Fire Behavior in Masticated Forest Fuels: Lab and Prescribed Burn Experiments

A Thesis

Presented in Partial Fulfillment of the Requirements for the

Degree of Master of Science

with a

Major in Natural Resources

in the

College of Graduate Studies

University of Idaho

by

Zachary David Lyon

Major Professor: Penelope Morgan, Ph.D.

Committee Members: Robert Keefe, Ph.D., Eva Strand, Ph.D., Peter Robichaud, Ph.D.

Department Administrator: Randy Brooks, Ph.D.

November 2015

AUTHORIZATION TO SUBMIT THESIS

This thesis of Zachary David Lyon, submitted for the degree of Master of Science with a major in Natural Resources and titled "Fire Behavior in Masticated Forest Fuels: Lab and Prescribed Burn Experiments," has been reviewed in final form. Permission, as indicated by the signatures and dates given below, is now granted to submit final +copies to the College of Graduate Studies for approval.

Major Professor____Date______________
Penelope Morgan, Ph.D.

Committee
Members ____Date______________
Robert Keefe, Ph.D.

____Date______________
Eva Strand, Ph.D.

____Date______________
Peter Robichaud, Ph.D.

Department
Administrator ____Date______________
Randy Brooks, Ph.D.

ABSTRACT

Managers masticate fuels to alter fire behavior, but how the resulting compact fuels burn is poorly understood. We burned 52 lab fuel beds and 75 field plots in 3 replicate, 30-yr old ponderosa pine (*Pinus ponderosa*) stands in fall after summer 2014 thinning. A mean 367-492 trees ha^{-1} remained after 30-72% of trees were masticated. Depth (8.1-13.7 cm) and loading (4.5 - 14.4 kg m^{-2}, 45-60% were 0.6 - 2.5 cm). Pine needles facilitated ignition with flame lengths usually <1 m, rate of spread 0.3-3.5m min^{-1}, and smoldering duration varied in the field, <1 hour in the lab regardless of 10-hr fuel moisture. Flame lengths and rates of spread were low and variable in masticated fuels, considerably less than the untreated controls. Two mastication treatments (coarse and fine) did not have statistically different fire behavior. Predictive equations based on lab experiments over-estimated flame length and consumption in prescribed burn experiments.

Keywords: consumption, flame length, fuels treatment, plantation, ponderosa pine, rate of spread

ACKNOWLEDGEMENTS

This project is funded by the Joint Fire Science Program project # 13-1-05-7, the University of Idaho Experimental Forest, and by USDA Rocky Mountain Research Station, Forest Service under agreement 12-JV-11221637-136. A. Argona, C. Reeves, H. Graham, J. Brumbaugh, C. Reeves, K. Satterburn, J. Byrne, J. Sandquist, and W. Tinkham assisted with field sampling. B. Austin and the University of Idaho Experimental Forest staff provided logistical support. Lab experiments were conducted in the University of Idaho IFIRE combustion lab. H. Heward, L. Johnson, J. Larsen, C. Bell, R. Becker, UIEF staff, and 21 students in the FOR 427 Prescribed burning lab helped with field burning. P. Robichaud, and E. Strand reviewed earlier drafts of this manuscript. P. Sikkink and J. Reardon advised us on sampling protocol and methods for particle characterization.

TABLE OF CONTENTS

AUTHORIZATION TO SUBMIT THESIS ii
ABSTRACT iii
ACKNOWLEDGEMENTS iv
TABLE OF CONTENTS v
LIST OF FIGURES vi
LIST OF TABLES vii
FIRE BEHAVIOR IN MASTICATED FUELS 1

INTRODUCTION

Mastication background 1
Research objectives 3

METHODS

Study area 4
Pre-treatment field measurements 4
Post-mastication, pre-burn data collection 5
Particle characterization 6
Lab experiments 6
Field experiments 8
Statistical analyses 8

RESULTS

Stand description 9
Lab experiments 10
Field experiments 10
Predicted vs observed 11

DISCUSSION

Fire behavior 11
Predicted vs observed 12
Comparison to other findings 12
Limitations 12
MANAGEMENT IMPLICATIONS 13
CONCLUSIONS 14
REFERENCES 15

LIST OF FIGURES

Figure 1: Study area and project layout 23
Figure 2: Fuel bed proportions 24
Figure 3: Laboratory experiment box plots 25
Figure 4: Field experiment box plots 26
Figure 5: Laboratory fuel bed 27

LIST OF TABLES

Table 1: Trees per hectare 19
Table 2: Treatments average fuel loadings....................20
Table 3: Lab experiment ANOVA summary 21
Table 4: Predicted vs observed values....................22

FIRE BEHAVIOR IN MASTICATED FOREST FUELS: LAB AND PRESCRIBE BURN EXPERIMENTS

Zachary D. Lyon, Aaron Sparks, Camille Stevens-Rumman, Penelope Morgan,

Rob Keefe, and Alistair M.S. Smith

To be submitted to Forest Ecology and Management

ABSTRACT

Managers masticate fuels to alter fire behavior, but how the resulting compact fuels burn is poorly understood. We burned 52 lab fuel beds and 75 field plots in 3 replicate, 30-yr old ponderosa pine (*Pinus ponderosa*) stands in fall after summer 2014 thinning. A mean 367-492 trees ha^{-1} remained after 30-72% of trees were masticated. Depth (8.1-13.7 cm) and loading (4.5 - 14.4 kg m^{-2}, 45-60% were 0.6 - 2.5 cm). Pine needles facilitated ignition with flame lengths usually <1 m, rate of spread 0.3-3.5m min^{-1}, and smoldering duration varied in the field, <1 hour in the lab regardless of 10-hr fuel moisture. Flame lengths and rates of spread were low and variable in masticated fuels, considerably less than the untreated controls. Two mastication treatments (coarse and fine) did not have statistically different fire behavior. Predictive equations based on lab experiments over-estimated flame length and consumption in prescribed burn experiments.

Keywords: consumption, flame length, fuels treatment, plantation, ponderosa pine, rate of spread

INTRODUCTION

Mastication background

Fuel treatments are being used to decrease fire intensity (Kreye et al., 2011), and provide defensible space for firefighters (Collins et al., 2009), especially near homes and in municipal watersheds. Mechanical fuel treatments are designed to decrease the intensity of crown fires and high severity fires (Agee and Skinner, 2005), yet our ability to effectively predict fire behavior in the mixed fuels resulting from mechanical treatments, such as mastication, is limited. With many large fires in recent decades (Westerling et al., 2006) and more predicted for the future (Littell et al., 2009; Spracklen et al., 2009), wildland fires frequently threaten people and property. Changes in fire frequency, size, and severity pose challenges for those managing large fires while also protecting people and property (Moghaddas and Craggs, 2007; Stewart et al., 2007). As the wildland urban interface expands into fuels that will burn when fires ignite under hot, dry, and windy conditions (Radeloff et al., 2005), so does the need for fuel treatments.

Mastication is done with a rotary head mounted on an excavator or front-end loader to chip or shred stems to redistribute large amounts of standing trees and shrubs as surface fuels, reducing vertical continuity (Kane et al., 2006; Kane et al., 2009). Mastication has become an increasingly common fuels treatment around homes (Glitzenstein et al., 2006; Kane et al., 2009). Compared to using fire alone, mastication decreases fire intensity by reducing fuel depth, limits smoke by fostering smoldering combustion (Glitzenstein et al., 2006), and reduces the risk of escaped fire when used as a pretreatment to prescribed burning. However, the duration of smoldering may increase the depth and density of fuel beds. Mastication reduces ladder fuels and canopy density (Hartsough et al., 2008), and may be followed with prescribed burning to further reduce surface fuels (van Wagtendonk, 1996; Hartsough et al., 2008). Managers use mastication to treat large areas with relatively low labor costs (Vitorelo and Varner, 2009.

