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Mastication and prescribed fire impacts on fuels in a 25-year old ponderosa pine plantation, southern Sierra Nevada

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ABSTRACT

Due to increases in tree density and hazardous fuel loading in Sierra Nevadan forests, land management is focusing on fuel reduction treatments to moderate the risk of catastrophic fires. Fuel treatments involving mechanical and prescribed fire methods can reduce surface as well as canopy fuel loads. Mastication is a mechanical method which shreds smaller trees and brush onto the surface fuel layer. Little data exist quantifying masticated fuel beds. Despite the paucity of data on masticated fuels, land managers desire fuel loading, potential fire behavior and fire effects such as tree mortality information for masticated areas. In this study we measured fuel characteristics before and after mastication and mastication plus prescribed burn treatments in a 25-year old ponderosa pine (*Pinus ponderosa* C. Lawson) plantation. In addition to surface fuel characteristics and tree data collection, bulk density samples were gathered for masticated material. Regressions were created predicting masticated fuel loading from masticated fuel bed depth. Total masticated fuel load prior to fire treatment ranged from 25.9 to 42.9 Mg ha^{-1}, and the bulk density of masticated fuel was 125 kg m^{-3}. Mastication treatment alone showed increases in most surface fuel loadings and decreases in canopy fuel loads. Masticated treatment in conjunction with prescribed burning reduced both surface and canopy fuel loads. Detailed information on fuel structure in masticated areas will allow for better predictions of fire behavior and fire effects for fire in masticated fuel types. Understanding potential fire behavior and fire effects associated with masticated fuels will allow managers to make decisions on the possibility of mastication to create fuel breaks or enhance forest health.

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1. Introduction

During the early 1900s fire was considered a threat in the U.S. to forests and was actively suppressed (Pollet and Omi, 2002; Sugihara and Barbour, 2006). Fire exclusion has increased tree density, as well as the vertical and horizontal continuity of fuels in some areas (Parsons and DeBenedetti, 1979; Taylor, 2000; Peterson et al., 2003). Today, larger and more contiguous expanses of forests contain hazardous levels of fuel loads (Skinner et al., 2006). The reduced role of wildfire in the Sierra Nevada mountains is one factor that has affected the resilience of these forest ecosystems, raising the probability of stand-replacing fires (Skinner et al., 2006; Stephens et al., 2009).

Due to shifts toward increased fuel loads and higher density forests, land management has focused on efforts to reduce fuels on the landscape. The National Fire Plan (USDA-USDI, 2000), 10-Year Comprehensive Strategy (WGA, 2001), and Healthy Forests Restoration Act (HFRA, 2003) have begun to move priorities toward fuel reduction in order to moderate the risk of catastrophic fires. Fuel treatments can be used to reduce fire behavior characteristics that enhance the suppressability of wildland fires in populated areas; however, using fuel treatments to reduce fire's role on the landscape will only perpetuate excessive fuel load conditions (Reinhardt et al., 2008). Large fires have historically occurred and may be a tool to reduce fuels on the landscape and revive more historic, low and mixed severity fire regimes (Keane et al., 2008). Treatment areas have been shown to have lower burn severity and tree mortality than the surrounding landscape after large, severe fires (Strom and Fulé, 2007).

Due to high fuel loadings, fuel treatments involving multiple entries may be necessary to adequately reduce fuels in both the surface and canopy strata (Peterson et al., 2003). High tree density and very low canopy base heights make prescribed burning a difficult tool to use without incurring undesired levels of tree mortality. Mastication treatments are becoming a popular fuel

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treatment technique used in conjunction with prescribed burning or as a stand-alone treatment. Mastication is a mechanical method that uses a tracked vehicle to grind brush and small diameter trees into smaller pieces that are left on site. Mastication changes the arrangement of fuels but not necessarily the loads (Harrod et al., 2009). Mastication alone is an attractive alternative for fuel reduction because it has none of the risks involving smoke and air quality associated with prescribed burns (Glitzenstein et al., 2006). Mastication used in conjunction with prescribed burning can reduce both canopy and surface fuel loads (Stephens and Moghaddas, 2005; Harrod et al., 2009).

Despite the increasing use of mastication for fuel treatment, potential draw-backs are associated with this treatment type. Mastication removes ladder fuels, raises canopy base height and decreases canopy bulk density; however, these fuels are added to the surface fuel load (Glitzenstein et al., 2006; Kane et al., 2006). An elevated surface fuel load can yield higher surface fire intensity (Wagle and Eakle, 1979; Rothermel, 1983). Due to extended residence times, masticated fuels can also produce heat above lethal levels for plants (Busse et al., 2005; Knapp et al., 2008), potentially leading to high levels of tree mortality. Additionally, post-masticated stands are generally open to increased solar radiation and wind, which lowers fuel moistures when few groundcover plants are present. These effects on wind and fuel moisture may increase potential fire behavior in treated areas, contrary to treatment goals (Pollet and Omi, 2002).

