Research Article

Prescribed Burning in Ponderosa Pine: Fuel Reductions and Redistributing Fuels near Boles to Prevent Injury

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ABSTRACT

Fire suppression and other factors have resulted in high wildfire risk in the western US, and prescribed burning can be an effective tool for thinning forests and reducing fuels to lessen wildfire risks. However, prescribed burning sometimes fails to substantially reduce fuels and sometimes damages and kills valuable, large trees. This study compared fuel reductions between spring and fall prescribed burns and tested whether removing (i.e., raking) fuels within 1 m of boles reduced fire damage to ponderosa pine (*Pinus ponderosa* Douglas ex Lawson & C. Lawson). In 2007 and 2008, raking was applied to alternating trees along 18 transects in central Oregon, USA. Fuels surrounding 292 trees were burned in fall 2010, and fuels surrounding 216 trees were burned in spring 2012. Both seasons of burn affected most fuel size classes similarly, with one

RESUMEN

La supresión de incendios y otros factores han resultado en un alto riesgo de incendios en el oeste de los EEUU, y las quemas prescriptas pueden ser una herramienta efectiva para ralear los bosques, reducir los combustibles y disminuir así el riesgo de incendios. Por supuesto, algunas veces las quemas prescriptas fallan en reducir sustancialmente los combustibles y también pueden quemar árboles valiosos. Este estudio compara las reducciones entre quemas prescriptas llevadas a cabo en otoño y primavera y trata de probar si la remoción de combustibles (por ejemplo por rastrillado) dentro del perímetro de 1 m alrededor de los troncos reduce el daño por fuego al pino ponderosa (*Pinus ponderosa* Douglas ex Lawson & C. Lawson). En 2007 y 2008, el rastrillado fue aplicado alternativamente a árboles ubicados en 18 transectas en el centro de Oregon, EEUU. Los combustibles que rodeaban a 292 árboles fueron quemados en otoño de 2010 y los que rodeaban a 216 árboles fueron quemados en primavera de 2012. Ambas estaciones de quema afectaron la mayoría de las clases de combustible de manera similar, con la

exception being duff, which was more fully consumed in fall than in spring. Where fall burning occurred, raking reduced the percentage of dead cambium samples from 24.3 ±4.9% to 6.4 ±3.0% (point estimates ±95% confidence intervals), in addition to reducing bole scorch. Conversely, where spring burning occurred, injury of not-raked trees was milder, so raking did not have the potential to greatly reduce damage. Redistributing fuels away from boles would be more beneficial under relatively dry conditions when duff is prone to extensive smoldering. Our study and most other studies suggest that duff is, on average, drier in fall than in spring, so raking would tend to afford more protection from fall burns than from spring burns. The little tree mortality that occurred was split nearly evenly between raked trees (25) and not-raked trees (30), so raking did not appreciably increase survival in this study. However, the finding that raking reduced injury suggests that it may reduce mortality from more intense burns.

excepción del mantillo, que fue mucho más consumido en otoño que en primavera. Cuando la quema fue en otoño, el rastrillado redujo el porcentaje de muerte del cambium de las muestras del 24.3 ±4.9% al 6.4 ±3.0% (estimaciones medias ± 95% intervalo de confianza), reduciendo además el quemado del tronco. De manera inversa, cuando las quemas fueron en primavera, las heridas a los árboles no rastrillados fue menor, lo que implicó que el rastrillado no tuvo el potencial de reducir el daño por quema. La redistribución de los combustibles lejos de los troncos podría entonces ser más beneficiosa bajo condiciones relativamente secas, cuando el mantillo tiende a permanecer ardiendo por mucho tiempo. Nuestro estudio, así como otros, sugieren que, en promedio, el mantillo está más seco en otoño que en primavera, por lo que el rastrillado tenderá a brindar mayor protección en fuegos de otoño que aquellos que ocurren en primavera. La escasa mortalidad de árboles ocurrida fue dividida en mitades casi iguales entre árboles rastrillados (25) y no rastrillados (30), por lo que en este estudio, el rastrillado no incrementó significativamente la supervivencia de los árboles. Por supuesto, el resultado de que el rastrillado reduce el daño por heridas sugiere que esta técnica puede reducir la mortalidad en el caso de quemas intensas.

Keywords: bark char, fuels reduction, ponderosa pine, post-fire mortality, prescribed fire, raking, season of burn, tree protection

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INTRODUCTION

Fire suppression has led to high accumulations of fuels over millions of hectares of seasonally dry forests in the western United States (Parsons and DeBenedetti 1979). Consequently, recent wildfires have tended to be larger and more severe (McKenzie *et al.* 2004), and this trend may continue as climates become warmer and drier. Prescribed burning is often used to reduce fuel as well as encourage tree regeneration; improve wildlife habitat; control weeds, insects, and diseases; and maintain biodiversity (e.g., Wallace *et al.* 1997, Abella and Springer 2015). Where prescribed burning effectively reduces fuels, subsequent wildfires have reduced severities, flame lengths, and crown ignitions so that they are less damaging to trees and easier to control (Fernandes and Botelho 2003, Kent *et al.* 2015).