Fuel beds created by mastication are compact and comprised of shredded and chipped wood pieces with higher surface area-to-volume ratios than common woody fuels (Kane et al., 2009). Mastication fuels also have different particles (less cylindrical pieces and more rectangular shaped pieces) (Kane et al., 2009) mixed throughout the fuel bed (Hood and Wu, 2006). Over time, changes in particle size, quantity and distribution influence how masticated fuels burn (Knapp et al., 2011; Kreye et al., 2012). With time, masticated fuels become more compact (Kane et al., 2009), particles decompose, litter accumulates on the surface (Knapp et al., 2011), and fuel moisture fluctuates (Nelson and Hiers, 2008), all of which likely influence fire behavior (van Wagtendonk et al., 1998). Kreye et al. (2014) reviewed the few studies that have evaluated the effects of mastication on fire behavior in the compact, shredded fuels that result from mastication. They found that mastication often produces lower intensity fires with slower rates of spread than the non-masticated areas of the same cover type (Kreye et al., 2014). Understory grasses and shrubs often increase in abundance as masticated fuels age (Glitzenstein et al., 2006), further influencing changes in fuel bed structure by introducing more potential fuel. These changes can alter the way fire behaves as masticated fuel beds age (Glitzenstein et al., 2006) with smoldering combustion increasing as the fuel beds become more compact (Valette et al., 1994).

Most research quantifying fire behavior in masticated fuels has been done in laboratories where conditions can be readily controlled (Kreye et al., 2011). After cases where fires burned in masticated fuels (Bass et al., 2012) under wildfire conditions, it is clear that we need to understand how fire behaves in masticated fuels and design experiments to test the effects of different variables beyond the laboratory. The timing between mastication and fire can vary (Kobziar et al., 2009), so it is important to determine how the changing fuels will burn. One way to look at changing fuel beds and the effect it has on fire behavior is to observe fire in different mastication types. Coarse treatments with more large chunks of woody material could accelerate decomposition compared to all fine chips (T. Jain, personal communication), but they could also decrease the bulk density of the fuel bed and increase fire intensity (Burgan and Rothermel, 1984).

With well-designed laboratory experiments, the interacting effects of fuel moisture, fuel depth, and particle size and shape on fire behavior can be evaluated. It is unknown, however, how well observations from laboratory experiments can be used to predict fire behavior in experimental prescribed burns and to operational burns because the combination of variables in nature cannot all be matched in the lab.

Research objectives

We were motivated by these larger questions about the effectiveness of mastication fuel treatments to alter fire behavior and influence fire managers' ability to suppress wildfires in the wildland urban interface. We compared fire behavior and effects in both lab and field experiments using two types of mastication and varying fuel moistures.

Specifically, we

1) Compared fire behavior (flame length and rate of spread) and consumption in two different mastication treatmentsproduced from the same standing vegetation, one with finer and one with coarser pieces of fuel, as influenced by fuel moisture and depth of fuel. We expected that flame lengths and rates of spread of fires would be reduced with increasing fuel moisture.
2) Evaluate how well lab results could be used to predict observed results in fire behavior and consumption in field burns.. We expected that statistical models based on lab results would be useful in predicting flame length, rate of spread, and consumption in field experiments even though lab burns differed from field burns that were affected by slope, wind, duff, soil, and fuel bed variability due to mastication equipment, trees, and shrubs.

METHODS

Study area

We chose three stands for this study, all dominated by ponderosa pine (*Pinus ponderosa*) in the West Fork area of the Hatter Creek drainage on the University of Idaho Experimental Forest (UIEF) located east of Potlatch, ID (Figure 1). The stands were planted in 1982 after they were clearcut and burned, leaving few residual large logs and stumps. The stands were remarkably uniform, although a small amount of pre-commercial thinning had been done (roughly 1 ha in each) in two of the stands and a pollarding experiment was implemented in a small portion of one of those stands as well (R. Keefe, 2014). The overstory was primarily dominated by ponderosa pine, but there was a Douglas-fir (*Pseudotsuga menziesii*) component to the overstory in the downslope half of one of the stands. The understory was composed of ninebark (*Physocarpus malvaceus*), Rocky Mountain maple (*Acer glabrum*), snowberry (*Symphoricarpos albus*), and oceanspray (*Holodiscus discolor*); the tall shrubs reached into the lower branches of the tree crowns and held fallen pine needles draped in the shrub stems.

The Vassar silt loam soils are deep, well-drained soils formed from volcanic ash and loess on top of weathered granitic bedrock (NRCS, 2014). The area falls in the Northeastern Valleys climate division (NOAA, 2014). The climate is continental with cool winters (2^{o} C mean minimum 1980-2013), and warm summers (15^{o} C mean monthly maximum temperature 1980-2013) (NOAA, 2014). The mean annual precipitation for the area is 540 mm, with an average of 740 mm of snowfall during the winter (NOAA, 2014).

Each stand is roughly 4 ha in size with the plots in the upslope half of each stand. Three treatments (coarse mastication, fine mastication, burn only) were randomly assigned to one of three 50 m X 150 m strips in each of three stands (Figure 1). There are 10 plots in each mastication and five in each control strip.

Pre-treatment field measurements

Before mastication treatments, we measured a randomized sample of six plots within each mastication treatment. Within each 10 X 10 m plot, we used modified Brown's (1974) transects to measure fuel loads. The 1-hr (0-0.64 cm) and 10-hr (0.64-2.54 cm) time lag fuels were measured from 5 to 7 m, 100-hr (2.54-7.62 cm) time lag fuels from 7 to 10 m, and 1000-hr (7.62-20.32 cm) time lag fuels from 0 to 10 m on each of three transects running down hill starting at 0, 5, and 10 m from the top left plot corner. Litter and duff depths were measured at 0 m, 5 m, and 10 m on each transect. The diameter at breast height (DBH, 1.4 m above the ground) for trees with DBH greater than 5 cm, stump diameter, crown base height (CBH) for live trees, and total height were measured for all trees using a laser hypsometer. All trees were numbered and tagged so that we could later determine which trees were remaining after treatments. Height and diameter were estimated for trees less than 5cm DBH or less than 1.4 m tall. All trees were identified to species. Overstory tree canopy cover was estimated using a densiometer (Ganey and Block, 1994; Lemmon, 1956) facing each of four directions (NE, NW, SE, SW) at the middle of each quadrant of the plot; these values were averaged for each plot. Five 1-m^2 micro-plots (Figure 3) were used to estimate abundance of coarse woody debris (>7.62 cm) (Brown et al., 2003) following Hood and Wu (2006) and Keane and Dickinson (2007) sampling protocols.

Mastication

Our mastication was done with two treatments: fine and coarse. The coarse treatment was achieved by having the operator section the trees in lengths of approximately 0.5 m with the mastication head. In contrast, the operator lopped the top and then masticated whole tree stems more slowly in the fine treatment. We expected this to create deeper fuel beds in the coarse treatment due to the presence of more large pieces than in the fine treatment.

Post-mastication, pre-burn data collection

Sampling protocol for pre-treatment measurements were adapted from Sikkink, (2014, personal communication) to gather appropriate measurements to meet the needs of our project while also enabling comparison with another ongoing project designed to characterize masticated fuels created by different treatments and sampled at longer times since mastication in mixed conifer forests (Sikkink et al. 2014, personal communication). We are in the process of developing new Fuel Characteristic Classification System fuel beds and fire behavior fuel models for the masticated fuels characterized in our project and theirs.