Although mastication treatments are being implemented more frequently than in past decades, only recently have a few studies been conducted on fuel loads or potential fire behavior created from such treatments (Busse et al., 2005; Stephens and Moghaddas, 2005; Glitzenstein et al., 2006; Knapp et al., 2008; Harrod et al., 2009). Methods are currently being developed to accurately assess masticated fuel beds (Hood and Wu, 2006; Kane et al., 2006). No fuel models exist specifically for masticated fuel beds. Knapp et al. (2008) found an average of SB1 (low load activity fuel) and SB2 (moderate load activity fuel) predicted observed flame heights and rates of spread well although these fuel models incorporate lower 1- and 10-h fuel loadings and higher fuel bed depths than were found in the study (Scott and Burgan, 2005). Unlike down woody fuel, fuel bed bulk densities are difficult to estimate in the field, as they require drying and weighing fuel samples (Brown, 1981). Few studies have calculated bulk densities for masticated materials as of yet (Hood and Wu, 2006; Kane et al., 2006). Additionally, universal masticated fuel bulk density equations are unlikely to accurately describe masticated fuel because vegetation type, machinery type, climate and other factors influence masticated bulk density (Kane et al., 2006).

Detailed information on masticated fuel beds is necessary to understand potential fire behavior and fire effects in these fuel types. Little information has been documented about fire behavior in masticated fuel beds (Glitzenstein et al., 2006; Knapp et al., 2008). Previous descriptions of fire behavior in masticated fuel beds are derived from models (Stephens and Moghaddas, 2005; Glitzenstein et al., 2006), with little field data from wildfire or prescribed fire. Additional data on masticated fuel beds could aid in the creation of masticated fuel models. Masticated fuel models calibrated with observed fire behavior could produce more accurate fire behavior predictions and would aid in the planning of fuel treatments and suppression operations. Empirical information on the combustion of masticated fuels would help land managers understand ecosystem processes such as fuel consumption, plant mortality and nutrient cycling (Reinhardt et al., 2008).

In this study we gathered data on fuel loads and characteristics in masticated and masticated plus prescribed burned areas of the Red Mountain fuel treatment area on the Sequoia National Forest in California. Specifically, the objectives of this research were to (1) estimate pre- and post-treatment canopy, live understory, surface and ground (duff) fuel characteristics, and (2) develop on-site bulk densities for masticated and ground fuels for use in characterizing fuels. This data will support fire behavior predictions and tree mortality analysis in conjunction with this project. Fuel treatment planning efforts will benefit from the ability to estimate masticated fuel loading and associated potential fire behavior.

2. Methods

2.1. Study location

This study was conducted in the Red Mountain fuel treatment area located on the Greenhorn Ranger District of the Sequoia National Forest at roughly latitude 35°39′N, longitude 118°36′W. Red Mountain is an area that was replanted with ponderosa pine (*Pinus ponderosa* C. Lawson) after a 1011 ha wildfire in 1970. The study plots are located between 1580 and 2010 m in elevation and are found generally on slopes less than 30%. The site is dominated by ponderosa pine, about 25 years old at the time of treatment and 10 m tall, which in some pre-treatment areas forms a nearly continuous canopy. 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 patches throughout the area. The understory consists of limited amounts of Sierra gooseberry (*Ribes roezlii* Regel), birchleaf mountain mahogany (*Cercocarpus montanus* Raf. var. *glaber* (S. Watson) F.L. Martin) and greenleaf manzanita (*Arctostaphylos patula* Greene) and low densities of annual and perennial grasses and forbs. The mean annual precipitation for nearby weather stations at elevations representative of the lower elevation plots was 63–75 cm of rain and 33 to over 100 cm of snow.

2.2. Study design

The study was designed to be a random block design with four blocks, each 200 by 405 m (8.1 ha), at each of four sites. Within each site a control plus the three treatments (mastication, mastication plus prescribed fire, and mastication/pull-back/fire) were randomly assigned to the blocks. The blocks were located randomly in planned treated areas using ArcMap (ESRI, 2005). Four replicate plots were placed within each block for a total of 64 plots installed pre-treatment. Because not all areas planned for treatment were treated, the study design incurred some modifications, making it unbalanced (Table 1). If treated plots showed no masticated material in the data or photographs post-treatment, the plots were left out of analysis for pre- and post-treatment datasets. Data were also gathered on masticated plots after mastication, but before burning in order to gain more information on masticated materials. All areas that were planned to be treated with prescribed fire received treatment. Data analysis completed in this study were based on pre-treatment data gathered in 2005 and post-treatment data gathered in 2008.

Table 1
Number of plots read for each year/treatment combination.

