MASTICATED FUEL BEDS: CUSTOM FUEL MODELS, FIRE BEHAVIOR, AND FIRE EFFECTS

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INTRODUCTION

Mechanical mastication is a relatively new tool for treating shrub and small tree fuels, and is being widely used to reduce fire hazard in areas where application of prescribed fire is impractical due to proximity to homes or smoke management issues. By chopping these ladder fuels into small chunks, standing live and dead fuels are converted to more compact, dead, surface fuels, which are usually left on the forest floor to protect the soil from erosion and to retain nutrients. In some cases, mastication may make the subsequent introduction of prescribed fire easier. When we initiated this work, very little was known about how masticated fuel beds burn. Masticated pieces are often highly fractured and fragmented, with a high surface area-to-volume ratio, and the total amount of biomass can be considerable. It was expected that the highly fragmented nature of the fuels would tend to increase fire-line intensity, but that this increase might also be offset by compaction of the fuel bed. In addition, prolonged heating duration with burning and the resulting mortality of residual trees and damage to soils were a concern. Because standard fuel models did not adequately represent masticated fuel beds, and because the fuel loading inputs for masticated fuels had not been developed, managers had no means of estimating fire behavior in masticated fuel beds.

The objectives of our research were to:

A. Characterize fuel beds resulting from mastication in key vegetation types in California and southern Oregon in order to evaluate the effect of variables such as site quality, length of time since last major disturbance, mastication equipment, and intensity of mastication treatment on the amount of material and the nature of the fuel bed.

B. Conduct drying experiments and burns of masticated fuels under controlled laboratory conditions to determine how particle fragmentation and particle moisture content influences fire behavior.

C. Conduct small-scale burning experiments to evaluate the potential for soil heating damage, and determine the effect of soil moisture and soil type on heat penetration.

D. Validate and calibrate custom fuel models for masticated fuel beds by comparing observed fire behavior and effects for prescribed burns in the field with modeled fire behavior and effects.

Fuel Bed Characterization

Methods

Ten recently masticated sites were selected both within previously installed studies (4) and sites identified by local managers (6) to investigate variability in fuel loading across northern California and southern Oregon (Appendix A). All mastication treatments used a front-end or boom-mounted masticator with either a rotating drum or blade style head and were conducted between November 2002 and May 2005. The vegetation masticated within each of the study sites varied but was dominated by shrub species (e.g., *Arctostaphylos* spp., *Ceanothus* spp.) and/or small hardwood tree species (e.g., *Lithocarpus densiflorus*, *Arbutus menziesii*), typically under an emerging canopy of conifers.

Surface fuel loading was estimated for each study site using two methods: (*i*.) the planar intercept method (Brown 1974), and (*ii*.) a destructive plot-based sampling method. Fifteen planar intercept transects were completed and 15 plot samples collected at each site, except for the two sites that were prescribed burned, where a total of 40 points were sampled (10 per burn unit). The plot based method involved placing a 50 cm x 50 cm metal frame at a set point adjacent to the Brown's fuel transect, collecting all organic material within the frame (cutting woody fuels intersecting the frame with a saw or clipper), sorting the material according to size category, drying in an oven for at least 72 hours and weighing. Fuel bed depth data were collected both within the plot frame and along each Brown's transect.

In order for the information collected along the Brown's transects to be useful for estimating fuel loading, we also collected data on specific gravity and average squared quadratic mean diameter within each woody fuel size class from a sample of the fuels collected within the plots, and measured the average particle angle in the field at each site. Standard ANOVA methods were used to detect differences among sites for all fuel bed variables, and the relationship between Brown's and plot-based methods for estimating fuel loading was explored with linear regression. Cluster analysis was used to determine the standard fuel models (Anderson 1982; Scott and Burgan 2005) that these masticated fuel beds were most similar to.

Summary of Findings

Total woody fuel loading, estimated with the plot-based method, varied widely, ranging from 15 to 63 Mg/ha across sites (Table 1). However, the relative proportions of fine woody fuels in the different size categories (1 hr, 10 hr, and 100 hr) were generally quite consistent across sites. Ten hour fuels were by far the dominant category, followed by 100 hr and then 1 hr fuels. Average fuel depth ranged from 2.9 to 6.9 cm across the ten sites.

