RESEARCH ARTICLE

THE EFFECTS OF RAKING ON SUGAR PINE MORTALITY FOLLOWING PRESCRIBED FIRE IN SEQUOIA AND KINGS CANYON NATIONAL PARKS, CALIFORNIA, USA

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ABSTRACT

Prescribed fire is an important tool for fuel reduction, the control of competing vegetation, and forest restoration. The accumulated fuels associated with historical fire exclusion can cause undesirably high tree mortality rates following prescribed fires and wildfires. This is especially true for sugar pine (*Pinus lambertiana* Douglas), which is already negatively affected by the introduced pathogen white pine blister rust (*Cronartium ribicola* J.C. Fisch. ex Rabenh). We tested the efficacy of raking away fuels around the base of sugar pine to reduce mortality following prescribed fire in Sequoia and Kings Canyon national parks, California, USA. This study was conducted in three prescribed fires and included 457 trees, half of which had the fuels around their bases raked away to mineral soil to 0.5 m away from the stem. Fire effects were assessed and tree mortality was recorded for three years after prescribed fires. Overall, raking had no detectable effect on mortality: raked trees averaged 30% mortality compared to 36% for unraked trees. There was a significant effect, however, between the interaction of raking and average pre-treatment forest floor fuel depth: the predicted probability of survival of a 50 cm dbh tree was 0.94 vs. 0.96 when average pre-treatment fuel depth was 0 cm for a raked and unraked tree, respectively. When average pre-treatment forest floor fuel depth was 30 cm, the predicted probability of survival for a raked 50 cm dbh tree was 0.60 compared to only 0.07 for an unraked tree. Raking did not affect mortality when fire intensity, measured as percent crown volume scorched, was very low (0% scorch) or very high (>80% scorch), but the raking treatment significantly increased the proportion of trees that survived by 9.6% for trees that burned under moderate fire intensity (1% to 80% scorch). Raking significantly reduced the likelihood of bole charring and bark beetle activity three years post fire. Fuel depth and anticipated fire intensity need to be accounted for to maximize the effectiveness of the treatments. Raking is an important management option to reduce tree mortality from prescribed fire, but is most effective under specific fuel and burning conditions.

Keywords: bark beetles, fire intensity, GLMM, large tree retention, restoration

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INTRODUCTION

A century of fire exclusion has dramatically shifted forest structure and fuel availability so that many western US forests are more prone to severe fires than in the past (Keeley and Stephenson 2000, Agee and Skinner 2005, Westerling *et al.* 2006, Littell *et al.* 2009). Major efforts have been proposed on a national level to reduce forest fuels to levels closer to what they were prior to large scale fire suppression to reduce the risk of large, severe wildfires (Keeley and Stephenson 2000, Agee and Skinner 2005, Sun 2006). Prescribed fire has been used by land managers as one of the primary tools to achieve these goals (Parsons and Botti 1996, Stephens and Ruth 2005).

Prescribed fire has been used in many different fire-dependent ecosystems and regions as an important tool for forest restoration. Prescribed fire has been used extensively in the ponderosa pine (*Pinus ponderosa* C. Lawson) forests of the southwestern US (Allen *et al.* 2002, Kolb *et al.* 2007), longleaf pine (*Pinus palustris* Mill.) forests of the southeastern US (Varner *et al.* 2005, Lavoie *et al.* 2010), mixed conifer forests of the Pacific Northwest (Agee 1993, Busse *et al.* 2000), and many others. Prescribed fire can alter ecosystem properties and functions including the reduction of fuel loads, altered structure and composition of communities, and enhanced nutrient cycling (Vose 2000, Neary *et al.* 2005). By restoring natural forest processes through prescribed fire, managers can improve forest health, reduce fire hazard, and potentially make forests more resilient to climate change (Mutch and Cook 1996, Covington *et al.* 1997, Millar *et al.* 2007). However, a common concern with prescribed fire, especially after long periods of fire exclusion, is that fire behavior will be outside the historical range due to high fuel loads and changes to forest structure that have occurred during the previous period of fire exclusion (McHugh and Kolb 2003, Varner *et al.* 2005, Kolb *et al.* 2007). Methods to mitigate possible undesired effects of the re-introduction of fire may therefore be warranted.

Among western US conifers, sugar pine (*Pinus lambertiana* Douglas) is a species that has experienced an apparent shift in health due to the change in forest structure and dynamics relating to fire suppression and the invasive pathogen, white pine blister rust (*Cronartium ribicola* J.C. Fisch. ex Raben). Specifically, following >100 years of fire exclusion, sugar pine experiences high mortality in response to fire, a trend displayed by most tree species within the mixed conifer forest type (Mutch and Parsons 1998, van Mantgem *et al.* 2004). Post-fire death of sugar pine is a management concern because the effects of blister rust could be compounded by fire or beetle outbreaks (Paine *et al.* 1998). There is potential for widespread mortality as observed in other white pine species because sugar pine displays moderate to low levels of genetic resistance to this pathogen, which is also continuing to evolve and overcome host resistance (Kinloch and Comstock 1981, Kinloch 1992, Kendall and Keane 2001). When populations are already weakened by blister rust, additional fire-caused mortality could potentially contribute to extirpation, especially in the face of changing climate and fire regimes (van Mantgem *et al*. 2004, Bigler *et al.* 2005, Parker *et al.* 2006). Positive correlations between blister rust and bark beetle activity have also raised concerns that sugar pine may be experiencing elevated levels of beetle activity prior to prescribed fire and that interactions between these pathogens may lead to elevated mortality following fire (Thomas and Agee 1986, van Mantgem *et al.* 2004, Kulakowski and Veblen 2007).

Managers have expressed a need to develop strategies to protect sugar pine from short-term negative effects of fire. Tree mortality from fire can occur from direct effects of the fire such as crown scorching and cambium injury, as well as from indirect effects such as increased beetle activity (Hood 2010). While crown scorch is often ascribed as being the best predictor of tree mortality (Fowler and Seig 2004), cambial injury is also an important contributing factor to mortality (Peterson and Ryan 1986, Hood *et al.* 2007*a*, Kolb *et al.* 2007). Cambial tissues are killed when temperatures reach 60 °C (Dickinson and Johnson 2004). Consumption of fuel, particularly duff due to its potential prolonged release of heat, at the base of the tree, has been found to be an accurate predictor of cambium mortality for ponderosa pine (Ryan and Frandsen 1991). Tree mortality from cambium injury is of particular concern in areas that have experienced long periods of fire exclusion, which allows the depth of forest floor fuels to exceed historical ranges.