	Pre-treatment 2005	Post-mastication, pre-burn 2006	Post-treatment 2008
Masticated	7	7	7
Masticated/fire	11	11	11
Masticated/pull-back/fire	8	8	8
Control	16	0	16

2.3. Treatments

Treatments were conducted by personnel on the Sequoia National Forest. Treatments included mastication, mastication followed by prescribed fire, and mastication followed again by prescribed fire where masticated material was manually "pulled-back" from tree boles to the drip line of trees prior to burning with the intention to reduce cambial heating and fine root damage during the burn. 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 prescription included leaving trees over 38 cm diameter at breast height (DBH) and thinning to a density of approximately 61 trees ha^{-1}. Hardwoods and sugar pine were high priority "leave" trees and white fir and incense cedar were the lowest priority. Prescribed burning was completed on December 5 and 6, 2007. Air temperature during the burn ranged from 5 to 15 °C and relative humidity ranged from 30 to 100%, precipitation began while the last unit was burned. Litter moistures ranged from 8 to 12%. The KBDI was 476 and other than 2 days of trace precipitation 0.3 cm of rain fell 24 days prior to the burn. Wind speed during the burn ranged from 5 to 13 km h^{-1} with gusts to 21 km h^{-1}. Ignition patterns of the prescribed burns were spot and strip firing patterns. Spot firing is the ignition of separate, small dots and strip firing is the ignition of lines. Spot firing tends to produce lower fire intensity as the small fires burn together within the burn unit, and the spacing within both spot and strip firing patterns can influence fire intensity. The units were ignited starting from the uphill side of the unit and working downhill, unless wind direction dictated different.

2.4. Field data collection

Four plot centers were placed at even intervals along a 200 m transect running the length of each treatment unit within each block. Plots were 0.1 ha, as defined by a radius extending 17.85 m from the plot center. Overstory trees, with a diameter at breast height (DBH) greater than 15 cm were measured in this plot. Pole-sized trees (DBH 2.5–15 cm) were measured in an 8.92 m radius plot originating from the same plot center as the 0.1 ha plot. Data recorded for overstory and pole trees included: tag number, species, DBH, height to live crown base, total height, and canopy position (dominant, co-dominant, intermediate, or suppressed). Species, DBH, and total height were measured for all snags.

From the plot center, a 15.24 m transect was placed along a random bearing for measurement of surface and ground fuel loads. The planar-intercept method was used to measure surface fuels (Van Wagner, 1968; Brown, 1974). One-hour ($\leq$0.64 cm diameter) and 10-h (>0.64 cm to $\leq$2.54 cm diameter) time lag fuels were tallied in the first 1.83 m. One-hundred-hour (>2.54 cm to $\leq$7.62 cm diameter) time lag fuels were counted in the first 3.66 m of the transect and the diameters of rotten and sound 1000-h (>7.62 cm diameter) time lag fuels were measured along the entire transect. Post-treatment, downed woody fuels were tallied separately as "natural" or "masticated." Masticated fuel depth was measured at the corners and center of a 1 m $\times$ 1 m frame centered at 1.5, 7.6 and 13.7 m along the fuel transect in each plot. Ocular estimates of percent cover of masticated material were recorded in these frames (Hood and Wu, 2006). Litter, duff and fuel bed depth were measured in 10 equidistant intervals along the transect. Live understory vegetation was measured in a one meter-wide belt transect centered on the transect and included percent cover, density class and type for each shrub, forb and grass species present (Burgan and Rothermel, 1984).

In 2006, after mastication treatment but before the prescribed burn treatment, mastication samples were gathered in order to derive site-specific depth to weight relationships for use in estimating masticated fuel loads. One 30 cm $\times$ 30 cm frame was randomly placed in each masticated plot with areas of 100% cover of masticated fuel. The depth of the masticated fuel bed was measured, and so were litter and duff layers, if present. Masticated, litter and duff layers were gathered from within the frame and bagged separately. Material was clipped at the edge of the frame as necessary (Kane et al., 2006). In a lab, these samples were floated to remove soil and rocks (Rau et al., in press), then dried and weighed after remaining at 75 °C for 72 h, or until no change in weight was detectable. Regressions were created in SPSS v10.1.0 (SPSS Inc., 2000) for each of the masticated, litter and duff layers with depth of the layer as the predictor variable and weight per unit area as the response variable.

