Mastication and Prescribed Fire Influences on Tree Mortality and Predicted Fire Behavior in Ponderosa Pine

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ABSTRACT

The purpose of this study was to provide land managers with information on potential wildfire behavior and tree mortality associated with mastication and masticated/fire treatments in a plantation. Additionally, the effect of pulling fuels away from tree boles before applying fire treatment was studied in relation to tree mortality. Fuel characteristics and tree mortality data were gathered before and after treatments in a 25-year-old ponderosa pine (*Pinus ponderosa* C. Lawson) plantation. A random block design was used with three treatments plus a control at each of four blocks. Four plots were established as subsamples within each of the treatment and control sections of each block. Potential wildfire behavior for posttreatment fuel conditions was modeled for 90th and 97th percentile fire weather. Predicted rates of spread and flame lengths were higher for fuel conditions resulting from the mastication treatments than for the masticated/fire treatments or the controls. Torching and crowning indices indicated that higher windspeeds would be necessary to promote torching for areas treated with mastication/fire than for mastication or the controls. Tree mortality was 32 and 17% the first year after burning in masticated/fire and masticated/pull-back/fire plots, respectively, and 49 and 27% the second year. Our potential wildfire behavior results indicate that the risk of crown fire can be somewhat reduced by mastication and further reduced if mastication is followed up with prescribed fire to consume surface fuels. However, moderate levels of tree mortality seem inevitable when burning masticated fuels in a plantation and may only marginally be reduced by pulling fuels away from tree boles, which increases treatment costs.

Keywords: fire behavior, fuel treatment, ponderosa pine, southern Sierra Nevada

Fire has been an integral ecosystem process in the Sierra Nevada for thousands of years; however, recent land management strategies and climate patterns have affected forest condition to support extreme fire behavior (Agee and Skinner 2005, Sugihara and Barbour 2006). Postfire rehabilitation in many fire-adapted ecosystems across California has included establishing plantations despite a potential for extreme fire behavior and a lack of knowledge of the efficacy of fuel treatments in plantations (Kobziar et al. 2009). The fire hazard associated with increased fuel loads has prompted land managers to undertake hazardous fuel reduction treatments (USDA-US Department of the Interior 2000, Healthy Forest Restoration Act 2003). In many cases, it is not possible to reintroduce fire to areas having excessive fuel loads without unacceptable risk of an escaped fire and/or undesirable fire effects. Therefore, mechanical treatments may be desired to modify fuels prior to applying prescribed fire treatments. It has been shown empirically and with fire behavior modeling that these combined treatments are very effective at reducing fire behavior to acceptable levels (Agee and Skinner 2005, Stephens and Moghaddas 2005, Stephens et al. 2009, Vaillant et al. 2009).

Mastication has been used frequently over the past decade to modify fuel structure as a stand-alone treatment or prior to prescribed burning. Mastication can be used to reduce ladder fuels by converting smaller-diameter trees and shrubs into surface fuels and to convert large downed woody debris into smaller surface fuels that can be left on site. Reducing ladder fuels and increasing the height to live crown aids in reducing the risk of surface fire transitioning to crown fire (Agee and Skinner 2005). With the appropriate masticator head, mastication can also be used to prune lower branches of trees, increasing the height to live crown base. Land managers may use mastication rather than treatments involving fire to avoid the risk of an escaped fire and/or the restrictions associated with meeting air quality standards (Glitzenstein et al. 2006).

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This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.39 in.; meters (m): 1 m = 3.3 ft; kilometers (km): 1 km = 0.6 mi; hectares (ha): 1 ha = 2.47 ac; metric ton (t): 1 t = 2,205 lb; megagram (Mg): 1 Mg = 2,205 lb.