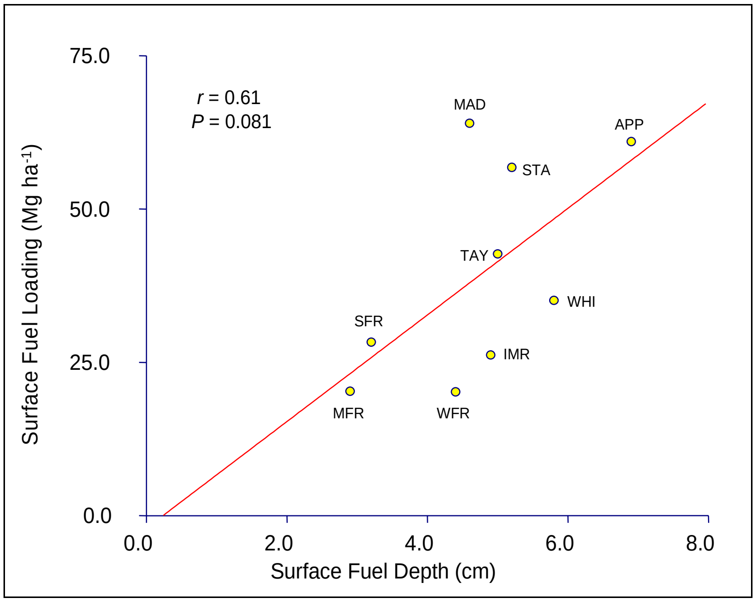
The Brown's method substantially under-estimated the loading of 1 hr fuels. The difference between the Brown's and the plot-based methods remained even when constants for specific gravity, average squared quadratic mean diameter, and particle angle measured specifically for masticated fuels were used. Due to the depth and complexity of masticated fuel beds, it is difficult to count intercepts of the fine fuels along a transect line. Conversely, the plot-based method is limited in sampling area, and does not appear to adequately capture 100 hr and 1000 hr fuels. To obtain the most accurate woody fuel loading estimates, we therefore recommend a hybrid approach, using a plot-based method for 1 hr and 10 hr fuels, and Brown's transects for the 100 hr and 1000 hr fuels.

Because collecting fuel loading data is time consuming, managers may often not have the resources to obtain accurate estimates of loading. Measuring depth and converting to mass based on a depth: mass relationship might provide an alternative. However, we did not find a significant relationship between depth and mass across sites (Figure 1). The poor predictive capacity is likely due to variation in fuel bed bulk density due to different shrub species being masticated, mastication machinery (the rotating drum masticators tended to chop material into finer particles, creating a more compact fuel bed), and masticator effort (amount of time spent by the operator). There was a strong within-site relationship between fuel depth and mass at 8 of the 10 sites. Another approach for obtaining a rough fuel loading estimate is to use our fuel loading photo series, available on-line (http://www.fs.fed.us/psw/programs/ecology_of_western_forests/projects/masticated_fuels/).

Table 1. *Fuel loading for mechanically masticated areas from the plot-based sampling method by timelag fuel moisture class. Post-hoc tests were completed with a Kruskal-Wallis multiple comparison test; values that share the same letter within each column were not significantly different.*

Site	***n***	**1 hr**	**10 hr**	**100 hr**	**1000 hr**	**Total woody**	**Litter**	**Duff**	**Fuel depth**
		-- Mg/ ha						--------------------------------------	(cm)
APP	15	12.3[ab]	24.6[abc]	8.6	5.3	50.7[ab]	10.3[abc]	6.7[bc]	6.9[a]
CFR	40	7.6[bc]	21.4[abc]	8.1	2.2	39.3[abc]	8.6[ab]	12.4[abc]	*n/a*
IMR	15	6.2[bc]	13.8[bcd]	3.6	0.0	23.6[bcd]	2.6[cd]	7.5[bc]	4.9[ab]
MA	15	23.5[a]	34.8[a]	5.1	0.0	63.4[a]	0.6[d]	19.6[ab]	4.6[ab]
MF	15	4.7[bc]	8.2[cd]	1.3	3.1	17.4[bd]	2.9[cd]	15.0[abc]	2.9[b]
SFR	15	5.2[bc]	11.1[bcd]	6.6	0.0	22.9[bcd]	5.4[abc]	5.7[bc]	3.2[b]
STA	15	15.7[a]	25.0[ab]	4.8	1.3	46.9[ac]	9.9[a]	25.9[a]	5.2[ab]
TAY	15	13.2[ab]	21.7[abcd]	2.1	0.0	37.0[abc]	5.6[abc]	27.9[a]	5.0[ab]
WF	40	4.4[c]	9.4[d]	1.6	0.0	15.3[d]	4.8[abc]	5.9[c]	4.4[ab]
WHI	15	11.8[ab]	16.4[abcd]	3.5	0.0	31.8[abcd]	3.3[bcd]	7.0[abc]	5.8[a]
P		***<0.001***	***< 0.001***	*0.089*	*0.264*	***< 0.001***	***< 0.001***	***< 0.001***	***< 0.001***
Average		10.5	18.6	4.5	1.2	34.8	5.4	13.4	13.4

Figure 1. *Relationship between surface fuel depth (cm) and surface fuel loading (Mg/ha) across mastication study sites. Equation of line: surface fuel loading = -2.05 + 8.70*depth.*



Masticated fuel bed values were substantially different from any of the published standard fuel models (Anderson 1982, Scott and Burgan 2005), forming a distinct grouping in cluster analysis. Within the 10 masticated fuel sites sampled for this study, subgroupings appeared to separate the lower fuel loading masticated sites from the high fuel loading masticated sites. The SFR site was an outlier, with higher live fuel mass (data not shown) than the other sites.