One management option is to remove forest floor fuels around the base of individual trees via raking. Raking can alter the effects of fire for individual trees and reduce mortality by decreasing the amount of fine root damage and cambial death that can occur (Swezy and Agee 1991, Haase and Sackett 1998, van Mantgem and Schwartz 2004). Reduced mortality may occur directly as a result of diminished fire injury, or indirectly by decreasing the chance of beetle attack of injured trees following fire (Thomas and Agee 1986, Perrakis and Agee 2006, Breece *et al.* 2008).

Raking was first mentioned as a way to counter undesirably high rates of mortality that occurred following prescribed fires in ponderosa pine forests, especially for large trees (Thomas and Agee 1986, Sackett *et al.* 1996). Raking has been used to reduce localized fuels in many different forest types and regions, including mixed conifer forests in the Pacific Northwest (Swezy and Agee 1991, Perrakis and Agee 2006), ponderosa pine forests in the southwestern US (Fulé *et al.* 2002, Jerman *et al.* 2004, Fowler *et al.* 2010*b*), and longleaf pine forests in the southeastern US (Williams *et al.* 2006). Raking and other methods including leaf blowing are being used more frequently in the western United States with mixed results (Hood 2010). Raking was found to successfully reduce mortality in young ponderosa pine stands by van Mantgem and Schwartz (2004), and in both large and small pine trees by Laudenslayer *et al.* (2008). However, several other studies have found raking to have little effect on tree mortality or stem charring (Fulé *et al.* 2002, Fowler *et al.* 2010*b*).

There are several reasons why the removal of fuels by raking may have produced varied results in previous studies. There has not been a standard depth or width at which raking treatments are applied among studies. Some studies have raked litter and duff away from the base of the stem as little as 0.3 m (Fulé *et al.* 2002), while others have cleared away fuels over continuous large areas up to 0.2 ha (Feeney *et al.* 1998). The depth of raking has also differed dramatically across studies, with some removing all fuels down to mineral soil (Laudenslayer *et al.* 2008), others cleared away only litter (Jerman *et al.* 2004), and others removed the duff but then replaced the litter layer (Covington *et al.* 1997, Kolb *et al.* 2001). At least one study conducted by Williams *et al.* (2006) compared several different treatments, including different methods of fuels removal, and found that all treatments significantly reduced mortality of longleaf pine compared to a control, but the methods did not differ from each other.

Heterogeneous fuels, forest type, and season of burning also affect mortality and the effectiveness of fuels removal treatments (Kaufmann and Covington 2001, Busse *et al.* 2005, Perrakis and Agee 2006). The timing of post-fire mortality assessment has differed between studies, with some studies revisiting trees only one year post-fire, while others have assessed post-fire mortality over several years. Often the cause of mortality was not reported and it can be unclear whether death was caused directly by the fire or another agent such as beetles that invaded after fire. In addition, many of these studies suffered from low sample sizes or included only one replicate per treatment. Studies have also tended to focus on low-severity burns and rarely encompass the range of burn severities that can occur during prescribed fires (Hood 2010).

In this study we tested whether raking away fuels from the base of sugar pine trees could be an effective management approach for reducing mortality following prescribed fire and, if so, under what conditions raking was most effective. Specifically, we tested the effect of raking on tree mortality rates, from direct effects including crown scorch, litter and duff consumption, and stem charring, and indirect effects of post-fire beetle activity. This study examined over 450 trees across three sites within Sequoia and Kings Canyon national parks, California, USA. These parks are ideal locations in which to examine these questions because of their long history of prescribed burning, and because the sites contain large numbers of sugar pine across a wide range of sizes and ages, i.e., old-growth forest conditions.

METHODS

Study Sites

The study was conducted in Sequoia and Kings Canyon national parks in the Sierra Nevada of California. This area is characterized by a Mediterranean climate of wet winters and dry summers with most precipitation falling as snow (Stephenson 1988). Mean annual temperatures within the parks range from a low of 0 °C during the winter to 18 °C during the summer. Soils are generally coarse loams derived from decomposed granite (Huntington and Akeson 1987). Three sites, Cabin Creek, Redwood Canyon, and Wall Spring, were located in old-growth mixed conifer forest spanning an elevation of 1800 m at Redwood Canyon to 2300 m at Cabin Creek.

Cabin Creek is located in Sequoia National Park (36°37’ N, 118°50’ W). Tree species include white fir (*Abies concolor* [Gord. & Glend.] Lindl. ex Hildebr.), red fir (*Abies magnifica* A. Murray), Jeffrey pine (*Pinus jeffreyi* Balf.), sugar pine, and California black oak (*Quercus kelloggii* Newberry). Fuels were categorized as a mix of fuel models 5, 8, 9, and 10 (Anderson 1982). During 8-10 November 2006, 178 ha (435 ac) were prescribe-burned using drip torch and aerial ignitions. Weather and ignition patterns produced a mixture of backing and heading fires. This was the first time this site had burned in at least 60 years. This fire occurred after the first precipitation event of the fall, resulting in relatively high fuel moisture. Winds ranged from 0 km h^{-1} to 8 km h^{-1}, with gust up to 11 km h^{-1}. Minimum relative humidity was 33 % and maximum temperature was 18 °C.

Redwood Canyon is in a giant sequoia-mixed conifer forest located in Kings Canyon National Park (36°42’ N, 118°55’ W) and had last burned in 1970 by a prescribed fire (Kilgore 1973). Tree species included giant sequoia *(Sequoiadendron giganteum* [Lindl.] J. Buchholz*)*, white fir, sugar pine, incense-cedar *(Calocedrus decurrens* [Torr.] Florin*)*, ponderosa pine, and California black oak. Fuels were categorized as a mix of fuel models 8, 9, 10, and 14 (Anderson 1982). The moisture content of the 1000 h fuels three days prior to ignition ranged from 16 % to 31 %. A 250 ha (619 ac) prescribed fire was ignited and burned from 5 to 9 July 2006. Ignition was accomplished through a combination of drip torch and aerial ignitions, which produced a mixture of both backing and heading fires. During the fire, winds ranged from 0 km h^{-1} to 8 km h^{-1}, minimum relative humidity ranged between 26 % and 75 %, and maximum temperature reached 27 °C.