Despite the recent surge in the use of mastication as a fuel treatment option, few studies have been conducted on potential fire behavior or fire effects associated with mastication or combined masticated/fire treatments (Stephens and Moghaddas 2005, Glitzenstein et al. 2006, Kobziar et al. 2009). Fuel models representing masticated fuel conditions for use in fire behavior modeling have not been well developed at the time of this publication (Glitzenstein et al. 2006, Kane et al. 2009, Battaglia et al. 2010). Fires in masticated fuels when soil is dry can produce heat above lethal levels for plant roots (Busse et al. 2010). An understanding of likely ecological effects should be made available to managers planning to use mastication as a fuel treatment.

Mastication used in combination with prescribed burning can reduce both canopy and surface fuel loads (Stephens and Moghaddas 2005, Reiner et al. 2009). However, in young, dense plantations, such as the one in this study, managers are often concerned with whether tree mortality associated with burning residual mastication fuels outweighs the benefits of further reductions in potential fire behavior. Managers are also interested in whether pulling masticated fuel away from tree boles would decrease mortality from prescribed burning. This study should aid in decisionmaking regarding these management options.

This study quantified tree mortality and compared potential wildfire behavior between treatment conditions in a young ponderosa pine (*Pinus ponderosa* C. Lawson) plantation in the southern Sierra Nevada in California. Tree mortality results were based on field data. Baseline tree mortality data were gathered after the mastication treatment but before the prescribed burn treatment (postmastication/preburn). Postmastication-and-fire tree mortality data were gathered for two growing seasons after the prescribed fire treatments were completed, allowing for conclusions to be drawn on the tree mortality effects of prescribed burning residual mastication fuels. Modeled results were intended to reflect potential wildfire behavior immediately posttreatment to allow land managers to weigh the risk of potentially extreme wildfire behavior against tree mortality from these types of these treatments.

Methods

Study Location

Study plots were located in the Red Mountain fuel treatment project area, on the Kern River Ranger District of the Sequoia National Forest (latitude 35° 39′ N, longitude 118° 36′W). Study plots were located at elevations between 1,580 and 2,010 m, with slopes less than 30%. A wildfire burned through this area in 1970, after which the area was replanted as a plantation with ponderosa pine. The site is dominated by dense 10-m-tall ponderosa pine that was about 25 years old at the time of treatment. Prior to treatment, the tree canopy was nearly continuous in some areas, and mean trees per hectare ranged from 833 to 956 (Reiner et al. 2009). Black oak (*Quercus kelloggii* Newberry), canyon live oak (*Quercus chrysolepis* Liebm.), white fir (*Abies concolor* [Gord. & Glend.] Lindl. ex Hildebr.), sugar pine (*Pinus lambertiana* Douglas), and incense-cedar (*Calocedrus decurrens* [Torr.] Florin) occur in isolated patches throughout the area. The limited understory consists of Sierra gooseberry (*Ribes roezlii* Regel), birchleaf mountain mahogany (*Cercocarpus montanus* Raf. var. *glaber* [S. Watson] F.L. Martin), greenleaf manzanita (*Arctostaphylos patula* Greene), and low densities of annual and perennial grasses and forbs. Nearby weather stations Breckenridge (latitude 35° 27′N, longitude 118° 35′W, elevation 2301 m) and Posey E3 (latitude 35° 48′N, longitude 118° 38′W, elevation 1512 m) show mean annual precipitations of 27 and 74 cm, respectively; however, precipitation varies greatly over short distances in this area.

Study Design

The study design was a random block design with 4 blocks at each of 4 sites (16 blocks). Within each site, a control plus three unique treatments were randomly assigned to the four blocks. Each block measured 200 by 405 m (8.1 ha). Four replicate plots were placed within each block, for a total of 64 plots installed. Of the 16 plots installed for each treatment type, 7 masticated plots, 11 masticated/fire plots, and 8 masticated/pull-back/fire plots were successfully treated and included in analysis (Reiner et al. 2009).

