

Moisture Dynamics in Masticated Fuelbeds: A Preliminary Analysis

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Abstract—Mastication has become a popular fuels treatment in the Western United States, but predicting subsequent fire behavior and effects has proven difficult. Fire behavior and effects in masticated fuelbeds have been more intense and erratic in comparison with model predictions. While various particle or fuelbed characteristics in these fuels may contribute to the inaccuracy of model predictions, an increase in particle surface area to volume ratio by the mastication process may affect moisture dynamics. The prediction of fuel moisture is critical to predicting fire behavior and effects in prescribed fire or wildfire scenarios. Moisture dynamics in masticated fuels is characterized here by analyzing desorption rates in masticated and intact manzanita and compared with pine and maple dowels under laboratory experiments. Preliminary analysis shows that desorption rates are similar in masticated and intact manzanita as well as pine dowels by comparing relative moisture contents throughout desorption as well as by calculating response times using the timelag concept. These results held true both at the particle and fuelbed level, although masticated manzanita and pine dowels were both found to desorb moisture more quickly as individual particles compared to within fuelbeds. Particle density was strongly linked to desorption although it is not fully explored in terms of its significance as compared with other physical properties. Physical and chemical differences due to particle weathering and species differences may play significant roles as well. While this may be some of the first work to address the effects of mastication on moisture dynamics in forest fuels, future work should focus on other aspects where fuelbed or particle characteristics in masticated fuels may influence fire behavior and effects.

Introduction

Mechanical mastication of forest fuels has become a popular method of reducing fire risk by disrupting the vertical continuity of shrub and small-tree fuels. While mastication projects are being conducted over large areas in the Western United States, little is known about the effects of mastication on subsequent fire behavior. Prescribed fires have occurred within masticated sites resulting in unexpected fire behavior and effects (Knapp and others 2006). Currently, fire modeling systems are poor at predicting fire behavior parameters in these types of treatments. Changes in moisture dynamics due to increases in surface area:volume ratios associated with the fractured nature of masticated fuels may be a primary reason for inaccurate fire behavior predictions.

Fuel moisture is a primary predictor of fire behavior. Understanding the response of fuel moisture to changes in environmental conditions is required to predict daily or seasonal fuel moisture. The adsorption and desorption of moisture in fuels during a change in environmental conditions occur differently (Blackmarr 1971) and are referred to as sorption hysteresis. The resulting

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equilibrium moisture content following desorption is higher than the equilibrium moisture content resulting from the adsorption process across various environmental conditions (relative humidity and temperature). Desorption of moisture is critical because it occurs when fuels are drying in response to decreases in relative humidity and/or increases in ambient air temperature. The irregular shape of masticated fuel particles, resulting in a higher surface area to volume ratio, may affect the way in which fuel moisture responds to diurnal or seasonal changes in environmental conditions. Fuel moisture values that are input into fire behavior/effects models and fire danger rating systems (for example, BehavePlus and NFDRS) are often estimated from the weighing of standard ½ inch ponderosa pine dowels.

To address the deficiencies in prediction of fire behavior in masticated fuelbeds we evaluated fuel moisture during desorption in mechanically masticated fuels (*Arctostaphylos manzanita ssp. wieslanderii*) at the particle and fuelbed scale and compared them to standard fuels (*Pinus ponderosa*) as well as similar density fuels (*Acer* sp.). Two experiments were conducted addressing: (1) desorption at the individual particle level and (2) desorption at the fuelbed level. The results presented here are a preliminary analysis, and ongoing research is currently investigating site, species, and time since treatment level differences.

Methods

Mechanically masticated fuels were collected from a fuelbreak in the Six Rivers National Forest near the community of Mad River, CA, approximately 50 miles east of the Pacific Ocean. The site was dominated by dense common manzanita (*Arctostaphylos manzanita ssp. wieslanderii*) greater than 6 ft tall prior to treatment. The elevation of the study site is 940 ft with a 6 percent slope and a NW aspect. Mastication was conducted in December 2004. Within the site, all woody fuels were collected from the surface down to mineral soil at four 2 x 2 m plots. Collected fuel was transported to the laboratory for desorption experiments under controlled conditions. Desorption experiments were conducted on individual fuel particles (experiment 1) as well as constructed fuelbeds (experiment 2). Desorption rates were analyzed in two ways: (1) by comparing relative moisture contents over time using analysis of variance and (2) by estimating response times in terms of the original timelag concept as developed by Byram (1963).

