Red Mountain Mastication Study

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I. Abstract

Due to increases in tree density and hazardous fuel loading in Sierra Nevada forests, land management is focusing on fuel reduction treatments to moderate the risk of catastrophic fire. 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 exists characterizing fuel beds after mastication or mastication/prescribed burn treatments nor the associated fire behavior or effects of these fuel beds. The purpose of this study is to provide land managers with information on fuel characteristics, potential fire behavior and tree mortality associated with mastication and mastication/prescribed burn treatments.

This project focused on three types of treatments, mastication, mastication plus prescribed burning and mastication plus prescribed burning after fuels were "pulled-back" from the boles of trees. Fuel characteristics and tree mortality data were gathered before and after 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. Fire behavior measurements were gathered during the prescribed burn treatment using video cameras, thermocouples and passive flame height sensors. Potential fire behavior estimates using 90th and 97th percentile weather, similar to wildfire conditions, were derived using FMAPlus along with post-treatment fuel data.

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}, both within the range found in other studies. Mastication treatment alone showed increases in most surface fuel loads and decreases in canopy fuel loads. Masticated treatment in conjunction with prescribed burning reduced both surface and canopy fuel loads. Rates of spread and flame lengths as predicted with FMAPlus using 90th and 97th percentile weather and post-treatment fuel conditions for masticated plots were higher in masticated than masticated/burned plots. Torching and crowning indices from FMAPlus indicated that higher winds would be necessary to promote torching in plots treated with mastication and prescribed fire and the probability of active crown fire was reduced slightly for all treated plots. Post-treatment tree mortality, as measured in the field at the end of the first growing season, was 38 % for mastication/burn and 28 % for mastication/pull-back/burn treatments. Detailed information on fuel load and structure in mastication treatments will allow for better predictions of fire behavior and fire effects associated with this treatment; allowing managers to make informed decisions regarding mastication as an option for reducing hazardous fuels and enhancement of forest health.

II. Summarized Findings

Masticated fuel characteristics (as measured post-mastication, pre-prescribed burn)

- Mean fuel load showed considerable variation, ranging from 25.9 to 42.9 Mg ha^{-1}.
- Mean fuel mass fell mostly into the 10- and 100-hr size classes, at 37 and 59 % respectively.
- Mean percent cover showed considerable variation, ranging from 8 to 25 %.
- Mean fuel depth showed considerable variation, ranging from 2.1 to 3.4 cm.
- Masticated fuel load (Mg ha^{-1}) can be predicted for the study site by multiplying 12.5 by the average masticated fuel depth (cm).
- The bulk density of masticated material for this site is 125 kg m^{-3}.

Natural surface fuel and canopy fuel characteristics

- Non-masticated, downed woody fuel showed few significant changes before and after both mastication, and prescribed burn treatments.
- Mean tree height increased significantly after mastication and mastication/burn treatments.
- Mean trees per hectare decreased significantly with all treatments.
- Decreases in mean basal area were statistically significant for the mastication with prescribed burn treatments. A decrease in mean basal area occurred for the mastication-only treatment, but was not statistically significant due to high variability.
- Mean canopy base height increased significantly with all treatments.
- Mean canopy bulk density decreased by 38, 54 and 50 % for masticate-only, masticate/burn and masticate/pull-back/burn treatments, respectively.

Prescribed fire characteristics

- The maximum temperature recorded by the thermocouples placed at 4 cm below the soil surface ranged from 9 to 43 C (48 to 109 F), much lower than temperatures at the soil surface and fuel surface, which ranged from ambient temperature to 1200 C (the thermocouple failure point).
- The period of time where temperatures exceeded the lethal threshold for plant material, 60 C, was up to 476 min.

Predicted fire behavior

- Predicted fire behavior under 90th and 97th percentile weather conditions for post-treatment fuel conditions showed that mean rate of spread would be higher for the masticate-only treatment than treatments with combined mastication/underburn, and the untreated control.
- Flame length was predicted to be higher for the masticate-only treatment than treatments with combined mastication/underburn, and the untreated control.
- Treatments with combined mastication/underburn showed higher torching indices than masticate-only, and the untreated control. This indicates that higher winds would be necessary to produce torching in combined mastication/underburn units given post-treatment fuel conditions.

Prescribed fire effects (measured post-mastication, post-prescribed burn)

- Mean percent scorch was 74 and 75 % for masticate/burn and masticate/pull-back/burn treatments, respectively.
- Mean percent mortality was 38 and 28 % for masticate/burn, and masticate/pull-back/burn treatments, where masticated fuel was pulled back to the drip line of trees before burning.

Predicted fire effects for post-treatment fuels

- Predicted post-wildfire mortality from FMAPlus using post-treatment fuels and 97th percentile weather conditions was 87 % for masticate units, 57 % for control units, 28 % for masticate/burn units and 30 % for masticate/pull-back/burn units.

III. Background and Purpose

During the early 1900s fire was considered a threat to U.S. 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 DeBendetti, 1979; Taylor, 2000; Peterson et al., 2003). Today, larger and more contiguous expanses of forests contain hazardous levels of fuels (Skinner et al., 2006). The reduced role of wildfire in the Sierra Nevada range 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).

With recognition of the problems associated with increased fuel loads and higher density forests, land management has focused on efforts to reduce hazardous fuel loads on the landscape. The National Fire Plan (USDA-USDI, 2000), 10-Year Comprehensive Strategy (WGA, 2001), and Healthy Forests Restoration Act (HFRA, 2003) have shifted priorities toward hazardous fuel reduction in order to moderate the risk of catastrophic fires. Fuel treatments can be used to reduce certain fire behavior characteristics, resulting in an improved capability to suppress wildland fires in populated areas; however, using fuel treatments to reduce fire's role across the greater 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 exhibit lower burn severity and tree mortality than the surrounding landscape after large, severe fires (Strom and Fulé, 2007).

Due to high fuel loads, fuel treatments involving multiple entries may be necessary to adequately reduce fuels in both the surface and canopy strata (Peterson et al., 2003). High surface fuel loads, high tree density, and low canopy base heights make prescribed burning a difficult tool to use without risking escaped fires, or sustaining undesired levels of tree mortality. Mastication treatments are becoming a popular fuel treatment technique used in conjunction with vegetation removal, prescribed underburning, 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, adding to the surface fuel load. Mastication changes the arrangement of fuels but not necessarily the loads (Harrod et al., 2009). Logistically, using mastication alone is an attractive alternative to prescribed burning since the risks, and restrictions associated with air quality are not an issue (Glitzenstein et al., 2006). Mastication used in conjunction with prescribed burning can reduce both canopy and surface fuel loads (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 (Wagel 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. These effects on wind and fuel moisture have the potential to increase 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. However, these fuel models incorporate lower 1- and 10-hr fuel loads 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 cause great variations in particle size and compactness, which in turn influence masticated bulk density (Kane et al., 2006).

Detailed information on masticated fuel beds is necessary to understand potential fire behavior and fire effects. Little information has been documented about fire behavior in masticated fuel beds (Glitzenstein et al., 2006; Knapp et al., 2008). Several 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. 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 characteristics and tree mortality before and after mastication treatments and prescribed underburn treatments with an investigation of the Red Mountain fuel treatment project on the Sequoia National Forest in California. Fire behavior data were gathered during the prescribed burn treatments. Specifically, the objectives of this research were to 1) estimate fuel characteristic changes in canopy, live understory, surface, and ground (litter and duff) fuel loads associated with the treatments, 2) develop on-site bulk densities for masticated and ground fuels for use in characterizing fuels, 3) begin to associate masticated fuel characteristics with potential fire behavior by quantifying fire behavior during the prescribed burn, 4) estimate potential wildfire behavior characteristics for post-treatment fuel conditions, and 5) assess tree mortality in relationship to treatments. Fuel treatment planning efforts will benefit from the ability to estimate masticated fuel loads, associated potential fire behavior, and tree mortality.

IV. Study Description and Location

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 35º 39' N, longitude 118º 36'W. Red Mountain is an area that was replanted with ponderosa pine (*Pinus ponderosa* C. Lawson) after a 1,011 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 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 to 75 cm of rain, and 33 to over 100 cm of snow.