Treatments

The three treatments studied were mastication-only (masticated), mastication followed by prescribed fire (masticated/fire), and mastication followed by prescribed fire where masticated material had been manually “pulled back” from tree boles to the drip line of trees prior to burning (masticated/pull-back/fire). The objective of pulling masticated material away from tree boles was to test the influence of shallow root and cambial heating from the prescribed fire on tree mortality. Mastication was completed between the fall of 2005 and the summer of 2006 with a vertical shaft mastication head mounted to an excavator boom. The mastication prescription included leaving trees over 38 cm dbh and thinning to a density of approximately 61 trees ha^{-1}. Prescribed burning was completed on Dec. 5 and 6, 2007. Air temperature during the burn ranged from 5 to 15°C. Relative humidity generally ranged from 33 to 57% during the burning of most units, until rain began to fall during the completion of the burn in the last block. Litter moistures ranged from 8 to 12% as calculated from nine surface litter samples collected across the units the mornings before the burns. The Keetch-Byram drought index (Keetch and Byram 1968), on a scale of 0–800, was 476. A light rain (0.3 cm) fell 24 days prior to the burn. Windspeed during the burn ranged from 5 to 13 km $hour^{-1}$ with gusts to 21 km $hour^{-1}$. Ignition patterns of the prescribed burns included both spot and strip firing. Spot firing is the ignition of separate, small dots, and strip firing is the ignition of continuous lines parallel to the slope. Generally, the units were ignited starting from the uphill side of the unit working downhill, unless wind direction dictated differently.

Field Data Collection

Four plot centers were placed at even intervals along a 200-m transect running the length of each treatment block. Overstory trees (dbh > 15 cm) were measured in a 0.1-ha circular plot. Pole-sized trees, dbh 2.5–15 cm (National Park Service, US Department of the Interior 2003), were measured in a 0.025-ha plot with the same plot center. Data recorded for overstory and pole-sized trees included tag number, species, dbh, height to live crown base, total height, and canopy position (dominant, codominant, intermediate, or suppressed). From the plot center, a 15.24-m transect was placed along a random bearing for a direct measurement of surface fuel loads. The planar-intercept method was used to measure surface fuels (Van Wagner 1968, Brown 1974). Posttreatment, downed woody fuels were tallied separately as natural or masticated, so that regular downed woody material could be computed separately from masticated material. Masticated fuel depth was measured at the corners

Table 1. Weather and fuel moisture parameters for 90th and 97th percentile scenarios derived from data from the Breckenridge Remote Automated Weather Station (RAWS) from 1987 to 2007 processed in FireFamily Plus (Bradshaw and McCormick 2004).

Weather parameter	90th	97th
6.1-m windspeed (km hour^{-1})[a]	19.3	29.0
Temperature (°C)	28.3	30.6
Relative humidity (%)	8	3
1-hour fuel moisture (%)	3.5	3.2
10-hour fuel moisture (%)	3.8	3.5
100-hour fuel moisture (%)	6.6	5.3
Herbaceous fuel moisture (%)	32.8	30.8
Woody fuel moisture (%)[b]	70	70
Foliar moisture (%)[b]	100	90

[a] Probable maximum 1-minute windspeed simulating wind gusts (Crosby and Chandler 2004).
[b] These moisture parameters were fixed and not based on RAWS data.

and center of a 1 × 1-m frame centered at 1.5, 7.6, and 13.7 m along the fuel transect. Masticated fuel samples were collected using 30 × 30-cm frame and used in determining masticated fuel loads on the basis of depth measurements (Reiner et al. 2009). Litter, duff, fuel bed depth, and live understory vegetation were measured as described in Reiner et al. (2009).

Pretreatment data were collected in 2005. Postmastication/preburn data were collected in 2006 to assemble baseline tree mortality data before the prescribed burn treatment was implemented. Crown scorch (foliage discolored but not consumed) and foliage consumption maximum heights, as well as 1-year postburn surface and canopy fuels used in fire behavior modeling were gathered the spring of 2008 following the burn. Tree mortality data were gathered one and two growing seasons after the prescribed burn, in October 2008 and October 2009, for overstory and pole-sized trees. Tree mortality was determined based on the presence/absence of green needles or buds.