Experiment 1

Masticated manzanita particles with an average diameter between 6.35 mm (¼ inch) and 25.4 mm (1 inch) were selected (n=19) for analysis of moisture desorption along with 1.27 x 12.7 cm (½ inch x 5 inch) standard ponderosa pine dowels (n=10) for comparison. Masticated particles were measured for minimum and maximum diameter at two equidistant 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 measured by submersion of individual particles in water and measuring the resulting buoyant force as recorded on a balance whereby

$$\text{specific gravity} = \text{oven dry weight (g)} / \text{buoyant force (g)}$$

Masticated manzanita particles and pine dowels were oven dried at 60 °C for 72 hours, weighed, and submerged in a water bath for 7 days. Following the water bath all particles were weighed and subsequently placed in a temperature and humidity controlled room (4.5 x 3.2 m). Temperature and humidity were controlled at 28 percent relative humidity (± 2.7 percent) and 23 °C (± 1.6 °C) by sealing off all ventilation and the use of a Comfort-Aire® BHD-301 electronic dehumidifier. All particles were placed on racks to allow desorption of moisture until equilibrium moisture content was reached. Fuel particles were weighed periodically for 384 hours during the desorption process. Temperature and relative humidity data were recorded hourly throughout the experiment.

Moisture content (m) of fuel particles at time t was calculated by

$$m_t = (\text{fuel weight}_t - \text{oven dry weight}) / \text{oven-dry weight}$$

Fuel moisture content was converted to relative moisture content (Fosberg 1970) for comparing desorption rates and to estimate time lag response times by

$$E = (m_t - m_f) / (m_i - m_f)$$

where:

- E = relative moisture content
- m_t = moisture content at time t
- m_f = final moisture content
- m_i = initial moisture content

Relative moisture was compared across time periods ($t = 0, 10, 24, 50, 100,$ and 288 hours) between masticated manzanita and pine dowels using GLM analysis of variance. Relative moisture contents were regressed with specific gravity as well as average diameter for both fuel types at time periods ($t = 10, 24, 50, 100, 288$ hours). Specific gravity was regressed with average diameter as a predictor for both fuel types as well.

The timelag concept developed by Byram (1963) is a common method of describing moisture responses in fuels resulting from changes in environmental conditions. Relative moisture content (E) is the remaining fraction of moisture that is evaporable at a specific time during desorption from initial moisture content to an equilibrium moisture content following a change in temperate and/or relative humidity. Nelson (1969) described the timelag parameter as characteristic of physical and chemical processes that follow an exponential decay function and that E could be described in terms of response time (τ) by

$$\frac{m_t - m_f}{m_i - m_f} = E = Ke^{-\frac{t}{\tau}}$$

where

- $K = 1$ when at $t = 0, m_t = m_i$
- e = base of natural logarithm
- t = time (hours)
- τ = response time (hours) for which $1/e$ (.368) of the change between two steps remains

The logarithmic form of this equation (below) can be differentiated to calculate the rate of change in relative moisture content and the resulting slope defined in terms of τ since the logarithmic form will be linear under the theoretical negative exponential function. Response time can then be calculated by solving this equation for τ .

$$\frac{d}{dt}(\ln E) = -\frac{1}{\tau}$$

Empirical studies (Anderson 1990; Mutch and Gastineau 1970; Nelson 1969) have shown that moisture response in forest fuels does not follow a pure negative exponential function. Different techniques have therefore been used to describe response times (τ) throughout desorption and adsorption processes. While response time may be thought of in terms of the time required for 63.2 percent ($1 - 1/e$) of the total change to occur as moisture is adsorbed or desorbed from an initial stable state to that of equilibrium at another stable state, this response time fluctuates throughout the process. Since moisture response does not follow a pure exponential decay function, the derivative of its true function should result in a nonlinear function where its slope will not be constant. Response time (τ) fluctuates throughout the process because the instantaneous rate of change along the differentiated logarithmic form of E changes across time (t). The instantaneous rate of change at a single time (t) can result in the calculation of a constant response time (τ), but may only be true at that particular time point.