2.5. Data analysis

Downed woody fuel loads were calculated from fuel counts (Brown, 1974). Litter, duff, and masticated fuel loads were calculated using the site-specific regressions formulated from samples. Surface fuel bed bulk densities were calculated by totaling fuel load estimates for 1-, 10-, 100-, 1000-h downed woody, litter (no duff) and masticated fuels and dividing by the maximum fuel bed depth. Biomass of live understory fuel, including shrubs, forbs and grasses, was estimated using calculations found in the BEHAVE Fuel Subsystem NEWMDL program v2.0 (Burgan and Rothermel, 1984). Canopy base height and canopy bulk density were computed using Fuels Management Analyst Plus (FMAPlus) v3.0.8 (Fire Program Solutions/Acacia, 2008). Fuels Management Analyst Plus is a program which computes canopy fuel characteristics and fire behavior using accepted equations from the literature. Fuels Management Analyst Plus calculates canopy fuel characteristics from field data (tree species, DBH, tree crown ratio, tree crown position and tree height) (Stephens and Moghaddas, 2005). Black oak was not included in canopy fuel calculations because it is deciduous and was unlikely to contribute to available canopy fuel. However, canyon live oak was included in canopy fuel calculations because it is sclerophyllous, and has been known to carry crown fire (Griffin, 1978). Canyon live oak is not a species supported in FMAPlus, therefore, for canyon live oak we substituted tanoak (*Lithocarpus densiflorus* (Hook. & Arn.) Reh.), which is also sclerophyllous.

Fuel load data were analyzed using PROC GLIMMIX in SAS v9.2 (SAS Institute, 2008). Due to the unbalanced design, type III errors were used to determine significance. Prior to analysis, data were tested for normality using Kolmogorov–Smirnov tests, stem and leaf diagrams and detrended normal Q–Q plots in SPSS and residual plots were analyzed in SAS v9.2. For variables that were determined to be non-normal, alternative distributions were assigned in PROC GLIMMIX. A Tukey–Kramer post hoc test was used to determine differences between individual year/treatment combinations where significant differences were found.

3. Results

3.1. Regression analysis

Depth-to-weight relationships for masticated fuel were fairly strong and so were used in calculating fuel loadings from depths (R^2 0.78) (Table 2). A linear regression through the origin was used to represent the masticated fuel depth-to-weight relationship (Fig. 1). The relationship of depth to weight for litter, R^2 = 0.65, showed the most variation between our masticated fuel, litter and duff regressions. This variation was due in part to the fact that only one litter depth measurement was taken per sample and litter depth was variable depending on the level of settling of pine needles. Litter

Table 2
Regression equations, predicting fuel weight (Mg ha^{-1}) from fuel depth (cm) and coefficients, standard error of the coefficients, R^2 and number of samples.

Fuel type	Equation	a	SE	R^2	n
Litter	$y = a \times x$	0.473	0.084	0.65	18
Duff	$y = a \times x$	10.703	1.196	0.82	17
Woody	$y = a \times x$	12.489	1.605	0.78	18

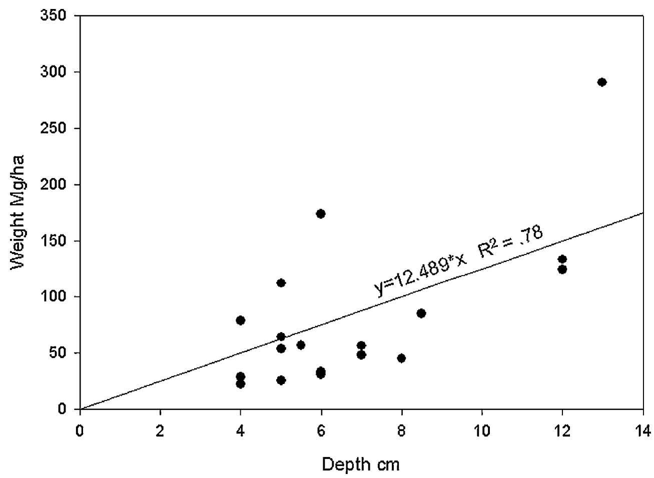

Fig. 1. Scatter plot and regression line for masticated fuel.

bulk density for the samples collected on this study was 4.7 kg m^{-3}, whereas litter bulk densities reported by van Wagtendonk (1998) were 36.0 and 32.6 kg m^{-3} for ponderosa and Jeffrey pine (*Pinus jeffreyi* Balf.), respectively in sites in various parts of the Sierra Nevada. Because our litter bulk density differed from previously published bulk densities and had an acceptable R^2, we chose to use this site-specific equation in calculating litter fuel loads. The duff regression held the strongest relationship between litter, duff and masticated fuel regressions with an R^2 = 0.82. The duff samples had lower variation than litter or masticated samples. The bulk density of duff in this study was 107 kg m^{-3}, which was lower than the duff bulk density of 155 kg m^{-3}, reported by van Wagtendonk (1998) for ponderosa pine. Similar to litter, because our bulk densities for duff differed from other studies and had a strong R^2, we used this regression equation to calculate duff fuel loads.