Drying rate and fire behavior consequences of particle fragmentation

Methods

Because masticated particles are often highly shattered and cracked, it was thought that these fuels might dry more rapidly than sections of intact stems. To investigate whether this was the case, drying rates of 10 hr masticated *Arctostaphylos manzanita* particles (average diameter between 6.35 mm and 25.4 mm) were compared with 12.7 mm diameter ponderosa pine dowels (the diameter of a 10 hr fuel stick). Minimum and maximum diameters of masticated particles were measured at two locations along the longitudinal axis of the particle. The arithmetic mean of the four measurements was used as average diameter. Specific gravity of masticated fuels and pine dowels was also determined by submersing individual particles in water and measuring the resulting buoyant force as recorded on a balance. After the masticated manzanita particles and pine dowels were oven dried at 60ºC for 72 hours, they were submerged in a water bath for seven days, weighed, and then placed in a room with temperature and humidity controlled (RH = 28 %, temperature = 23 ºC) with electronic dehumidifier. All particles were placed on racks to allow desorption of moisture until equilibrium moisture content was reached. Fuel particles were weighed periodically (t = 0, 10, 24, 50, 100, & 288 h) during the drying process.

Recognizing that drying rates of fuels on a rack might be different than actually seen in a fuel bed, the same experimental procedures outlined above were repeated for a second drying experiment, where the fuel particles were labeled and placed within the upper portion of masticated fuel beds in contact with other masticated particles. These laboratory masticated fuel beds were constructed in 26 x 38 cm aluminum baking pans, and had a depth averaging 6 cm, similar to the depth found in the field. In addition to masticated manzanita particles and pine dowels, intact (round, unmasticated) manzanita stems of similar diameter, and maple dowels (having a specific gravity closer to manzanita than pine) were also included in this experiment.

In order to better understand the role of fuel moisture on fire behavior in masticated fuel beds, fuel beds were created in the same aluminum baking pans in the laboratory from collections made at two sites: Mad River (fuel beds composed primarily of *Arctostaphylos manzanita)*, and Taylor Ridge (fuel beds composed primarily of *Ceanothus velutinus).* Four fuel moisture levels were created: 11, 9, 7 and 2.5 percent, by drying in a controlled environment similar to the previous experiments. Fuel beds were burned under laboratory conditions on a burn table at Humboldt State University. Thermocouples were placed on the fuel bed and at 20, 60, 100, and 140 cm above the fuel bed. Fuel beds were burned on a scale to measure the weight loss rate during the combustion process. During the burn, temperatures were recorded every second using a CR-1000 datalogger. Maximum flame height was measured along with flaming and smoldering time during combustion. Mass loss rate was used to calculate energy release in terms of fireline intensity using published heat content of *Arctostaphylos* and *Ceanothus*. Percent combustion was calculated by subtracting the final weight of the fuel following combustion from the initial weight at the start of the burning process. The experiment was replicated four times.

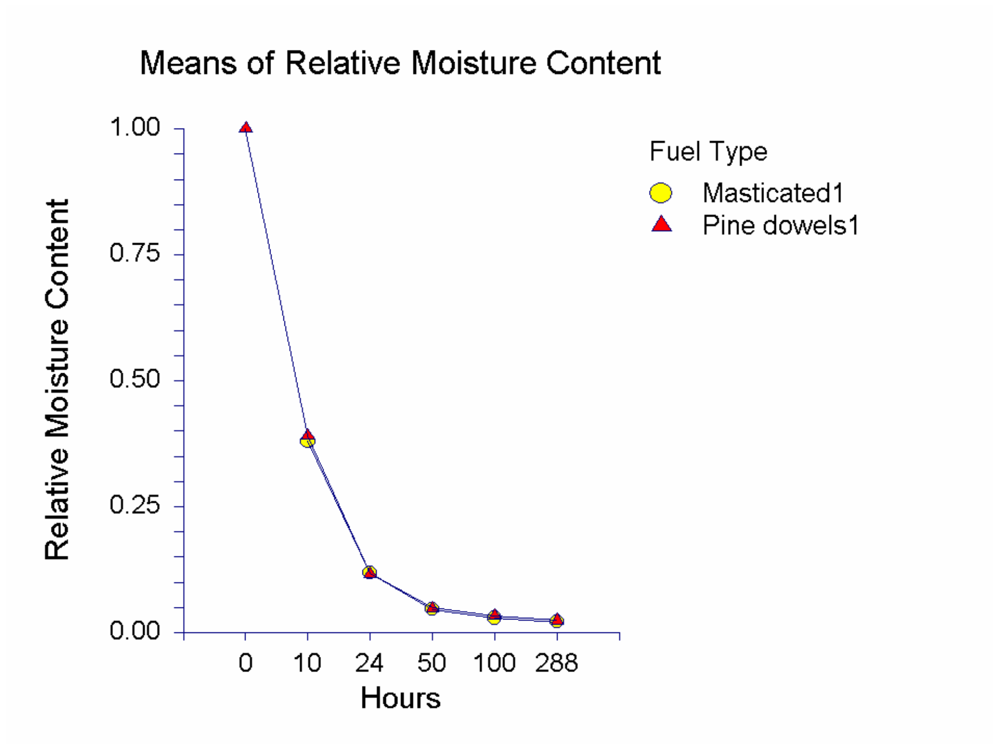
[Note: this burning experiment differs somewhat from the one originally proposed, which called for treatments being different levels of fuel bed compaction/ time since mastication. Our field survey showed limited variation in compaction among sites, and the range of values were likely insufficient to differentially influence fire behavior. We therefore believed that fuel moisture treatments would provide more meaningful information, and redesigned the experiment accordingly.]