Study design

The study was designed to be a random block design with four blocks, each 200 by 405 m (8.1 ha), at four sites. Within each site an untreated control plus three treatments (masticate-only, masticate with underburn, and masticate/pull-back/burn) were randomly assigned to the blocks. Four replicate plots were placed within each block for a total of 64 plots installed with data collected pre-treatment. Data were also gathered on masticated plots after mastication, but before burning in order to gain more information on masticated fuel beds. Because not all areas planned for treatment were successfully implemented, 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. All areas that were planned to be treated with a prescribed underburn received treatment. Data was collected on all plots following the prescribed underburn treatment.

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

Treatment	Pre-treatment (2005)	Post-mastication, pre-burn (2006)	Post-treatment (2008)
Masticate	7	7	7
Masticate/burn	11	11	11
Masticate/pull-back/burn	8	8	8
Control	16	0	16

Treatments

Treatments were implemented by the Sequoia National Forest. Treatments included mastication-only, mastication followed by prescribed underburn, and mastication followed by prescribed underburn where masticated material had been manually "pulled-back" from tree boles to the drip line of trees prior to burning. The intention of the masticated fuel pull-back was to test a treatment method with the potential for reducing 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}. 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 %, with precipitation beginning during the burning of the last unit. Litter moistures ranged from 8 to 12 %. The KBDI was 476. Other than two days of trace precipitation, 0.3 cm of rain fell 24 days prior to the burn. Precipitation began while the last unit was burned. 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 included both spot and strip firing. Spot firing is the ignition of separate, small dots and strip firing is the ignition of lines. The units were ignited starting from the uphill side of the unit and working downhill, unless wind direction dictated different.

Fuels 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 DBH greater than 15 cm were measured in this plot. Pole-sized trees (DBH 2.5 to 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.

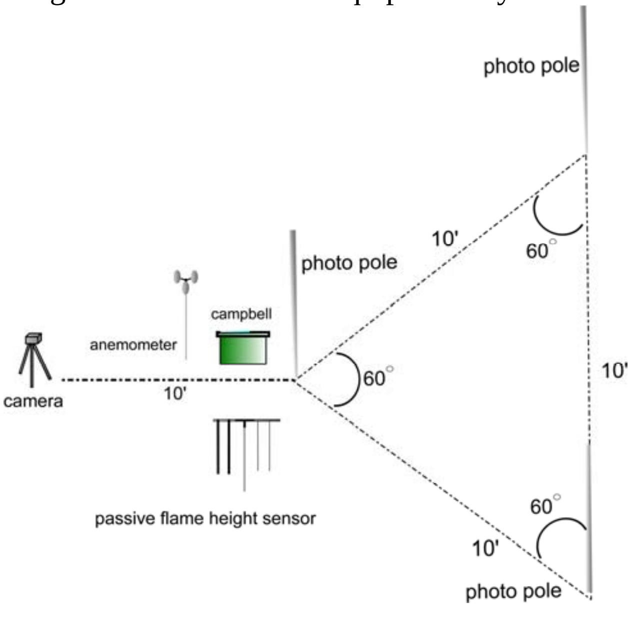
From the plot center, a 15.24 m transect was placed along a random bearing for measurement of surface and ground fuel loads. The planar-intercept method was used to measure surface fuels (VanWagner, 1968; Brown, 1974). One and 10-hr time lag fuels were tallied in the first 1.83 m. One-hundred h fuels were counted in the first 3.66 m and the diameters of rotten and sound 1000-hr 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 x 1m frame centered at 1.5, 7.6 and 13.7 m along the fuel transect in each plot (Hood and Wu, 2006). Ocular estimates of percent cover of masticated material were recorded in these frames. 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 x 30 cm frame was randomly placed in each masticated plot within 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 NCSS v2004 (Hintze, 2001) for each of the masticated, litter and duff layers. Layer depth was the predictor variable, and weight per unit area was the response variable. These regressions were used to calculate fuel loads for masticated, litter, and duff layers.

Fire behavior and fire effects data collection

Fire behavior data was collected using equipment placed in plots immediately prior to the burn. Within each plot, one color video camera, housed in fire-resistant case upon a tripod (Kautz, 1997), was set to record the prescribed fire. Photo poles marking 0.3 m, 0.6 m and 0.9 m of height in alternating red and white sections were placed in a 3 m equilateral triangle, located 3 m away from the video camera (Figure 1). Distances and bearings between photo poles and the camera were recorded. A passive flame height sensor was placed near the first photo pole, within view of the camera. A data logger was buried near the first photo pole, but out of view of the camera. The data logger was linked to thermocouples to measure temperature and an anemometer to measure wind. Sensors were placed to measure rate of spread, however, because the plots were burned with a strip firing pattern and not free-burning, these data were not analyzed.

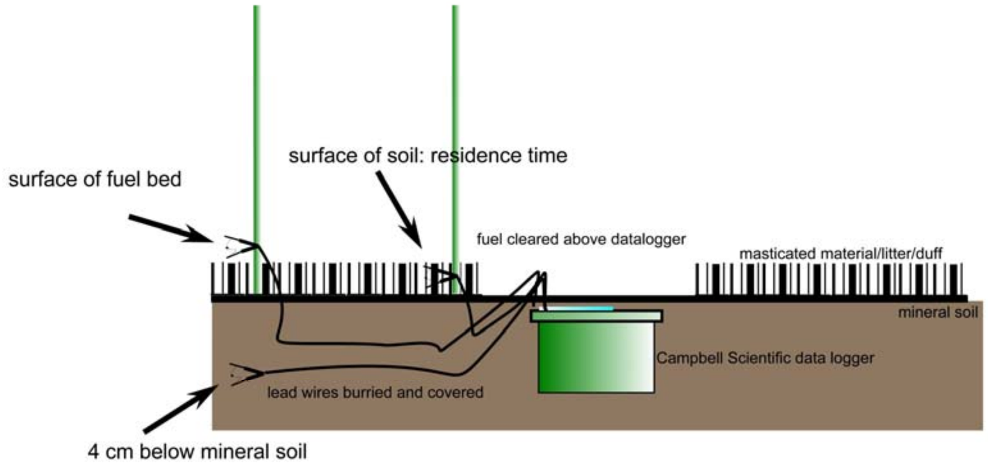
Figure 1
Diagram of fire behavior equipment layout.



Flame length and flame height were gathered separately with two different methods. A minimum of 20 still photos were created from the video camera footage of the fire front passing in front of the camera. Flame heights were visually estimated from these photos using the photo poles as a gauge. Flame heights were measured with passive flame height sensors. The passive flame height sensors were created from conduit forming a “T,” with the vertical bar of the “T” being 2 m long, and fitted over a piece of rebar secured in the ground for vertical support. Lengths of 0.127 and 0.079 cm (0.050 and 0.031 in) diameter solder were hung from the horizontal pole of the “T.” These lengths of solder were measured before and after the burn and the portion of solder burned was computed. Regressions were used to convert the length of solder burned to a flame height using equations for 18 gauge (0.050 in diameter) and 20 gauge (0.036 in diameter) solder (Simard et al., 1989).

Surface and sub-surface temperatures were recorded during the burns with type K thermocouples and logged on Campbell Scientific data loggers (Campbell Scientific, Inc.). Fuels were cleared in a 0.3 X 0.3 m area above the data logger to avoid any possibility of heat damage. Approximately 1 m away from the buried data logger, two thermocouples were placed at the surface of the fuel bed and two were buried 4 cm below the soil surface, with fuels replaced after thermocouple placement (Figure 2). Additionally, two thermocouples were located near the edge of the fuel complex, adjacent to the area cleared above the data logger so that thermocouple lead wires would be least affected by heat and thermocouples could capture heat residence time. Time above 60 C, the point of protein coagulation and plant tissue death (Neary et al., 1999), was analyzed. Factors such as tree size and bark thickness also effect tree cambium mortality (Ryan and Frandsen, 1991), and so the time above 150 C was also analyzed.

Figure 2
Diagram of thermocouple and data logger layout.



Weather observations were recorded hourly by two Fire Effects Monitors during the prescribed fire treatment, in areas adjacent to the burns, but out of the smoke. Weather observations included temperature, relative humidity, wind speed and wind direction. On-site wind speeds were also measured using an anemometer which logged data on the Campbell Scientific. Nine soil moisture and nine litter fuel moisture samples were taken the mornings of the prescribed burns.