Wall Spring is located in Giant Forest, Sequoia National Park (36°33’ N, 118°46’ W). This site is in a giant sequoia-mixed conifer forest that had not burned in at least 100 years (Caprio and Swetnam 1995). Tree species included white fir, giant sequoia, sugar pine, incense cedar, red fir, ponderosa pine, and California black oak. The site contained fuel models 5, 8, 9, 10, and 14 (Anderson 1982). The site was prescribed burned 30 September through 2 October 2007 using drip torches and a mixture of backing and heading fires. Winds ranged from 3 km h^{-1} to 11 km h^{-1}, minimum relative humidity ranged between 22% and 44%, and maximum temperature reached 20 °C.

Experimental Design

One-hectare plots were randomly located within Cabin Creek (10 plots), Redwood Canyon (10 plots), and Wall Spring (7 plots). Plots in Redwood Canyon were located within an 84 ha area of the 250 ha burn unit to exclude areas with low sugar pine density. Prior to each fire, sugar pine with a diameter at breast height (dbh) $\geq$10 cm were tagged and measured within each plot. Tree size (dbh and height); tree vigor, measured as a visual assessment of crown health following methods developed by Salman and Bongberg (1942); blister rust infection status (present or absent); and beetle activity (present or absent) were recorded. Average litter and duff depth was calculated for each tree by averaging the depth of litter and duff at each cardinal direction at the base of the tree. To reduce soil disturbance and expedite data collection, the maximum duff layer depth was censored at 30 cm. The censoring of the duff depth measurements caused average duff depth to be underestimated in 1% of the trees. These trees with censored data were evenly split between raked and unraked trees, however, so any bias due to the censoring of the data would be similar between raked and unraked trees. Average forest floor fuel depth was also calculated by averaging the total depth of litter, duff, and surface fuels in each cardinal direction.

Raking treatments were assigned by randomly selecting a treatment for the first tagged tree within a plot and then alternating treatments for each successive tree to ensure an equal number of raked and unraked trees within each plot. Raked trees had all the forest floor fuels removed down to mineral soil for a 0.5 m radius around the base of the tree (Figure 1). The forest floor fuels that were removed were scattered broadly in the general vicinity. Trees that were within 0.5 m of other trees, logs, or stumps that could not be removed using fire rakes and loppers were not assigned a treatment and were excluded from the analysis. If other sugar pine trees were within 1 m of a previously tagged tree, they were not assigned a treatment and excluded from the analysis.

Within a month following each prescribed fire, crown scorch (percent of crown volume scorched, maximum scorch height), stem char (percent of basal stem circumference charred, max stem char height), and consumption of litter and duff were measured. Scorch and char heights were measured using an Impulse handheld laser rangefinder (Laser Technologies, St. Paul, Minnesota, USA), and percent crown volume scorch was visually estimated. Litter and duff consumption was measured by using a duff pin placed at the uphill side of the unraked trees at the top of the litter layer prior to fire, measuring from the top of the pin down to any unconsumed litter or duff or mineral soil

Figure 1. A raked tree prior to the prescribed burn in Redwood Canyon, Kings Canyon National Park, California, USA. Forest floor fuels were removed from the base of the tree to mineral soil, to a distance of 0.5 m, using hand rakes and loppers.

following the fire. Duff pins were not installed for raked trees because all of the litter and duff at the base of the tree had been removed. The vigor of each tree and beetle activity were monitored for three summers following the fires. There were several areas within each burn unit that did not burn. Trees within these areas were excluded from the analysis, reducing the final sample sizes to 58, 153, and 246 trees in Cabin Creek, Redwood Canyon, and Wall Spring, respectively, for a total of 457 trees.

Data Analysis

Data were analyzed using the lme4 package (Bates and Maechler 2009) within the R statistical package version 2.11.1 (http://www.r-project.org). Given the hierarchal nature of the data, a generalized linear mixed effects model (GLMM) approach was used. For each model, we first compared the mixed effects model to a generalized linear model containing only fixed effects to evaluate the need for using the more complex GLMM structure. Akaike Information Criterion (AIC) was used to evaluate whether including random effects in the model was necessary, and a change in AIC >2 was used as the cutoff to indicate a meaningful change in model fit (Burnham and Anderson 2002). For all models in which individual trees were used as the sample unit, a GLMM structure in which plot was treated as a random effect nested within the burn unit consistently had a lower AIC score than a general linear model that ignored the spatial autocorrelation of trees within plots.

The analysis focused on several questions including the effect of raking and site conditions on tree mortality, the influence of fire intensity on the effectiveness of the raking treatments, and the effect of raking on post-fire beetle activity. First, we evaluated the effects of raking and pre-fire variables including blister rust infection status, beetle activity, tree vigor, tree height, dbh, average litter, average duff, average forest floor fuel depth, and slope on post-fire tree mortality. An interaction term for each fixed effect with treatment was included in the initial model to test whether the efficacy of the raking treatment was dependent on the state of the other variables. Only pre-treatment variables were included in this model to evaluate under which fuel and forest structure conditions raking would be most effective, independent of fire effects. Change in AIC >2 was used to evaluate whether the removal of any of the fixed effects terms and their interactions substantially reduced model fit.