It is common to plot E as a function of time (t) on a semilogarithmic axis and the resulting curves partitioned into separate linear portions. Response times are then calculated for the separate linear sections. Nelson (1969) described two timelags, or “response times,” τ_1 and τ_2 , which represent the initial stage of drying and the final stage of drying, respectively, but these were separated by a curvilinear portion in the middle. Mutch and Gastineau (1970) found two linear portions occurred in desorption and adsorption of reindeer lichen. Anderson (1990) studied more than one timelag period whereby $E = 0.63, 0.86,$ and 0.95 , respectively, for the first three timelag periods. All of these studies have used standard conditions of 80 °F and a step change from 90 percent RH to 20 percent RH for desorption and the reverse for adsorption. Qualitative analysis can be conducted by plotting E over time on a semilogarithmic axis and comparing different fuel types in terms of response times over various described timelag sections to show the variation in moisture response of different fuels as Anderson (1990) did with Douglas-fir needles, lodgepole pine needles, ½ inch square pine sticks, and lichen. Linton (1962) and Viney and Hatton (1989) described a different use of the term “timelag” in regard to the lag time of fuel moisture behind that of a theorized equilibrium moisture content that would occur on a diurnal cycle of changing temperature and relative humidity under field conditions. Viney and Hatton (1989) and Viney and Catchpole (1991) therefore suggested using the term “response time” as the time with which 63.2 percent of evaporable moisture content has been lost between a shift in two stable conditions, which usually occurs under laboratory experiments. Nonetheless the timelag concept and the use of “response times” are widely used in fire and fuels research and management and can be analyzed through empirical methods without having detailed information regarding specific fuel characteristics.

To address this nonlinearity in the research presented here, piecewise polynomial curve fitting was conducted to separate plots of the natural logarithm of E over desorption time (t) into two linear portions for both fuel types over 7 days of desorption. Linear-linear piecewise models were used to partition the curves into two (τ_1 and τ_2) timelag sections. Response times (τ) were then calculated for each timelag section. A response time for the entire desorption process (T), whereby 63.2 percent of the evaporable moisture had in fact been lost, was compared with calculated response times of timelag

sections τ_1 and τ_2 for each fuel type. This response time (T) is not defined by the differential equation above, but rather by estimating the average time that 63 percent of the evaporable moisture had in fact been lost within each fuel type during desorption experiments.

Experiment 2

Twelve fuelbeds were created using masticated manzanita particles from the Mad River fuel break. Fuels were separated into traditional 1-hour (<6.35 mm diameter) and 10-hour (6.36 to 25.4 mm diameter) fuel categories. Fuels greater than 25.4 mm in diameter were excluded from experimentation because they compose a minor component of fuel loading in masticated sites in the region (Kane and others 2006). Each fuelbed was constructed of 294 g of 1-hour fuels and 435 g of 10-hour fuels, matching proportions and loading of masticated fuels on the site (Kane and others 2006). Fuelbed heights were 5 to 7 cm and were created in 26 x 38 cm aluminum baking pans.

Five manzanita particles between 6.36 and 25.4 mm average diameter (10-hour fuels) were selected within each fuelbed and marked with wire and metal tags. Two of these manzanita particles were intact while three were fractured from mastication. Intact particles did not appear to be physically altered, or fractured, by the mastication process. These five marked particles were placed at the upper layer of their respective fuelbeds whereby the upper surface of each was exposed to the atmosphere directly above the fuelbed, representing the driest portion of the fuelbed.

Pine (*Pinus ponderosa*) and maple (*Acer* sp.) dowels were also marked with wire and tags and added to all fuelbeds. Two pine dowels (12.5 x 127 mm) and two maple dowels (12.8 x 127 mm) were placed at the upper layer of each fuelbed to compare moisture dynamics with that of the manzanita particles.

All fuelbeds were submerged in a water bath for 7 days, drained and placed in the humidity-controlled environment as in experiment 1. Temperature and humidity were controlled at 31 percent relative humidity (± 3.4 percent) and 24 °C (± 1.0 °C). Holes were placed in the bottoms of each pan and pans were elevated on wooden slats to allow excess moisture to drain throughout desorption. Fuelbeds were allowed to desorb moisture for 336 hours. Fuelbeds and marked particles were weighed throughout the experiment. Average diameters of all particles (manzanita, pine dowels, and maple dowels) were then measured in the same manner as experiment 1. Fuelbeds were oven dried at 60 °C for 72 hours. Specific gravity for all marked particles was calculated using the same methods as experiment 1. Fuel moisture content and relative moisture content values were calculated for marked particles and the fuelbeds themselves. For fuelbed moisture content, weights of pine and maple dowels were subtracted at each time point to obtain fuelbed moisture values of the manzanita particles exclusively.