Unfortunately, prescribed burning effects on fuels vary widely, and prescribed burns do not consistently cause the large reductions in fuels needed to reduce severity, frequency, and extent of future wildfires (e.g., Fonda and Binney 2011, Price *et al.* 2015). For example, Kauffman and Martin (1989) found fuel reductions ranged from 15% to 92% at mixed-conifer sites in northern California, USA. In addition to varying among burns, fuel reductions can also vary widely among fuel size classes within burns (e.g., Vaillant *et al.* 2015). For example, Vaillant *et al.* (2009) found that 100-hour fuels were reduced 10% to 50% while 1-hour fuels were reduced 90% to 98% in California stands of firs and pines. Fuel moisture contents are a critical factor in explaining variation in prescribed fire effects on fuels, although factors such as wind speed, slope, and temperature also play a role (Fernandes *et al.* 2008). A potential strategy for increasing fuel consumption involves timing prescribed fires to periods when fuel moisture contents are appropriately low (Varner *et al.* 2007). In the western US, fuels tend to be covered by snow in winter and dangerously dry and flammable in summer, so prescribed burns typically occur in spring and fall. A few studies have found that fall burns outperformed spring burns at reducing fuels, presumably because fuels were drier during fall (Knapp *et al.* 2005, Perrakis and Agee 2006, Fettig *et al.* 2010). For example, in ponderosa pine (*Pinus ponderosa* Douglas ex Lawson & C. Lawson) and Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) stands of the southern Sierra Nevada Mountains, California, USA, Stephens *et al.* (2009) found nearly four times as much 1-hour, 10-hour, and 100-hour fuels remaining after spring burns than after fall burns. However, Kauffman and Martin (1989) found that late spring burns reduced litter and duff more effectively than late fall burns, illustrating that fuels are not universally drier and more extensively consumed in fall than in spring. Fuel moisture is difficult to measure at the time of burning and even more difficult to predict ahead of time when planning burns (Engber *et al.* 2013, Varner *et al.* 2016). Therefore, because it is difficult to plan burns based on fuel moisture data, additional studies comparing fuels reductions between spring burns and fall burns will be useful for determining if managers should favor one of these seasons over the other when planning fuels reduction treatments.

A potential problem with prescribed burning in any relatively dry period is that combustion of large quantities of litter and duff near boles can damage or kill cambium (e.g., Ryan and Frandsen 1991) and fine roots (e.g., Swezy and Agee 1991), thereby killing valuable (i.e., large) trees (Kolb *et al.* 2007, Varner *et al.* 2007). In addition to killing trees directly, heat damage can render trees more susceptible to mortality from drought, diseases, and insects (Wyant *et al.* 1986, Hood *et al.* 2015). One idea for reducing heat damage and mortality has been to use rakes or leaf blowers to redistribute litter and duff away from boles prior to burning. Since the time this strategy was first considered, however, there has been concern that raking might mechanically injure fine roots, and that removing fine fuels might increase evaporation and drought stress, in which case raking might have net negative effects even if it does reduce heat damage. To test this, Noonan-Wright *et al.* (2010) compared growth and mortality of raked and not-raked ponderosa and Jeffrey pines in the absence of fire in northern California. Five years post raking, the authors found no significant effect of raking on growth rate or mortality, suggesting that this practice is not particularly damaging to trees. A few studies have compared prescribed burning damage and mortality between raked and not-raked trees. Swezy and Agee (1991) found that raking away fuels did not significantly affect heat damage to ponderosa pines in southern Oregon, USA. Conversely, Fowler *et al.* (2010) found that redistributing fuels with rakes and leaf blowers reduced heat damage to ponderosa pine cambium in northern Arizona, USA, and Hood

(2007) found that raking reduced ponderosa and Jeffrey pine cambium injury and red turpentine beetle (*Dendroctonus valens* LeConte) infestation in the northern Sierra Nevada Mountains of California. Raking did not reduce mortality in these studies because litter and duff consumption was too limited to kill trees. Conversely, in a California study of sugar pine (*Pinus lambertiana* Douglas) forests, Nesmith *et al.* (2010) observed appreciable mortality of not-raked trees (i.e., 36%). These authors found a similarly high mortality rate among raked trees (i.e., 30%), suggesting that raking would be of minor benefit in these forests. However, prior to and following burning, trees of this study were appreciably impacted by white pine blister rust (*Cronartium ribicola* J.C. Fisch. ex Rabenh) and bark beetles (Curculionidae: Scolytinae), so the high mortality in this study may have been caused by these factors instead of fire damage. If so, then Nesmith *et al.* (2010) may represent another case in which fire intensity was too low for raking to be effective.

To date, no individual studies have measured both fuel consumption and effects of raking, so it is unclear whether or not raking can protect trees under burn conditions amenable to reducing fuels. In this central Oregon study of large ponderosa pines, we measured changes in fuels and tree damage and mortality after imposing a raking treatment and two burn treatments (i.e., spring burn and fall burn). One objective in burning in both spring and fall was to add to existing data comparing fuel reductions between these seasons. Our other objective was to quantify how effects of raking change with increasing fuel consumption, and burning in both spring and fall elevated our chances of being able to study raking under a range of fuel consumption levels. We hypothesized that raking would reduce heat damage in fall more than in spring, because litter and duff left in place near the bole would have lower moisture contents in fall and thus cause more heating (Varner *et al.* 2007). A better understanding of how effects of raking change with increasing fuel consumption should help managers determine when and where raking treatments will be potentially useful for reducing tree damage.

METHODS

Between the summers of 2007 and 2008, 508 circular fuel measurement areas (hereafter, plots) containing one centrally located ponderosa pine ≥15 cm DBH (diameter at breast height) were established along 18 transects placed at random across the study area, subject to the constraint that they did not overlap, in the Malheur National Forest in central Oregon (~44° 07′ 05.88″ N, 118° 54′ 52.10″ W; Figure 1). Historically, the area has received periodic selective logging, thinning, and cattle grazing every year for several decades, but has been subjected to no prescribed burning or documented large wildfires. Plot sizes varied with tree sizes. Specifically, plot radii were set equal to the drip line of the focal tree (Figure 2), with the drip line assumed to be 3.4 m, 3.8 m, 4.8 m, and 5.4 m from the bole of trees measuring 15 cm to 35 cm, >35 cm to 38 cm, >38 cm to 56 cm, and >56 cm DBH, respectively (Hann 1997). Alternating

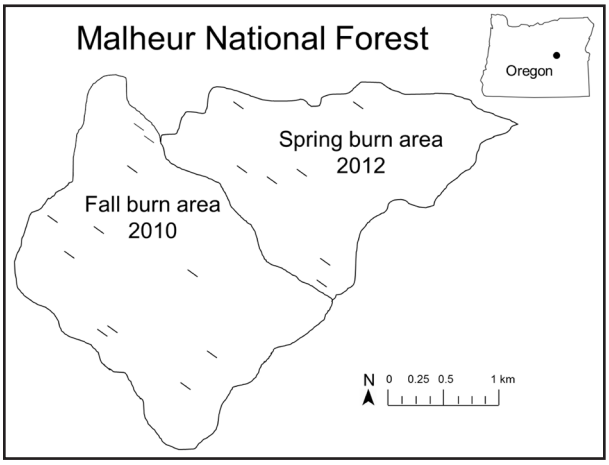

Figure 1. Locations of transects (lines) in this prescribed burn study. Dot on inset indicates location of the study in Oregon, USA.