The effect of fire intensity on the efficacy or the raking treatment was investigated using mixed effects logistic regression. Fire intensity is defined as "the energy released during various phases of the fire" (Keeley 2009), and crown scorch is a commonly used proxy for fire intensity (Van Wagner 1973, Williams *et al.* 1998, Twidwell *et al.* 2009). We used percent crown volume scorched instead of maximum crown scorch height or relative scorch height as our measure of fire intensity because it is viewed as a more accurate assessment of crown scorch (Peterson 1985, Twidwell *et al.* 2009). The effect of fire intensity on raking treatment efficacy was tested by including an interaction between raking and fire intensity category in a GLMM model. Low intensity was defined as trees with crowns that were not scorched ($n = 172$), moderate intensity was defined as trees with percent crown volume scorched between 1% and 80% ($n = 181$), and high intensity was defined as trees with a percent crown volume scorched >80% ($n = 104$). A crown scorch value of 80% was chosen for the high intensity cutoff because this is within the range (75% to 90%) often cited as causing death in conifers (McHugh and Kolb 2003, Fowler *et al.* 2010*a*). A crown scorch value of 0% was chosen for the low intensity category cutoff because this includes all trees that burned under conditions that did not produce enough heat to damage the crown.

We investigated the effect of raking on several measures of fire effects including percent of basal stem circumference charred, maximum stem char height, and post-fire beetle activity. The linear mixed effects model residuals of percent of basal stem circumference charred displayed a highly non-normal distribution, so this modeling approach was not appropriate for these data. The distribution of percent of basal stem circumference charred was u-shaped, with many uncharred trees and many trees with boles that were completely charred at the base. Therefore, the average plot level percent of basal stem circumference charred was calculated and plot was used as the sample unit for this analysis instead of individual trees. A log (x + 1) transformation was applied to meet assumptions of normality. The effect of treatment on percent of the circumference of the bole that was charred was then modeled using multiple linear regression.

Maximum stem char height data displayed a highly skewed distribution with many uncharred trees. We analyzed these data in two steps in which maximum stem char height was first modeled as binary (charred or uncharred) using a logistic GLMM model. The effect of raking on average maximum stem char height was then examined separately using a linear mixed effects model for only those trees that were charred ($n = 273$). This is an approach suggested by Fletcher *et al.* (2005) to model skewed data that have many zeros.

The effect of the raking treatment on presence or absence of beetles was also analyzed with GLMM methods. Fixed effects in the initial model included all the pre-fire variables plus percent crown volume scorched, and an interaction of each with treatment. A drop in AIC >2 was again used to compare model fit between alternative models and to select the final model.

RESULTS

Of the 457 sugar pine trees in the study, 150 (33 %) were dead three years following prescribed burning. Mortality of raked trees averaged 11 %, 46 %, and 24 % compared to 10 %, 43 %, and 38 % for unraked trees at Cabin Creek, Redwood Canyon, and Wall Spring, respectively. Most mortality occurred in the first two years following fire, and average annual mortality had dropped to 2.3 % and 2.9 % for raked and unraked trees, respectively, three years post-fire (Figure 2). Pre-fire tree vigor, dbh, height, blister rust infection status, beetle activity, duff depth, and litter depth were all similar between treatments (Table 1). The pre-fire variables that best predicted tree mortality three years post-fire included burn unit, dbh, average forest floor fuel depth, and treatment (Table 2). Other factors including slope, pre-fire beetle activity, pre-fire tree vigor, and presence of blister rust did not improve model fit. The best fitting model indicated that probability of mortality decreased with increasing dbh and increased with increasing average forest floor fuel depth, and that there was a significant interaction between raking and average forest floor fuel depth (Table 3). Raking had no detectable effect on mortality when average forest floor fuel depth was low, but it significantly reduced mortality when average forest

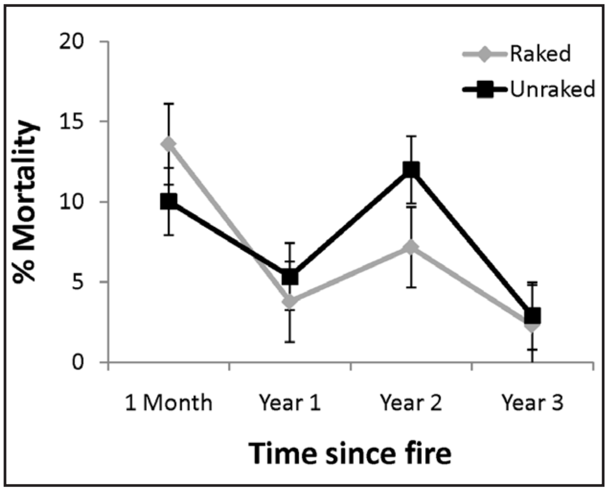

Figure 2. Average annual mortality of sugar pine following prescribed fire in Sequoia and Kings Canyon national parks, California, USA. Health status was assessed one month, and one, two, and three years following a prescribed burn. Whiskers indicate standard errors.

Table 1. Summary of pre-treatment conditions prior to three prescribed fires for raked and unraked sugar pine trees in Sequoia and Kings Canyon national parks, California, USA. *N* is sample size, Vigor is average crown vigor score, Infection is number of trees that displayed symptoms of blister rust, Beetles is number of trees that showed signs of beetle activity, Litter and Duff are the average depth of litter and duff measured at four locations at the base of each tree, respectively. No statistically significant differences were found between raked and unraked trees. Numbers in parentheses are standard deviations.

Burn	*N*	Treatment	dbh (cm)	Height (m)	Vigor	Infection	Beetles	Litter (cm)	Duff (cm)
Cabin Creek	28	Raked	61.7 (43.6)	20.8 (14.1)	1.4 (0.6)	5	0	4.6 (2.8)	5.7 (5.1)
	30	Unraked	59.4 (47.8)	18.6 (13.6)	1.6 (0.6)	3	1	4.4 (3.0)	4.8 (5.6)
Redwood Canyon	76	Raked	58.7 (44.5)	25.9 (16.0)	1.7 (0.9)	22	12	4.1 (2.9)	3.4 (2.3)
	77	Unraked	57.6 (40.9)	26.2 (15.9)	1.5 (0.9)	22	8	3.3 (1.7)	3.3 (2.2)
Wall Spring	122	Raked	34.7 (33.8)	17.5 (14.7)	1.6 (0.8)	33	9	4.7 (3.4)	4.1 (2.8)
	124	Unraked	31.2 (25.0)	16.4 (12.5)	1.6 (0.9)	32	9	4.6 (3.0)	4.3 (3.0)
Average	75 (47)	Raked	51.7 (14.8)	21.4 (4.2)	1.6 (0.2)	20.0 (14.1)	7.0 (6.2)	4.5 (0.3)	4.4 (1.2)
	77 (47)	Unraked	49.4 (15.8)	20.4 (5.1)	1.6 (0.1)	19.0 (14.7)	6.0 (4.4)	4.1 (0.7)	4.1 (0.8)