Specific gravity was compared across fuel types using GLM analysis of variance (see table 1 in the Results section). Relative moisture content was compared between the following fuel types: masticated manzanita, intact manzanita, pine dowels, and maple dowels, at time periods 10, 24, 50, 100, and 288 hours using GLM analysis of variance. Timelag response times were calculated using the same methods as experiment 1 for all four fuel types from individual marked particles. Response times were also calculated for the 12 fuelbeds. Results of timelag response times for both experiments 1 and 2 were combined and reported under experiment 2 results (see table 2 in the Results section).

Results

Desorption Experiment 1

Average diameters of masticated manzanita particles ($n=19$) ranged from 7.84 to 20.44 mm, while diameters of pine dowels ($n=10$) ranged from 12.34–12.57 mm. Masticated manzanita particles were significantly higher in density with a mean specific gravity of 0.69 (± 0.011) as compared with pine dowels with a mean specific gravity of 0.48 (± 0.025).

Relative moisture content did not differ significantly between masticated manzanita fuels and pine dowels (fig. 1) across time periods $t = 0, 10, 24, 50, 100, 288$ hours ($\alpha = 0.05$). Variation in relative moisture content appears to be higher in masticated manzanita than that of pine dowels (fig. 2), although the Levene's test rejected homogenous variance between fuel types at 10 hours of desorption only.

Average diameter and specific gravity were related ($r^2 = 0.427$) within masticated manzanita particles, but not within pine dowels ($r^2 = 0.002$; fig. 3). In masticated manzanita linear regression resulted in a stronger relationship between relative moisture content and diameter in early stages of desorption (fig. 4), while relative moisture content had a stronger relationship with specific gravity in later stages. Relationships of relative moisture content with both diameter and specific gravity became less strong as particles approached equilibrium moisture content. In ponderosa pine dowels relative moisture content was strongly related to specific gravity in early stages also (fig. 5), but relative moisture content and average diameter was not related at all. It of course should be noted that variation in diameters of pine dowels was minuscule and these results were expected.

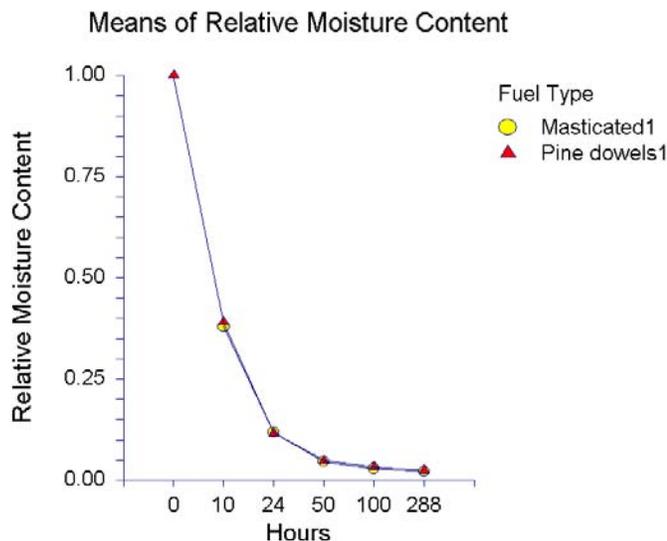


Figure 1—Relative moisture content in standard 10-hour pine dowels and masticated manzanita fuel particles at throughout desorption.