Fire Behavior Modeling

Fire behavior modeling was based on data representing the 90th and 97th percentile weather conditions, typical of weather conditions during wildfires. The percentile weather conditions were calculated with weather data from May 1 through October 15 from the Breckenridge Remote Automated Weather Station between 1987 and 2007 using FireFamily Plus, version 3.0.5 (Bradshaw and McCormick 2004) (Table 1). After 20-ft (6.1-m) windspeeds were determined, a slight increase was applied to account for the influence of wind gusts (Crosby and Chandler 2004). Postmastication-and-fire fuel conditions were used to explore the effects of masticated versus masticated/fire treatments on predicted fire behavior during these weather conditions. After the mastication and fire treatments, mean woody fuel load (not including 1,000 hours) in plots treated only with mastication was roughly 50 Mg ha^{-1}, whereas in plots where treatment included fire, means were less than 6 Mg ha^{-1}. Mean litter fuel loads were 2.1 and 2.2 Mg ha^{-1} in masticated and control plots, respectively, and were 0.7 Mg ha^{-1} in both masticated/fire and masticated/pull-back/fire (Reiner et al. 2009).

Fire behavior modeling was performed using Fuels Management Analyst (FMAPlus) v3.0.8 (Fire Program Solutions 2008). FMAPlus computes fire behavior and effects using established equations from the literature (Stephens and Moghaddas 2005). Inputs in addition to weather include tree data (species, dbh, tree height, crown ratio, crown position), surface fuel model, slope, and wind reduction factor. A wind reduction factor of 0.3, for partially sheltered fuels, was used for control plots and treated plots assigned a timber fuel model, and 0.4 was used for unsheltered fuels in treated plots assigned a slash model (National Wildfire Coordinating group 2006). Foliar moistures of 100 and 90% were chosen for the 90th and 97th percentile conditions, respectively, because they represent conditions conducive to wildfire spread (Keyes 2006).

Fuel models (Scott and Burgan 2005) were selected to represent each plot by comparing model fuel loads and fuel bed depths to summarized field data. Fuel model selection was reviewed by a Fire Behavior Analyst (FBAN) and a fire manager familiar with these fuel types and expected fire behavior (Andrews and Queen 2001, Scott and Burgan 2005). These reviewers suggested different fuel models in cases where fire behavior seemed uncharacteristic given the fuel and weather conditions. Generally, SB1 (low load activity fuel) and SB2 (moderate load activity fuel) were chosen to represent masticated plots, TL1 (low load compact conifer litter) was chosen to represent masticated/fire and masticated/pull-back/fire plots, and TL6 (moderate load broadleaf litter) or TL8 (long-needle litter) were chosen for control plots. Although no fuel models currently exist that describe the characteristics of masticated fuel beds, SB1 and SB2 were chosen to approximate the fire behavior in masticated fuels because they yielded the type of fire behavior the FBAN expected under the particular slope and weather regimes modeled.

Data Analysis

Mean and standard error values were calculated for predicted fire behavior parameters, including flame length, rate of spread, and torching and crowning indices. Means and standard errors were computed for fire behavior results, but means comparison tests were not run because these data do not meet the test assumptions. Torching index is defined as the 20-ft (6.1-m) windspeed at which surface fire is expected to transition to crown fire. Crowning index is the 20-ft (6.1-m) windspeed where active crown fire is possible. Unrealistically high windspeeds were excluded by truncating windspeed at 129 km hour^{-1}, which was a natural break point in a histogram of the data and near the highest windspeed recorded at the Breckenridge RAWS (142 km hour^{-1}). We used PROC GLIMMIX in SAS v9.2 (SAS Institute 2008) to compare tree characteristics between pretreatment (2005) and 1-year postmastication-and-fire (2008). We also used the GLIMMIX procedure to compare tree mortality (percentage dead) between control, masticated/fire, and masticated/pull-back/fire treatments and year since burn treatment. The GLIMMIX procedure in SAS accounted for the repeated measure nature of the data by using a spatial correlation error term, which was appropriate for this analysis because the year variable was not equally spaced (i.e., 2006, 2008, 2009). A Tukey's post hoc test was applied to determine individual mean differences.