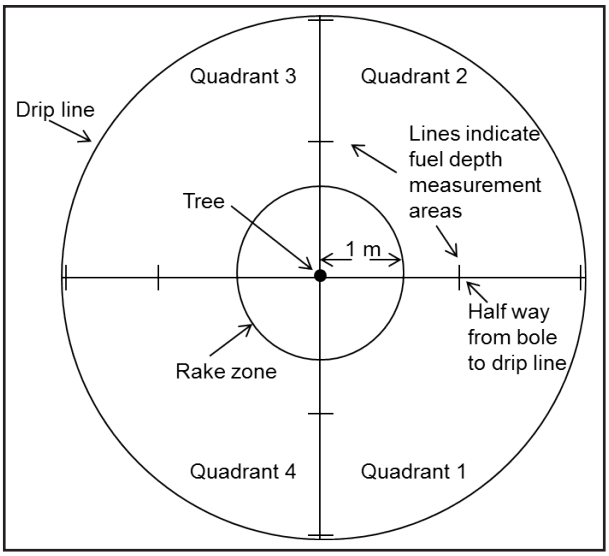

Figure 2. Layout of plots for a prescribed burning study. Fuels were removed from the rake zone. Then, litter and duff depths were measured at the eight indicated positions, and larger fuels were measured in the four quadrants.

trees along transects received raking to remove fuels within 1 m of the bole (hereafter, the rake zone).

To allow for recovery of fine roots potentially injured by raking, fall prescribed burning occurred three years after raking and spring burning occurred four years after raking. Plots surrounding 292 trees along 11 transects were burned in fall (on 13 October 2010 or 20 October 2010), and plots surrounding the remaining 216 trees along seven remaining transects were burned in spring (on 13 May 2012 or 15 May 2012). Drip torches were used as needed to burn the fall and spring burn areas (Figure 1). Temperature, relative humidity, and wind speed ranges for fall and burns were 14 °C to 18 °C, 17% to 37%, and 1.6 km hr^{-1} to 8.0 km hr^{-1}, respectively. Temperature, relative humidity, and wind speed ranges for spring burns were 19 °C to 26 °C, 16% to 27%, and 0.0 km hr^{-1} to 8.0 km hr^{-1}, respectively. Visual estimates of flame heights were similar for both burns (~30 cm to 60 cm).

Fuels were measured just after raking and again just after burning using the following methods. The litter and duff layer was measured at eight points surrounding each tree (Figure 2). Raking completely removed larger fuels from the rake zone, but it was not feasible to completely remove very fine duff. Consequently, just after raking, ~3 cm of duff remained in rake zones surrounding raked trees, compared to ~8 cm surrounding not-raked trees. In accordance with Fosberg and Deeming (1971) and Cohen and Deeming (1985), sticks measuring >0 cm to 0.6 cm, >0.6 cm to 2.5 cm, >2.5 cm to 7.6 cm, >7.6 cm to 15.24 cm, and ≥15.25 cm diameter at their centers were classified as 1-hour, 10-hour, 100-hour, and ≥1000-hour fuels, respectively. For ≥1000-hour fuels, numbers, diameters, and lengths of logs were measured within each quadrant (Figure 2). For other fuel size classes, numbers, diameters, and lengths were estimated by measuring one 1.0 m^2 frame randomly placed within each quadrant outside the rake zone (Figure 2). Litter and duff depths were converted to Mg ha^{-1} using the bulk density conversion of van Wagtendonk *et al*. (1998), and other fuels were converted to Mg ha^{-1} by converting stick count, length, and diameter data to volumes and applying the specific gravity conversions of Brown (1974).

Tree damage following fall and spring burns was measured in the summers of 2011 and 2012, respectively. The maximum height of bole scorch, a visual bole scorch rating, and cambium mortality were recorded for each tree quadrant (Figure 2). Bole scorch ratings of 0 to 3 were assigned to trees with (0) no evidence of fire damage, (1) light scorching of bark edges, (2) bark surface uniformly scorched except deep fissures, and (3) fire damage beneath the bark surface (Ryan 1983, Ryan and Noste 1985). To assess cambium mortality, a drill fitted with a 2.54 cm (diameter) hole saw was used to extract a sample 2 cm above mineral soil level in the four tree quadrants. Trees were evaluated annually for

three years post burn for spring burns and for four years post burn for fall burns to assess delayed mortality from heat damage and bark beetles.

Analysis

Bole scorch rating, bole scorch height, and percent crown scorch were zero for substantial numbers of trees. To accommodate the mixtures of zeros and continuous data, we modeled responses of each tree using a common two-stage modeling approach (Gelman and Hill 2007). The first-stage models estimated the probabilities tree damage variables were non-zero, and the second-stage models estimated damage variables conditional on them being non-zero. The first-stage models were mixed effects probit models for binary data (Albert and Chib 1993), and the second-stage models were mixed effects linear models with responses transformed to natural logarithms. Both models included transects as random effects and hill slope, DBH, total fuel within the drip line, raking, season of burn, and raking × season of burn interactions as fixed effects. Extensive zeros precluded use of the two-stage model for analyzing the cambium mortality data, so bootstrap confidence intervals were used to estimate percent cambium mortality for raked and not-raked trees that burned in spring and in fall (Efron and Tibshirani 1993). To estimate prescribed burning effects on the various fuel size classes, we calculated average post-burn fuels minus average pre-burn fuels for each transect and fit a multivariate linear regression with season of burn as a predictor. We constructed FORTRAN programs to fit the models (Intel Corporation 2013), and assessed model fit using posterior predictive checking procedures that compared the observed data to data simulated from the fitted models (Gelman *et al.* 2014).