The following spring after the prescribed burn treatment, crown scorch (foliage discolored but not consumed) and torch (foliage consumed) heights were measured. An estimation of tree mortality, based on presence/absence of green needles or buds was also taken at the end of the first growing season (October) after the prescribed fire treatment.

Fire behavior model calibration

Several preliminary fire behavior runs were completed in FMAPlus (Fire Program Solutions, 2008) prior to running all data in order to calibrate fuel model choice. Fire behavior fuel models from Scott and Burgan 2005 were used in this study. Some calibration runs were performed with 90th percentile weather conditions. In these calibration runs, fire behavior outputs, weather, and chosen fuel models were scrutinized by an experienced Fire Behavior Analyst in conjunction with photos and fuels data associated with the plots. Different fuel models were tried until predicted fire behavior most closely correlated with the Fire Behavior Analyst's expectations.

Additional calibration runs were completed using actual weather conditions and fire behavior observed during the prescribed fires. High and low end weather scenarios were derived from hourly weather observations taken on site during the burning of each unit. Canopy characteristics were derived from measured tree data that was entered into FMAPlus. Multiple runs were performed in order to test several potential fuel models approximating pre-burn conditions. Fire behavior characteristics predicted by FMAPlus were compared to observed fire behavior. Flame length was the most reliable fire behavior characteristic for calibration of observed to modeled fire behavior. Because strip and spot firing ignition techniques were used, observed rates of spread could not approximate free-burning head fire, on which the surface spread rate is based in FMAPlus (Rothermel, 1972; Rothermel, 1983).

Fire behavior modeling

Fire behavior modeling was completed in FMAPlus using 90th and 97th percentile weather with post-treatment fuel conditions to explore the affect of the treatment on potential fire behavior during wildfires. The 90th and 97th percentiles were calculated with weather data from May 1st through October 15th from the Breckenridge RAWS between 1987 and 2007 using Fire Family Plus (Table 2). These higher weather percentiles approximate conditions that could be expected during wildfires. Percentiles were calculated using the three predominant winds: South, Southwest and Southeast. Twenty-foot (6.1 m) windspeeds were obtained from the percentile weather report using the spread component, then applying a slight increase to simulate the dominant influence that wind gusts have on fire behavior (Crosby and Chandler, 2004). Fuel moistures were also obtained from the percentile weather report, but using the energy release component. Relative humidities were obtained from the frequency distribution report.

Table 2
Weather parameters for 90th and 97th percentile weather scenarios.

Weather parameter	90th percentile scenario	97th percentile scenario
Probable max 1 min 20-foot windspeed (mph)	12	18
Temperature F	83	87
Relative humidity (%)	8	3
1-hr h fuel moisture (%)	3.5	3.2
10-hr fuel moisture (%)	3.8	3.5
100-hr fuel moisture (%)	6.6	5.3
Herbaceous fuel moisture (%)	32.8	30.8
Woody fuel moisture (%)	70	70
Foliar moisture (%)	100	90

FMAPlus computes fire behavior and effects using established models (Stephens and Moghaddas, 2005). Inputs in addition to weather include tree data (species, DBH, crown ratio, crown position), surface fuel model, slope and wind reduction factor. Fuel model choices (Scott and Burgan, 2005) for each plot were based on the results of calibration runs, photos and summarized fuel data. A wind reduction factor of 0.3 was used for control plots and treated plots assigned a timber fuel model and 0.4 was used for treated plots assigned a slash model (National Wildfire Coordinating Group, 2006) Foliar moistures of 90 and 100 % were chosen because they approximate weather conditions conducive to wildfire spread (Keyes, 2006).

Data analysis

Litter, duff and masticated fuel depth-to-weight regressions were created using NCSS statistical software for exploratory and regression analysis. Litter, duff, and masticated fuel loads were calculated using these site-specific regressions. Surface fuel bed bulk densities were calculated by totaling fuel load estimates for 1-, 10-, 100-, 1000-hr downed woody, litter 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 FMAPlus. Fuel load data were analyzed using PROC GLIMMIX in SAS v9.2 (SAS Institute, 2008). A Tukey-Kramer post hoc test was used to determine differences between individual year/treatment combinations where significant differences were found.

Custom masticated fuel models

Custom fuel models were created in order to explore the possibility that fuel models built from actual field data more accurately describe the fire behavior in masticated fuels. Data from 2006 (post-mastication, pre-burn), were divided into low, medium and high masticated fuel load groups. The median fuel bed depth and natural 1-, 10-, 100-, and 1000-hr fuel loads, and masticated fuel loads were computed for each group. Masticated fuels were then divided into 1-, 10-, 100-, and 1000-hr fuels according to ratios found after tabulation of fuels tallied as "masticated" along Brown's transects. These masticated loads were then added to the natural downed woody loads for total fuel load by time lag class for custom fuel modeling. Weather observations and anemometer readings gathered during the prescribed burn were used along with fire behavior observed during the burn to calibrate the custom fuel models. Fuel bed depth was changed from the values observed in the field so that predicted fire behavior better represented actual fire behavior observations during the prescribed burn.

V. Results

Masticated fuel bed regressions

Depth-to-weight relationships for masticated fuel were fairly strong and were used in calculating fuel loads from depths ($R^2 = 0.78$) (Table 3). A linear regression through the origin was used to represent the masticated fuel depth to weight relationship (Figure 3). 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 varied depending on the level of settling of pine needles. Litter bulk density for the samples collected for 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.

Figure 3
Scatter plot and regression line for masticated fuel.

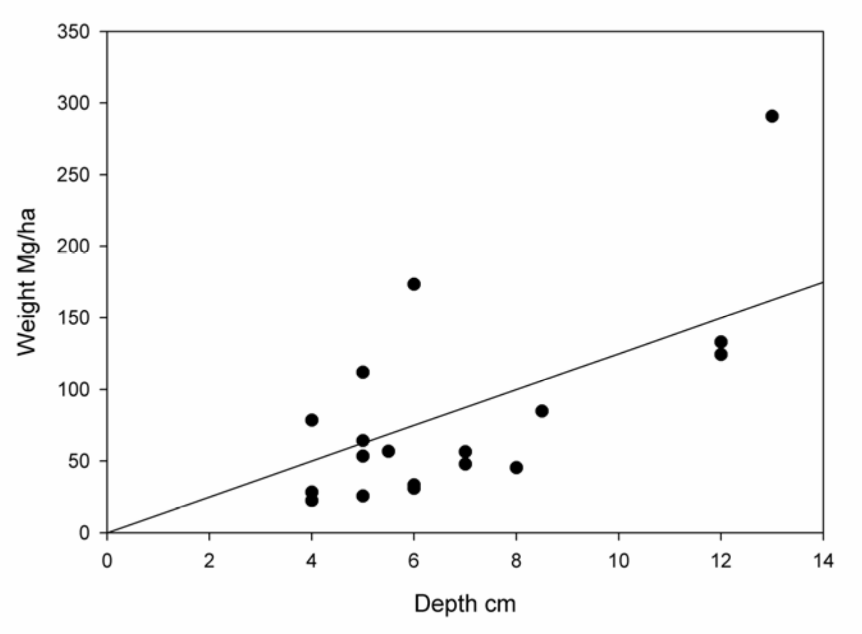


Table 3
Regression equations predicting fuel weight (Mg ha^{-1}) from fuel depth (cm).

Fuel type	Equation	a	R^2	n
Litter	*y=a*x*	0.4734	0.6525	18
Duff	*y=a*x*	10.703	0.8248	18
Masticated	*y=a*x*	12.489	0.7809	18

Surface and ground fuel

Looking at all mastication treatment types, the structure of masticated fuels measured in 2006 (post-mastication, and pre-burn), showed considerable variation. Mean masticated fuel load ranged from 25.9 to 42.9 Mg ha^{-1}, masticated fuel bed depth ranged from 2.1 to 3.4 cm, and percent cover ranged from 8 to 25 %.