After the mastication treatments were implemented during early June 2014, three plots within each mastication strip were sampled in early August to record fuel bed characteristics. The plot sizes were 5 m X 7 m. On these plots within each mastication strip, we removed all fuels within four 0.5 m X 0.5 m square subplots in the corners of the plots; this material was used for particle characterization in the lab and in burn experiments in the lab. Total fuel bed depth was measured as were depths of masticated fuel, litter, and duff. All tag numbers of the trees remaining after mastication were recorded. Masticated fuel was collected between our sampling plots to use for constructing replicate fuel beds for burning in the laboratory.

Masticated Fuel Characterization

The fuel samples retrieved from the field were brought to the University of Idaho IFIRE combustion lab and sorted. All fuels were dried at 90º C for 48 hours and then weighed to determine the dry weight of each size class. Woody fuels were sorted by hand into 1-hr, 10-hr, 100-hr, and 1000-hr time lag size classes. The criteria used for determining which time lag class a particle was classified into was based upon the smallest diameter that comprised the majority of the fuel particle. Litter and duff samples were dried, and the litter was separated from the duff and each was weighed. Dry weights were taken to determine the average proportion that each size class contributes to the total fuel bed loading (Brewer et al., 2013).

Lab experiments

Fuel sorting and lab burning experiments were conducted in the IFIRE combustion lab on the University of Idaho campus.

Fuel beds burned in lab experiments:

For each treatment strip, we calculated average fuel loading by calculating the mean of the four destructively sampled subplots in the corner of each sampled plot, and the resulting mean across three sampled plots. Fuel beds used in lab experiments were constructed to be consistent with the average particle size distribution and bulk densities from in-situ fuels beds measured in the field, using both the material from the subplots and pieces from bulk material collected from between the plots. The fuel beds burned in the lab were constructed to have the average weight of each size class (1-, 10-, and 100-hr fuels) present and the average weight of litter. We have multiple levels of fuel moisture (see below), produced from drying the masticated fuels and allowing them to equilibrate to the desired fuel moisture ranges. Fuel moisture was calculated as a percent of oven-dry weight using the following equation: mc%= (wet weight - oven-dry weight)/oven-dry weight. To represent the conditions present in field plots, two thirds of the total litter weight was placed below the masticated fuel, and the remaining one third was placed on top of the masticated fuel. This was done to represent the existing litter load below the masticated fuel beds prior to mastication, and then the additional litter that fell on top of the masticated fuel beds between the time of mastication and the time the plots were sampled, as we observed when we collected the fuel from the masticated treatmentts. Each fuel bed was 0.75 m X 0.75 m. The fuel beds were then either compressed or fluffed to reach the target fuel bed depth (average for the strip) (Figure 5).

Fuel Moisture:

Fuels were burned under three different ranges of moistures (5-10%, 10-15%, and 15%+) for all fuels in the fuel bed. Once oven dry, fuels were allowed to equilibrate naturally in our fuels storage shed to reach moisture conditions to burn under 5-10% (dry moisture range). For both the 10-15% (ambient moisture range) and 15%+ (wet moisture range), fuels were placed on wire mesh shelves within a portion of the shed contained in large plastic sheets. We placed a humidifier, small fan, and heater inside the plastic to increase the moisture available to the fuels and to circulate air to prevent condensation of moisture on the fuel surfaces. We periodically checked the fuel moistures using both oven drying and an electronic moisture meter (Timbermaster protimeter) to ensure that our fuels were within the desired moisture range.

Ignition and Observations:

Fuel beds were ignited from one end using ethyl alcohol to start combustion. Top-down pictures were taken of each fuel bed before and after combustion (roughly 1 meter above the fuel bed). Depth of remaining fuels was measured at each of the four corners and in the center before and after burning to determine depth of consumption. The fuels remaining after both flaming and smoldering were complere were classified into 10-hr and 100-hr fuels, removed and weighed. Ash was then swept and weighed with remaining 10-hr and 100-hr fuels to determine total weight consumption to be compared to initial fuel bed dry weight.

Fire Behavior Measurements:

A video camera was placed adjacent to the fuel bed to record flame heights and duration of flaming and smoldering combustion. A wire grid 140 cm tall and 80 cm wide, with spacing between wires of 10 cm X 10 cm, was placed behind the fuel bed as a reference for determining the recorded flame lengths and rate of spread on video. The videos for each burn were later analyzed to quantify flame length (m) and rate of spread (m/min) at three points midway through the burn (chosen from the middle of the fuel bed) to calculate an average flame length and rate of spread for each fuel bed burned.

Field experiments

The 5 m x 7 m plots were burned within the masticated and control treatments (Figure 2). Flame length, rate of spread, and consumption measurements were made in the field similarly to those made during lab burns. The prescribed burns were conducted on 19 and 20 October 2014 in the upslope half of each treatment in all three stands. The temperature for both burn days ranged from 16 to 26^{o} C during the burn operation with relative humidity ranging from 26 – 52% measured with a sling psycrometer with the lowest temperature and highest relative humidity occurring at the end of each burn day. Winds were dominantly from the southwest at 1 - 3 mph. In each stand, 25 plots were burned with 10 plots located in each mastication strip. Each strip included 5 replicates of two moisture levels (wet and dry) (Figure 1). To create these two distinct levels of moisture in the masticated fuels, large plastic sheetswere placed over half of the plots in each mastication strip two weeks prior to burning and following a rain event. Just prior to burning each stand, the plastic was removed and fuel samples were collected for all 1-, 10-, 100-, and 1000-hr fuels to measure fuel moisture in all of the plots. In one stand, a protimeter was used to measure fuel moisture content due to lack of bags to collect fuel samples. At the three plots (same plots as post-mastication sampling described above) in each mastication strip, we installed a 3 X 3 grid of nine duff pins (Figure 1) just prior to burning, and depth of fuel bed consumption was measured at each duff pin one week following the prescribed burn.

Ignition began on the upper edge of the stands in parallel strips to create a solid black line. Ignition continued in parallel strips that followed contours. Ignition was by people carrying drip torches in their gloved hands. All plots were ignited across the bottom using a hand-held drip torch; fires were allowed to spread uphill through the plot. In the instances where fires did not spread through the plot, all edges of the plot were ignited.

Flame length and rate of spread were recorded by trained field observers at each plot; we used multiple observers with one at each plot. At the three plots in each mastication treatment where destructive samples were take, a camera was positioned adjacent to the long side of each of these plots to record flame length and rate of spread against a stationary pole used for mounting a radiometer above the plot.

Statistical analyses

For the laboratory experiments, we used box-plots to visually determine the normality of the distribution of fire behavior (flame length and rate of spread) and effects (consumption). Individual analyses of variance (ANOVAs) were done for each response variable (flame length, rate of spread, and consumption) to test the hypothesis of no difference (α=0.05) associated with treatment coarse vs. fine mastication), 1-hr fuel moisture content, and 10-hr fuel moisture content (Ott and Longnecker, 2010).

For the field experiments, we used box-plots to evaluate the normality of the distribution of fire behavior (flame length and rate of spread) and effects (consumption). Individual ANOVAs were used to test for significance (α=0.05) between the factors of treatment, 1-hr fuel moisture content, and 10-hr fuel moisture content to compare the effects of predictor variables to the effects of predictor variables in the lab (Ott and Longnecker, 2010). Prior to analysis, we checked for colinearity between 1-hr fuel moisture content and 10-hr fuel moisture content (Ott and Longnecker, 2010).