3.2. Surface and ground fuel loads

Masticated fuel load and depth means and standard errors were compared between pre-treatment (2005), post-mastication (2006) and post-mastication/burn (2008) years. In plots which received only the mastication treatment, mean mastication depths and loads increased slightly from 2006 to 2008, however this increase was less than half of one standard error (Table 3). Mean masticated fuel loads decreased from 25.9 and 35.0 to 5.3 Mg ha^{-1} and 2.6 Mg ha^{-1} in masticated plus fire and masticated/pull-back/fire plots, respectively, between 2006 and 2008. Our total masticated fuel load prior to fire treatment ranged from 25.9 to 42.9 Mg ha^{-1}, which was within the range found by Kane et al. (2006), of 15.3–50.7 Mg ha^{-1} for masticated material. Mean masticated fuel depths were relatively unchanged between 2006 and 2008 in masticated plots, but decreased after prescribed burns from 2.1 and 2.8 cm to 0.4 and 0.2 cm in masticated plus fire and masticated/pull-back/fire plots, respectively. Differences in mean depths of masticated fuel occur between the three treatments prior to the fire, exemplifying the variability in which masticated fuel may occur.

When fuel bed bulk densities were computed with all surface fuels (including litter), bulk densities increased after mastication and decreased from post-mastication (2006) to post-burn (2008) for masticated/pull-back/burned plots only. The bulk density of only masticated material found in this study was 125 kg m^{-3}, similar to the bulk density of 136 kg m^{-3} presented by Hood and Wu (2006) for the masticated fuel layer in a ponderosa pine-Gambel oak (*Quercus gambelii* Nutt.) sites, which were located on the San Juan National forest in southwestern Colorado. Total surface bulk densities from this study are not comparable to Hood and Wu (2006) due to difference in total fuel bed depth measurement methods. Masticated fuel were found to be distributed into 1-, 10-, 100- and 1000-h timelag classes as 1, 37, 59 and 3%, respectively. The dominance of 10- and 100-h fuels in this study differed from the relative abundance of 1 and 10 h fuels found by Kane et al. (2006) where percentages of 1-, 10-, 100- and 1000-h timelag classes for masticated fuel were 30, 53, 14 and 3%, respectively. Mean percent cover of masticated fuels were 17, 8 and 25% for masticated, masticated/burned and masticated/pull-back/burned plots in 2006, respectively.

Non-masticated, downed woody fuel showed few significant changes before and after mastication and burn treatments, p-values were 0.469, 0.946, 0.896 and 0.031 for 1-, 10-, 100- and 1000-h fuels, respectively. In mastication/pull-back/fire units, 1-h fuel loads decreased from 0.05 to 0.02 Mg ha^{-1} (Table 4). In both control and masticated plots, slight increases in 1 h and 10 h fuels were seen from 2005 to 2008. Minor decreases in 10-h fuel occurred following burn treatments in masticated plus fire plots, but not masticated/pull-back/fire plots. One-hundred hour fuel load means decreased from 1.02 and 2.08 to 0.26 and 0 Mg ha^{-1} in masticated plus fire and masticated/pull-back/fire plots, respectively. Although the overall year by treatment p-value for 1000 h fuel loads was significant at the 0.05 level, variability was high in 1000 h fuel and no differences were found in the Tukey–Kramer

Table 3
Mean (standard error) for masticated fuel loadings, masticated fuel depth and fuel bed bulk density for pre-treatment (2005), post-mastication (2006) and post-fire (2008) years for masticated, masticated/fire and masticated/pull-back/fire plots.

Year	Treatment	Masticated fuels (Mg ha^{-1})	Masticated fuel depth (cm)	Fuel bed bulk density (kg m^{-3})[a]
2005	Masticated	n/a	n/a	27 (6)
2005	Masticated/fire	n/a	n/a	27 (7)
2005	Masticated/pull-back/fire	n/a	n/a	22 (7)
2006	Masticated	42.9 (12.5)	3.4 (1.0)	32 (5)
2006	Masticated/fire	25.9 (5.3)	2.1 (0.4)	30 (5)
2006	Masticated/pull-back/fire	35 (6.3)	2.8 (0.5)	57 (9)
2008	Masticated	48 (15.4)	3.8 (1.2)	47 (16)
2008	Masticated/fire	5.3 (1.5)	0.4 (0.1)	29 (7)
2008	Masticated/pull-back/fire	2.6 (1.1)	0.2 (0.1)	12 (4)

[a] Fuel bed bulk density calculated from 1-h, 10-h, 100-h, 1000-h, litter, masticated fuel loads and fuel bed depth.

Table 4
Mean (standard error) 1-h, 10-h, 100-h and 1000-h down woody fuel loadings and p-values for pre- and post-treatment masticated, masticated/fire, masticated/pull-back/fire and control plots.