RESULTS

Tree size, slope, and fuel variables are reported in Table 1. Compared to spring burning, fall burning caused a much greater reduction in duff and likely a slightly greater reduction in litter outside the rake zone (Table 2). Burns both seasons nearly eliminated 1-hour and 10-hour fuels while not substantially im-

Table 1. Means and (SD) of variables influencing ponderosa pine responses to prescribed burns.

Treatment	DBH (cm)	Tree height (m)	Hill slope (degrees)	Pre-burn total fuels (Mg ha^{-1})
Fall not-raked	57.6 (20.9)	26.8 (8.4)	14.0 (4.8)	251.1 (74.0)
Fall raked	62.9 (18.3)	28.9 (7.8)	13.3 (5.2)	217.0 (67.5)
Spring not-raked	63.7 (17.5)	29.1 (7.7)	6.0 (4.2)	219.1 (100.8)
Spring raked	62.9 (18.9)	28.0 (8.2)	6.0 (3.6)	187.7 (51.4)

Table 2. Means and (SE) of fuel variables measured prior to (Pre) and after (Post) fall and spring prescribed burns (Mg ha^{-1}).

Timing	Duff	Litter	1 hour	10 hour	100 hour	≥1000 hour	Total fuels
Fall							
Pre	45.5 (3.1)	12.3 (1.4)	0.3 (0.06)	45.6 (9.4)	16.1 (2.2)	114.2 (11.6)	234.1 (19.4)
Post	15.0 (2.1)*[a]	3.7 (0.3)*	0.0 (0.0)*	2.6 (0.1)*	12.1 (0.6)	112.1 (9.6)	146.6 (10.6)*
Spring							
Pre	34.5 (3.8)	13.5 (0.9)	0.3 (0.06)	51.7 (13.2)	11.1 (1.6)	92.3 (17.0)	203.8 (24.7)
Post	39.5 (2.6)	7.8 (0.4)*	0.0 (0.0)*	2.3 (0.2)*	12.7 (1.8)	67.9 (7.1)*	129.6 (8.2)*

[a] Each asterisk denotes a significant effect ($P < 0.05$) of burning on a fuel class within a burn timing.

pacting 100-hour fuels (Table 2). The ≥1000-hour fuels were the dominant fuel class, and these fuels were reduced more by spring burning than by fall burning (Table 2).

In the absence of raking, fall burning caused more cambium mortality than spring burning (Figure 3), and fall burning caused a greater probability of bole scorch than spring burning (Spring burn, not-raked confidence interval [CI] of Figure 4A). Raking reduced cambium mortality during both burn seasons (Figure 3) and all three bole scorch variables during fall (Fall burn, raked CIs of Figure 4).

Not-raked trees likely experienced a lower probability of crown scorch in fall than spring (Spring burn, not-raked CI of Figure 5A). There is some evidence that raking reduced the probability that flames reached crowns during fall (Fall burn, raked CI of Figure 5A) but not spring (Spring burn, raked CI of Figure 5A). Among trees in which flames did reach crowns, there is evidence that raking reduced the extent of crown scorch in fall (Figure 5).

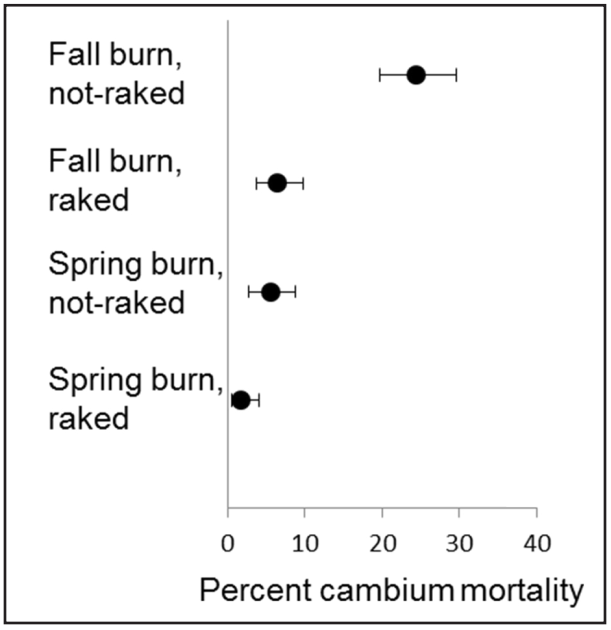

Figure 3. Point estimates (dots) and 95% CIs (lines) indicating percent cambium mortality of trees subjected to spring or fall burning. Fuels in close proximity to trees were removed (raked) or left in place (not-raked).

Heat damage appeared slightly greater among trees with relatively high fuel levels between the bole and the drip line (Figures 4 and 5). Trees with larger than average diameters (i.e., DBH) experienced greater maximum bole scorch heights (Figure 4C) and lower than average probabilities of crown scorch (Figure 5A). Trees growing on steeper than average slopes experienced greater than average bole scorch heights (Figure 4C) and crown damage (Figure 5).

Over the post-fire monitoring period, 55 of our 508 study trees died: 18 from heat damage and 37 from infestation by western pine beetle (*Dendroctonus brevicomis* LeConte). Mortality directly due to heat damage was low for fall raked (6%), fall not-raked (6%), spring raked (0%), and spring not-raked (1%) trees. Corresponding mortality rates due to beetles following burning were 8%, 12%, 5%, and 3%, respectively. There were no significant effects of raking on mortality.