Regression equations were developed from the lab results for flame length, rate of spread, and consumption by choosing the best linear model with the greatest overall F value. The regression equations were then used to calculate predicted field results. We used these results to determine the degree to which field observed fire behavior agreed with or differed from the flame length, rate of spread, and consumption predicted from laboratory experiments.

RESULTS

Study Area

Tree density was reduced by 30-70% across the three stands (Table 1); the trees removed were the source of the masticated fuels. The dominant species were ponderosa pine with <5% Douglas-fir. Masticated trees had an average diameter at breast height of 14.1 ± 5.6 cm, average height of 9 ± 2.9 m, and average canopy base height of 4.6 ± 3.6 m (Table 2).

After mastication, fuel bed depth ranged from 1.9 to 5.7 cm across the three stands with total fuel depth ranging from 8.1 cm- 13.7 cm across the three stands (Table 2) but fuel bed depth did not differ for coarse and fine treatments ($P = 0.3068$). The 10-hr time lag sized pieces made up the majority of the fuel beds in all stands and treatments (Figure 2). Neither the dry weight of 10-hr nor total fuel differed ($P > 0.001$ for both). Similarly, the weight of 1000-hr time lagsized pieces did not differ for coarse and fine treatments ($P > 0.001$). Masticated fuels were distributed on top of pre-existing litter. Churning from the machine implementing the treatment resulted in a mixture of masticated fuels with pre-existing litter. Litter from newly fallen needles (summer and fall 2014) accumulated on top of the fuel beds before they were burned. Tracks from the machine also contributed to compaction of fuels in a grid pattern in the stand and exposed soil, especially on steeper microsites within the stands.

Lab Burning Experiments

Flame length was low, ranging from 0.1 m to 1.4 m even under very dry conditions. Flame length was greatest in the dry fuel moisture range and lowest in the wet fuel moisture range for both fine and coarse treatments. Average flame length was similar between coarse and fine treatments for each moisture range (Figure 3). Flame length was influenced by both 1-hr and 10-hr fuel moisture contents. Flame length was influenced by treatment, 1-hr proportion, 10-hr proportion, 1-hr fuel moisture, and 10-hr fuel moisture. The 10-hr proportion influenced flame length ($F = 19.389$ and $P < 0.001$), and 10-hr fuel moisture was significant ($F = 99.595$ and $P < 0.001$).

Rate of spread (m/min) was low and variable (Figure 3), ranging from 0.02 m/min to 0.32 m/min even under very dry conditions. Rate of spread was less variable in the coarse treatment (Figure 3). Rate of spread was greatest in the dry fuel moisture range and lowest in the wet fuel moisture range for both fine and coarse treatments. Rate of spread was influenced by both 1-hr and 10-hr fuel moisture contents. Rate of spread was influenced by treatment, 1-hr proportion, 10-hr proportion, 1-hr fuel moisture, and 10-hr fuel moisture. Both the 10-hr proportion ($F = 8.967$ and $P < 0.001$) and the10-hr fuel moisture ($F = 109.164$ and $P < 0.001$) influenced the rate of spread.

Consumption, measured as reduction in fuel bed depth, was more variable in the fine treatment than the coarse treatment across all fuel moisture ranges (Figure 3). Consumption was influenced by treatment, 1-hr proportion, 10-hr proportion, 1-hr fuel moisture, and 10-hr fuel moisture. The ANOVA results showed that treatment ($F = 7.381$ and $P < 0.001$), and 1-hr proportion ($F = 169.803$ and $P < 0.001$) (Table 3).

Field Burning Experiments

Flame length was variable across both treatments. Average flame length in the fine treatment was 0.76 m ± 0.31 m, with a maximum of 1.40 m. Average flame length in the coarse treatment was 0.28 m ± 0.18 m with a maximum of 0.90 m. Maximum flame length in the control treatment was 0.80 m in the surface fuels before it spread into the areas that had not been masticated; there pine needles draped in tall shrubs burned readily and contributed to flame lengths exceeding five m.

Rate of spread was variable across both fine and coarse treatments. Average rate of spread in the fine treatment was 1.21 m min^{-1} ± 1.33 m min^{-1}, with a maximum of 6.00 m min^{-1}. Average rate of spread in the coarse treatment was 1.10 m min^{-1} ± 1.05 m min^{-1}, with a maximum of 4.00 m min^{-1}. Maximum rate of spread in the areas that had not been masticated was 3.00 m min^{-1} in the surface fuels except where pine needles draped in tall shrubs burned readily.

Fuel bed consumption was variable across both fine and coarse treatments. It ranged from 0 cm to >20 cm. Average consumption in the fine treatment was 4.47 cm ± 3.10 cm. Average consumption in the coarse treatment was 3.12 cm ± 2.34 cm. Consumption occurred up to 6 days following ignition through long-duration smoldering.

Predicted vs Observed

Predicted from regression equations developed from lab observations exceeded observed field values (Table 4). The regression equation for flame length included the predictor variables of 10-hr fuel proportion and 10-hr fuel moisture content ($F = 57.26$ and $P < 0.001$). The regression equation for consumption included the predictor variables of treatment, 10-hr fuel proportion, and 1-hr fuel proportion ($F = 61.56$ and $P < 0.001$).

DISCUSSION

Fire behavior in masticated fuels was less than in untreated controls

Mastication was effective in reducing fire behavior in both the lab and field experiments. With both our coarse and fine mastication treatments, fire behavior (flame length and rate of spread) was reduced compared to the untreated controls. Flame lengths were reduced to 1/3rd to the untreated plots where tall shrubs and needle drape lead to flame lengths exceeding 3 m once the surface fire became established in the needle drape on the standing shrubs. With the redistribution of standing vegetation to the forest floor, the compact fuel beds of irregularly shaped pieces lead to a reduction in rate of spread to a point that would be more easily controlled than untreated areas. Although there was an overall reduction in flame lengths and rates of spread following mastication, variable pockets of available fuels (greater amounts of needles and 1- and 10- hr fuels) lead to limited times and locations of higher flame lengths and rates of spread during the field burning experiments.

Predicted flame length and measured consumption are greater than observed/measured

The predicted flame length and consumption values, although good predictions based on the regression equations (Table 4), were consistently greater than the field observations due to the presence of duff and exposed soil in the field burns. The presence of duff and soil in the field, and their associated moisture and heat sink capacities is likely to have produced the lower flame lengths and fuel consumption measurements that we experienced in our field prescribed burns. Fuel beds in the field included some fuels that were mixed with soil and duff from the mastication treatment which likely contributed to the lower than expected flame lengths and consumption. The influence of these mixed fuel beds, wind, and slope need to be further evaluated in the lab with comparing lab results when field observations/measurements.

Comparison to other findings in mastication

This masticated fuel loading in our experiments was similar to that documented by others in ponderosa pine as summarized by Kreye et al. (2014), with the exception of a higher average 10-hr fuel loading (Battaglia et al., 2010). The fuel loading of our mastication was lower than documented in forests dominated by other species than ponderosa pine (Busse et al., 2005). Our observed flame lengths in ponderosa pine were similar to those observed by others burning in masticated fuel beds elsewhere as summarized by Kreye et al. (2014). Our fuel beds were similar in depth to other mastication studies, but we observed higher flame length and rate of spread when our average fuel bed depth was greater than other mastication studies summarized by Kreye et al. (2014). The prescribed burns we conducted were under more moderate weather conditions compared to burns in masticated fuels in ponderosa pine forests elsewhere (Busse et al., 2005), which suggests that the litter incorporated into the fuel beds we burned greatly influenced observed fire behavior.

