	0.131	0.895992		
Giant Sequoia	−3.87E+00	1.14E+00	−3.411	0.000646	***	0.02
Incense-cedar	−1.05E+00	5.71E−01	−1.848	0.064594	.	0.35
Ponderosa pine	8.02E−01	6.38E−01	1.257	0.208663		
Sugar Pine	1.23E+00	5.80E−01	2.112	0.034649	*	3.41
White fir	−3.05E−01	7.13E−01	−0.427	0.66903		
Stand B	3.25E+00	8.24E−01	3.943	8.06E−05	***	25.71
Stand C	2.50E+00	8.26E−01	3.023	0.002505	**	12.12
Stand D	2.54E+00	1.02E+00	2.502	0.012365	*	12.67
Stand E	−1.33E+01	1.11E+03	−0.012	0.990506		
Stand F	1.39E+00	1.17E+00	1.187	0.235048		
Prune: PCVS	3.78E−02	1.38E−02	2.727	0.006389	**	1.04
AIC	271.4					

Table A5
Young conifer plantation post-burn mortality model results for full model with DBH and HCB as well as stand as a random effect, 2–3 years following prescription burns. Note lack of statistical significance of both pruning and the interaction of pruning with PCVS. * indicates $p = 0.01–0.05$; *** indicates $p < 0.001$.

Mortality full model with stand as a random effect
glmer(bin.mort3 ~ bin.pr * cent.cvb_pct + Spp + cent.dbh + cent.hcb + (1|CompGap), family = binomial, data = dat3)

	Estimate	Std. error	z value	Pr(>|z|)	Significance	Odds ratio
(Intercept)	−0.54	0.66	−0.83	0.41		0.58
Prune	−0.88	0.54	−1.62	0.10		0.42
PCVS	0.04	0.01	5.91	0.00	***	1.04
Sequoia	−3.12	0.71	−4.39	0.00	***	0.04
Incense-cedar	−1.11	0.55	−2.03	0.04	*	0.33
Ponderosa pine	−0.17	0.58	−0.30	0.77		0.84
Sugar pine	1.24	0.56	2.22	0.03	*	3.46
White fir	0.02	0.67	0.03	0.97		1.02
DBH	−0.02	0.03	−0.68	0.49		0.98
HCB	0.05	0.10	0.44	0.66		1.05
Prune × PCVS	0.02	0.01	1.47	0.14		1.02
AIC	307.5					

Table A6
Young conifer plantation post-burn mortality model results for full model with DBH and HCB as well as stand treated as fixed effects. Note lack of statistical significance of both pruning and the interaction of pruning with PCVS. * indicates $p = 0.01–0.05$; ** indicates $p = 0.001–0.01$; *** indicates $p < 0.001$.

Mortality model with stands as fixed effects
glm(formula = bin.mort3 ~ bin.pr * cent.cvb_pct + cent.dbh + cent.hcb + Spp + CompGap, family = binomial, data = dat3)

	Estimate	Std. error	z value	Pr(>|z|)	Significance	Odds ratio
(Intercept)	−1.76E+00	7.46E−01	−2.36E+00	1.81E−02		
Prune	−8.39E−01	5.50E−01	−1.53E+00	1.27E−01		
PCVS	3.84E−02	6.91E−03	5.56E+00	2.64E−08	***	1.04
DBH	−2.06E−02	3.08E−02	−6.68E−01	5.04E−01		
HC	2.42E−02	1.05E−01	2.31E−01	8.18E−01		
Giant sequoia	−3.15E+00	7.17E−01	−4.40E+00	1.09E−05	***	0.04
Incense-cedar	−1.15E+00	5.63E−01	−2.05E+00	4.04E−02	*	0.32
Ponderosa pine	−9.22E−02	6.04E−01	−1.53E−01	8.79E−01		
Sugar pine	1.21E+00	5.70E−01	2.12E+00	3.44E−02	*	3.34
White Fir	−1.38E−02	6.75E−01	−2.00E−02	9.84E−01		
Stand B	2.40E+00	5.72E−01	4.19E+00	2.79E−05	***	10.97
Stand C	1.56E+00	5.70E−01	2.73E+00	6.41E−03	**	4.74
Stand D	1.33E+00	8.28E−01	1.61E+00	1.08E−01		
Stand E	−1.46E+01	1.13E+03	−1.30E−02	9.90E−01		
Stand F	1.30E+00	8.64E−01	1.50E+00	1.33E−01		
Prune: PCVS	1.65E−02	1.08E−02	1.53E+00	1.27E−01		
AIC	300.8					

References

Agee, J.K., Skinner, C.N., 2005. Basic principles of forest fuel reduction treatments. For. Ecol. Manage. 211 (1), 83–96. http://dx.doi.org/10.1016/j.foreco.2005.01.034.