Table 2. A sample of the models tested to predict three-year post-fire mortality of sugar pine using pre-fire variables. All models were mixed effects logistic regression models in which the random effect was plot. Fixed effects varied by model and included raking treatment (Treat), pre-fire blister rust infection status (InfStatus), pre-fire beetle activity (BeetAct), pre-fire tree vigor (Vigor), burn unit (BurnUnit), average litter depth (Avg.Litter), average duff depth (Avg.Duff), average forest floor fuel depth (Avg.Fuel), dbh, and slope. The model in bold was selected as the final model based on AIC. Log L is the Log likelihood value, K is the number of parameters, and AIC is the Akaike Information Criterion score for each model.

Fixed effects variables	Log L	K	AIC	Δ AIC
Treat×(InfStatus+BeetAct+Vigor+BurnUnit+Avg.Fuel+DBH+Slope)	-212.6	24	475.2	22.0
Treat×(Avg.Litter+Avg.Duff)+BurnUnit+DBH+InfStatus+Vigor+BeetAct	-212.3	22	470.7	17.5
Treat× Avg.Fuel+BurnUnit+DBH+InfStatus+Vigor+BeetAct	-218.2	14	466.3	13.1
Treat×(Avg.Litter+Avg.Duff)+BurnUnit+DBH	-217.8	12	461.7	8.5
Treat×(Avg.Litter+Avg.Duff)+BurnUnit+DBH	-219.2	9	458.4	5.2
Treat×Avg.Duff+Avg.Litter+BurnUnit+DBH	-220.6	8	459.2	6.0
Treat+Avg.Duff+Avg.Litter+BurnUnit+DBH	-221.5	7	459.0	5.8
Treat×Avg.Fuel+BurnUnit+DBH	**-218.6**	**7**	**453.2**	**-**
Treat+Avg.Fuel+BurnUnit+DBH	-220.8	6	455.7	2.5

floor fuel depth was high (Figure 3). The predicted probability of survival of a 50 cm dbh tree at Wall Spring with an average forest floor fuel depth of 0 cm was virtually the same for raked vs. unraked trees (0.94 compared to 0.96, respectively). In contrast, when average forest floor fuel depth was 30 cm, the predicted probability of survival for raked trees was 0.60 compared to 0.07 for unraked trees.

When only large trees with a dbh $\geq$50 cm were considered, the parameters that best predicted three-year post-fire mortality were slightly different and included dbh, average litter depth, and average duff depth. When all trees were used, models that included average forest floor fuel depth consistently had lower AIC scores than models with separate measures of litter and duff depth when the other

Table 3. Mixed effects logistic regression of factors that influenced sugar pine mortality three years post fire in Sequoia and Kings Canyon national parks, California, USA. Fixed effects were burn unit (BurnUnit), dbh, average forest floor fuel depth (Avg.Fuel), raking treatment (Unraked), and the interaction between average forest floor fuel depth and raking treatment. Plot was treated as a random effect. Estimate is the coefficient from the GLMM, with associated standard error (SE) and *P*-value.

Mixed effects logistic regression			
Fixed effect	**Estimate**	**SE**	***P*-value**
(Intercept)	2.191	0.829	0.008
Redwood Canyon	-3.170	0.853	≤0.001
Wall Spring	-1.237	0.868	0.154
Average fuel	-0.076	0.040	0.055
Unraked	0.543	0.523	0.300
dbh	0.034	0.005	≤0.001
Avg. fuel unraked	-0.119	0.056	0.034

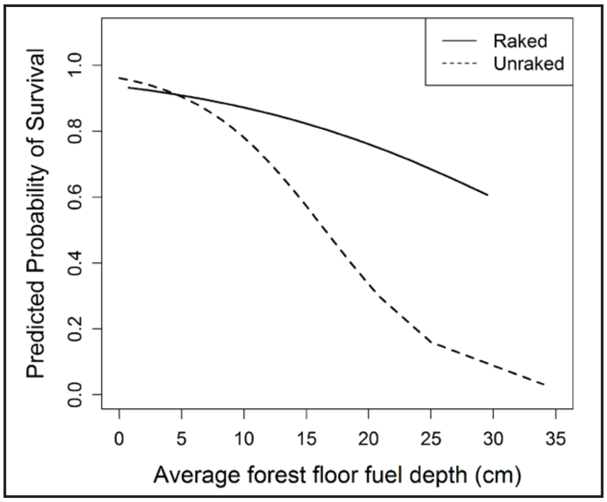

Figure 3. Effect of average forest floor fuel depth on predicted probability of survival of raked vs. unraked sugar pines three years following prescribed fire in Sequoia and Kings Canyon national parks, California, USA, using logistic mixed effects regression. Predicted probabilities assume the site is Wall Spring and dbh is 50 cm.

fixed effects were the same (Table 2). For large trees, however, substituting average duff depth for average forest floor fuel depth in the final model resulted in a lower AIC score (ΔAIC = 2.84).

Raking was more effective at reducing mortality under conditions of moderate fire intensity compared to trees that experienced low or high intensity fire (Table 4). Raking significantly increased the proportion of trees that survived by 9.6% for trees that burned under moderate intensity (1% to 80% crown volume scorched) compared to a small, insignificant increase of 2.9% when fire intensity was low (0% crown volume scorched), or even a reduction of 4.2% in survival when fire intensity was high (81% to 100% crown volume scorched).

Table 4. Effect of fire intensity on raking treatment efficacy for sugar pine in Sequoia and Kings Canyon national parks, California, USA. Three-year post-fire mortality was modeled using logistic mixed effects regression. Trees were assigned to a fire intensity category based on percent crown volume scorched. Low intensity = scorch (percent crown volume scorched) = 0% (*n* = 172), Moderate intensity = scorch between 1% and 79% (*n* = 181), or High intensity = scorch% >80% (*n* = 104). Fixed effects in the models were burn unit, raking treatment, and fire intensity category, and an interaction between raking and fire intensity category. Plot was included as a random effect. Estimate is the coefficient from the GLMM, with associated standard error (SE) and *P*-value.