DISCUSSION

Duff, a fuel that can damage ponderosa pines when smoldering near the bole (Ryan and Frandsen 1991), was more fully consumed by fall burns than by spring burns in our study (Table 2). This finding is consistent with Perrakis and Agee (2006), who found litter plus duff was reduced more by fall burning (30%) than by spring burning (6%) in southern Oregon mixed conifer forests, and also with Knapp *et al*. (2005), who reported more litter plus duff consumption from fall burning (94%) than from spring burning (74%) in mixed conifer forests in Sequoia National Park, California. Duff consumption presumably generated more heat near the bole in fall than in spring, thus explaining why, in the absence of raking, bole damage was more extensive in fall than in spring (Figures 3 and 4).

Our findings, along with those of Perrakis and Agee (2006) and Knapp *et al*. (2005), suggest that raking will tend to offer more protec-

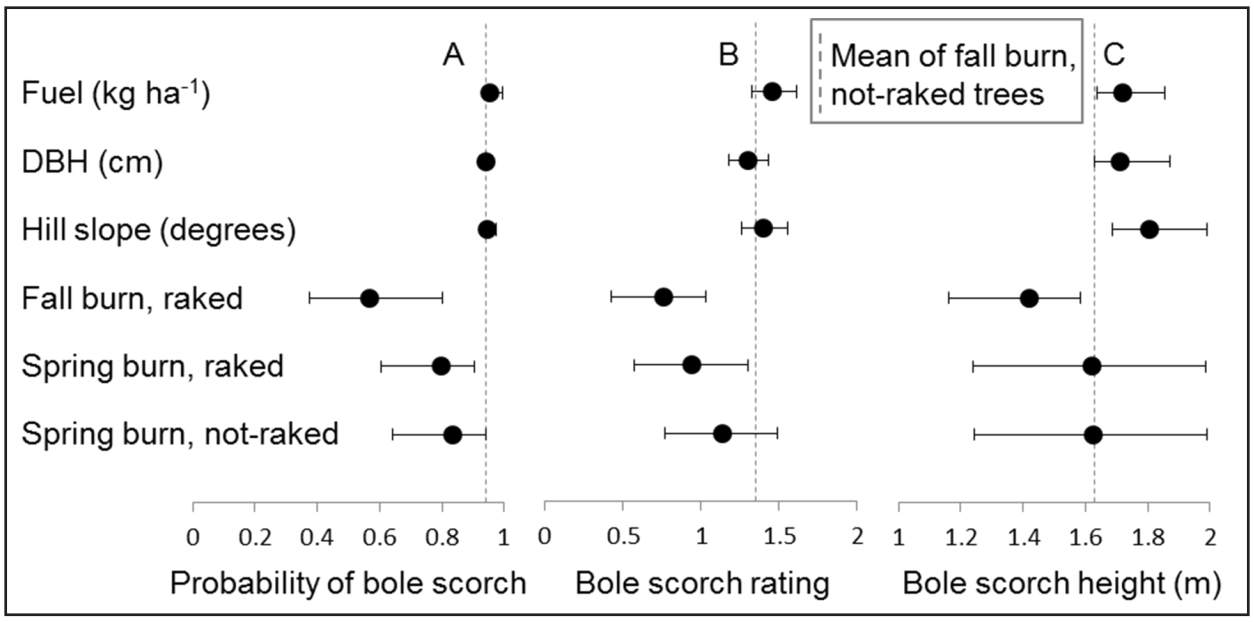

Figure 4. Point estimates (dots) and 95% CIs (lines) on parameters from statistical models. Parameters describe effects of listed variables on A) probabilities that ponderosa pine boles were scorched, B) a visual bole scorch rating, and C) the maximum height of bole scorch. Vertical axes denote means for fall-burned, not-raked trees (i.e., baseline treatment), so CIs that do not overlap vertical axes are significantly different than the baseline ($P < 0.025$). In estimating effects of the variables on bole scorch rating and height, trees that did not experience bole scorch were excluded from the analysis. Fuel, DBH, and hill slope CIs indicate effects of elevating these variables 1.0 SD above their mean, so, for example, the fuel CI indicates that trees surrounded by greater than average fuel levels experienced slightly greater than average bole scorch height.

tion to trees in areas burned in fall than in spring, because fall burns tend to consume more litter and duff and thereby generate more heat near the bole. Additionally, Kauffman and Martin (1989) also found that early fall burns consumed more litter and duff than did early spring burns. However, these same authors also found that late spring burns reduced litter and duff more than late fall burns did, so while fall burns tend to consume more litter and duff, there are exceptions. Although wind speeds, temperatures, and other factors have important impacts on fire behavior (Fernandes *et al.* 2008), differences in fuel moisture contents are presumably the primary factor in explaining why litter and duff tend to be more fully consumed in fall than in spring. Given that fuel moisture is a key driver of fuel consumption, it seems that, compared to season of burn, fuel moisture content would be a more reliable predictor of how much fuel a burn will consume and, by extension, how much protection raking will provide. However, fuel moisture contents are difficult to measure and predict (Engber *et al.* 2013, Varner *et al.* 2016). In the absence of reliable fuel moisture data, the heuristic that fall burns tend to consume more fuels than spring burns should be useful for planning burns and deciding whether or not to use raking.