Limitations of the study

This study has limitations. First, duff was not included in the lab burns and has the potential to influence the duration of smoldering combustion and influencing fuel moisture content of the associated woody fuel. Excluding duff allowed us to replicate our burns in a way that would be consistent with the burning methods of our sister study in Missoula, and we found that we did not have a good way to represent the average duff composition from the field in our lab burns. Duff consumption is one of the contributors to more variable fire behavior and consumption observed in the field. Third, although we sampled fuel moisture for different size classes throughout the one-year old fuels on the plots, it is unlikely that the full variations of fuel moistures was able to be captured due to the variation throughout each mastication treatment. During treatment, additional factors that may affect fire behavior in masticated fuels but are not represented in fuel models are 1) the extent to which equipment compacts and crushes fuels during treatment and exposes soil, and 2) the orientation and spatial pattern of that exposure. Equipment used in our treatments traveled up and down slope and swung radially, thus creating tread disturbances that served as localized fuel breaks perpendicular to the flaming front.

MANAGEMENT IMPLICATIONS

There has been little research conducted with the goal of quantifying fire behavior in masticated fuels. In this study we were able to analyze the effect of mastication treatment type, fuel loading, and fuel moisture content on fire behavior and consumption. Mastication treatments effectively reduced the flame length, rate of spread, and consumption. These did not differ for coarse and fine treatments, and given that the fine treatment took longer to implement and is therefore more costly (R. Keefe, unpublished data), and because the resulting large fuel chunks may decompose faster than fine chips (T. Jain, personal communication), we recommend it. With the increased application of mastication as a fuels treatment to reduce wildfire hazard, our results are useful for understanding potential fire behavior. Although masticated fuels don’t often burn under wildfire situations, this fuel treatment is being increasingly applied in fire-prone landscapes and we must expect that such treatments will burn in future wildfires. Furthermore, some managers are using mastication to treat fuels prior to prescribed burning (Jeff Handel, Nez Perce Tribe, personal communications). Managers also need to understand the tree mortality and implications for regrowth of shrubs, as well as the longevity of mastication treatment benefits, ; all will be monitored in the future in our treatment areas. Because of the compact fuel beds comprised of irregularly shaped pieces, mastication can pose resistance to controlling wildfire, especially when fuel beds are deep, because the fuels smolder for an extended period of time (>3 days in our field burns) and have the possibility of producing and igniting from embers along control lines (Bass et al., 2012). To better understand how fire will behave if/when it reaches a mastication fuels treatment, new fuel models are needed for managers to predict fire behavior to support decisions about allocating fuel treatments and preparing for and conducting fire suppression. Because the mastication treatment broke up the vertical continuity of the stand, the more compact fuel beds and absence of ladder fuels caused flame lengths and rate of spread to be moderated compared to the untreated portions of the stand where fire established into the needle drape which allowed for more extreme fire behavior.

CONCLUSION

We analyzed fire behavior (flame length and rate of spread) and consumption in two mastication treamtnents (coarse and fire). With 30-70% of the trees in our ponderosa pine plantations were masticated, fuel beds were 8.1-13.7 cm in depth, 0.65 – 2.28 kg m^{-2} mean fuel loadingof which 40-60% were fuels 0.6-2.5 cm diameter. We used two mastication treatments and an un-masticated control to collect fire behavior and fuel consumption data in the field with replicated laboratory experiments for both mastication treatments. Relative to the controls, flame length and rate of spread were substantially reduced reflecting the shallow, compact fuel beds. However, the compact fuel beds smoldered for a long time (1-2 hours in the lab, 4-6 days after ignition in the field). Overall, fuel loading, fire behavior, and consumption did not differ between coarse and fine treatments. Our results support the use of mastication as a fuels treatment with the intent of reducing fire intensity, but also poses the question of potential ramifications of the long-duration smoldering combustion once the compact fuel beds do ignite.

REFERENCES

Agee, J.K., Skinner, C.N., 2005. Basic principles of forest fuel reduction treatments. *Forest Ecology Management* 211(1-2), 83-96.

Bass, B., Zimmerman, T., Romero, F., Harnick, D., Williams, T., Ratzlaff, J., Close, K.,Clark, D., Mathewson, T., 2012. Lower north fork prescribed fire, prescribed fire review. State of Colorado Department of Natural Resources, 152.

Battaglia, M.A., Rocca, M.E., Rhoades, C.C., Ryan, M.G., 2010. Surface fuel loadings within mulching treatments in Colorado coniferous forest. *Forest Ecology and Management* 260, 1557-1566.

Brewer, N.W., Smith, A.M.S., Hatten, J.A., Higuera, P.E., Hudak, A.T., Ottmar, R.D., Tinnkham, W.T., 2013. Fuel moisture influences on fire-altered carbon in masticated fuels: an experimental study. *Journal of Geophysical Research: Biogeosciences* 118, 30-40.

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

Brown, J.K., Reinhardt, E.D., Kramer, K.A., 2003. Coarse woody debris: managing benefits and fire hazard in the recovering forest. USDA Forest Service, Rocky Mountain Research Station. General Technical Report RMRS-GTR-105.

Burgan, R.E., Rothermel, R.C., 1984. BEHAVE: fire behavior prediction and fuel modeling system—FUEL subsystem. National Wildfire Coordinating Group. PMS 439-1.

Busse, M.D., Bussea, M.D., Fiddler, G.O., Shestak, C.J., Powers, R.F., 2005. Lethal soil temperatures during burning of masticated forest residues. *International Journal of Wildland Fire* 14, 267-276.

Collins, B.M., Stephens, S.L., Moghaddas, J.J., Battles, J., 2009. Challenges and approaches in planning fuel treatments across fire-excluded forested landscapes. *Journal of Forestry* January/February, 24-31.

Ganey, J.L. and Block, W.M., 1994. A comparison of two techniques for measuring canopy closure. *Western Journal of Applied Forestry* 9(1), 21-23.

Glitzenstein, J.S., Streng, D.R., Achtemeier, G.L., Naeher, L.P., Wade, D.D., 2006. Fuels and fire behavior in chipped and unchipped plots: Implications for land management near the wildland/urban interface. *Forest Ecology and Management* 236, 18-29.

Hartsough, B.R., Abrams, S., Barbour, R.J., Drews, E.S., McIver, J.D., Moghaddas, J.J., Schwilk, D.W., Stephens, S.L., 2008. The economics of alternative fuel reduction treatments in western United States dry forests: financial and policy implications from the national fire and fire surrogate study. *Forest Policy and Economics* 10 (6), 344-354.

Hood, S., Wu, R., 2006. Estimating fuel bed loadings in masticated areas. In: Andrews, P.L., Butler, B.W. (Eds.), Fuels management - how to measure success. USDA Forest Service Proceedings, RMRS-P-41, Portland, OR, 333-340.

Kane, J.M., Varner, J.M., Knapp, E.E., 2009. Novel fuelbed characteristics associated with mechanical mastication treatments in northern California and south-west Oregon, USA. *International Journal of Wildland Fire* 18, 686-697.

Kane, J.M., Knapp, E.E., Varner, J.M., 2006. Variability in loading of mechanically masticated fuel beds in northern California and southwestern Oregon. USDA Forest Service Proceedings RMRS-P-41.

Knapp, E.E., Varner, J.M., Busse, M.D., Skinner, C.N., Shestak, C.J., 2011. Behavior and effects of prescribed fire in masticated fuelbeds. *International Journal of Wildland Fire* 20, 932-945.