Summary of Findings

Relative moisture content did not differ significantly between masticated manzanita fuels and pine dowels (Figure 2) at any time period during the drying process. Therefore, the process of mastication did not affect the drying rate for material of similar size. Variation in relative moisture content appeared to be somewhat higher in masticated manzanita than in the pine dowels, although the Levene's test of heterogeneity of variance was not significant.

While fuel particles within fuel beds dried more slowly than individual particles not in contact with each other, little difference between masticated particles and unmasticated 10 hour fuel particles were found. The entire fuel bed dried more slowly than particles lying on top of the fuel bed. Any changes in fire behavior associated with mastication are probably not going to be due to alteration of drying properties of particles within a fuel size category, but may be the consequence of creating smaller particle sizes and increasing the surface to volume ratio.

Figure 2. *Relative moisture content of standard 10 hr pine dowels and masticated manzanita fuel particles throughout the drying process.*



As expected, flame height was significantly greater for masticated fuels at lower moisture levels than masticated fuels at higher moisture levels, and the amount to time required for flaming combustion was reduced (Table 2).

Table 2. *Fire behavior and combustion of masticated Arctostaphylos manzanita fuel beds at different fuel moisture levels in laboratory burns.*

Fuel Moisture Treatment (%)	Flaming time (min)	Smoldering time (min)	Maximum Flame Height (cm)
2.5	13.2[a]	57.2[a]	80[a]
7	17.3[ab]	70.1[a]	64[ab]
9	17.4[ab]	68.3[a]	60[ab]
11	22.3[b]	48.8[a]	51[b]

[ab] No significant difference (ά = 0.05) between treatments with shared letter.

Soil heating: effect of soil moisture and soil type

Methods

Forty-eight 1 m x 1 m burns in constructed masticated fuel beds were conducted on the grounds of the Redding Silviculture Laboratory in Redding, CA. Factorial treatments included three soil textures (pumice sand, loam, clay) in full combination with four soil moisture contents (approximately 10, 20, 30, and 40 % on a volumetric basis), all replicated four times.

Soil temperatures were measured at 0, 2.5, 5, 10, and 15 cm depths in undisturbed soil using thermocouples (K type) connected to temperature data loggers. Large intact soil cores (30 cm diameter, 15 cm high) were collected from field sites representative of the three soil textures. Upon return to the Redding Lab, the cores were saturated with water and allowed to slowly dry to the desired moisture contents. When ready, each core was placed in a 15 cm deep hole dug in the ground, thermocouple leads were pushed into the center of each soil core, and extra soil packed around the soil core. Masticated residues (134.5 Mg/ha), similar to the highest fuel loading plots within high fuel loading sites in the field survey, were added to the soil surface at a bulk density matching the conditions found at our field sites, and ignited with a drip torch along the downwind side of the fuel bed.

Air temperature, relative humidity, wind speed, wind direction, flame length, and rate of spread were recorded during each burn. Soil temperatures were measured for 24 hours following ignition, providing sufficient time for the soils to recover to ambient temperature. Data from all burns were used in multiple regression analysis to predict maximum soil temperature as a function of soil moisture, soil texture, soil depth, and heat load (degree hours above the ambient temperature at 2.5 cm soil depth).