Alexander, M.E., 1982. Calculating and interpreting forest fire intensities. Can. J. Bot. 60 (4), 349–357. http://dx.doi.org/10.1139/b82-048.

Alexander, M.E., Cruz, M.G., 2012. Interdependencies between flame length and fireline intensity in predicting crown fire initiation and crown scorch height. Int. J. Wildl. Fire 21 (2), 95–113. http://dx.doi.org/10.1071/WF11001.

Collins, B.M., Das, A.J., Battles, J.J., Fry, D.L., Krasnow, K.D., Stephens, S.L., 2014. Beyond reducing fire hazard: fuel treatment impacts on overstory tree survival. Ecol. Appl. 24 (8), 1879–1886. http://dx.doi.org/10.1890/14-0971.1.

Collins, B.M., Kelly, M., van Wagtendonk, J.W., Stephens, S.L., 2007. Spatial patterns of large natural fires in Sierra Nevada wilderness areas. Landscape Ecol. 22 (4), 545–557. http://dx.doi.org/10.1007/s10980-006-9047-5.

Crotteau, J.S., Ritchie, M.W., Varner, J.M., 2014. A mixed-effects heterogeneous negative binomial model for postfire conifer regeneration in Northeastern California, USA. For. Sci. 60 (2), 275–287.

Crotteau, J.S., Varner, J.M., Ritchie, M.W., 2013. Post-fire regeneration across a fire severity gradient in the southern Cascades. For. Ecol. Manage. 287, 103–112.

Engber, E.A., Varner, J.M., 2012. Predicting Douglas-fir sapling mortality following prescribed fire in an encroached grassland. Restor. Ecol. 20 (6), 665–668. http://dx.doi.org/10.1111/j.1526-100X.2012.00900.x.

Fahnestock, George R., Hare, R.C., 1964. Heating of tree trunks in surface fires. J. For. 62 (11), 799–805.

Fowler, J.F., Sieg, C.H., 2004. Postfire Mortality of Ponderosa Pine and Douglas-Fir. A Review of Methods to Predict Tree Death USDA Forest Service General Technical Report RMRS-GTR-132. Rocky Mountain Research Station, Fort Collins, Colorado.

Fulé, P.Z., Swetnam, T.W., Brown, P.M., Falk, D.A., Peterson, D.L., Allen, C.D., Aplet, G. H., Battaglia, M.A., Binkley, D., Farris, C., Keane, R.E., 2014. Unsupported inferences of high-severity fire in historical dry forests of the western United States: response to Williams and Baker. Glob. Ecol. Biogeogr. 23 (7), 825–830. http://dx.doi.org/10.1111/geb.12136.

Goforth, B.R., Minnich, R.A., 2008. Densification, stand-replacement wildfire, and extirpation of mixed conifer forest in Cuyamaca Rancho State Park, southern California. For. Ecol. Manage. 256 (1), 36–45. http://dx.doi.org/10.1016/j.foreco.2008.03.032.

Gonzalez, P., Battles, J.J., Collins, B.M., Robards, T., Saah, D.S., 2015. Aboveground live carbon stock changes of California wildland ecosystems, 2001–2010. For. Ecol. Manage. 348, 68–77. http://dx.doi.org/10.1016/j.foreco.2015.03.040.

Harrod, R.J., Ohlson, P.L., Flatten, L.B., Peterson, D.W., Ottmar, R.D., 2009. A User's Guide to Thinning with Mastication Equipment. USDA Forest Service, Pacific Northwest Region, Okanogan-Wenatchee National Forest.

Kane, J.M., Varner, J.M., Knapp, E.E., 2009. Novel fuelbed characteristics associated with mechanical mastication treatments in northern California and southwestern Oregon, USA. Int. J. Wildl. Fire 18 (6), 686–697. http://dx.doi.org/10.1071/WF08072.

Keyes, C.R., O'Hara, K.L., 2002. Quantifying stand targets for silvicultural prevention of crown fires. West. J. Appl. For. 17 (2), 101–109.

Knapp, E.E., Estes, B.L., Skinner, C.N., 2009. Ecological Effects of Prescribed Fire Season: A Literature Review and Synthesis for Managers General Technical Report No. PSW-GTR-224. USDA Forest Service, Pacific Southwest Research Station.

Knapp, E.E., Varner, J.M., Busse, M.D., Skinner, C.N., Shestak, C.J., 2011. Behaviour and effects of prescribed fire in masticated fuelbeds. Int. J. Wildl. Fire 20 (8), 932–945. http://dx.doi.org/10.1071/WF10110.