The mean masticated fuel load measured pre-burn, ranged from 25.9 to 42.9 Mg ha^{-1}, which is within the range found by Kane et al. (2006), of 15.3 to 50.7 Mg ha^{-1}. In 2008, following prescribed underburn treatments, mean masticated fuel load decreased from 25.9 to 5.3 Mg ha^{-1} in mastication/burn plots, and 35.0 to 2.6 Mg ha^{-1} in mastication/pull-back/burn plots (Table 4).

Following mastication treatments in 2006, the mean depth of masticated fuel was 3.4, 2.1, and 2.8 cm for masticate-only, masticate/burn, and masticate/pull-back/burn plots, respectively. Following the prescribed underburn treatment in 2008, mean fuel bed depth for the masticate-only treatment remained relatively unchanged, but was reduced from 2.1 to 0.4 cm with masticate/burn, and 2.8 to 0.2 cm with the masticate/pull-back/burn treatment.

Total fuel bed bulk density was computed by combining values of all natural fuels (excluding duff) with masticated fuel. Total fuel bulk density increased post-mastication for all treatments; possibly due to the compaction of natural fuels during implementation of the mastication treatments, and/or the addition masticated material which is a more dense fuel bed. In 2006, post-mastication, the total fuel bed bulk density increased from 27 to 32 kg m^{-3} with masticate-only, from 27 to 30 kg m^{-3} with mastication/burn, and increased most, from 22 to 57 kg m^{-3}, with the mastication/pull-back/burn treatment. In 2008, post-burn, total fuel bed bulk density increased from 32 to 47 kg m^{-3} with masticate-only, decreased slightly from 30 to 29 kg m^{-3} with mastication/burn, and decreased considerably from 57 to 12 kg m^{-3} with the mastication/pull-back/burn treatment.

The bulk density of the masticated fuel bed (no natural fuel) was found to be 125 kg m^{-3}. This value is similar to the bulk density of 136 kg m^{-3} presented by Hood and Wu (2006) for the masticated fuel layer in ponderosa pine-Gambel oak (*Quercus gambelii* Nutt.) sites 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 mass was found to be distributed into 1-, 10-, 100-, and 1000-hr timelag classes as 1, 37, 59 and 3 %, respectively. The dominance of 10- and 100-hr fuels in this study differed from the relative abundance of 1- and 10-hr fuels found by Kane et al. (2006), where percentages of 1-, 10-, 100-, and 1000-hr timelag classes for masticated fuel were 30, 53, 14 and 3 %, respectively. Mean percent cover of masticated fuels were 17, 8 and 25 % for masticate-only, masticate/burned and masticate/pull-back/burned treatments in 2006 (pre-burn), respectively.

Table 4
Mean and (standard error) for masticated fuel load, masticated fuel depth, and total fuel bed bulk density for pre-treatment (2005), post-mastication (2006) and post-burn (2008) years for masticate, masticate/burn and masticate/pull-back/burn treatments.

Status (Year)	Treatment	Masticated fuel load (Mg ha^{-1})	Masticated fuel depth (cm)	Total fuel bed bulk density (kg m^{-3})*
Pre-treatment (2005)	Masticate	n/a	n/a	27 (6)
	Masticate/burn	n/a	n/a	27 (7)
	Masticate/pull-back/burn	n/a	n/a	22 (7)
Post-mastication (2006)	Masticate	42.9 (12.5)	3.4 (1.0)	32 (5)
	Masticate/burn	25.9 (5.3)	2.1 (0.4)	30 (5)
	Masticate/pull-back/burn	35.0 (6.3)	2.8 (0.5)	57 (9)
Post-burn (2008)	Masticate	48.0 (15.4)	3.8 (1.2)	47 (16)
	Masticate/burn	5.3 (1.5)	0.4 (0.1)	29 (7)
	Masticate/pull-back/burn	2.6 (1.1)	0.2 (0.1)	12 (4)

* Fuel bed bulk density calculated from 1-, 10-, 100-, 1000-hr, litter, masticated fuel loads and fuel bed depth.

Natural (non-masticated) downed woody fuel showed few significant changes following both mastication and burn treatments. Minor decreases in 10-hr fuel occurred following burn treatments in masticate/burn plots, but not in masticate/pull-back/burn plots (Table 5). One-hundred hour fuel load means decreased from 1.02 to 0.26 in masticate/burn, and 2.08 to 0.0 Mg ha^{-1} in the masticate/pull-back/burn treatment. Although the overall year by treatment p-value for 1000-hr fuel loads was significant at the 0.05 level, variability was high in 1000-hr fuel and no differences were found in the Tukey-Kramer post-hoc tests. One, 10- and 1000-hr natural fuel loads all increased after treatment in the mastication-only plots.

Table 5
Mean and (standard error) 1-, 10-, 100-, and 1000-hr down woody fuel loads and p-values for pre-treatment (2005) and post-burn (2008) for masticate, masticate/burn, masticate/pull-back/burn, and control plots.

Status (Year)	Treatment	1-hr ($Mg\ ha^{-1}$)	10-hr ($Mg\ ha^{-1}$)	100-hr ($Mg\ ha^{-1}$)	1000-hr ($Mg\ ha^{-1}$)
Pre-treatment (2005)	Masticate	0.19 (0.07)	0.79 (0.28)	0 (0)	17.4 (6.9)
	Masticate/burn	0.04 (0.02)	1.44 (0.99)	1.5 (0.67)	14.1 (7.2)
	Masticate/pull-back/burn	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)
Post-burn (2008)	Masticate	0.22 (0.11)	1.38 (0.75)	0 (0)	57.4 (21.0)
	Masticate/burn	0.05 (0.03)	0.06 (0.06)	0.26 (0.25)	3.4 (1.7)
	Masticate/pull-back/burn	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

The fuel bed depth mean with masticated-only treatment increased from 6.6 to 25.7 cm (Table 6). Units treated with mastication/burn and mastication/pull-back/burn showed decreases in fuel bed depth on the order of 0.5 cm, whereas fuel bed depth in control units increased slightly from 2005 to 2008. Mean fuel bed depth changes between 2005 and 2008 were statistically significant with a p-value of 0.044. 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.

Mean litter loads in this study ranged from 0.9 to 2.2 Mg ha^{-1} in pre-treatment and control plots, which is somewhat lower than values reported for ponderosa pine in van Wagtendonk (1998), 5.6 Mg ha^{-1}, and van Wagtendonk (1974), 4.4 Mg ha^{-1}. Mean litter fuel load increased from 1.3 to 2.1 Mg ha^{-1} with the masticate-only treatment, and from1.5 to 2.2 Mg ha^{-1} for the control, however these changes were not statistically significant (Table 6). Mean litter load decreased slightly from 0.9 to 0.7 Mg ha^{-1} with masticate/burn, and from 1.4 to 0.7 Mg ha^{-1} with the masticate/pull-back/burn treatment; similar to results found by Stephens and Moghaddas (2005).

Mean duff load ranged from 20.4 to 26.4 Mg ha^{-1} in pre-treatment and control plots, which is lower than values reported for ponderosa pine in van Wagtendonk (1998), 113 Mg ha^{-1}. Mean duff load decreased with masticated treatments and control plots; however, due to the high variability in these units, differences were not statistically significant. Duff load showed significant decreases with burn treatments; from 21.4 to 0.8 Mg ha^{-1} with masticate/burn, and from 26.4 to 2.0 Mg ha^{-1} with masticate/pull-back/burn.

Forest floor fuel load, the sum of litter and duff, ranged from 23 to 29 Mg ha^{-1} in pre-treatment and control plots, which is similar to values reported for young and mature ponderosa pine in Kittredge (1955), 20 to 48 Mg ha^{-1}.

Pre-treatment, live understory fuel load means varied from 0.004 to 0.034 Mg ha^{-1} (Table 6). In all treated units, live understory load means showed slight increases with treatment. However, due to the patchy nature of herbaceous plant abundance in the study site, live understory loads were highly variable and showed no statistically significant changes.

Table 6
Mean and (standard error) fuel bed depth, litter, duff and live understory fuel loads and p-values for pre-treatment (2005) and post-burn (2008) for masticate-only, masticate/burn, masticated/pull-back/burn and control treatments. Means followed by the same letter are not significantly different.