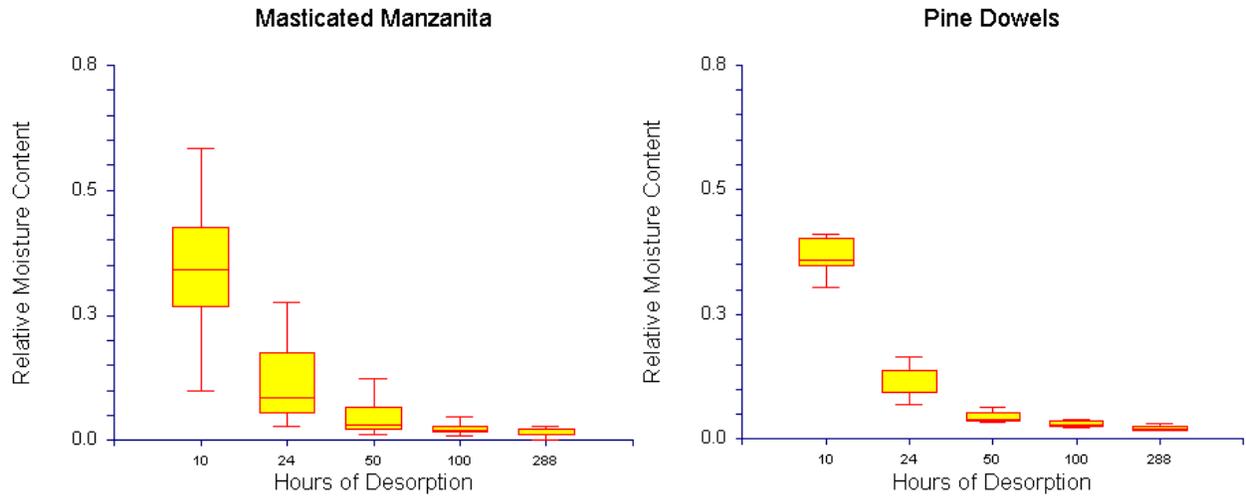


Figure 2—Variation in relative moisture content at 10, 24, 50, 100, and 288 hours of desorption in masticated manzanita fuel particles and standard 10-hour pine dowels.

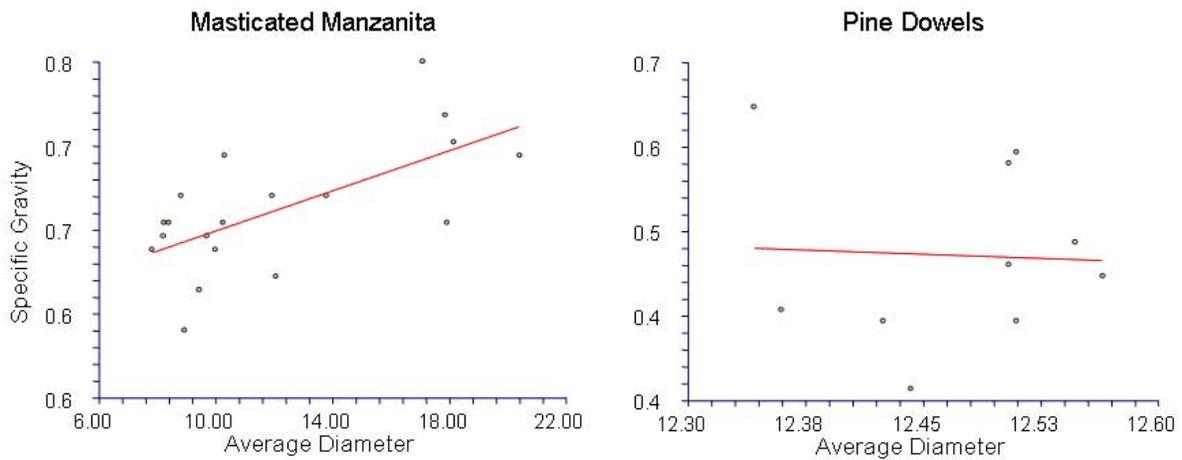


Figure 3—Relationship of specific gravity and average diameter in masticated manzanita ($r^2 = 0.472$) and ponderosa pine dowels ($r^2 = 0.002$).