Mixed effects logistic regression			
Fixed effects	**Estimate**	**SE**	***P*-value**
Intercept	-1.917	0.906	0.034
Redwood Canyon	-1.101	0.672	0.101
Wall Spring	-1.941	0.654	0.003
Unraked	1.141	0.854	0.181
Low intensity	6.563	0.920	<0.001
Moderate intensity	4.861	0.795	<0.001
Unraked: low intensity	-1.393	1.100	0.205
Unraked: moderate intensity	-1.940	0.922	0.035

Raking significantly reduced the occurrence of stem charring, but the effectiveness of raking was dependent on average forest floor fuel depth (Figure 4). The occurrence of stem

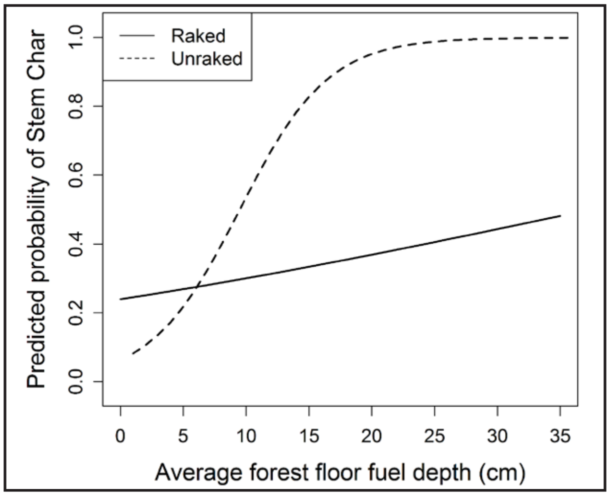

Figure 4. Effect of average forest floor fuel depth on the likelihood of stem char of raked vs. unraked sugar pine three years following prescribed fire in Sequoia and Kings Canyon national parks, California, USA, using logistic mixed effects regression. Predicted probabilities assume that the site is Cabin Creek, dbh is 50 cm, and trees displayed no signs of blister rust infection.

charring was also dependent on burn unit, dbh, and white pine blister rust infection status (Table 5). Interestingly, when only trees that were charred were considered, there was no significant difference between char heights due to raking, or any other factors (linear mixed effects regression, raking coefficient = -0.195, SE = 0.184, P = 0.292), illustrating that the primary effect of raking on stem char was to reduce the likelihood of charring, but not the maximum height of the charring if it did occur. While char height was not affected by raking, average percent of basal stem circumference charred was significantly lower in raked trees (19.4%) compared to unraked trees (59.2%; linear regression, raking coefficient = 1.034, SE = 0.401 P = 0.013).

Post-fire beetle activity was strongly associated with pre-fire beetle activity, burn unit, and raking, and was significantly lower in raked trees compared to unraked trees (Table 6). Beetle activity increased every year after fire, though at a decreasing rate (Figure 5). Raking resulted in a 25%, 22% and 29% drop in beetle activity one, two, and three years post-fire, respectively. Redwood Canyon displayed significantly higher beetle activity two years post-fire, but beetle activity was similar among burn units one and three years post-fire (Table 6).

Table 5. Mixed effects logistic regression results of factors that influenced the occurrence of stem charring on sugar pine three years post-fire in Sequoia and Kings Canyon national parks, California, USA. Fixed effects in the model were burn unit (BurnUnit), white pine blister rust infection status (InfStatus), raking (Unraked), average forest floor fuel depth (Avg.Fuel), dbh, an interaction between raking and forest floor fuel depth, raking and burn unit, and raking and white pine blister rust infection. Plot was treated as a random effect. Estimate is the coefficient from the GLMM, with associated standard error (SE) and P-value.

Mixed effects logistic regression			
Fixed effects	**Estimate**	**SE**	***P*-value**
Intercept	-1.732	0.779	0.026
Redwood Canyon	0.694	0.847	0.413
Wall Spring	-0.648	0.902	0.472
Unraked	-1.264	0.859	0.141
Avg.Fuel	0.031	0.035	0.376
dbh	0.012	0.004	0.003
InfStatus	0.286	0.400	0.475
Unraked: Redwood Canyon	2.622	0.846	0.002
Unraked: Wall Spring	4.525	0.909	<0.001
Unraked: Avg.Fuel	0.254	0.074	<0.001
Unraked: InfStatus	-1.953	0.657	0.003

DISCUSSION

Raking did not detectably reduce mortality when all trees were considered; however, it was effective at reducing mortality under specific conditions. Raking was most beneficial in areas where high levels of forest floor fuels had accumulated. This is consistent with previous studies that found that manipulating fuel depths, particularly duff depth, was an effective way for reducing cambial injury following prescribed fire (Hood *et al.* 2007*b*, Laudenslayer *et al.* 2008). While consumption of the duff

Table 6. Effect of raking treatment on beetle activity one, two, and three years post-fire for sugar pine in Sequoia and Kings Canyon national parks, California, USA. Beetle activity was modeled using mixed effects logistic regression. Fixed effects were burn unit (BurnUnit), raking treatment (Unraked), and pre-fire beetle activity (Beetles). Plot was treated as a random effect. Estimate is the coefficient from the GLMM, with associated standard error (SE) and *P*-value.