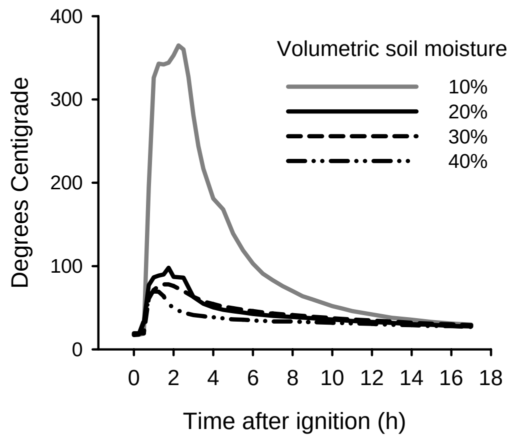
To validate the laboratory burning results, soil temperatures were also measured in the field during eight prescribed burns. Four experimental units were burned in the spring of 2005 at the Challenge Experimental Forest and an additional four units were burned in the spring of 2006 near Whitmore, CA (details below). Thermocouples were placed at 0, 2.5, 5, and 10 cm in the soil profile at multiple locations within each unit prior to the burns. Fuel load, fuel moisture, and soil moisture in the vicinity of each thermocouple station were recorded prior to burning.

Summary of Findings

Maximum temperatures on the soil surface during burning of the constructed fuel beds in the laboratory ranged from 350 to 1080 ^{o}C. As expected, an incremental drop in temperature was found with increasing soil depth. Temperatures ranged from 43 to 370 ^{o}C at 2.5 cm; from 35 to 308 ^{o}C at 5 cm; from 29 to 74 ^{o}C at 10 cm; and from 27 to 51 ^{o}C at 15 cm.

Soil temperatures were strongly affected by soil moisture but not by soil texture (Figure 3). Regression analysis identified soil moisture ($p < 0.001$), soil depth ($p < 0.001$), and surface heat load ($p < 0.001$) as significant independent variables. In contrast, soil texture was not significant ($p = 0.872$).

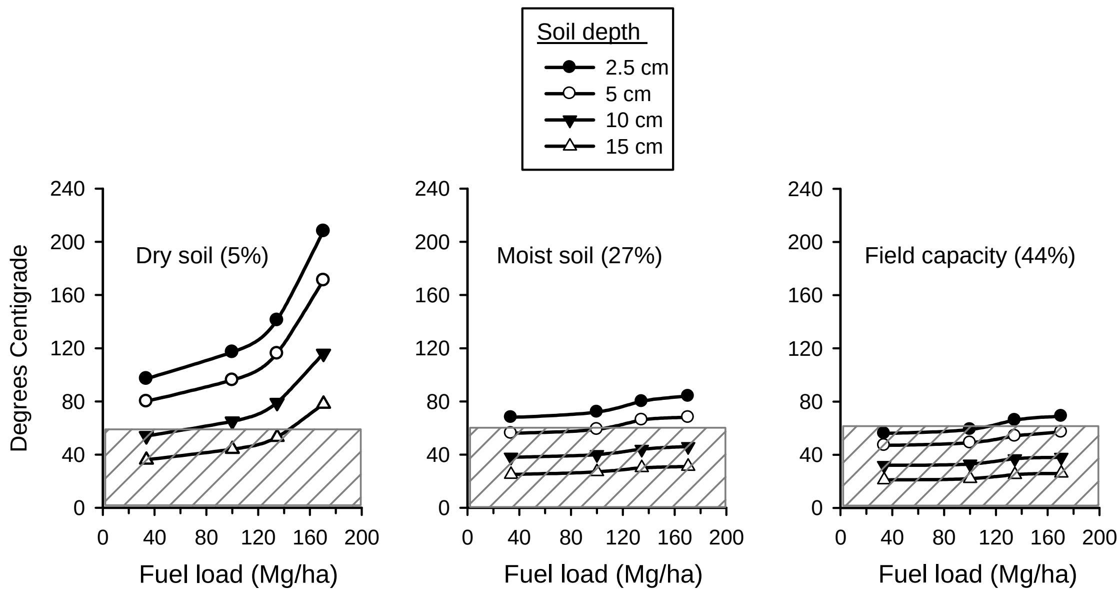
Figure 3. *Effect of soil moisture on maximum soil temperature. Response curves are for pumice sand soil at a depth of 2.5 cm and a masticated fuel load of 134.5 Mg/ha.*



Because this study was conducted at only one fuel loading level, we combined the experimental results of this study with previous findings of soil heating (Busse et al. 2005) to develop soil temperature response curves for a broad range of fuel loads (Figure 4). These data confirm that lethal temperatures (> 60 ^{o}C) are mostly superficial when soils are moist. Temperatures exceeded the lethal threshold to a depth of only 2.5-5 cm in moist soil regardless of fuel load, yet surpassed this threshold to a depth of 10-15 cm in dry soil.

These results suggest that most roots and soil organisms will likely be unaffected by burning of masticated fuels in all but the driest of soils. Burning when soils are moist (>20% volumetric moisture) should inhibit damaging temperatures below 2.5 to 5 cm in the mineral soil. As a field validation, the eight spring prescribed burns were conducted when soils were moist, ranging from 18 to 45% volumetric soil moisture content. Corresponding soil temperatures in nearly all cases were well beneath the lethal threshold, averaging 36 ^{o}C at 2.5 cm and only 28 ^{o}C at 5 cm in the mineral layer. Based on this research, we recommend burning masticated fuels when soils are moist to avoid damaging roots and soil organisms.