While raking reduced bole damage, it did not eliminate it. Over half of the raked trees experienced bole scorch (Figure 4A), and some raked trees experienced cambium mortality (Figure 3). Apparently, materials outside our 1.0 m rake zone often burned hot enough to scorch trees, suggesting that larger fuel removal zones might sometimes be needed to fully prevent damage. Alternatively, because it was infeasible to completely rake away very

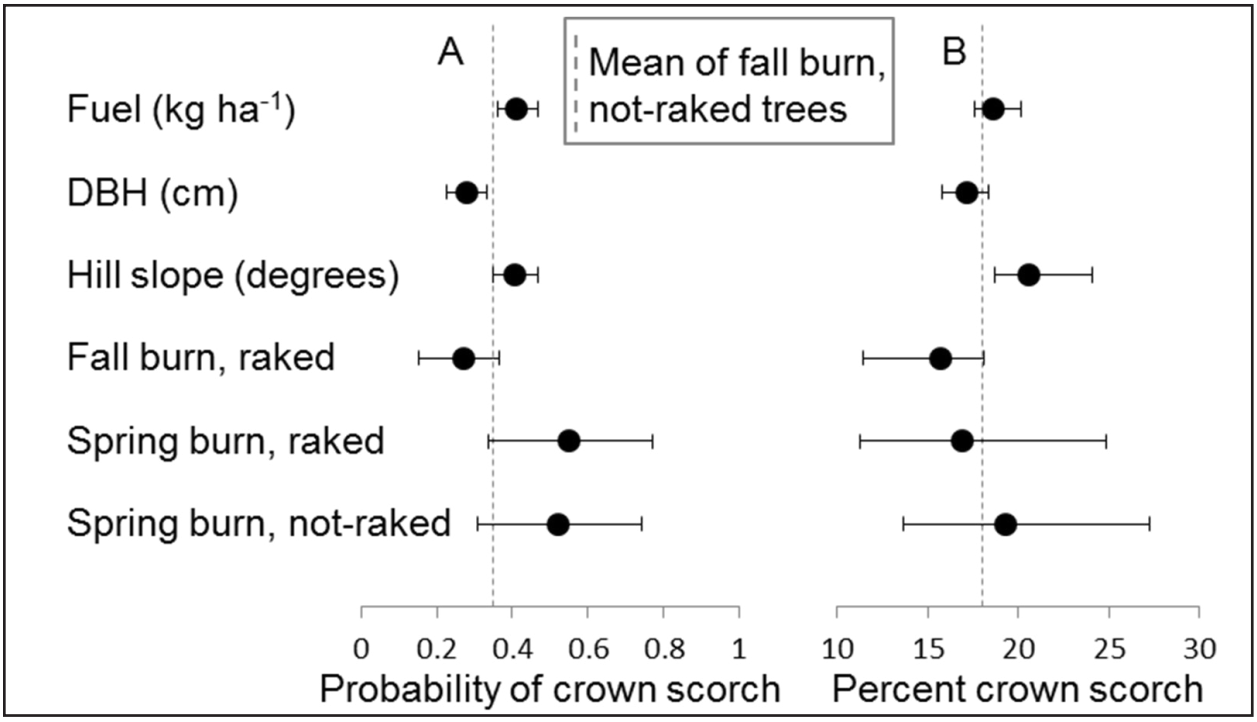

Figure 5. Point estimates (dots) and 95% CIs (lines) on parameters from statistical models. The parameters describe effects of listed variables on A) probabilities that ponderosa pine crowns were scorched, and B) among trees that were scorched, the percentage of the crown that was scorched. Vertical axes are positioned at the mean for fall-burned, not-raked trees (i.e., baseline treatment), so CIs that do not overlap vertical axes are significantly different than the baseline ($P < 0.025$). In estimating effects of the variables on percent crown scorch, trees that did not experience crown scorch were excluded from the analysis. Fuel, DBH, and hill slope CIs indicate effects of elevating these variables 1.0 SD above their mean, so, for example, trees with greater than average DBH experienced lower than average probability of crown scorch.

fine duff, and because some litter likely accumulated over the three to four years between raking and burning, small quantities of litter and duff were present in rake zones at the time of burning, and consumption of this material may have contributed to damage of raked trees. Removing fine duff with additional tools, such as the leaf blowers employed by Fowler *et al*. (2010), may further reduce bole damage, as might burning sooner following raking.

A priori, we did not expect some fuels to be more fully consumed in fall and other fuels to be more fully consumed in spring, so the finding that duff was more fully consumed in fall and ≥1000-hour fuels were more fully consumed in spring was unexpected (Table 2). The mechanism behind this variation in responses is unclear. Additionally, because of the small size of our rake zone, the evidence that raking reduced crown damage from fall burns was somewhat unexpected (Figure 5). However, Hood (2007) also found that raking slightly reduced crown damage. Raking appears to reduce the likelihood that flames spread up the bole to the crown. Heat damage to crowns can reduce tree growth (Bird and Scholes 2002), so preventing crown scorch can be valuable even in cases in which it does not kill trees.

Although raking reduced tree damage, it did not appreciably reduce tree mortality in our study (mortality was <5% after raking). Low mortality among both raked and not-raked trees has been a consistent feature of studies involving large, high-value trees

(Swezy and Agee 1991, Hood 2007, Fowler *et al.* 2010). Therefore, none of the studies have provided direct evidence that raking reduces mortality from prescribed burns capable of killing large trees (e.g., Kolb *et al.* 2007). However, a few studies indirectly suggest that raking may reduce large-tree mortality from intense prescribed burns. In particular, van Mantgem and Schwartz (2004) found that raking reduced prescribed burning mortality of small ponderosa pines (5 cm to 15 cm DBH) from 40% to 4% in the Sierra Nevada Mountains of California. Also, Dalrymple and Safford (2013) found that large Jeffery pines in the Lake Tahoe Basin of California were significantly less likely to be killed by wildfires if they had naturally low fuel levels near their boles, and Nesmith *et al.* (2010) made the same observation on large sugar pines subjected to prescribed burns in Sequoia and Kings Canyon national parks in California. Additional research remains necessary to determine whether or not raking and other fuel removal treatments can reduce mortality. This research seems particularly important given the fact that the burns that are most capable of killing trees tend to be the ones that most effectively reduce fuels (McCaw *et al.* 1997). However, reducing prescribed fire damage can be advantageous even when the damage does not result in mortality, because heat damage can reduce tree growth (Berryman 1986, Valor *et al.* 2015) and carbon sequestration (Wiechmann *et al.* 2015).