	Year 1			**Year 2**			**Year 3**		
Fixed effects	**Estimate**	**SE**	***P*-value**	**Estimate**	**SE**	***P*-value**	**Estimate**	**SE**	***P*-value**
Intercept	-1.436	0.427	<0.001	-1.532	0.393	<0.001	-1.124	0.414	0.007
Redwood Canyon	0.669	0.503	0.183	1.174	0.446	0.008	0.495	0.497	0.320
Wall Spring	-0.599	0.520	0.249	-0.075	0.451	0.869	-0.422	0.509	0.407
Unraked	0.552	0.231	0.017	0.469	0.217	0.031	0.615	0.216	0.004
Beetles	2.198	0.406	<0.001	1.726	0.390	<0.001	2.250	0.431	<0.001

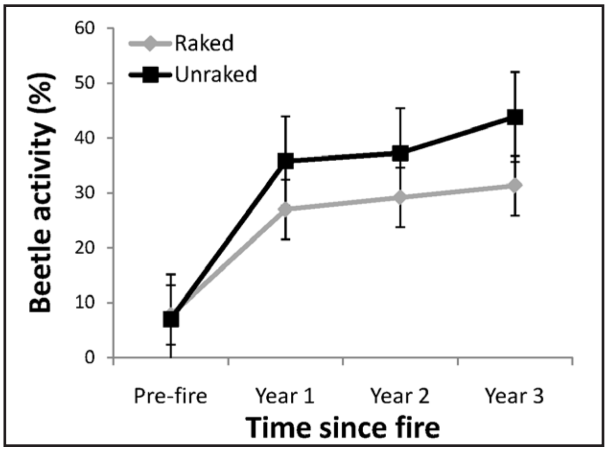

Figure 5. Average proportion of raked and unraked sugar pine trees that displayed signs of beetle activity following prescribed fire in Sequoia and Kings Canyon national parks, California, USA. Whiskers indicate standard errors.

layer has been shown to be an important factor causing tree mortality due to its sustained release of heat at the base of the tree (Ryan and Frandsen 1991, Varner *et al.* 2007), we found a better relationship between mortality and average forest floor fuel depth (combined average depth of duff, litter, and surface fuels) than average duff depth alone. One possible explanation for this is that there were many small trees in our study as our minimum dbh threshold for raking was 10 cm. Therefore, the combustion of deep litter layers and small surface fuels, as well as duff, may have created enough heat to damage the cambium of smaller trees with thinner bark, increasing the importance of the litter layer and small surface fuels compared to studies that focused only on large trees. Indeed, when only large trees (dbh ≥ 50 cm) were considered, average duff depth was a better predictor of mortality than average forest floor fuel depth. Some of the effect of average forest floor fuel depth on mortality may have been better explained by larger spatial scale variation in fuel loads and ladder fuels that were not captured at the individual tree scale. However, fuel loads varied widely among plots, even within the same burn unit, and some of this plot level variation in fuel loads would have been captured as plot level random effects in the models.

Along with average forest floor fuel depth, the effectiveness of the raking treatment varied by site. Each site was different in respect to topography, exposure, time since last burn, and timing of the burn. These differences led to burn severities that varied substantially among sites and greatly influenced sugar pine mortality rates. Where fire intensity was high, as at Redwood Canyon, the usefulness of the raking treatment was reduced, resulting in little difference in mortality between raked and unraked trees. The main source of mortality following fire is often attributed to crown scorch (Ryan and Reinhardt 1988, Keyser *et al.* 2006), and raking does little to mitigate this. When fire intensity was low, most trees survived, regardless of whether the duff and litter were removed from the base, and the raking treatment provided little benefit, as at Cabin Creek. Several studies that used fuels treatments under low intensity burns also found no difference in mortality rates between treated and untreated trees (Swezy and Agee 1991, Fulé *et al.*2002) . The largest difference in mortality between raked and unraked trees in this study was at Wall Spring, which displayed moderate fire intensity compared to the other two sites. The interaction between treatment efficacy and fire intensity provides a mechanism to explain the mixed results of the effect of raking on reducing tree mortality that have been reported in the past. By measuring multiple fires that differed in fire intensity, this study demonstrated that treatment effects on mortality are not uniform across different fire intensities, and that it is important to account for this factor when assessing the effects of raking treatments on mortality.

There were no significant interactions between the raking treatment and factors associated with pre-fire tree health, including beetle activity, blister rust infection status, and crown vigor in terms of the effect of raking on post-fire tree mortality. Therefore, the effectiveness of the raking treatment did not vary significantly due to pre-fire tree health. Other research, however, has found that tree health, measured as annual growth rate, was a significant predictor of mortality following fire (van Mantgem *et al*. 2003). More research is needed to identify the extent to which pre-fire tree health controls post-fire mortality and how this may influence the effectiveness of raking.

Raking significantly reduced the occurrence of stem charring, and the magnitude of the effect of the raking treatment was influenced by blister rust infection status, average forest floor fuel depth, and burn unit. One of the symptoms of blister rust is cankers that often exude large quantities of pitch. The interaction of blister rust infection status and raking may be caused by unraked infected trees having highly flammable pitch on the main bole, leading to a higher likelihood of stem charring. By reducing the occurrence of stem charring, raking can reduce mortality rates directly by reducing cambium necrosis as well as indirectly by reducing a tree's susceptibility to beetle attacks (Ferrell 1996, Bradley and Tueller 2001). Stem charring may facilitate beetle attacks by reducing tree defenses such as bark thickness and resin production immediately following fire (Wallin *et al.* 2003, Yongblood *et al.* 2009, Fettig *et al.* 2010). While most beetle activity that was observed occurred in the charred areas of the lower bole, possibly by red turpentine beetle (*Dendroctonus valens* LeConte), which is rarely a direct cause of mortality, beetle attack often occurs by multiple species simultaneously (Breece *et al.* 2008, Wallin *et al*. 2008), and the presence of the red turpentine beetle has been found to be associated with western pine beetle (*Dendroctonus brevicomis* LeConte) in ponderosa pine (Perrakis and Agee 2006). Raking reduced beetle activity significantly following fire, which may lead to further differences in mortality between raked and unraked trees in the future as trees recently attacked by beetles continue to die.

Raking away forest floor fuels at the base of sugar pine reduced the occurrence of stem charring and beetle activity following prescribed fire. These factors contributed to a reduction in mortality associated with raking treatments. Raking was particularly effective when forest floor fuel depth was high. While dbh was a significant predictor of average duff depth, in our study, the correlation between them was low (adjusted R^2 = 0.27, 0.03, and 0.06 at Cabin Creek, Redwood Canyon, and Wall Spring, respectively). It is often the large trees that accumulate these deep duff and litter layers at their bases without the occurrence of fire because of the large amount of bark and needles that they drop annually. These are also the trees that managers are often most concerned about losing during prescribed fire. Targeting large trees for raking treatments may therefore be a simple and effective way to increase probability of survival.