Figure 4. *Predicted maximum soil temperatures during burning of masticated fuels as a function of soil moisture, soil depth, and fuel load. The gray-shaded area in each graph represents sub-lethal temperatures for roots. Volumetric soil moisture content is shown in parentheses in the graph titles. Field capacity is equivalent to the maximum available water content found within 24 hours of a saturating rainfall.*



Fire behavior and effects in prescribed burns

Methods

Four prescribed burns, each approximately 0.4 ha in size, were conducted at each of two masticated fuels study sites, Challenge and Whitmore, where dense shrubs dominated by *Arctostaphylos* sp. and *Ceanothus* sp., occurred under a stand of young ponderosa pine trees. The replicated experimental design at both sites had been previously established as part of a National Fire Plan funded study. The "Challenge" site was located on the Challenge Experimental Forest, Plumas National Forest (Elev. 850 m), while the "Whitmore" site was located on private timberland near the town of Whitmore in Shasta County (Elev. 700 m). Units had been masticated with a Rayco forestry mower in March 2003 (Challenge) and May 2003 (Whitmore). The prescribed burns at Challenge were conducted in May and June 2005 and the prescribed burns at Whitmore were conducted in June 2006.

Prior to the burns a total of 253 trees at Challenge and 302 trees at Whitmore were tagged, and diameter at 1.37 m, height to base of live crown, and total tree height measured. At Challenge, a subset of 130 trees of average size were selected and half were randomly assigned to a raking treatment (fuels removed around the base of trees out to 0.5 m) in order to separate mortality as a result of bole damage from mortality caused by crown scorch or root kill. Loading of woody fuels and litter were both visually estimated under the canopy of each tree in the raking experiment, according to a rough scale where 1 = low, 2 = moderate, and 3 = high.

Ignition was accomplished primarily though strip-head fires, with strips approximately 2 m apart. On steeper slopes at Challenge, strip-head fires resulted in excessive scorching given the relatively small size of the trees, and firing in these areas was adjusted to primarily backing. When possible, flame length and rate of spread were opportunistically estimated for both heading and backing fires. These estimates were compared to predictions of fire behavior from BehavePlus, using standard fuel models (Anderson 1982, and Scott and Burgan 2005).

Post-burn fire severity was quantified at both sites in the months after the burns. Scorch height and height of bole char on both the uphill and downhill sides of each tree were measured, and percentage of the bole circumference at the base of the tree that experienced fire and percentage of crown volume scorched were visually estimated. At Challenge, each tree was re-visited in July 2006, and again in September 2007, and status (live, dead, or dead and down) noted. Secondary mortality at the Whitmore site has only been evaluated once so far (June 2007). Significance of factors contributing to tree mortality was determined using PROC GLIMMIX in SAS, with mortality as the dependent variable, fire damage measurements and pre-burn fuel loadings as independent variables (fixed effects), and unit as a random effect.

Summary of Findings

Flame lengths for backing and head fires were similar at both sites (Table 3). Rate of spread for heading fires was approximately two times faster at Challenge than at Whitmore, a difference likely due to steeper slopes at Challenge.

Table 3. Fire behavior parameters for prescribed burns in masticated fuels at two sites.

	Site	
Variable	**Challenge**	**Whitmore**
Fuel moisture – 10hr (%)	13.2	12.5
Fuel moisture – duff (%)	83.0	29.8
Soil moisture (%)	36.6	23.5
Flame length-backing (m)	0.35	0.29
Flame length-heading (m)	0.72	0.73
Rate of spread-backing (m/hr)	4.3	4.4
Rate of spread-heading (m/hr)	57.3	26.8
Scorch height (m)	9.9	5.5

When actual measured fuel values (loading and depth) were used to create a custom fuel model, BehavePlus indicated that the fuel bed would not burn under our prescription conditions. This may be a limitation of Rothermel's fire spread equation (Rothermel, 1972) used in BehavePlus, which appears to be overly sensitive to fuel bed depth/ bulk density. Erroneous predicted lack of burning in highly compacted fuel beds has also been reported by others (Glitzenstein et al. 2006). Instead of creating custom fuel models, we therefore chose among existing fuel models that best estimated fire behavior. Flame length and rate of spread were well predicted using an average of two standard slash fuel models (sb1 and sb2, Scott and Burgan 2005). However, scorch height measured on the residual trees was substantially greater than predicted. Scorch height at Challenge (high fuel loading) was nearly four times model predictions, while scorch height at Whitmore (low fuel loading) was approximately twice model predictions. The high heat content of the woody shrub fuels and long flaming duration likely contributed to higher than expected crown scorch, despite the relatively slow rate of spread.