Kobziar, L.N., McBride, J.R., Stephens, S.L., 2009. The efficacy of fire and fuels reduction treatments in a Sierra Nevada pine plantation. *International Journal of Wildland Fire* 18, 791-801.

Kreye, J.K., Brewer, N.W., Morgan, P., Varner, J.M., Smith, A.M.S., Hoffman, C.M., Ottmar, R.D., 2014. Fire behavior in masticated fuels: a review. *Forest Ecology and Management* 314, 193-207.

Kreye, J.K., Varner, J.M., Knapp, E.E., 2012. Moisture desorption in mechanically masticated fuels: effects of particle fracturing and fuelbed compaction. *International Journal of Wildland Fire* 21, 894-904.

Kreye, J.K., Varner, J.M., Knapp, E.E., 2011. Effects of particle fracturing and moisture content on fire behaviour in masticated fuelbeds burned in a laboratory. *International Journal of Wildland Fire* 20(2), 308-317.

Lemmon, P.E., 1956. A spherical densiometer for estimating forest over story density. *Forest Science* 2(1), 314-320.

Littell, J.S., McKenzie, D., Peterson, D.L., Westerling, A.L., 2009. Climate and wildfire area burned in western U.S. ecoprovinces, 1916-2003. *Ecological Applications* 19(4), 1003-1021.

Moghaddas, J.J., Craggs, L., 2007. A fuel treatment reduces fire severity and increases suppression efficiency in a mixed conifer forest. *International Journal of Wildland Fire* 16, 673-678.

Nelson, R.M. Jr., Hiers, J.K., 2008. The influence of fueled properties on moisture drying rates and time lags of longleaf pine litter. *Canadian Journal of Forest Research* 38, 2394-2404.

NOAA National Divisional Climate Data, 2014. Idaho climate division 1: Panhandle. Accessed May 2, 2014. http://www.ncdc.noaa.gov/cag/.

NRCS, 2014. Soil Survey for Latah County, ID. Accessed May 2. 2014. http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx.

Ott, L., and Longnecker, M.T., 2010. An introduction to statistical methods and data analysis, Brooks/Cole Cengage. Learning, Belmont CA.

Radeloff, V.C., Hammer, R.B., Stewart, S.I., Fried, J.S., Holcomb, S.S., McKeefry, J.F., 2005. The wildland–urban interface in the United States. *Ecological Applications* 15(3), 799–805.

Reiner, A.L., Vaillant, N.M., Fites-Kaufman, J., Dailey, S.N., 2009. Mastication and prescribed fire impacts on fuels in a 25 year old ponderosa pine plantation, southern Sierra Nevada. *Forest Ecology and Management* 258, 2365-2372.

Spracklen D.V., Mickley L.J., Logan J.A., Hudman R.C., Yevich R., Flannigan M.D., Westerling A.L., 2009. Impacts of climate change from2000 to 2050 on wildfire activity and carbonaceous aerosol concentrations in the western United States. *Journal of Geophysical Research, D, Atmospheres* 114, D20301.

Stewart, S.I., Radeloff, V.C., Hammer, R.B., Hawbaker, T.J., 2007. Defining the wildland-urban interface. *Journal of Forestry* 105, 201-207.

Valette, J., Gomendy, V., Marecha, J., Houssard, C., Gillon, D., 1994. Heat transfer in the soil during very low-intensity experimental fires: the role of duff and soil moisture content. *International Journal of Wildland Fire* 4(4), 225-237.

van Wagtendonk, J.W., Benedict, J.M., Sydoriak, W.M., 1998. Fuel bed characteristics of Sierra Nevada conifers. *Western Journal of Applied Forestry* 13 (3), 73-84.

van Wagtendonk, J.W., 1996. Use of a deterministic fire growth model to test fuel treatments. In: Sierra Nevada Ecosystem Project, vol. II. Final Report to Congress. Centers for Water and Wildland Resources. University of California, Davis, 1155–1166.

Vitorelo, B., Han, H-S., Varner, J.M., 2009. Masticators for fuel reduction treatment: equipment options, effectiveness, costs, and environmental impacts. Proceedings of the 2006 Council On Forest Engineering (COFE) meeting, Lake Tahoe, CA, 11

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., Swetnam, T.W., 2006. Warming and earlier spring increase western US forest wildfire activity. *Science* 313, 940-943.

Table 1: Stand density (trees ha-1) of prescribed fire experimental burn plots at University of Idaho Experimental Forest pre- and post-mastication treatments (mean ± standard deviation).

	Stand 341	**Stand 332**	**Stand 353**
Pre-mastication	1208±275	1325±311	700±195
Post-mastication	392±156	367±65	492±215
Percent removed	68%	72%	30%

Table 2: Fuel loading (mean ± standard deviation) by time lag size class and total fuel bed depth in each mastication treatment in each as calculated from twelve 0.5 m X 0.5 m plots per treatment of three replicate stands.

Stand	Treatment	1 hour (kg m^{-2})	10 hour (kg m^{-2})	100 hour (kg m^{-2})	1000 hour (kg m^{-2})	Litter (kg m^{-2})	Total Load (kg m^{-2})	Depth (cm)
353	Fine	0.10 ± 0.10	0.48 ± 0.48	0.12 ± 0.22	0.00 ± 0.00	0.24 ± 0.33	0.94 ± 1.13	8.06 ± 6.24
	Coarse	0.06 ± 0.05	0.37 ± 0.37	0.04 ± 0.09	0.04 ± 0.14	0.14 ± 0.19	0.65 ± 0.84	10.31 ± 9.56
341	Fine	0.17 ± 0.14	0.51 ± 0.45	0.09 ± 0.14	0.09 ± 0.33	0.20 ± 0.15	1.05 ± 1.21	10.62 ± 8.84
	Coarse	0.22 ± 0.14	0.46 ± 0.32	0.09 ± 0.16	0.00 ± 0.00	0.24 ± 0.18	1.01 ± 0.81	11.85 ± 9.91
332	Fine	0.39 ± 0.14	0.93 ± 0.64	0.14 ± 0.13	0.11 ± 0.44	0.23 ± 0.18	1.58 ± 1.54	13.72 ± 7.48
	Coarse	0.33 ± 0.40	0.94 ± 0.83	0.25 ± 0.41	0.36 ± 0.58	0.40 ± 0.53	2.28 ± 2.75	12.97 ± 8.95

Table 3: ANOVA summary table showing degrees of freedom (DF) and significance of predictor variables (F statistic and probability of greater F) on flame length, rate of spread, and consumption response variables for laboratory burns. Treatment is either fine or coarse mastication. Ten Proportion and One Proportion are the dry weight proportion of 10-hr and 1-hr fuels respectively. Ten FMC is the 10-hr fuel moisture content (%). One FMC is the 1-hr fuel moisture content (%).