Status (Year)	Treatment	Fuel bed depth (cm)	Litter load (Mg ha^{-1})	Duff load (Mg ha^{-1})	Live understory load[1] (Mg ha^{-1})
Pre-treatment (2005)	Masticate	6.6 (1.3)ab	1.3 (0.3)	24.3 (5.6)	0.026 (0.012)
	Masticate/burn	4.3 (1.1)ab	0.9 (0.1)	21.4 (3.5)	0.022 (0.010)
	Masticate/pull-back/burn	4.8 (1.7)ab	1.4 (0.2)	26.4 (4.4)	0.034 (0.010)
	Control	8.7 (1.5)ab	1.5 (0.2)	23.8 (3.2)	0.004 (0.002)
Post-burn (2008)	Masticate	25.7 (6.4)a	2.1 (0.4)	20.4 (7.3)	0.115 (0.112)
	Masticate/burn	3.7 (0.3)b	0.7 (0.1)	0.8 (0.5)	0.035 (0.017)
	Masticate/pull-back/burn	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

[1] Live understory fuel load includes live portions of shrubs, grasses, and forbs.

Canopy fuel

Mean tree height generally increased with treatment, and trees per hectare and basal area decreased with treatment (Table 7). Mean tree height increases were statistically significant with mastication and mastication/burn treatments, according to the Tukey's test. Tree density decreased significantly with all treatments. Basal area decreased significantly with all burn treatments. Basal area reductions are evident with the masticate-only treatment; however, due to high levels of variability, these reductions were not shown to be statistically significant according to the Tukey's test. Control plots remained relatively unchanged. These results are analogous to those found by Stephens and Moghaddas (2005) who found basal area reduction in masticate/burn plots (55.1 to 39.3 m^2 ha^{-1}), were greater than reductions in masticate-only plots (40.9 to 51.9 m^2 ha^{-1}).

Table 7
Mean and (standard error) tree height, trees density, basal area, and p-values for pre-treatment (2005) and post-burn (2008) for masticate-only, masticate/fire, masticate/pull-back/fire and control. Means followed by the same letter are not significantly different.

Status (Year)	Treatment	Tree height (m)	Tree density (stems ha^{-1})	Basal area (m^2 ha^{-1})
Pre-treatment (2005)	Masticate	7.9 (0.7)c	956 (20)a	30.6 (0.4)ab
	Masticate/burn	8.0 (0.3)c	937 (9)a	27.5 (0.2)a
	Masticate/pull-back/burn	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
Post-burn (2008)	Masticate	12.7 (0.8)a	270 (32)b	23.2 (4.4)abc
	Masticate/burn	11.6 (0.5)ab	208 (71)b	9.6 (1.4)c
	Masticate/pull-back/burn	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

Mean canopy base height increased significantly from 1.0 to 6.5 m with mastication/burn, and 1.1 to 5.5 m with masticate/pull-back/burn treatments (Table 8). Canopy base height increased with the masticate-only treatment, 0.6 to 1.8 m; but this change was not statistically significant according to Tukey-Kramer results.

Mean canopy bulk density decreased by 38, 54 and 50 % in masticate, masticate/burn, and masticate/pull-back/burn plots, respectively. Tukey-Kramer results showed that these individual decreases in canopy bulk density were not significantly different.

Table 8
Mean and (standard error) canopy base height and canopy bulk density and p-values for pre-treatment (2005) and post-burn (2008) for masticate-only, masticate/fire, masticate/pull-back/fire and control. Means followed by the same letter are not significantly different.

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

Prescribed fire behavior observations

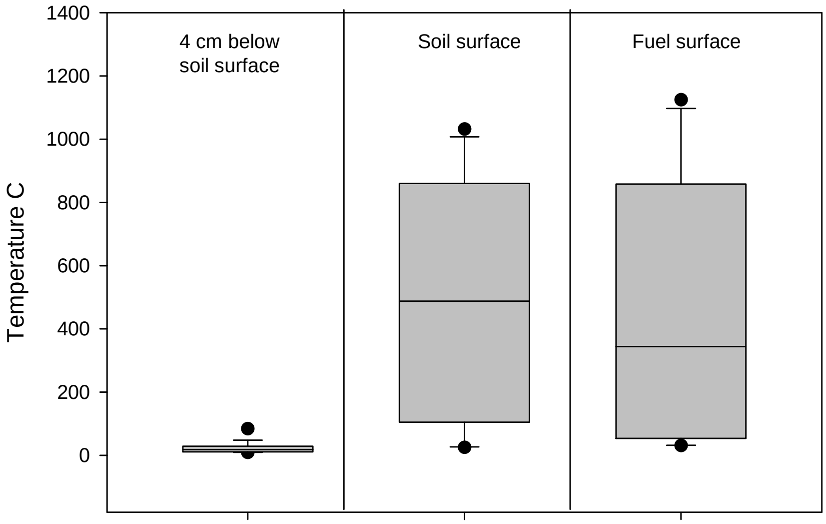
Mean flame height measurements as recorded by the passive flame height sensors were 106 and 97 cm for masticate/burn, and masticate/pull-back/burn treatments (Table 9). Considering standard errors of 14 and 17, these two treatments had roughly the same maximum flame heights. Fire behavior recorded by Fire Effects Monitors during the prescribed burn included flame heights of 1 to 3 ft (0.3 to 0.9 m) with occasional single tree torching the first day; and flame heights of 1 to 4 ft (0.3 to 1.2 m) with occasionally single tree torching the second day. These observations confirm measurements recorded by passive flame height sensors.

Table 9
Mean, standard error, and confidence intervals (CI) for flame height (cm) measured using passive flame height sensors.

Treatment	Mean flame height (cm)	Standard error	Lower 95% CI	Upper 95% CI	n
Masticate/burn	106	14	74	137	14
Masticate/pull-back/burn	97	17	54	140	11

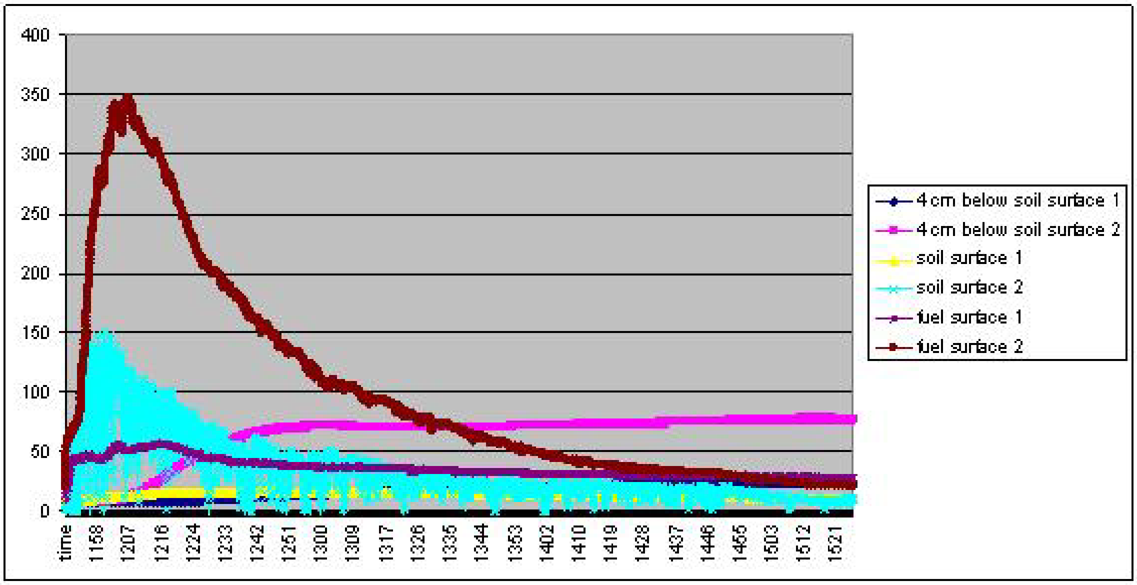
Temperatures recorded by thermocouples attached to Campbell data loggers recorded a wide variety of temperatures, but several trends can be seen (Figure 4). The maximum temperature recorded at 4 cm below the soil surface ranged from 9 to 43 C (48 to 109 F); much lower than temperatures at the soil surface and fuel surface. Maximum temperatures recorded at the soil surface, and fuel layer surface ranged from ambient temperature to roughly 1200 C, the maximum temperature type K thermocouples are capable of recording.