Mortality of trees after the burns at Challenge was not significantly affected by raking fuels from the base (mortality was 25% and 30% with and without raking, respectively, one year after the burns; 30%, and 35% with and without raking, respectively, two years after the burns (p = 0.767)). The raking treatment was not totally effective in preventing bole damage; some bark on slightly more than half of the raked trees still caught fire as a result of radiant heat. However, the average level of bark char was much lower on raked trees than unraked trees (34% vs. 97% of bole circumference charred). Mortality appeared to be primarily due to crown scorch. When all variables (raking treatment, diameter at breast height (dbh), woody fuel load, litter fuel load, bark char height – high side, bark char height – low side, percentage of crown volume scorched (PCVS), and percentage of bole circumference charred, were analyzed together with status two-years post fire as the dependent variable, only PCVS was significant ($p < 0.001$). For the full tree data set (raking experiment plus all other tagged trees), PCVS was still the dominant explanatory variable ($p < 0.001$). Diameter at breast height was also significant ($p = 0.010$), with smaller trees more prone to die. Bole char height (downhill or low side) was nearly significant (p = 0.052).

At the lower fuel loading Whitmore site, only 5% of trees had died one year after the prescribed burns. Tree diameter ($p < 0.001$) and PCVS ($p < 0.001$) were the strongest predictors of mortality, with bark char height – high side ($p = 0.076$) and bark char height – low side (p = 0.062) approaching significance.

Using correction factors for crown scorch estimated from the prescribed burns, mortality of residual trees at each site with a wildfire (head fire) is predicted to be high, even under mild fire weather conditions (Table 4).

By reducing fuel bed depth, mastication may moderate fire behavior, but high loadings of surface fuels can still result in substantial mortality of residual trees when burned. Even so, it is possible to reduce masticated fuel loads using prescribed fire. In this study, the high soil moisture levels at the time of the burns limited heat penetration into the soil. Under these conditions, the major cause of initial mortality appeared to be due to crown scorch, which can be mitigated by adjusting firing techniques (i.e. greater use of backing fire, narrow strips), and burning when air temperature is low.

Table 4. *Predicted mortality of residual trees at each of ten masticated fuels sites with a head fire under different fire weather conditions. Fire weather predicted using FireFamilyPlus, crown scorch predicted using BehavePlus, and tree mortality predicted using FOFEM.*

	Percentile Weather			
Site	**37.5**	**80**	**90**	**97.5**
	----------------- % mortality ------------			
APP	100	100	100	100
CFR	80	95	97	98
IMR	71	91	94	96
MAD	89	95	95	95
MFR	99	99	99	99
SFR	100	100	100	100
STA	99	99	99	99
TAY	91	94	94	94
WFR	89	99	99	99
WHI	84	89	92	98
Average	90.2	96.1	96.9	97.8

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Appendix A. List of sites where the fuel surveys and prescribed burns were conducted.

		Activity	
Site name	**Field Location description**	**Fuel loading survey**	**Prescribed burns**
Applegate (APP)	Bureau of Land Management, near Ruch, OR	X	
Taylor Ridge (TAY)	Klamath National Forest, on Taylor Ridge	X	
Shasta (SFR)	Shasta-Trinity National Forest, SE of Black Butte	X	
Iron Mountain (IMR)	Bureau of Land Management, near Keswick, CA	X	
Whiskeytown (WHI)	Whiskeytown National Recreation Area, W of Redding, CA (National Park Service)	X	
Mad River (MAD)	Six Rivers National Forest, near Mad River	X	
Whitmore (WFR)	Private timber land (managed by W.M. Beaty and Associates, Inc.), near Whitmore, CA	X	X
Challenge (CFR)	Challenge Experimental Forest, on the Plumas National Forest	X	X
Sierraville (SFR)	Tahoe National Forest, near Bear Valley Campground	X	
Stanislaus (STA)	Stanislaus National Forest, near Columbia	X	

Appendix B. Crosswalk between proposed and delivered FFS outreach activities.