FL~Treatment+Ten Proportion+One Proportion+Ten FMC+One FMC

	DF	Sum Sq	Mean Sq	F value	Pr(>F)
Treatment	1	0.005	0.005	0.085	0.772
Ten Proportion	1	1.055	1.055	19.389	**<0.001**
One Proportion	1	0.096	0.096	1.786	0.190
Ten FMC	1	5.421	5.421	99.595	**<0.001**
One FMC	1	0.059	0.059	1.079	0.304
Residuals	48	2.613	0.054		

ROS~Treatment+Ten Proportion+One Proportion+Ten FMC+One FMC

	DF	Sum Sq	Mean Sq	F value	Pr(>F)
Treatment	1	0.0056	0.0056	2.809	0.100
Ten Proportion	1	0.01788	0.01788	8.967	**<0.001**
One Proportion	1	0.00095	0.00095	0.474	0.494
Ten FMC	1	0.21772	0.21772	109.164	**<0.001**
One FMC	1	0.0004	0.0004	0.199	0.658
Residuals	48	0.09573	0.00199		

Cons~Treatment+Ten Proportion+One Proportion+Ten FMC+One FMC

	DF	Sum Sq	Mean Sq	F value	Pr(>F)
Treatment	1	7.67	7.67	7.381	**0.009**
Ten Proportion	1	0.71	0.71	0.68	0.414
One Proportion	1	176.42	176.42	169.803	**<0.001**
Ten FMC	1	0	0	0.001	0.977
One FMC	1	0.16	0.16	0.15	0.700
Residuals	48	49.87	1.04		

Table 4: Predicted field results (± 95% confidence interval) calculated from regression equations developed from lab results vs. observed field results (mean ± standard error).

Stand	Treatment	Predicted Flame Length (m)	Observed Flame Length (m)	Predicted Consumption (cm)	Measured Consumption (cm)
353	Fine	1.5 ± 0.1	0.9 ± 0.5	5.4 ± 2.4	4.5 ± 1.2
	Coarse	1.3 ± 0.2	0.4 ± 0.5	8.3 ± 3.0	2.9 ± 1.6
341	Fine	1.7 ± 0.2	0.7 ± 0.1	9.1 ± 1.3	2.1 ± 0.7
	Coarse	1.5 ± 0.1	0.3 ± 0.0	10.4 ± 3.4	3.8 ± 1.0
332	Fine	1.6 ± 0.1	0.4 ± 0.1	9.2 ± 4.5	6.9 ± 2.3
	Coarse	1.4 ± 0.0	0.2 ± 0.0	11.2 ± 2.4	2.7 ± 1.2

From Lab
Flame Length= 2.72-2.27 (10-hr proportion)-0.06 (10-hr FMC)
Consumption= -6.14(Treatment)+19.30 (10-hr proportion)+44.07 (1-hr proportion)

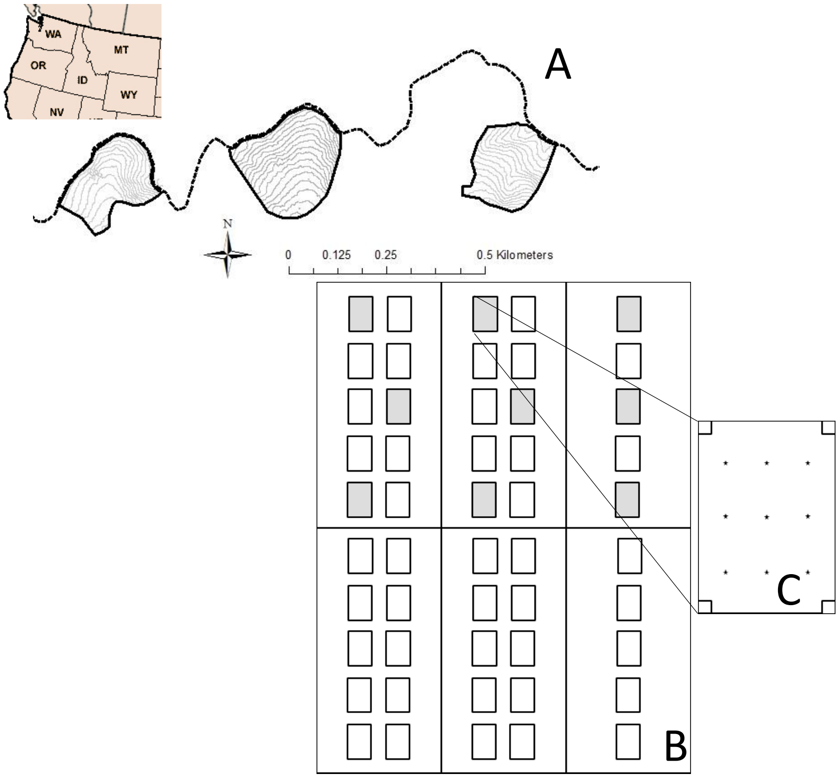

Figure 1. Map of project location (A), study stands (green polygons) located within the University of Idaho Experimental Forest (B), treatment layout within stands (C), and layout of the 25 plots, each 5 m X 7 m, within treatments (D). Grayed plots were sampled for fuel loading. In each sampled plot, four corners were 0.5 m X 0.5 m destructive samples where all masticated fuels and litter/duff were collected for lab characterization of fuel bed. Grid of 3 X 3 dots shows location of duff pins used to measure depth consumption (cm) of fuel beds in sampled plots following prescribed burning. Duff pins are spaced 1m from left and right plot edge, and 1.5 m between pins (left to right). From top, first duff pin is 1m down from plot edge, and 2.5 m between pins (top to bottom).

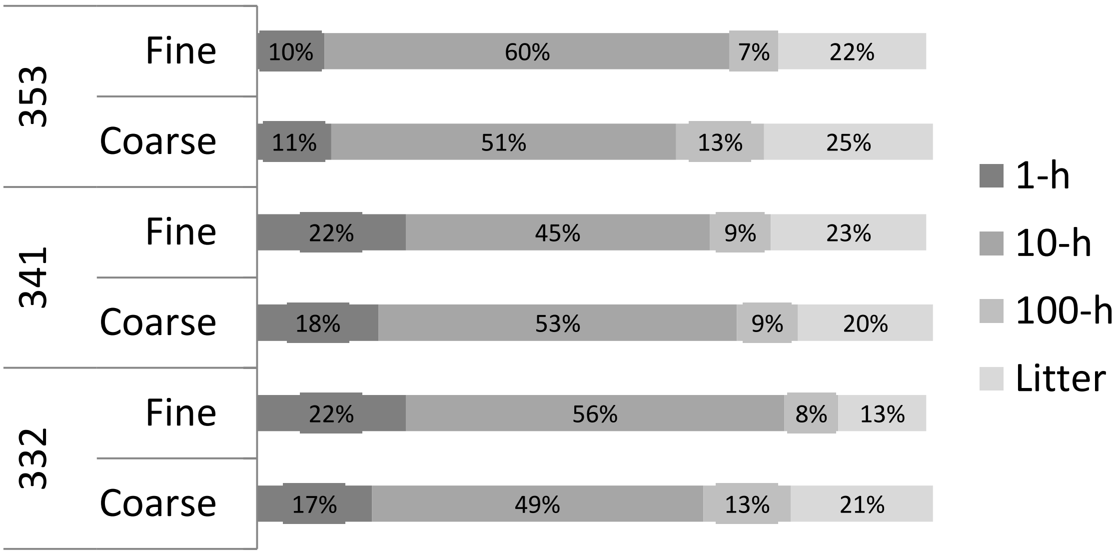

Figure 2. Proportions by dry weight of fuel beds made up of each time lag size fuel class in each mastication treatment strip. Proportions are based on characterized fuels from destructive samples.