Figure 4
Instantaneous maximum temperatures recorded during prescribed burns at 4 cm below the soil surface, at the soil surface, and at the fuel layer surface.



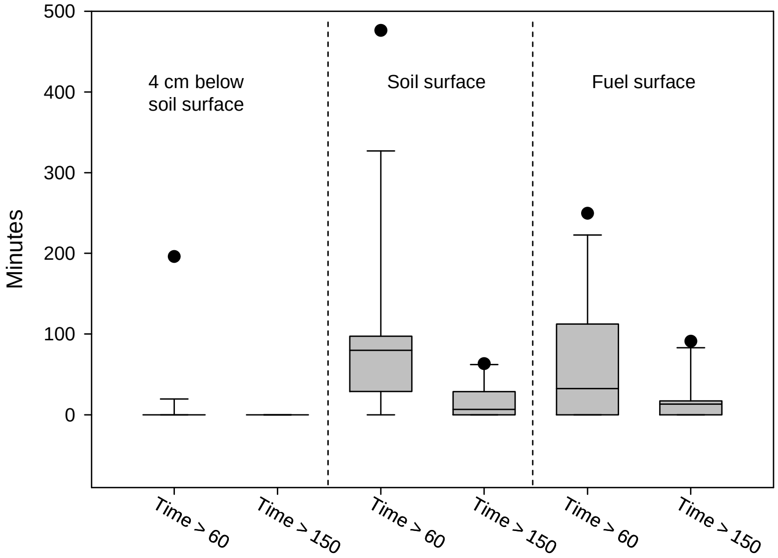
Temperatures recorded generally spiked as the fire front approached and passed, and dropped slowly back to ambient levels after smoldering consumed fuels. A graph of the temperature at each thermocouple through time for an example plot shows temperatures at the fuel and soil surface spiking less than 20 min after the first temperature increase (Figure 5). Temperature increases at 4 cm below the soil surface lag behind the surface temperatures. Minor differences in location of the subsurface and surface thermocouples can change recorded temperature drastically.

Figure 5
Example temperature readings over time for a set of thermocouples placed in a fuels plot during the prescribed burn.



Residence time of heat above 60 C (the lethal threshold for plant tissue) and 150 C, was determined for thermocouples at 4 cm below the soil surface, at the soil surface, and at the fuel bed surface. Residence time followed similar trends as the maximum temperatures. Most thermocouples placed 4 cm below the soil surface did not record temperatures above 60 C (Figure 6). Residence time for temperatures greater than 60 C was highest at the soil surface. It is possible that residence time for temperature at the fuel surface was limited (shorter times than existed in reality) since the thermocouple lead wires were more exposed, thus more prone to failure.

Figure 6
Residence time, in minutes, of prescribed burn temperatures above 60 and 150 C at 4 cm below the soil surface, at the soil surface, and at the fuel layer surface.



Residence time and flaming front depth are important fire behavior characteristics in addition to rate of spread and flame height. Residence time and flaming front depth can influence heat transmitted to soils and plant tissue. Temperature measurements from thermocouples can give estimates of residence time; however this study was not designed to compare masticated/burned with unmasticated/burned treatments. The plots within masticated blocks which showed no evidence of mastication were generally left out of analysis, except here, where temperature duration data were analyzed for the two "unmasticated" plots which were burned. Both thermocouples at the soil surface and fuel surface functioned; giving anecdotal data for unmasticated plots (Table 10). Only one thermocouple at 4 cm below the soil surface functioned, and so is not presented here. Mean and median times that temperature exceeded 60 and 150 C at the soil surface, where thermocouple lead wires were more protected from heat, were greater in masticated plots. Times above lethal temperatures at the fuel surface, measured with lead wires more exposed to heat, were greater in unmasticated plots. This could be due to lead wires failing quicker due to higher temperatures. These results are only anecdotal due to the low number of data points in unmasticated areas treated with prescribed fire.

Table 10
Range, mean, median, and number of observations for time above 60 and 150 C in minutes for masticated and unmasticated plots during prescribed burn treatment.

	Masticated				Unmasticated			
	Range	Mean	Median	n	Range	Mean	Median	n
Soil surface: time >60 C (min)	0-103	49	56	15	n/a	15	15	2
Soil surface: time >150 C (min)	0-63	15	5	15	2-3	2.4	2.4	2
Fuel surface: time >60 C (min)	0-250	58	33	15	5-127	86	65	4
Fuel surface: time >150 C (min)	0-91	18	12	15	0-74	32	11	4

Fire behavior model calibration

Fire behavior models were calibrated so that fuel model choices would lead to realistic fire behavior output. Actual weather conditions as well as fire behavior observations from the prescribed burn were used in this process. Weather during the prescribed underburns was typical of late fall burn conditions in the southern Sierra Nevada. Temperature ranged from 6 to 14 C. Relative humidity was generally 32 to 50 %, and rose as high as 79 % as a storm front arrived (Table 11). Slope ranged from 0 to 20 %, as mastication with this type of equipment is generally limited to a 35 % slope. Canopy bulk density can range from 0 in areas with no trees to 0.4 kg m^{-3} in very dense stands (Scott and Reinhardt, 2002). Canopy bulk density ranged from 0.0481 to 0.0513 kg m^{-3}, and canopy base height was 1.5 and 2.1 m in the two calibration plots, post-mastication treatment. Soil moisture ranged from 5 to 12 %, and litter moisture ranged from 8 to 12 % in samples gathered before prescribed burns. Because the litter moistures were not extremely different from the 1 h fuel moistures calculated in Fire Family Plus from weather conditions during the prescribed burns, the fuel moisture values calculated in Fire Family Plus for 1-, 10-, and 100-hr fuels were used in calibration runs.

Table 11

Weather, tree canopy characteristics, and slope inputs for fire behavior runs in FMAPlus.

Trial plot	Weather scenario	Eye-level wind km h^{-1} (m h^{-1})	Temperature (C)	RH (%)	CBH (m)	CBD (kg m^{-3})	Slope (%)
1	Low	3 (2)	10 (50)	50	1.5	0.0513	20
1	High	5 (3)	14 (58)	32	1.5	0.0513	20
2	Low	6 (4)	6 (43)	79	2.1	0.0481	0
2	High	21 (13)	9 (48)	41	2.1	0.0481	0

Fire behavior calibration runs for the two trial plots showed some similarities to fire behavior and effects which occurred during the prescribed burn. For plot 1, predicted flame length was within the observed range for the low weather conditions for the low load activity fuel, SB1, and were low compared to observed values for moderate load conifer litter, TL3 (Table 12). The rates of spread observed during the prescribed fire (ignited with spot and strip firing) can not be directly compared to predicted forward rates of spread of a free-burning fire. Predicted percent scorch was generally lower than the actual percent scorch, except for the high weather scenario for the second plot. For the first sample plot, predicted mortality ranged from 30 to 33 % and actual mortality was 46 %. The high end weather scenario over-predicted percent mortality for the second plot.

Table 12
Predicted values for flame length (m), percent scorch, and percent mortality compared to values observed in the field. The two validation plots shown use different fuel models at low and high end weather that was observed in the treatment unit during the prescribed burn.

Plot	Weather scenario	Fuel model	Flame length (m)	Visually est. flame length (m)	Predicted scorch (%)	Actual scorch (%)	Predicted mortality (%)	Actual mortality (%)
1	Low	SB1	0.6	0.3-0.6	6	77	32	46
1	High	SB1	0.7	0.3-0.6	8	77	33	46
1	Low	TL3	0.2	0.3-0.6	0	77	30	46
1	High	TL3	0.2	0.3-0.6	0	77	30	46
2	Low	SB1	0.7	0.3-1.5	0	83	31	47
2	High	SB1	1.7	0.3-1.5	100	83	99	47
2	Low	SB2	1.7	0.3-1.5	63	83	77	47
2	High	SB2	3.4	0.3-1.5	100	83	99	47

Note: visually estimated flame lengths were derived from video.