Proposed	Delivered	Status
Project website	http://www.fs.fed.us/psw/programs/ ecology_of_western_forests/projects/masticated_fuels/	Completed
Research paper	Busse, M., C. Shestak, E. Knapp, G. Fiddler, and K. Hubbert. Lethal soil heating during burning of masticated fuels: effects of soil moisture and texture. In preparation	Expected Summer 2008
Research paper	Knapp, E. E., M.D. Busse, J.M. Varner, C.N. Skinner, and R.F. Powers. Behavior and short-term effects of fire in masticated fuel beds. In preparation.	Expected Summer 2008
Research paper	Kane, J., J.M. Varner, and E.E. Knapp. Novel fuel bed characteristics associated with mechanical mastication treatments in Northern California and Southern Oregon.	In internal agency review
Publication summaries	Summary of findings of above three papers, intended for manager audience. [Note: because of strong interest and need for interim products, we wrote three short conference proceeding summaries for the Nov. 2006 Association for Fire Ecology Congress, which were also distributed to managers.]	At time of publication of above 3 papers
Preliminary custom fuel models	Based on the findings, we opted to develop correction factors for existing slash models instead. These corrections are available on the website, have been shared at a workshop for managers, and through written conference proceedings.	Completed
Fuel loading photo series	On-line photo series showing before and after mastication photographs and accompanying fuel load values post-mastication. http://www.fs.fed.us/psw/programs/ ecology_of_western_forests/projects/masticated_fuels/ fuelload.shtml	Completed
Workshop	Knapp, E., M. Busse, J.M. Varner, and C. Skinner. Mechanical fuel treatments using mastication: an evaluation of fuel loading, fire behavior, and fire effects. USDA Forest Service Region 5 Fuels and Vegetation Management Workshop, Reno, NV. Feb. 6-8, 2007.	Completed

In addition to proposed		
Thesis	Kane, J.M. 2007. Fuel loading and vegetation response to mechanical mastication fuels treatments. Department of Forestry and Watershed Management, Humboldt State University. M.S. Thesis.	Completed
Thesis	Kreye, J. Moisture dynamics and fire behavior in mechanically generated (masticated) fuel beds. Department of Forestry and Watershed Management, Humboldt State University.	In Review, Expected June 2008
Presentation	Busse, M., K. Hubbert, C. Shestak, G. Fiddler, E. Knapp, and R. Powers. Soil heating and potential biological damage during burning of masticated residues. Blodgett Experimental Forest Research Workshop, January 2006.	Completed
Presentation	Knapp, E., M. Busse, C. Skinner, and R. Powers. Fire behavior and effects when burning masticated fuels. Presentation to the Challenge Area Fire Safe Council. Brownsville, CA. May 10, 2006.	Completed
Presentation	Knapp, E. Presentation to USFS Region 5 annual fuels meeting. Discussed latest research on ecological effects of fuels treatments and on fire behavior and effects when burning masticated fuels. Redding CA. May 31, 2006.	Completed
Presentation	Knapp, E., M. Busse, and C. Shestak. Fire behavior and soil heating impacts with prescribed burning in masticated fuel beds. 1st Fire Behavior and Fuels Conference; How to Measure Success. International Association of Wildland Fire, Portland OR, March 28-30, 2006.	Completed
Presentation	Kane, J.M., J.M. Varner, and E.E. Knapp. Understory vegetation response to mechanical mastication treatments: Evidence for increasing resilience to wildfire in a young ponderosa pine forest. Ecological Society of Americal/ Society for Ecological Restoration joint meeting, San Jose, CA. Aug. 5-10, 2007.	Completed
Proceedings paper	Kane, J.M., E.E. Knapp, and J.M. Varner. 2006. Variability in loading of mechanically masticated fuel beds in northern California and southwestern Oregon. In Andrews, P.L., and Butler, B.W., comps., Fuel Management – How to Measure Success: Conference Proceedings, March 28-30, 2006, Portland OR. U.S.D.A. Forest Service, Proceedings RMRS-P-41, pages 341-350.	Completed

Proceedings paper	Knapp, E., M. Busse, J. Morgan Varner III, C. Skinner, and R. Powers. 2006. Behavior and short-term effects of fire in masticated fuel beds. Proceedings of the Third International Fire Ecology and Management Congress, Nov. 13-17, San Diego, CA. 3pp.	Completed
Proceedings paper	Kane, J., J.M. Varner, and E. Knapp. 2006. Initial understory vegetation response to mechanical mastication fuel treatments: balancing biodiversity and fire hazard reduction. Proceedings of the Third International Fire Ecology and Management Congress, Nov. 13-17, San Diego, CA. 3pp.	Completed
Proceedings paper	Busse, M., C. Shestak, E. Knapp, G. Fiddler, and K. Hubbert. 2006. Lethal soil heating during burning of masticated fuels: effects of soil moisture and texture. Proceedings of the Third International Fire Ecology and Management Congress, Nov. 13-17, San Diego, CA. 3pp.	Completed
Proceedings paper	Kreye, J., and J.M. Varner. 2007. Moisture dynamics in masticated fuel beds: a preliminary analysis. In Butler, B.W., Cook, W. (comps.) The fire environment – innovations, management, and policy; conference proceedings. March 23-27, 2007, Destin, FL. USDA Forest Service RMRS-P-46CD, Fort Collins, Co. Pgs 173-186.	Completed
Research paper	Kane, J.M., J.M. Varner, E.E. Knapp, and R.F. Powers. Initial vegetation response to mechanical mastication fuels treatments in a northern Sierra Nevada ponderosa pine forest.	In internal agency review