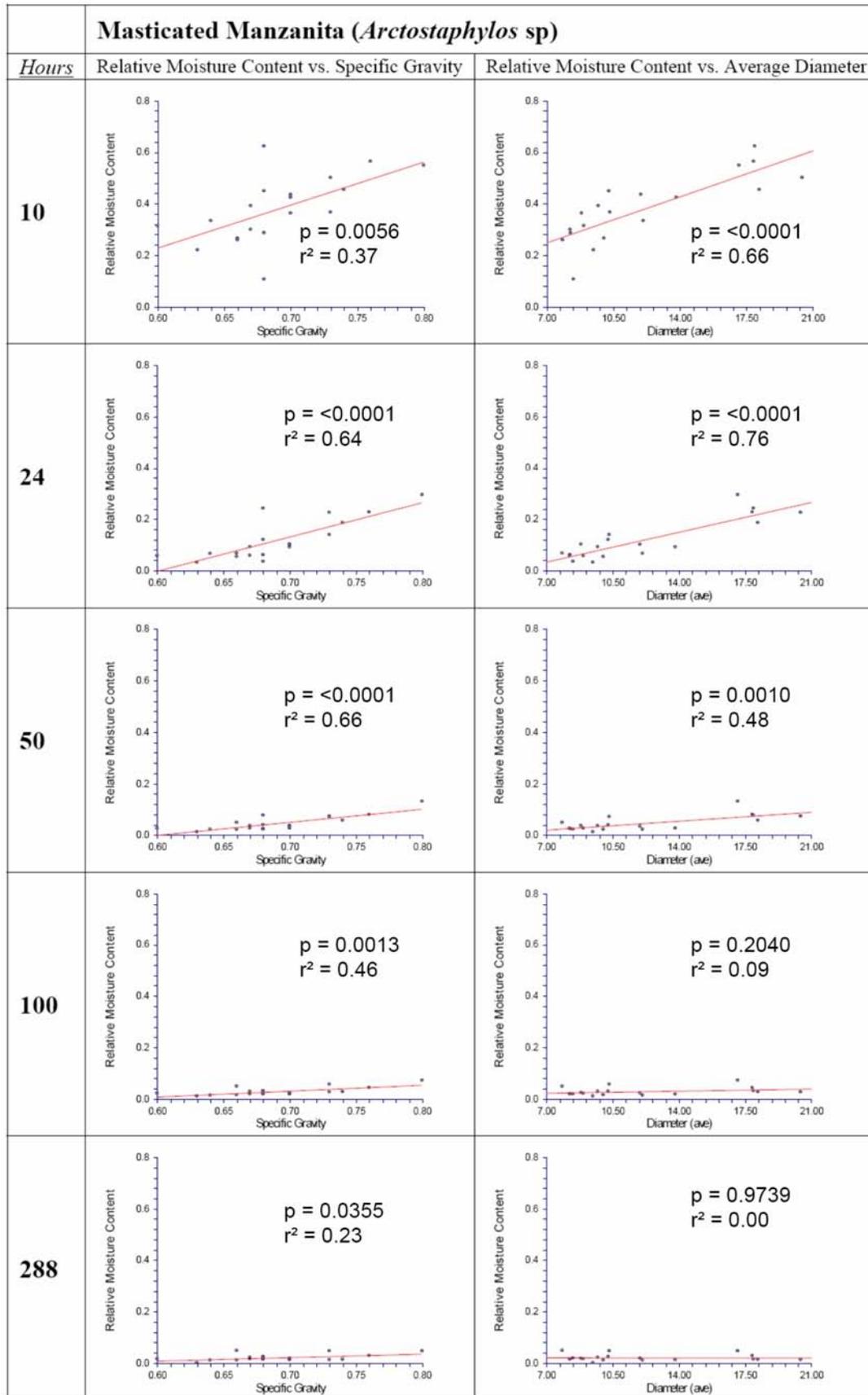


Figure 4—The relationship of relative moisture content with specific gravity and diameter at 0, 10, 24, 50, 100, and 288 hours of desorption in masticated manzanita. Results are from linear regression.