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LITERATURE CITED

Abella, S.R., and J.D. Springer. 2015. Effects of tree cutting and fire on understory vegetation in mixed conifer forests. Forest Ecology and Management 335: 281–299. doi: 10.1016/j.foreco.2014.09.009

Albert, J.H., and S. Chib. 1993. Bayesian analysis of binary and polychotomous response data. Journal of the American Statistical Association 88: 669–679. doi: 10.1080/01621459.1993.10476321

Berryman, A.A. 1986. Forest insects: principle and practice of population management. Plenum Press, New York, New York, USA.

Bird, T.L., and M.C. Scholes. 2002. Prescribed burning under mature *Pinus patula:* the effect of fire on tree growth. Discovery and Innovation 14: 139–146.

Brown, J.K. 1974. Handbook for inventorying downed woody material. USDA Forest Service General Technical Report INT-16, Intermountain Forest Range Experiment Station, Ogden, Utah, USA.

Cohen, J.C., and J.E. Deeming. 1985. The national fire danger rating system: basic equations. USDA Forest Service General Technical Report PSW-82, Pacific Southwest Forest and Range Experiment Station, Berkeley, California, USA.

Dalrymple, S.E., and H.D. Safford. 2013. Natural forest floor clearings around trees in Jeffrey pine forests reduce tree damage and mortality following wildfire. Forest Ecology and Management 310: 847–856. doi: 10.1016/j.foreco.2013.09.032

Efron, B., and R. Tibshirani. 1993. An introduction to the bootstrap. Chapman & Hall, New York, New York, USA.

Engber, E.A., J.M. Varner, C.J. Dugaw, L.N. Quinn-Davidson, and J.K. Hiers. 2013. Utility of an instantaneous moisture meter for duff moisture prediction in long-unburned longleaf pine forests. Southern Journal of Applied Forestry 37: 13–17. doi: 10.5849/sjaf.11-034

Fernandes, P.M., and H.S. Botelho. 2003. A review of prescribed burning effectiveness in fire hazard reduction. International Journal of Wildland Fire 12: 117–128. doi: 10.1071/WF02042

Fernandes, P.M., H.S. Botelho, F.C. Rego, and C. Loureiro. 2008. Using fuel and weather variables to predict the sustainability of surface fire spread in maritime pine stands. Canadian Journal of Forestry Research 38: 190–201. doi: 10.1139/X07-159

Fettig, C.J., S.R. McKelvey, D.R. Cluck, S.L. Smith, and W.J. Otrosina. 2010. Effects of prescribed fire and season of burn on direct and indirect levels of tree mortality in ponderosa and jeffrey pine forests in California, USA. Forest Ecology and Management 260: 207–218. doi: 10.1016/j.foreco.2010.04.019

Fonda, R.W., and E.P. Binney. 2011. Vegetation response to prescribed fire in Douglas-fir forests, Olympic National Park. Northwest Science 85: 30–40. doi: 10.3955/046.085.0103

Fosberg, M.A., and J.E. Deeming. 1971. Derivation of the 1- and 10-hour timelag fuel moisture for fire-danger rating. Research Note RM-207, USDA Forest Service, Rocky Mountain Forest and Range Experimental Station, Fort Collins, Colorado, USA.

Fowler, J.F., C.H. Sieg, and L.L. Wadleigh. 2010. Effectiveness of litter removal to prevent cambial kill-caused mortality in northern Arizona ponderosa pine. Forest Science 56: 166–171.

Gelman, A., J.B. Carlin, H.S. Stern, D.B. Dunson, A. Vehtari, and D.B. Rubin. 2014. Bayesian data analysis. Chapman & Hall, CRC Press, Boca Raton, Florida, USA.

Gelman, A., and J. Hill. 2007. Data analysis using regression and multilevel/hierarchical models. Cambridge University Press, New York, New York, USA.

Hann, D.W. 1997. Equations for predicting the largest crown width of stand-grown trees in western Oregon. Research publication 17. Oregon State University College of Forestry, Corvallis, Oregon, USA.

Hood, S. 2007. Prescribed burning to protect large diameter pine trees from wildfire—can we do it without killing the trees we're trying to save? Joint Fire Science Final Report: 03-3-2-04, Rocky Mountain Research Station, Fire Science Lab, Missoula, Montana, USA.

Hood, S., A. Sala, E.K. Heyerdahl, and M. Boutin. 2015. Low-severity fire increases tree defense against bark beetle attacks. Ecology 96: 1846–1855. doi: 10.1890/14-0487.1

Intel Corporation. 2013. Intel visual FORTRAN compiler professional edition 14.0. Intel Corporation, Santa Clara, California, USA.

Kauffman, J.R., and R.E. Martin. 1989. Fire behavior, fuel consumption, and forest floor changes following prescribed understory fires in Sierra Nevada mixed conifer forests. Canadian Journal Forest Research 19: 455–462. doi: 10.1139/x89-071

Kent, L.L.Y., K.L. Shive, B.A. Strom, C.H. Seig, M.E. Hunter, C.S. Stevens-Rumann, and P.Z. Fulé. 2015. Interactions of fuel treatments, wildfire severity, and carbon dynamics in dry conifer forests. Forest Ecology and Management 349: 66–72. doi: 10.1016/j.foreco.2015.04.004

Knapp, E.E., J.E. Keeley, E.A. Ballenger, and T.J. Brennan. 2005. Fuel reduction and coarse woody debris dynamics with early season and late season prescribed fires in a Sierra Nevada mixed conifer forest. Forest Ecology and Management 208: 383–397. doi: 10.1016/j.foreco.2005.01.016

Kolb, T.E., J.K. Agee, P.Z. Fulé, N.G. McDowell, K. Pearson, A. Sala, and R.H. Waring. 2007. Perpetuating old ponderosa pine. Forest Ecology and Management 249: 141–157. doi: 10.1016/j.foreco.2007.06.002

McCaw, W.L., R.H. Smith, and J.E. Neal. 1997. Prescribed burning of thinning slash in regrowth stands of karri (*Eucalyptus diversicolor*). 1. Fire characteristics, fuel consumption and tree damage. International Journal of Wildland Fire 7: 29–40. doi: 10.1071/WF9970029

McKenzie, D., Z. Gedalof, D.L. Peterson, and P. Mote. 2004. Climatic change, wildfire, and conservation. Conservation Biology 18: 890–902. doi: 10.1111/j.1523-1739.2004.00492.x

Nesmith, J.C.B., K.L. O'Hara, P.J. van Mantgem, and P. de Valpine. 2010. The effects of raking on sugar pine mortality following prescribed fire in Sequoia and Kings Canyon national parks, California, USA. Fire Ecology 6: 97–116. doi: 10.4996/fireecology.0603097

Noonan-Wright, E., S.M. Hood, and D.R. Cluck. 2010. Does raking basal duff affect tree growth rates or mortality? Western Journal of Applied Forestry 25: 199–202.