Results

Tree Characteristics

Mean tree height and canopy base height were calculated using FMAPlus for premastication-and-fire (2005) and postmastication-and-fire (2008) conditions and for the control plots (Table 2) as previously published in Reiner et al. (2009). After treatment, mean tree height increased in masticated and masticated/fire plots and canopy base height increased in masticated/fire and masticated/pull-back/fire plots. Mean tree dbh increased after all treatments (Table 2).

Table 2. Mean (standard error) tree height (TH), canopy base height (CBH), and diameter at breast height (dbh) for overstory and pole-sized trees combined in pretreatment and 1-year posttreatment masticated, masticated/fire, masticated/pull-back/fire, and control plots.

Year	Treatment	TH	CBH	dbh (cm)
		. . . .(m)	. . . .	
2005	Masticated	7.9 (0.7)^{a}	0.6 (0.1)^{a}	18 (2)^{b,c}
Pretreatment	Masticated/fire	8.0 (0.3)^{a}	1.0 (0.2)^{a}	18 (1)^{b,c}
	Masticated/pull-back/fire	9.2 (0.5)^{a,b,c}	1.1 (0.2)^{a}	20 (1)^{b}
	Control	8.7 (0.6)^{a,c}	0.9 (0.2)^{a}	20 (2)^{a,b,c}
2008	Masticated	12.7 (0.8)^{b}	1.8 (0.3)^{a,c}	25 (4)^{a}
1-year posttreatment	Masticated/fire	11.6 (0.5)^{b,c}	6.5 (0.6)^{b}	26 (1)^{a}
	Masticated/pull-back/fire	12.1 (0.5)^{b}	5.5 (0.8)^{b,c}	27 (2)^{a,c}
	Control	9.7 (0.6)^{a,b,c}	1.0 (0.2)^{a}	21 (1)^{a,c}
Year × treatment *P*-value		0.007	0.003	0.022

[a,b,c] Means followed by different letters are significantly different.

Table 3. Mean (standard error) for fire type, predicted flame length, and rate of spread by treatment for 90th and 97th percentile weather scenarios for 1-year posttreatment fuel conditions.

Treatment	Weather scenario	Fire type	Flame length (m)	Rate of spread (m min^{-1})
Masticated	90	44% SF, 56% PCF	1.8 (0.4)	4.2 (0.9)
Masticated	97	22% SF, 78% PCF	3.1 (0.7)	9.9 (2.0)
Masticated/fire	90	92% SF, 8% PCF	0.5 (0.3)	1.0 (0.7)
Masticated/fire	97	92% SF, 8% PCF	0.8 (0.6)	2.0 (1.5)
Masticated/pull-back/fire	90	100% SF	0.2 (<0.1)	0.3 (0.1)
Masticated/pull-back/fire	97	100% SF	0.2 (<0.1)	0.4 (<0.1)
Control	90	20% SF, 73% PCF, 8% ACF	2.5 (0.7)	6.3 (0.9)
Control	97	8% SF, 73% PCF, 27% ACF	7.1 (1.8)	18.0 (1.6)

SF, surface fire; PCF, passive crown fire; ACF, active crown fire plume dominated.

Table 4. Mean (standard error) 1-year posttreatment modeled torching index and crowning index by treatment for 90th and 97th percentile weather scenarios.