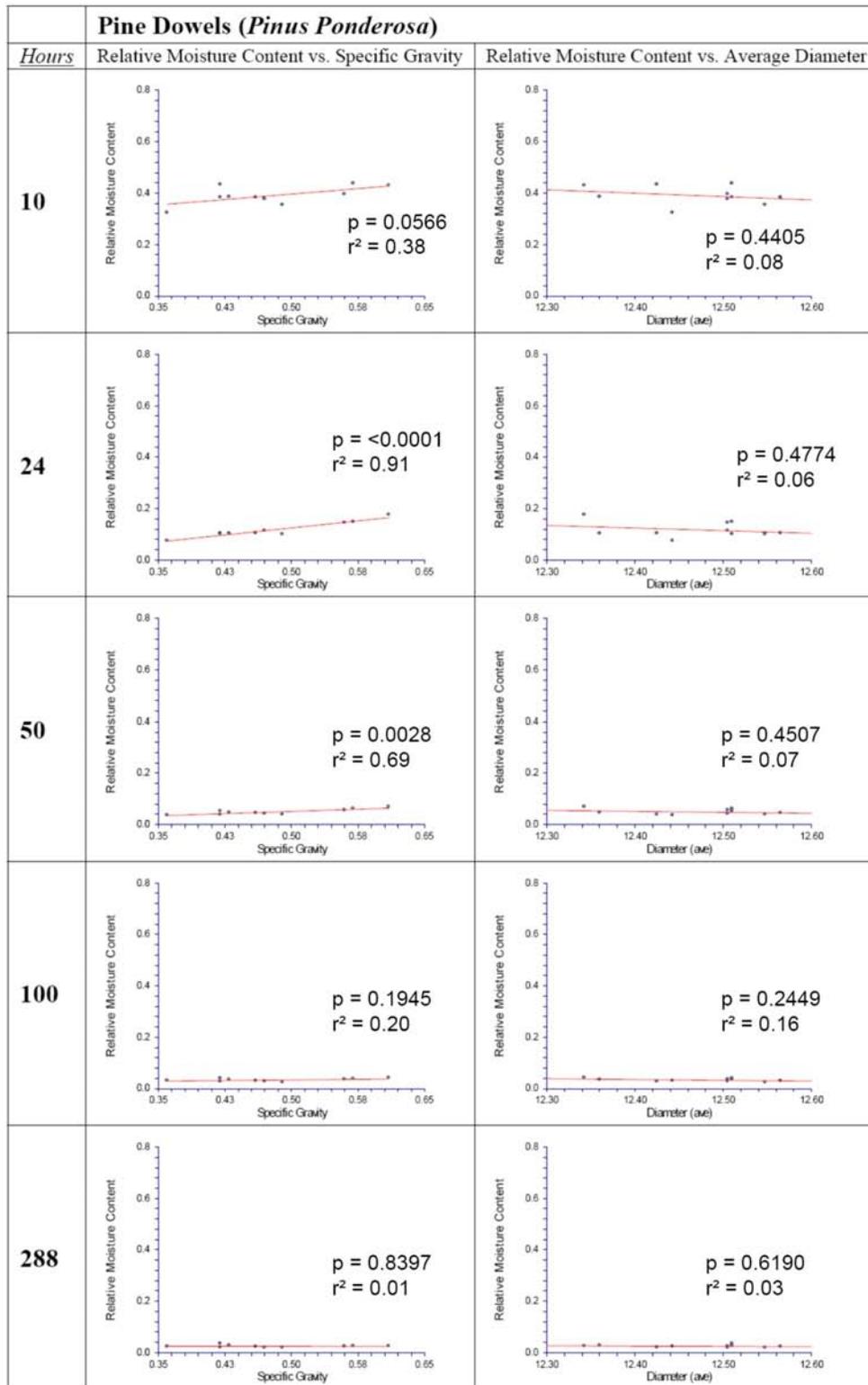


Figure 5—The relationship of relative moisture content with specific gravity and diameter at 0, 10, 24, 50, 100, and 288 hours of desorption in standard pine dowels. Results are from linear regression.

Desorption Experiment 2

Specific gravity differed significantly ($p < 0.001$) between pine dowels and all other fuel types (intact masticated, masticated, and maple dowels) used in the fuelbed experiments. Masticated manzanita was higher in specific gravity (0.70) than maple dowels (0.65), although the difference was not substantial. Intact manzanita did not differ from either masticated manzanita or maple dowels (table 1).

Table 1—Specific gravity of maple dowels, pine dowels, intact manzanita, and masticated manzanita used in desorption experiment 2.

Fuel type	Specific gravity	Std Error
Maple dowel ^a	0.65	0.011
Pine dowel ^c	0.47	0.011
Intact manzanita ^{ab}	0.68	0.012
Masticated manzanita ^b	0.70	0.0009

^{abc} No significant difference ($p < 0.001$) between fuel types with like notation.

Fuelbed relative moisture content differed significantly from all fuel types marked individually across time periods 10, 24, 50, 100, and 288 hours using the Tukey-Kramer multiple-comparison test $\alpha = 0.05$ (fig. 6). Relative moisture content of maple dowels was significantly different from all other fuel types. Pine dowels and intact manzanita did not differ in regards to relative moisture content. Relative moisture content of intact manzanita did not differ from masticated manzanita. It is apparent that desorption in intact manzanita, masticated manzanita, and pine dowels are fairly similar in comparison to maple dowels, which desorb more slowly at the fuelbed level.

The development of response times (τ) under the timelag concept yielded similar results as comparing relative moisture contents by fuel type. Linear portions developed for each fuel type are shown in figure 7. Results include those from experiments 1 and 2. Response times (τ) calculated from slopes (b) of linear sections, or timelag sections, are shown in table 2 by fuel type. Intact and masticated manzanita as well as pine and maple dowels all had

Table 2—Response times (τ_i) for piecewise linear portions and overall response time (T) where ~63 percent of evaporable moisture was actually lost.