Parsons, D.J., and S.H. DeBenedetti. 1979. Impact of fire suppression on a mixed-conifer forest. Forest Ecology and Management 2: 21–33. doi: 10.1016/0378-1127(79)90034-3

Perrakis, D.D.B., and J.K. Agee. 2006. Seasonal fire effects on mixed-conifer forest structure and ponderosa pine resin properties. Canadian Journal of Forest Research 36: 238–254. doi: 10.1139/x05-212

Price, O.F., J.G. Pausas, N. Govender, M. Flannigan, P.M. Fernandes, M.L. Brooks, and R.B. Bird. 2015. Global patterns in fire leverage: the response of annual area burnt to previous fire. International Journal of Wildland Fire 24: 297–306. doi: 10.1071/WF14034

Ryan, K., and N. Noste. 1985. Evaluating prescribed fires. USDA Forest Service General Technical Report INT-182, Intermountain Forest and Range Experiment Station, Ogden, Utah, USA.

Ryan, K.C. 1983. Techniques for assessing fire damage to trees. Pages 1–11 in: J.E. Lotan, editor. Proceedings of the symposium: fire—its field effects. Intermountain Fire Council, 19–21 October 1982, Jackson, Wyoming, USA.

Ryan, K.C., and W.H. Frandsen. 1991. Basal injury from smoldering fires in mature *Pinus ponderosa* Laws. International Journal of Wildland Fire 1: 107–118. doi: 10.1071/WF9910107

Stephens, S.L., J.J. Moghaddas, C. Edminster, C.E. Fiedler, S. Haase, M. Harrington, J.E. Keeley, E.E. Knapp, J.D. McIver, K. Metlen, C.N. Skinner, and A. Youngblood. 2009. Fire treatment effects on vegetation structure, fuels, and potential fire severity in western US forests. Ecological Applications 19: 305–320. doi: 10.1890/07-1755.1

Swezy, D.M., and J.K. Agee. 1991. Prescribed-fire effects on fine-root and tree mortality in old-growth ponderosa pine. Canadian Journal of Forest Research 21: 626–634. doi: 10.1139/x91-086

Vaillant, N.M., J. Fites-Kaufman, A. Reiner, E.K. Noonan-Wright, and S.N. Dailey. 2009. Effect of fuel treatments on fuels and potential fire behavior in California, USA, national forests. Fire Ecology 5: 14–29. doi: 10.4996/fireecology.0502014

Vaillant, N.M., E.K. Noonan-Wright, A.L. Reiner, C.M. Ewell, B.M. Rau, J.A. Fites-Kaufman, and S.N. Dailey. 2015. Fuel accumulation and forest structure change following hazardous fuel reduction treatments throughout California. International Journal of Wildland Fire 24: 361–371. doi: 10.1071/WF14082

Valor, T., J.R. Gonzalez-Olabarria, and M. Pique. 2015. Assessing the impact of prescribed burning on the growth of European pines. Forest Ecology and Management: 101–109. doi: 10.1016/j.foreco.2015.02.002

van Mantgem, P., and M. Schwarts. 2004. An experimental demonstration of stem damage as a predictor of fire-caused mortality for ponderosa pine. Canadian Journal of Forest Research 34: 1343–1347. doi: 10.1139/x04-001

van Wagtendonk, J.W., J.M. Benedict, and W.M. Sydoriak. 1998. Fuel bed characteristics of Sierra Nevada conifers. Western Journal of Applied Forestry 13: 73–84.

Varner, J.M., J.K. Kreye, J.K. Hiers, and J.J. O'Brien. 2016. Recent advances in understanding duff consumption and post-fire longleaf pine mortality. Pages 335–338 in: C.J. Schweitzer, W.K. Clatterbuck, and C.M. Oswalt, editors. Proceedings of the18th biennial southern silvicultural research conference. US Forest Service, Southern Research Station, and University of Tennessee, Department of Forestry, Wildlife and Fisheries, 2–5 March 2015, Knoxville, Tennessee, USA.

Varner, J.M., J.K. Hiers, R.D. Ottmar, D.R. Gordon, F.E. Putz, and D.D. Wade. 2007. Overstory tree mortality resulting from reintroducing fire to long-unburned longleaf pine forests: the importance of duff moisture. Canadian Journal of Forest Research 37: 1349–1358. doi: 10.1139/X06-315

Wallace, W., P.Z. Fulé, M.M. Moore, S.C. Hart, T.E. Kolb, J.N. Mast, S.S. Sackett, and M.R. Wagner. 1997. Restoring ecosystem health in ponderosa pine forests of the Southwest. Journal of Forestry 45: 23–29.

Wiechmann, M.L., M.D. Hurteau, M.P. North, G.W. Koch, and L. Jerabkova. 2015. The carbon balance of reducing wildfire risk and restoring process: an analysis of 10-year post-treatment carbon dynamics in a mixed-conifer forest. Climatic Change 132: 709–719. doi: 10.1007/s10584-015-1450-y

Wyant, J.G., P.N. Omi, and R.D. Laven. 1986. Fire induced tree mortality in a Colorado ponderosa pine/Douglas-fir stand. Forest Science 32: 49–59.