Treatment	Weather scenario (percentile)	Torching index	Crowning index
		. . . . .(km hour^{-1})	. . . . .
Masticated	90	39 (17)	56 (4)
Masticated	97	35 (16)	55 (4)
Masticated/fire	90	118 (11)	63 (6)
Masticated/fire	97	118 (11)	61 (6)
Masticated/pull-back/fire	90	129 (<0.1)	59 (11)
Masticated/pull-back/fire	97	129 (<0.1)	59 (11)
Control	90	10. (3)	36 (3)
Control	97	9 (3)	36 (3)

Potential Modeled Wildfire Behavior

Predicted flame lengths at the 90th and 97th percentiles were more than three times as high in masticated plots as in either masticated/fire or masticated/pull-back/fire plots, and they were even higher in control plots (Table 3). Predicted rates of spread were more than four times as high in masticated plots as in plots that received a burn treatment and higher yet in control plots for both 90th and 97th percentile weather. Predicted fire type was surface fire for 92 and 100% in masticated/fire and masticated/pull-back/fire plots, respectively (Table 3). Plots treated with only mastication were predicted to have 56 and 78% passive crown fire at 90th and 97th percentile weather, respectively. Active crown fire was predicted only in control plots.

Predicted torching indices were 118 km hour^{-1} in masticated/fire and 129 km hour^{-1} (the maximum value possible given truncation) in masticated/pull-back/fire treatments, indicating that unusually high winds would be necessary to produce torching after treatments including prescribed burning (Table 4). Torching indices were less than one-third as high in masticated plots than in plots treated with fire. Torching indices were less than one-third as high in control plots than masticated plots. This indicates that control plots are the most susceptible to torching, followed by masticated plots. Crowning indices for all treatments were generally similar. Crowning indices for control plots were 35–41% lower than all treated plots, indicating that all treatments studied produced fuel conditions more resistant to active crown fire than the untreated conditions.

Table 5. Mean (standard error) for percentage of tree mortality (percentage of dead trees) by treatment type for postmastication/preburn (2006), 1 year posttreatment (2008), and 2 years posttreatment (2009).

	Masticated/ fire	Masticated/ pull-back/fire	Control
	. . . .	.(%).	
Postmastication/preburn	1.3 (0.9)^{a}	0.8 (0.6)^{a}	1.0 (0.8)^{a}
1-year posttreatment	31.8 (13.1)^{b}	17.4 (10.2)^{a,b}	0.6 (0.5)^{a}
2-years posttreatment	48.6 (15.1)^{b}	26.5 (13.7)^{b}	0.7 (0.6)^{a}
Year × treatment *P*-value	0.006		

[a,b] Means followed by different letters are significantly different.

Scorch, Consumption, and Tree Mortality

Prescribed burning in the masticated units resulted in a great deal of crown scorch; however, less than 15% of the canopy was consumed (Table 5). Percentages of scorch for masticated/fire and masticated/pull-back/fire treatments were 74 and 75%, with standard errors of 4 and 3, respectively. Foliage consumption was slightly lower in units where masticated material was pulled back from trees; 8%, with a standard error of 3, versus 15%, with a standard error of 3, for the masticated/fire treatment.

Tree mortality, measured as the percentage of trees with an absence of green needles, was greater the second year after burning (Table 5). After the burn treatment, tree mortality in the masticated/fire and masticated/pull-back/fire treatments were both significantly different from the controls. The 1-year postmastication-and-fire tree morality was significantly higher than postmastication/preburn tree mortality for the masticated/fire treatment but not the masticated/pull-back/fire treatment, as indicated by the Tukey's post hoc test. Tree mortality was minimal in the control plots, and there were very few standing dead trees in the plots following mastication treatment.