While raking can be used on the scale of some prescribed burns, the time and resources that would be needed to apply raking at a landscape scale are not available in most situations, and other methods of reducing sugar pine mortality should be considered. Also, there are situations in which burn severity is expected to be relatively high, or fuel levels are already low, reducing the effectiveness of raking, and alternative treatment options would be more appropriate. Other possible treatment options include pruning (Brown *et al.* 2004), thinning (Stephens and Moghaddas 2005), modifying ignition techniques (McCallum 2009), changing season of burn (Swezy and Agee 1991), and shortening the time interval between burns (He and Mladenoff 1999). Pruning raises the distance to the base of the live crown, which can reduce the potential for crown fire spread (Keyes and O'Hara 2002). Reducing fuels through thinning treatments when combined with prescribed fire has been well documented as an effective method for reducing mortality (Harrod *et al.* 2009, Schwilk *et al.* 2009, Stephens *et al.* 2009). However, this method may not be an option in many areas like national parks and wilderness areas.

Thinning, pruning, and raking all require a substantial investment of resources to carry out and will often not be realistic options at the landscape level. Therefore, it is important to also consider simple changes in the timing and methods of prescribed fire ignition as potential methods of reducing mortality at a larger scale without required additional treatments. Burning during the winter when trees are dormant has been shown to reduce the effects of crown scorch, and burning under wetter fuel conditions can reduce fire intensity (Swezy and Agee 1991, Harrington 1993, Thies *et al.* 2005). However, there may be unintended ecological consequences for burning outside of the historical fire season, though these effects are often minor when compared to the alternative of taking no action at all (Knapp *et al*. 2009). In addition, burning under conditions when duff has high moisture content can result in low duff consumption, so that fuel reduction goals are not met (Hille and Stephens 2005). For restoration purposes, the benefits of reintroducing fire often outweigh any potential negative impacts for burning outside of the normal fire season. Changing firing patterns offers some promise for reducing mortality as well. Backing fires often burn at lower intensity than heading fires (Finney 2001). However, backing fires may produce higher levels of duff and litter consumption than heading fires due to a slower rate of spread, leading to a possible trade-off between fire intensity and fire severity, depending on ignition method. Once fire has been re-introduced to an area, maintaining a shorter fire return interval can also reduce fire intensity and result in increased survival, especially of the larger trees.

Raking treatments can be an efficient and relatively quick method for decreasing sugar pine mortality following prescribed fire. Raking rarely took longer than five minutes per tree and can be performed with the same tools that are commonly used to prepare the site for a prescribed fire. Raking time increased with increasing tree size and fuel depth. Hood *et al.* (2007*b*) found that raking took 16 min per person on average for large Jeffrey pine in California, and raking time increased with duff depth. Raking may not be appropriate under all conditions and Swezy and Agee (1991) and Kolb *et al.* (2007) have suggested that raking may negatively affect tree heath by killing fine roots within the duff layer. To avoid this, raking has sometimes been carried out at least one year prior to the fire to allow trees to recover from the loss of fine roots removed by raking and develop new roots deeper in the soil (Hood 2010). This may be less of a concern in ponderosa and Jeffrey pine forests, in which Noonan-Wright *et al.* (2010) found no negative effects of raking on growth rate and mortality in the absence of fire.

With relatively little additional cost or training of crews, raking may be a viable option for managers concerned about sugar pine survival following prescribed fire. However, is the potential increase in survival worth the additional effort expended or increased cost? In this study, the average size of the three prescribed fires was 166 ha and averaged 18 treatable (>10 cm dbh; could be raked) sugar pine per hectare resulting in an estimated 3000 sugar pine per fire. If it is assumed that average forest floor fuel depth must be at least 15 cm for raking to cause a meaningful change in probability of survival, this limits the pool of trees that would be considered for treatment. We found that raked trees with average forest floor fuel depth of 15 cm were 25 % more likely to survive than unraked trees, and roughly 10 % of the trees in our study met this criterion. The average fuel depth of these trees was 18.2 cm. Fire intensity is inherently patchy, however, and trees often burn under very low or very high fire intensity, in which the effect of the treatment does not affect mortality. For example, 228 of our 457 trees (50 %) had crown volume scorched values of either 0 % or 100 %. If we assume that half of the estimated 300 trees being considered for raking will burn under moderate fire severity, we can predict that the treatment will be effective for 150 of them. Our model predicts a 50 % greater probability of survival for raked vs. unraked trees (85 % vs. 35 %) when average fuel depth is 20 cm. This implies survival of 128 of 150 trees compared to only 53 trees surviving without the raking treatment. Therefore, of the 300 trees that we would have chosen to treat, we can estimate that raking will prevent the death of 75 trees. It will depend on the specific objectives of the manager to decide whether this potential increase in survival is worth the added cost and effort of raking. Managers should also consider the specific conditions of their site and the expected fire severity to evaluate the merits of raking. Due to the host of interacting factors that influence the efficacy of raking on reducing mortality, the impact of raking on post-fire mortality will likely continue to be mixed, depending on the specific site conditions and fire behavior patterns under which raking is applied (Fowler *et al.* 2010*b*, Hood 2010).

Raking was an effective means of reducing sugar pine mortality following prescribed fire under specific conditions. Raking had little effect on mortality when average forest floor fuel depth was low, but significantly reduced mortality when it was high. In addition, raking had little effect on mortality when fire intensity was low, as most trees survived regardless of raking. When fire intensity was high, raking did little to mitigate mortality. However, when fire intensity fell between these two extremes, raking was an effective method for reducing post-fire mortality. By measuring the effects of raking on mortality across a wide range of burn severities over multiple prescribed fires, we were able to demonstrate this interaction between fire intensity and the efficacy of raking treatments, and provide a mechanism to explain the contradictory results of previous studies. Along with the direct effect of raking on reducing stem charring, raking may also help prevent additional post-fire mortality from beetle attacks as beetle activity was significantly lower in raked trees compared to unraked trees following fire. The differences in mortality between raked and unraked trees may therefore become even larger over the next few years as beetle-attacked trees continue to die (Agee 2003).

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