Year	Treatment	1 h ($Mg\,ha^{-1}$)	10 h ($Mg\,ha^{-1}$)	100 h ($Mg\,ha^{-1}$)	1000 h ($Mg\,ha^{-1}$)
2005	Masticated	0.19 (0.07)	0.79 (0.28)	0 (0)	17.4 (6.9)
	Masticated/fire	0.04 (0.02)	1.44 (0.99)	1.5 (0.67)	14.1 (7.2)
	Masticated/pull-back/fire	0.05 (0.02)	0.43 (0.18)	1.02 (0.71)	13.9 (9.8)
	Control	0.02 (0.01)	1.08 (0.35)	2.08 (1.24)	52.1 (19.5)
2008	Masticated	0.22 (0.11)	1.38 (0.75)	0 (0)	57.4 (21.0)
	Masticated/fire	0.05 (0.03)	0.06 (0.06)	0.26 (0.25)	3.4 (1.7)
	Masticated/pull-back/fire	0.02 (0.01)	0.43 (0.13)	0 (0)	0 (0)
	Control	0.05 (0.02)	1.35 (0.33)	1.22 (0.61)	21.2 (7.3)
	Year × treatment p-value	0.469	0.946	0.896	0.031

Table 5
Mean (standard error) fuel bed depth, litter, duff and live understory fuel loadings and p-values for pre- and post-treatment masticated, masticated/fire, masticated/pull-back/fire and control plots. Means followed by the same letter are not significantly different.

Year	Treatment	Fuel bed depth (cm)	Litter ($Mg\,ha^{-1}$)	Duff ($Mg\,ha^{-1}$)	Live understory[a] ($Mg\,ha^{-1}$)
2005	Masticated	6.6 (1.3)ab	1.3 (0.3)	24.3 (5.6)	0.026 (0.012)
	Masticated/fire	4.3 (1.1)ab	0.9 (0.1)	21.4 (3.5)	0.022 (0.01)
	Masticated/pull-back/fire	4.8 (1.7)ab	1.4 (0.2)	26.4 (4.4)	0.034 (0.01)
	Control	8.7 (1.5)ab	1.5 (0.2)	23.8 (3.2)	0.004 (0.002)
2008	Masticated	25.7 (6.4)a	2.1 (0.4)	20.4 (7.3)	0.115 (0.112)
	Masticated/fire	3.7 (0.3)b	0.7 (0.1)	0.8 (0.5)	0.035 (0.017)
	Masticated/pull-back/fire	3.3 (0.3)b	0.7 (0.1)	2.0 (1.5)	0.137 (0.112)
	Control	10.2 (1.4)ab	2.2 (0.2)	20.4 (6.2)	0.010 (0.003)
	Year × treatment p-value	0.044	0.073	0.377	0.695

[a] Live understory includes live portions of shrubs, grasses, and forbs.

post hoc tests. One, 10- and 1000-h fuel loads all increased after treatment in the mastication-only plots.

Litter fuel load means increased from 1.3 and 1.5 $Mg\,ha^{-1}$ to 2.1 and 2.2 $Mg\,ha^{-1}$ in masticated and control treatment plots, respectively, however these changes were not significant (Table 5). Mean litter load decreased slightly in treatment units incorporating fire, similar to results found by Stephens and Moghaddas (2005). Litter fuel loads in this study ranged from 0.09 to 0.22 $kg\,m^{-2}$, in pre-treatment and control plots, somewhat lower than those for ponderosa pine in van Wagtendonk (1998), 0.56 $kg\,m^{-2}$, and van Wagtendonk (1974), 0.44 $kg\,m^{-2}$.

Mean duff load decreased from 21.4 and 26.4 $Mg\,ha^{-1}$ to 0.8 and 2.0 $Mg\,ha^{-1}$ in masticated plus fire and masticated/pull-back/fire plots, respectively. Mean duff load also decreased after treatment in masticated and control plots, however, due to the high variability in these units, differences were not significant. Total duff fuel load was 2.0–2.6 $kg\,m^{-2}$ in pre-treatment and control plots in our study, which is lower than that reported by van Wagtendonk (1998) in ponderosa which was 11.3 $kg\,m^{-2}$. Forest floor fuel load, the sum of litter and duff, ranged from 2.0 to 4.8 $kg\,m^{-2}$ according to Kittredge (1955) for young and mature ponderosa pine which is similar to our forest floor load in pre-treatment and control plots of 2.3–2.9 $kg\,m^{-2}$.

Pre-treatment, live understory fuel load means were variable between the different treatment units (Table 5). In all treated units, live understory load means showed slight increases after treatment. However, due to the patchy nature of herbaceous plant abundance in the study site, live understory loads were highly variable and showed no significant changes.

Fuel bed depth showed various changes between 2006 and 2008 depending which were significant at the 0.05 level (Table 5). The Tukey–Kramer post hoc test showed differences in post-treatment fuel bed depth between treatment units that received fire and those which were solely masticated. The fuel bed depth mean of masticated-only units increased from 6.6 to 25.7 cm. The units in which fire was included in the treatment showed decreases in mean fuel bed depth on the order of 0.5 cm, whereas mean fuel bed depth in control plots increased slightly post-treatment.