Discussion

Land managers are faced with a lack of accurate fuel models to aid in decisions involving fire behavior in masticated fuels. This project was an attempt to give broad, relative differences in potential fire behavior in postmasticated and postmasticated/burned areas to aid in near-term decisionmaking until more definitive methods for fire behavior prediction in masticated fuels are developed. The fuel models chosen to represent masticated fuel beds in this study were determined to perform well under 90th and 97th percentile weather; however, their performance under other weather scenarios, such as prescribed fire conditions, has not been calibrated by expert opinion. Similar research was conducted by Kobziar et al. (2009) in a central Sierra Nevada project that also focused on a plantation that was roughly 30 years old at the time of treatment. The plantation in Kobziar et al. (2009) was slightly different from that in our study because it receives higher annual precipitation (130 cm, 80% as snow), pre- and postmastication-and-fire mean tree heights ranged up to 4 m higher, and mean canopy base heights were generally higher. Surface fuel data collections varied slightly; however, our study generally had lower mean litter loads both pre- and postmastication-and-fire, lower mean woody fuel loads after treatments involving burning, but higher mean woody fuel loads after mastication treatments despite having lower mean woody fuel loads pretreatment.

Kobziar et al. (2009) modeled fire behavior using Fire Management Analyst (Carlton 2004) for both pre- and postmastication-and-fire conditions, and they found results generally analogous to ours for flame length and rate of spread. Kobziar et al. (2009) also found that masticated/fire treatments resulted in the lowest flame lengths and rates of spread, compared with control or other treatments. However, Kobziar et al. (2009) found that postmastication flame lengths were predicted to be higher than flame lengths in control plots, whereas we found flame lengths to be lower in mastication plots than control plots. This difference could be due to the higher litter loads in Kobziar et al. (2009) (5.8–26.1 t ha^{-1}) than in our study (0.7–2.2 Mg ha^{-1}) (Reiner et al. 2009) or the use of different surface fuel models (note that t ha^{-1} is equivalent to Mg ha^{-1}). Similar to Kobziar et al. (2009), we found torching indices to be higher in plots treated with both mastication and fire treatments than control or mastication-only plots.

Given the amount of tree scorch experienced in our study (about 75%), tree mortality ranging from 27 to 49% is fairly consistent with other studies involving prescribed fire. Stephens and Finney (2002) reported a model predicting mortality based on crown scorch in Sequoia National Park, California, in which roughly 50% of ponderosa pine 25 cm dbh died when 75% of the crown volume was scorched. Our results are also similar to McHugh and Kolb (2003), who compared crown damage, defined as the sum of scorch and foliage consumed, for ponderosa pine in Arizona after two wildfires and one prescribed fire. The curve that McHugh and Kolb (2003) reported showed that approximately 50% of trees died that had 85–90% crown damage. Under this methodology, crown damage from our study would be tallied as 79–83%. Masticated fuels were not reported to be a surface fuel component in either of these studies (Stephens and Finney 2002, McHugh and Kolb 2003).

Similar to other studies, a large portion of the total mortality observed 2 years after fire treatment had occurred within 1 year postmastication-and-fire. One year postmastication-and-fire, we found 65% of the total mortality in masticated/fire plots and 66% for masticated/pull-back/fire plots. Stephens and Finney (2002) found 82% of total postburn mortality for ponderosa pine in the first year after burning, 14% the second year, and 4% the third year. Hood et al. (2010) found 60–88% mortality in ponderosa and Jeffrey pine (*Pinus jeffreyi* Balf.) the second year after wildfires in the Sierra Nevada in a study where the average mortality for these species 1 year after fire was less than 40%.

Our results, similar to other studies, found pulling fuel back from the boles of trees to be potentially beneficial to tree survival. Although not statistically significant, mortality in our study was approximately 1 standard error, or 50% lower in plots where masticated material was pulled back from trees prior to burning than when material was left in place. Most of the data on pulling fuel back from tree boles to date is in regard to larger size classes of trees than those found in the plantations at Red Mountain. Gray and Blackwell (2008) found that pulling fuel away from larger trees with fire scars appeared to prevent or slow their ignition during prescribed burning in light fuels. However, Gray and Blackwell (2008) also note that heavier fuels that burn with longer durations are "more problematic" when the focus is on reducing tree mortality during fire. Jerman et al. (2004) reported on tree mortality after mechanical and fire treatments in northwestern Arizona for trees established after 1870. They found 35% mortality for trees in burned units with postthinning and lop/scatter slash fuels and 0% mortality in units where activity fuels were compacted and raked 0.5–1 m from the boles of trees. However, mean tree dbh for post-1870 trees in the Jerman et al. (2004) study ranged from 33.5 to 36.8 cm pretreatment, somewhat larger than the trees at Red Mountain (Table 2).