Knapp, E.E., Varner, J.M., Busse, M.D., Skinner, C.N., Shestak, C.J., 2012. Behaviour and effects of prescribed fire in masticated fuelbeds. Int. J. Wildl. Fire 20 (8), 932–945.

Kobziar, L.N., McBride, J.R., Stephens, S.L., 2009. The efficacy of fire and fuels reduction treatments in a Sierra Nevada pine plantation. Int. J. Wildl. Fire 18 (7), 791–801. http://dx.doi.org/10.1071/WF06097.

Kozlowski, T.T., Kramer, P.J., Pallardy, S.G., 1991. The Physiological Ecology of Woody Plants. Physiological Ecology. Academic Press, San Diego.

Kreye, J.K., Brewer, N.W., Morgan, P., Varner, J.M., Smith, A.M., Hoffman, C.M., Ottmar, R.D., 2014. Fire behavior in masticated fuels: a review. For. Ecol. Manage. 314, 193–207.

Kreye, J.K., Varner, J.M., Knapp, E.E., 2012. Moisture desorption in mechanically masticated fuels: effects of particle fracturing and fuelbed compaction. Int. J. Wildl. Fire 21 (7), 894–904. http://dx.doi.org/10.1071/WF11077.

Lezberg, A.L., Battaglia, M.A., Shepperd, W.D., Schoettle, A.W., 2008. Decades-old silvicultural treatments influence surface wildfire severity and post-fire nitrogen availability in a ponderosa pine forest. For. Ecol. Manage. 255 (1), 49–61. http://dx.doi.org/10.1016/j.foreco.2007.08.019.

Lyons-Tinsley, C., Peterson, D.L., 2012. Surface fuel treatments in young, regenerating stands affect wildfire severity in a mixed conifer forest, eastside Cascade Range, Washington, USA. For. Ecol. Manage. 270, 117–125. http://dx.doi.org/10.1016/j.foreco.2011.04.016.

Martin, R.E., 1963. A basic approach to fire injury of tree stems. In: Proceedings of the Second Annual Tall Timbers Fire Ecology Conference. Presented at the second annual tall timbers fire ecology conference, USDA Forest Service, Tallahassee, Florida, pp. 151–161.

Millar, C.I., Stephenson, N.L., Stephens, S.L., 2007. Climate change and forests of the future: managing in the face of uncertainty. Ecol. Appl. 17 (8), 2145–2151.

Miller, J.D., Safford, H.D., Crimmins, M., Thode, A.E., 2009. Quantitative evidence for increasing forest fire severity in the Sierra Nevada and southern Cascade Mountains, California and Nevada, USA. Ecosystems 12 (1), 16–32.

Nesmith, J.C., O'Hara, K.L., van Mantgem, P.J., de Valpine, P., 2010. The effects of raking on sugar pine mortality following prescribed fire in Sequoia and Kings Canyon National Parks, California, USA. Fire Ecol. 6 (3), 97–116. http://dx.doi.org/10.4996/fireecology.0603097.

O'Hara, K., Grand, L., Whitcomb, A., 2010. Pruning reduces blister rust in sugar pine with minimal effects on tree growth. Calif. Agric. 64 (1), 31–36.

O'Hara, K.L., York, R.A., Heald, R.C., 2008. Effect of pruning severity and timing of treatment on epicormic sprout development in giant sequoia. Forestry 81 (1), 103–110. http://dx.doi.org/10.1093/forestry/cpm049.

Powers, R.F., Oliver, W.W., 1990. Libocedrus decurrens Torr Silvics of North America, vol. 1. U.S. Department of Agriculture Forest Service, Washington, DC, pp. 173–180.

Reiner, A.L., Vaillant, N.M., Dailey, S.N., 2012. Mastication and prescribed fire influences on tree mortality and predicted fire behavior in ponderosa pine. West. J. Appl. For. 27 (1), 36–41.

Ryan, K.C., Knapp, E.E., Varner, J.M., 2013a. Prescribed fire in North American forests and woodlands: history, current practice, and challenges. Front. Ecol. Environ. 11 (s1), e15–e24.