Potential wildfire behavior

Summaries of fire behavior output from FMAPlus for 90th and 97th percentile weather conditions (approximating wildfire conditions), for post-treatment fuel conditions, showed mean predicted rate of spread was higher in the masticate-only treatment than control, or treatments with prescribed burning (Table 13). Mean rate of spread in masticate-only areas were predicted to be 10.2 and 16.1 chains h^{-1} (3.4 and 5.4 m min^{-1}) for 90th and 97th percentile weather, respectively. Control plots had the next highest predicted rate of spread of 3.1 and 4.7 chains h^{-1} (1.1 to 1.6 m min^{-1}) for 90th and 97th percentile weather, respectively, but were not within a standard error of the masticate-only rate of spread. The masticate/burn treatment had a predicted rate of spread 2.5 to 4.2 chains h^{-1} (0.8 and 1.4 m min^{-1}), and showed a large amount of variation. The masticate/pull-back/burn treatment had the lowest predicted rate of spread of all treatments.

Similar to rate of spread, predicted flame length was higher for the masticate-only treatment than other treatments or the untreated control (Table 14). Mean predicted flame length was 1.3 and 1.6 m in the masticate-only treatement for 90th and 97th percentile weather, respectively. These predicted values are greater than the objective for flame length as stated in the Sierra Nevada Forest Plan, of 1.2 m (4 ft). Predicted flame length in both the masticate/burn treatment and control ranged from 0.4 to 0.6 m. Predicted flame length in the masticate/pull-back/burn treatment was 0.2 m in both 90th and 97th percentile weather scenarios. Note that these results are summaries of fire behavior model outputs and have not been field verified.

Table 13
Mean and (standard error) for predicted flame length (meters), and rate of spread (meter/min and chains/hour) by treatment for 90th and 97th percentile weather.

Treatment	Weather scenario	Flame length (m)	Rate of spread (m/min)	Rate of spread (ch/h)
Masticate	90	1.3 (0.2)	3.4 (0.7)	10.2 (2.1)
Masticate	97	1.6 (0.3)	5.4 (1.1)	16.1 (3.4)
Masticate/burn	90	0.4 (0.2)	0.8 (0.5)	2.5 (1.6)
Masticate/burn	97	0.5 (0.2)	1.4 (0.9)	4.2 (2.8)
Masticate/pull-back/burn	90	0.2 (0)	0.3 (0)	0.9 (0)
Masticate/pull-back/burn	97	0.2 (0)	0.4 (0)	1.3 (0.1)
Control	90	0.5 (0)	1.1 (0.1)	3.1 (0.4)
Control	97	0.6 (0.1)	1.6 (0.2)	4.7 (0.6)

Torching and crowning indices, defined as the 20-ft windspeed at which torching is expected to initiate, or active crown fire is possible, show some difference between treatments. Treatments including prescribed burn had much higher torching indices than the masticate-only treatment or untreated control plots, indicating that higher winds would be necessary to produce torching given post-treatment fuel conditions (Table 14). The crowning index is slightly higher for treated than untreated plots, meaning that the ability of post-treatment stands to sustain active crown fire is only slightly lower than untreated plots. For the masticate-only treatment, the torching index was lower than the crowning index, indicating that torching could be initiated with only moderate windspeeds, whereas active crown fire would require higher windspeeds. Torching indices are very high for treatments that include prescribed fire, indicating that the likelihood of torching occurring in these stands is very small.

Table 14
Mean and (standard error), lower 95 % confidence intervals (LC) and upper 95 % confidence intervals (UC) for torching and crowning indices (m h^{-1}) by treatment.

	Torching index (mph)			Crowning index (mph)		
Treatment	Mean	LC	UC	Mean	LC	UC
Masticate	22 (10)	0	45	34 (2)	29	40
Masticate/burn	73 (7)	59	80	38 (4)	30	45
Masticate/pull-back/burn	80 (0)	0	0	36 (7)	21	52
Control	31 (8)	14	48	22 (2)	18	26

Note: all data shown are output from modeling 97th percentile weather, and predicted torching and crowning indices over 80 were truncated at 80 mph.

Tree mortality

Mean percent scorch and torch was measured in the field the first year following the implementation of the prescribed fire treatments. Analysis was performed for the treatments which included prescribed fire. Percent scorch for masticate/burn and masticate/pull-back-burn treatments were 74 and 75 %, respectively (Table 15). Percent torch was slightly lower for the masticate/pull-back/burn treatment, at 8 %, versus 15 % torch found for the masticate/burn treatment.

Mortality, measured in the field the first year after burn treatment by the presence or absence of green needles or buds, was greater in plots treated with prescribed fire (Table 15). Mean percent mortality was 1 and 0 % in masticated and control plots, respectively. Mean percent mortality was lower in plots where masticated fuel was pulled-back from tree boles; however, levels of variation marked by high standard errors make these results potentially insignificant.

Table 15
Mean and (standard error) for percent scorch, percent torch, and mortality of trees as measured in the field after prescribed burn treatments.

Treatment	Scorch (%)	Torch (%)	Mortality (%)	n
Masticate	0 (0)	0 (0)	1 (1)	9
Masticate/burn	74 (4)	15 (3)	38 (8)	12
Masticate/pull-back/burn	75 (3)	8 (3)	28 (10)	8
Control	0 (0)	0 (0)	0 (0)	16

If these post-treatment areas were to burn in wildfires at 90th and 97th percentile weather conditions, percent scorch, as predicted by FMAPlus, indicate different fire effects would be experienced between treatments (Table 16). Mean percent scorch in the masticate-only treatment was predicted to be the highest, at 71 and 89 % for 90th and 97th percentile weather, respectively. Percent scorch in control plots was lower than the masticate-only treatment, at 29 and 36 % for 90th and 97th percentile weather, respectively. No scorch was predicted by FMAPlus for treatments incorporating prescribed fire.

Mean probability of mortality predicted by FMAPlus for post-treatment fuel conditions during a potential wildfire was highest for the masticate-only treatment, and lowest for treatments with prescribed fire (Table 16). Probability of mortality was predicted at 72 and 87 % for the masticate-only treatment for 90th and 97th percentile weather, respectively. Probability of mortality was 52 and 57 % for the untreated control for 90th and 97th percentile weather, respectively. The probability of mortality in masticate/burn, and masticate/pull-back/burn treatments ranged from 27 to 30 %, and greater than one standard error lower than the masticate-only treatment or control.

Table 16
Mean and (standard error) for percent scorch, and percent probability of mortality predicted by FMAPlus by treatment for 90th and 97th percentile weather given post-treatment fuels.

Treatment	Weather scenario	Scorch (%)	Mortality (%)
Masticate	90	71 (3)	72 (3)
	97	89 (2)	87 (2)
Masticate/burn	90	0 (0)	27 (1)
	97	0 (0)	28 (1)
Masticate/pull-back/burn	90	0 (0)	29 (2)
	97	0 (0)	30 (2)
Control	90	29 (1)	52 (1)
	97	36 (1)	57 (1)

Custom fuel models

The median values of masticated fuel depth in masticated units were 0.4, 0.8 and 1.6 inches for the low, medium, and high masticated fuel load groups (Table 17). Total fuel bed depths were higher, and were used as starting values for custom fuel models.

Table 17
Median masticated fuel and fuel bed depth for low, medium and high masticated fuel loads.

Masticated fuel load	Masticated fuel depth (in)	Total fuel bed depth (ft)
Low	0.4	2.1
Medium	0.8	3.2
High	1.6	3.2

Moderate Load Conifer Litter (TL3), Low Load Activity Fuel (SB1) and Moderate Load Activity Fuel (SB2) fuel models were used as starting points for custom masticated fuel models for low, medium, and high fuel loads, respectively. Median values for masticated fuel loads were 13, 25, and 52 Mg ha^{-1} for low, medium, and high masticated fuel load levels, respectively. Masticated fuel was divided into 1-, 10-, 100-, and 1000-hr fuels according to on-site ratios found through sampling. These were then added to the natural down woody fuels according to timelag class. These total fuel loads were used as starting points for custom fuel models (Table 18). Custom fuel models best fit the fire behavior observed during the prescribed fire with the median 1-, 10- and 100-hr fuel loads computed along with lower fuel bed depth values. The standard values were kept for these models for live herb and shrub loads, surface area to volume ratios, heat content and moisture of extinction. These models were calibrated using prescribed fire conditions and behavior. Although they yield approximately realistic fire behavior results in low-end weather scenarios, they are not field tested for wildfire weather conditions.