The fire behavior results of this study should be viewed in terms of relative differences and not interpreted as individually accurate predictions. Fire behavior predictions using fuel models are highly dependent on the fuel models and modeling system used. Currently, no validated fuel models exist for masticated fuels. Creating and calibrating mastication-specific fuel models with linked fuels and fire behavior data is difficult because multiple data points should be gathered across several types of masticated fuel beds on free-burning, forward-moving fires in a variety of weather conditions. Although custom fuel models show some promise, they should be calibrated with observed or expected fire behavior (Andrews and Queen 2001). Existing or new fuel models that yield the most realistic fire behavior predictions for a particular fuel type may not be the fuel models that represent fuel characteristics the most accurately (Cruz and Fernandes 2008).

Additional research on fire behavior and effects associated with mastication treatments would improve the ability for land managers to make informed decisions based on the knowledge of potential benefits and drawbacks. Gathering data across broader geographic scales would add to our understanding of how topography, vegetation, climate, and mechanical equipment type relate to masticated fuel load and bulk density. As data are accumulated on masticated fuel beds, it would be possible to refine existing fuel models or create a new set of masticated fuel models. Calibration of these fuel models with fire behavior research would give fire managers and planners more insight on potential flame length, fire type, resultant tree mortality, and changes in soil nutrients and structure. Long-term monitoring of masticated fuels would help to define rates of decomposition of masticated fuels through time. Information on the deterioration of these fuels would improve estimates of fire behavior and fire effects several years after treatment, allowing land managers to develop appropriate follow-up treatment schedules. Longer term tree mortality data in masticated/fire treatments would show whether visible tree mortality would continue to increase with time or whether it would level off or even decline.

Conclusions

Fuel treatments should be undertaken on the basis of anticipated ecological effects and potential fire behavior in addition to the relative costs of mastication versus other treatment. Modeled fire behavior in our study and in Kobziar et al. (2009) indicate that mastication followed by prescribed fire may reduce flame lengths and rates of spread for potential fire behavior. Reduced canopy bulk density levels (Reiner et al. 2009) may also decrease predicted active crown fire. This study showed that high levels of tree mortality are possible with masticated/fire treatments in young, dense stands. Raking masticated material away from tree boles after treatment, prior to applying prescribed fire, adds to the cost of the treatment and did not reduce tree mortality significantly in a statistical sense. Slight reductions in mortality due to raking fuels away from tree boles are apparent in the data and warrant further investigation. If managers consider raking fuels away from the boles of smaller trees in attempt to increase postfire survivorship, efforts should be made to scatter fuels to avoid fuel pockets sending heat into tree canopies during prescribed burning.

The decision to use mastication should include consideration of the trade-offs between moderately high potential fire behavior immediately after the treatment and the possibility of lower potential fire behavior in future years. Although mastication can lead to intense surface fire immediately posttreatment, it is possible that potential surface fire behavior would lessen over time as masticated fuels compress and decompose (Jerman et al. 2004). The benefits of reduced crown fire potential gained from mastication treatments should be balanced with potentially greater surface fire behavior, which could increase resistance to control for firefighters trying to stop a wildfire. Continuous beds of burning masticated material could limit paths along which firefighters could move and would require more time of suppression personnel because of longer combustion residence times. However, crown fires are generally a more difficult fire type to manage than surface fires.

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