Ryan, K.C., Rigolot, E., Rego, F.C., Botelho, H., Vega, J.A., Fernandes, P.M., Sofronova, T. M., 2010. Prescribed fire applications in forest and woodlands: Integration of models and field studies to guide fire use. In: 3rd Fire Behavior and Fuels

Conference. Presented at the 3rd Fire Behavior and Fuels Conference, International Association of Wildland Fire, Spokane, Washington.
Ryan, K.C., Knapp, E.E., Varner, J.M., 2013b. Prescribed fire in North American forests and woodlands: history, current practice, and challenges. Front. Ecol. Environ. 11, 15–24.
Safford, H.D., Stevens, J.T., Merriam, K., Meyer, M.D., Latimer, A.M., 2012. Fuel treatment effectiveness in California yellow pine and mixed conifer forests. For. Ecol. Manage. 274, 17–28. http://dx.doi.org/10.1016/j.foreco.2012.02.013.
Shatford, J.P.A., Hibbs, D.E., Puettmann, K.J., 2007. Conifer regeneration after forest fire in the Klamath-Siskiyous: how much, how soon? J. For. 105 (3), 139–146.
Smith, S., 2015. California Conifers: Are Your Trees Susceptible? No R5-PR-O33. Forest Health Protection and USDA Forest Service Pacific Southwest Region, California.
Stark, D.T., Wood, D.L., Storer, A.J., Stephens, S.L., 2013. Prescribed fire and mechanical thinning effects on bark beetle caused tree mortality in a mid-elevation Sierran mixed-conifer forest. For. Ecol. Manage. 306, 61–67. http://dx.doi.org/10.1016/j.foreco.2013.06.018.
Stephens, S.L., Agee, J.K., Fule, P.Z., North, M.P., Romme, W.H., Swetnam, T.W., Turner, M.G., 2013. Managing forests and fire in changing climates. Science 342 (6154), 41–42. http://dx.doi.org/10.1126/science.1240294.
Stephens, S.L., Finney, M.A., 2002. Prescribed fire mortality of Sierra Nevada mixed conifer tree species: effects of crown damage and forest floor combustion. For. Ecol. Manage. 162 (2), 261–271. http://dx.doi.org/10.1016/S0378-1127(01)00521-7.
Stephens, S.L., Moghaddas, J.J., 2005. Silvicultural and reserve impacts on potential fire behavior and forest conservation: twenty-five years of experience from Sierra Nevada mixed conifer forests. Biol. Conserv. 125 (3), 369–379. http://dx.doi.org/10.1016/j.biocon.2005.04.007.
Thies, W.G., Westlind, D.J., Loewen, M., 2005. Season of prescribed burn in ponderosa pine forests in eastern Oregon: impact on pine mortality. Int. J. Wildl. Fire 14 (3), 223–231. http://dx.doi.org/10.1071/WF04051.
Thies, W.G., Westlind, D.J., Loewen, M., Brenner, G., 2006. Prediction of delayed mortality of fire-damaged ponderosa pine following prescribed fires in eastern Oregon, USA. Int. J. Wildl. Fire 15 (1), 19–29. http://dx.doi.org/10.1071/WF05025.
Thies, W., Westlind, D., Loewen, M., 2013. Impact of spring or fall repeated prescribed fire on growth of ponderosa pine in eastern Oregon, USA. West. J. Appl. For. 28 (3), 128–132. http://dx.doi.org/10.5849/wjaf.11-044.
Thompson, J.R., Spies, T.A., Ganio, L.M., 2007. Reburn severity in managed and unmanaged vegetation in a large wildfire. Proc. Natl. Acad. Sci. 104 (25), 10743–10748. http://dx.doi.org/10.1073/pnas.0700229104.
van Wagner, C.E., 1973. Height of crown scorch in forest fires. Can. J. For. Res. 3 (3), 373–378. http://dx.doi.org/10.1139/x73-055.
Wade, D.D., Johansen, R.W., 1986. Effects of Fire on Southern Pine: Observations and Recommendations. Southeastern Forest Experiment Station, Asheville, N.C.
Wade, D.D., Lundsford, J., 1990. Fire as a forest management tool: prescribed burning in the southern United States. Unasylva 41 (3), 28–38.
Weatherspoon, C.P., 1990. Sequoiadendron giganteum (Lindl) in Silvics of North America. In: Agriculture Handbook. U.S. Department of Agriculture Forest Service, Washington, DC.
Weatherspoon, C.P., Skinner, C.N., 1995. An assessment of factors associated with damage to tree crowns from the 1987 wildfires in Northern California. For. Sci. 41, 430–451.
Woolley, T., Shaw, D.C., Ganio, L.M., Fitzgerald, S., 2012. A review of logistic regression models used to predict post-fire tree mortality of western North American conifers. Int. J. Wildl. Fire 21 (1), 1–35.
York, R.A., Heald, R.C., Battles, J.J., York, J.D., 2004. Group selection management in conifer forests: relationships between opening size and tree growth. Can. J. For. Res. 34 (3), 630–641. http://dx.doi.org/10.1139/x03-222.
Züur, A., Ieno, E., Walker, N., Saveliev, A., Smith, G., 2010. Mixed Effects Models and Extensions in Ecology with R. Statistics for Biology and Health. Springer, New York, NY.