Table 18
Fuel characteristics incorporated for custom fuel models representing low, medium and high levels of masticated fuels.

	Custom fuel model mastication level		
Fuel characteristic	Low	Medium	High
1-hr load (t/a)	0.22	0.45	0.67
10-hr load (t/a)	5.8	10.1	19.7
100-hr load (t/a)	8.3	15.0	30.5
Fuel bed depth (ft)	0.5	0.6	0.8
Moisture of extinction (%)	20	25	25

VI. Management Implications

Care should be taken when interpreting the results from fire behavior models, few of which are validated under a broad range of free-burning fire conditions. Potential fire behavior results discussed in this report were based on the ability of several of the 40 fire behavior fuel models from Scott and Burgan (2005) to approximate fire behavior in masticated fuels during weather conditions typical of wildfire. As masticated fuels are a novel fuel type, and not described by current fuel models, fire behavior predicted for masticated fuel beds should be considered with caution. Custom fuel models could have the potential to give estimates of the relative changes in fire behavior; however the actual values of output should be considered with caution.

Unlike treatments where fuels are removed from the site, mastication trades crown fuel decreases for surface fuel increases, bringing some fire behavior and fire effect trade offs, that require consideration. 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 that include prescribed underburn reduce surface fuel loads (Wagel and Eakle, 1979; Stephens and Moghaddas, 2005; Vaillant et al., in press). While 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 surface fire behavior (Stephens, 1998). The likelihood of torching is still a moderate threat to stands treated with mastication only. The combination of mastication and prescribed burning reduces the likelihood of torching. From our results, pulling masticated material back from trees did not decrease percent scorch, but it did decrease percent torch, and tree mortality observed one year post-treatment. These results warrant further monitoring of tree mortality from this study, as the full effect of cambium and root damage resulting from the prescribed burn treatment may not have been evident at one year post-treatment

Care should be taken when planning mastication treatments that could yield deep, continuous layers of masticated material. Due to the amount of fuel incorporated in masticated fuel beds, residence time may be very long, making firefighter egress through these burning fuels difficult. Heat generated from burning masticated material may lead to undesireable levels of tree mortality. 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.

Predictive modeling showed that treating with mastication combined with prescribed underburning was effective for meeting desired fire behavior conditions when subjected to wildfire under 90th and 97th percentile weather. However, the fire effects resulting from the application of prescribed fire were not satisfactory under the conditions of this study site. Mean percent tree scorch was 74 and 75 %, and 1-year post treatment mortality was 38 and 28 % for mastication/burn, and mastication/pull-back/burn treatments. The predicted results of fire behavior under wildfire conditions for of mastication alone show that active crown fire potential is reduced, but surface flame lengths and rate of spread are greater than untreated areas. Furthermore, the predicted tree mortality is greater in areas treated with mastication alone, than areas untreated.

To carefully review the effectiveness of mastication or mastication/prescribed burn treatments we must have a clear picture of the fire behavior and fire effects goals of the fuels treatment program. If the goal of a mastication treatment is to reduce the likelihood of active crown fire, this goal may be met by mastication as well as mastication/prescribed burn treatments. However, if the reasoning behind reducing crown fire likelihood is to improve suppression capabilities, it should be noted that masticated fuel in this study showed the potential for greater surface flame lengths and rates of spread. Additionally, it should be noted that masticated fuels have high residence times which may require more time of firefighters to suppress and patrol than lighter surface fuels. Positive results of a fuel treatment would include more beneficial ecological impacts, were the area to burn in a wildfire. It is doubtful that areas treated with mastication only would experience beneficial fire effects for at least several years after mastication. High tree mortality could likely occur until masticated fuels begin to degrade. Areas treated with a combination of mastication and prescribed fire may have lower incidences of tree mortality and crown fire than untreated or mastication only treated areas if exposed to wildfire.

VII. Future Research

The ability to accurately quantify fuel loads will aid in determining fire effects (Knapp et al., 2005) and fire behavior associated with masticated fuel beds. One complicating factor of masticated fuel is that it compacts and decomposes over time, which alters how the material burns. Further research on the changes in litter, duff and masticated fuel bulk density at various lengths of time after mastication would aid in understanding how potential fire behavior and effects could change with time since mastication. More intensive data on masticated fuels including quantification of surface area to volume ratios would enhance fire behavior modeling. Gathering data across broader geographic scales would potentially allow and understanding to be built on how topography, vegetation, climate, as well as mechanical equipment type relate to masticated fuel load and bulk density. 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 in conjunction with fire behavior models could be accomplished through fire behavior research, or well documented anecdotal fire behavior data. Quantifying masticated fuel load 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.

Future research could benefit from investigation of more discrete fire behavior linked to microsite fuel characteristics. Although it is often difficult to determine when prescribed burns will take place, it is important to have adequate time to properly place sensitive fire behavior equipment in place before prescribed burns. Slight differences in thermocouple locations in the soil profile can give drastically different results. Although fire behavior equipment was placed inside the boundaries of plots where fuels were measured, collecting data on fuels at the exact location of thermocouples and passive flame height sensors could allow for better linkage of the relationships between fuels characteristics and fire behavior. More specific information could be gathered to define relationships between cambium heating (temperature and duration) and tree mortality by placing thermocouples directly adjacent to the cambium of trees, under the bark as done by Sackett and Haase (1992).

Future research quantifying fire behavior characteristics on free-burning wildfires between treated and untreated areas would improve our understanding of the effectiveness of fuel treatments. Additional research focusing on the fuel bed depth and residence time of masticated versus non-masticated fuel beds could yield information regarding potential fire effects in masticated areas. Information on fire rates of spread are difficult to obtain on prescribed fire, as firing patterns do not usually represent free-burning fire. Also, collection of fire behavior data during hot and dry conditions is unlikely to occur during prescribed fires. Understanding masticated fuel characteristics and how they realate to fire behavior and effects will help land managers make decisions on whether mastication or mastication plus burn treatments meet fuel treatment objectives.

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IX. Deliverables Cross-Walk Table

Proposed	Delivered	Status
Project Website	http://www.fs.fed.us./adaptivemanagement/projects/mastication/index.shtml	Completed
Annual Reports	JFS Annual Reports	Completed
Annual Briefings	Contacts were made by phone and email throughout the project. Visits to the District Office during the 2006 field season and during the prescribed burn.	Completed
Final Report	http://www.fs.fed.us./adaptivemanagement/projects/mastication/index.shtml	Completed
Publications	(1) “Mastication and prescribed fire impacts on fuels in a 25-year old ponderosa pine plantation, southern Sierra Nevada” (2) “Mastication and prescribed fire impacts on mortality and predicted fire behavior in a 25-year old ponderosa pine plantation, southern Sierra Nevada”	(1) Accepted pending revisions (2) In progress.
Presentations at Meetings	(1) “Red Mountain Mastication Study” (2) “Changes in surface and canopy fuels after mastication and mastication/prescribed fire treatments on the Red Mountain fuels project, Sequoia National Forest, CA” (3) “Mastication and prescribed fire impacts on mortality, fuels, and predicted fire behavior in a 25-year old ponderosa pine stand, southern Sierra Nevada” (4) “Red Mountain Mastication Study” (5) “Mastication and prescribed fire impacts on fuels, mortality and predicted fire behavior in a 25-year old ponderosa pine plantation, southern Sierra Nevada”	(1) Presentation to the USDA Forest Service Region 5 Fire Board of Directors, 2007 (2) Poster presented at Association for Fire Ecology Conference, December 2008. (3) Poster presented at “Fourth International Fire Ecology and Management Congress” December 2009 (4) Presented project information at an invited seminar at the Missoula Fire Sciences Lab, April, 2009 (5) Posters and presentations in preparation for upcoming conferences/meeting/workshops.
Managers’ Guide to Mastication	http://www.fs.fed.us./adaptivemanagement/projects/mastication/index.shtml	Completed, combined with final report.
Field Trip and Workshop	Field crews shared information with land managers in the field, June 19th, 2008.	Completed. Additional events may be scheduled for future dates.

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