3.3. Forest structure and fuels

Mean tree height generally increased with treatment ($p = 0.007$) and trees per hectare ($p = <0.001$) and basal area ($p = 0.003$) decreased with treatment (Table 6). Mean tree height increased significantly after mastication and mastication/burn treatments, according to the Tukey–Kramer post hoc test. Trees per hectare decreased significantly with all treatments and basal area decreased after treatments incorporating burning, but not mastication-only. Control plots remained relatively unchanged. These results are analogous to those found by Stephens and Moghaddas (2005) who found basal decreases in masticated/burn plots (55.1–39.3 $m^2\,ha^{-1}$) were greater than decreases in masticated-only plots (40.9–51.9 $m^2\,ha^{-1}$).

Both canopy base height and canopy bulk density showed significant changes due to treatment. Canopy base height changes had a p-value of 0.003 whereas the p-value for canopy bulk density was 0.048. Mean canopy base height increased from 1.0 and 1.1 m to 6.5 and 5.5 m in masticated plus fire and masticated/pull-back/fire plots, respectively (Table 7). Canopy base heights in mastication-only plots increased from 0.6 to 1.8 m after treatment, but this change was not significant according to Tukey–Kramer results. Canopy bulk density decreased by 38, 54 and 50% in masticated, masticated plus fire and masticated/pull-back/fire plots, respectively. Tukey–Kramer results showed that these individual decreases in canopy bulk density were not significantly different.

4. Discussion

Changes in downed woody and ground fuel loads generally mirrored previous research (Stephens and Moghaddas, 2005; Stephens et al., 2009). Despite a moderate degree of variability in

Table 6
Mean (standard error) tree height, trees per hectare, basal area and *p*-values for pre- and post-treatment masticated, masticated/fire, masticated/pull-back/fire and control plots. Means followed by the same letter are not significantly different.

Year	Treatment	Height (m)	Trees (ha^{-1})	Basal area ($m^2\,ha^{-1}$)
2005	Masticated	7.9 (0.7)c	956 (20)a	30.6 (0.4)ab
	Masticated/fire	8 (0.3)c	937 (9)a	27.5 (0.2)a
	Masticated/pull-back/fire	9.2 (0.5)abc	911 (12)a	29.9 (0.2)a
	Control	8.7 (0.6)bc	833 (11)a	29.4 (0.3)a
2008	Masticated	12.7 (0.8)a	270 (32)b	23.2 (4.4)abc
	Masticated/fire	11.6 (0.5)ab	208 (71)b	9.6 (1.4)c
	Masticated/pull-back/fire	12.1 (0.5)a	229 (84)b	10.7 (1.8)bc
	Control	9.7 (0.6)abc	828 (108)a	30.2 (1.6)a
	Year × treatment *p*-value	0.007	<0.001	0.003

the results, downed woody fuel generally showed decreases after burn treatments and increases after mastication treatments. Slight increases in downed woody fuel loads after prescribed fire treatments (such as 1-, and 10-h fuels, Table 4), could be due to deposition of fuels after scorching and torching of tree branches. Similarly, slight increases in litter depth between 2006 and 2008 in plots not exposed to fire could be due to additional litter deposition. Lower total litter loads in our study compared to other studies in the Sierra Nevada mountains are potentially due to our site being less productive, or having a lower snow pack compressing litter layers when compared to studies with sites across the Sierra Nevada (van Wagtendonk, 1974, 1998), or mixing of litter during mastication which could leave the litter layers less compact. Additionally, our definition of the litter layer was likely higher in the ground fuel profile than previous studies, leading to the upper, less compacted layers defining the litter bulk density. Litter fuel loads in this study ranged from 0.09 to 0.22 kg m^{-2}, which are more similar to those in ponderosa pine of the Southwest as reported by Sackett (1979), with an average litter biomass in ponderosa pine of 0.22 kg m^{-2}.

Because the regressions for woody, litter and duff fuels were created from data taken after mastication in 2006, there is the potential that these relationships do not accurately describe 2008 relationships. In masticated plots, masticated fuel depths did not change more than the standard error between 2006 and 2008. Similarly, mean duff fuel load did not change more than the standard error between pre- and post-treatment years. Because these depths did not change greatly between years, the regression equations created from samples gathered in 2006 were used in 2008 also. Litter depth did increase from pre- to post-treatment years in control plots; however, we expect that was caused by litter deposits rather than litter bulk density changes, therefore we used litter regressions from samples gathered in 2006 to compute 2008 fuel loads.