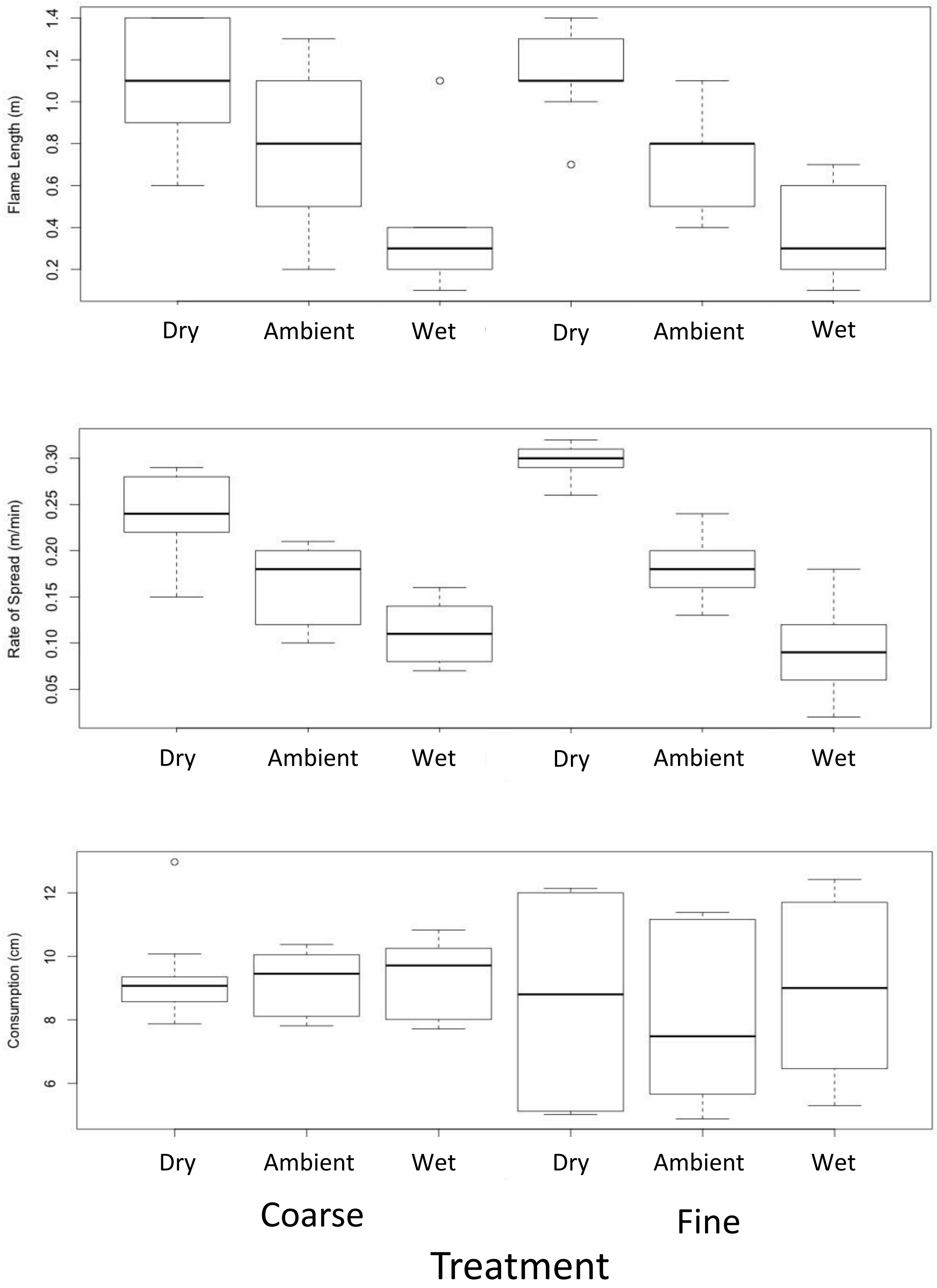

Figure 3. Lab experimental burn box-plots for flame length, rate of spread, and consumption as influenced by mastication type and fuel moisture range.

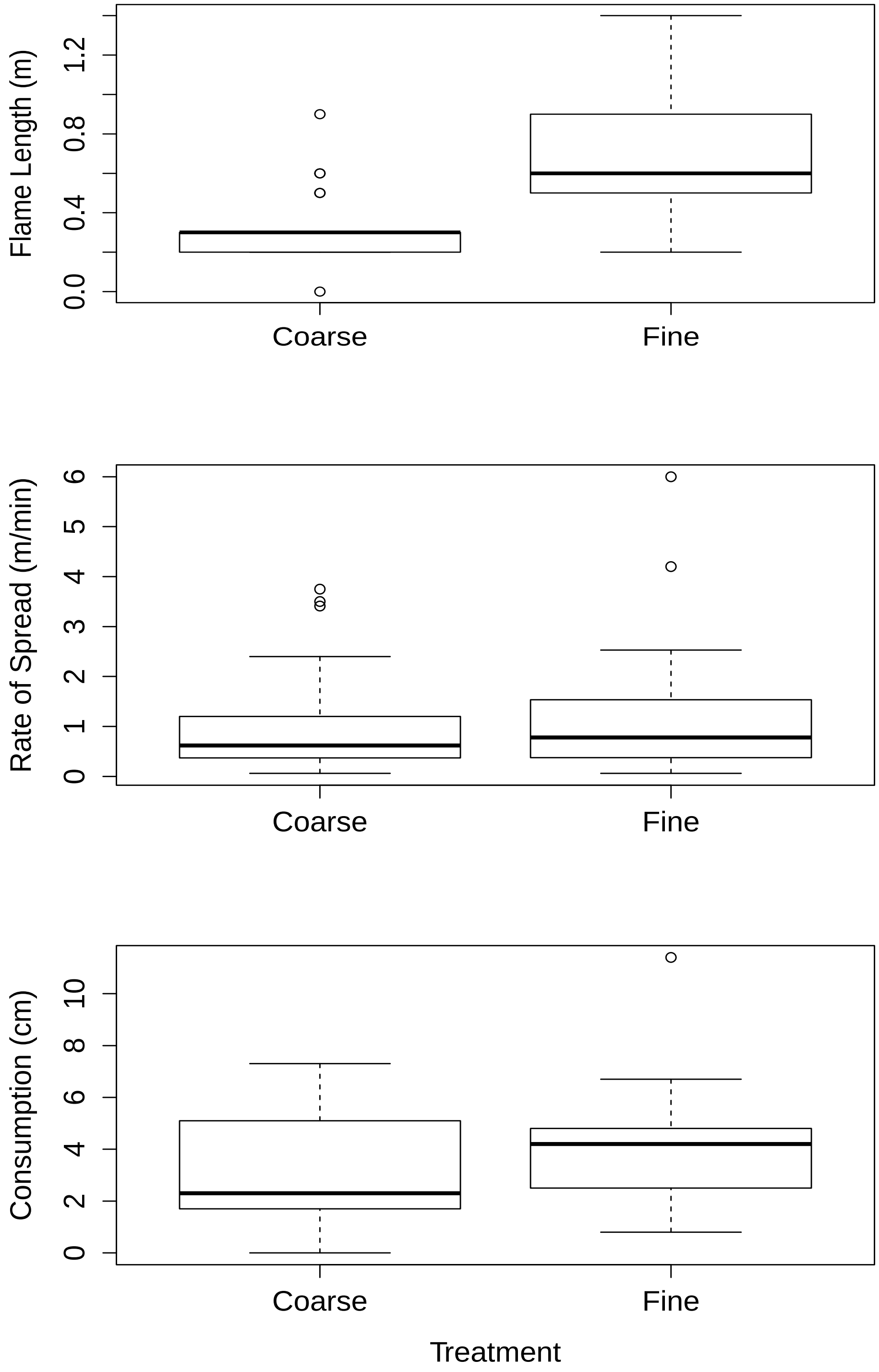

Figure 4. Field experimental burn box-plots showing flame length, rate of spread, and consumption as influenced by mastication type.

Figure 5. Before (top) and after (bottom) pictures of lab fuel bed burned. Fuel bed was laid out within a chalked 0.75 m X 0.75 m square.