Live understory fuel load, fuel bed depth and bulk density changes with treatments can shed light on the effects of the treatments on potential post-treatment fire behavior and fire effects. Although live understory fuel loads make up a very small part of total fuel load in this project, the amount of fine fuel associated with live grasses and herbs which cures and becomes available in late summer is important to fire rates of spread if quantities are sufficient so that cured understory fuel becomes the main surface fuel over litter (Rothermel, 1983; Scott and Burgan, 2005). Noticeable decreases in bulk density after burning for plots including the pull-back treatment could be due to surface fuels being concentrated in circles around the trees, making complete consumption of these fuels more probable. Increases in fine fuels from understory plants as well as decreased bulk densities after prescribed fire could yield higher potential rates of spread than desired for suppression, however the fire effects resultant from these light fuels could result in lower post-fire tree mortality.

Table 7
Mean (standard error) canopy base height and canopy bulk density and *p*-values for pre- and post-treatment masticated, masticated/fire, masticated/pull-back/fire and control plots. Means followed by the same letter are not significantly different.

Year	Treatment	Canopy base height (m)	Canopy bulk density (kg m^{-3})
2005	Masticated	0.6 (0.1)c	0.092 (0.009)
	Masticated/fire	1.0 (0.2)c	0.120 (0.013)
	Masticated/pull-back/fire	1.1 (0.2)c	0.124 (0.011)
	Control	0.9 (0.2)c	0.110 (0.019)
2008	Masticated	1.8 (0.3)bc	0.057 (0.006)
	Masticated/fire	6.5 (0.6)a	0.055 (0.009)
	Masticated/pull-back/fire	5.5 (0.8)ab	0.062 (0.01)
	Control	1.0 (0.2)c	0.111 (0.012)
	Year × treatment *p*-value	0.003	0.048

Our data supports results seen in other studies (Stephens and Moghaddas, 2005; Schwilk et al., 2009; Vaillant et al., 2009), in which mechanical treatments reduced canopy bulk density and increased canopy base height by removing smaller trees. The results of our Tukey's test showed significant increases in canopy base height in mastication/burn treatments whereas canopy base height changes in mastication-only treatments were not significant, similar to the slightly lower (although not significant) canopy bulk density in mechanical/fire treatments as seen in Stephens and Moghaddas (2005). Higher canopy base heights increase the amount of energy required to transition surface fire to crown fire (Van Wagner, 1977; Agee et al., 1999). Lower canopy bulk densities will reduce the likelihood of active crown fire (Van Wagner, 1977).

5. Conclusions

Fuel treatments should be designed based on desired ecosystem effects and potential fire behavior (Peterson et al., 2003; Reinhardt et al., 2008). Our results concur with previous research on fuel treatments, finding mechanical treatments to increase small-diameter surface fuel loads and decrease canopy fuel loads while treatments involving fire reduce surface fuel loads (Wagle and Eakle, 1979; Stephens and Moghaddas, 2005; Vaillant et al., 2009). In this study, mastication alone temporarily increased surface fuel loads and therefore potential residence time and flame depth. While mechanical treatments such as mastication can raise the canopy base height and reduce canopy bulk density, lessening the likelihood of crown fire, increased surface fuel loads resulting from these treatments have the potential to yield more intense fire behavior (Stephens, 1998). Care should be taken when planning mastication treatments that could yield thick, continuous mats of masticated material. Additionally, it has been noticed that continuous mats of masticated fuel can produce more intense fire behavior than experienced fire personnel may expect, and these levels of fire behavior could make escape through burning masticated materials difficult (personal communication Dan Felix, San Jacinto District Fuels Officer, San Bernardino National Forest). Heat generated from burning masticated material may lead to tree mortality greater than desired thresholds. Busse et al. (2005) found masticated fuel depths of 7.5 cm or greater had the ability to produce temperatures above 60 °C, the lethal threshold for plants, as deep as 10 cm below the soil surface. Although mastication treatments can be accomplished without the logistical difficulties associated with prescribed burning, forest health and potential fire behavior goals may not be met.

The ability to accurately quantify fuel characteristics will aid in determining fire effects (Knapp et al., 2005) and fire behavior associated with masticated fuel beds. Further research on the changes in litter, duff and masticated fuel bulk densities at various lengths of time after mastication would aid in understanding how potential fire behavior and effects could change with time since mastication. Future research could benefit from sampling intensities higher than conducted in this research for surface and masticated fuels to account for the high degree of variation found in the surface fuel stratum. As data are accumulated on masticated fuel beds in various vegetation types, climate zones, using different equipment types, it would be possible to refine existing fuel models (Scott and Burgan, 2005) or create a new set of masticated fuel models. Validation of these fuel models could be accomplished through fuels and fire behavior monitoring on prescribed burns or wildfires. Quantifying masticated fuel characteristics and potential fireline intensity could give greater insight to potential mortality due to cambial heating as well as changes to the nutrient content and structure of soils associated with the combustion of masticated fuel. Understanding masticated fuels and how they burn will help land managers make decisions on whether mastication or mastication plus burn treatments meet the objectives for fuel breaks, where suppression resources could better contain fires, or for forest restoration treatments, which wildfires could burn through yielding positive ecosystem effects.

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