Fuel type	Slope			r^2	Response time		
	J ^c	b_1	b_2		τ_1	τ_2	T
	<i>hours</i>	<i>----- $\times 10^{-2}$ -----</i>			<i>--- -hours --- -</i>		
Fuelbed	98	-1.41	-2.32	.977	71	43	70
Maple dowel ^a	61	-2.76	-1.36	.966	36	74	40
Pine dowel ^a	36	-5.00	-1.47	.950	20	68	23
Intact manzanita ^a	39	-5.38	-1.40	.943	19	71	20
Masticated manzanita ^a	36	-5.09	-1.52	.940	20	66	20
Pine dowel ^b	51	-7.94	-0.949	.976	13	105	10
Masticated manzanita ^b	51	-8.56	-0.687	.912	12	146	10

^a Fuel particles desorbing within fuelbeds (experiment 2).

^b Fuel particles desorbing individually (experiment 1).

^c J is the upper limit (hours) of the 1st piecewise linear portion of lnE vs. time (hours).

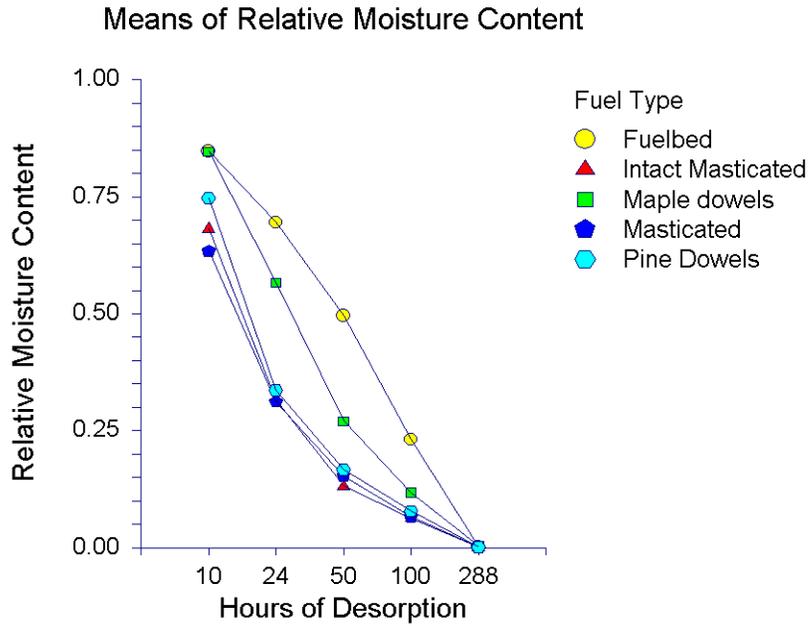


Figure 6—Relative moisture content in fuelbeds, intact manzanita (“intact masticated”), masticated manzanita, maple dowels, and pine dowels throughout desorption.

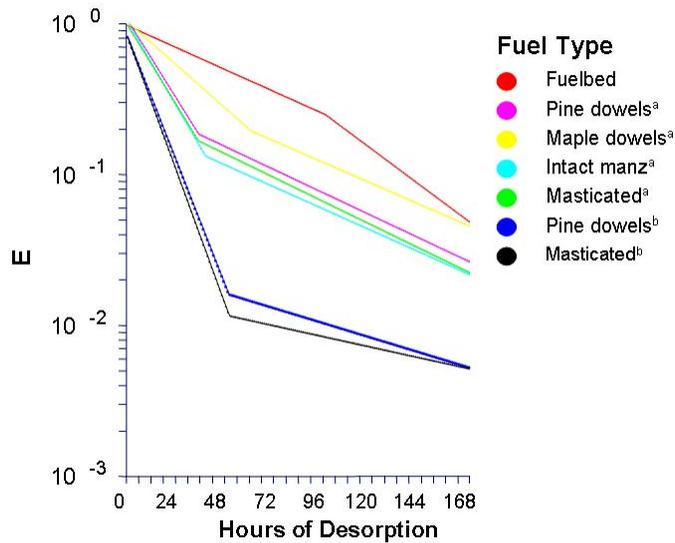


Figure 7—Fraction of evaporable moisture (E) throughout desorption developed from linear-linear regression using piecewise polynomial curve fitting. Response times (τ_i) are developed from the inverse of the slope of each linear portion.

initial timelag sections with shorter response times (τ_1) than that of later stages (τ_2). The transition between τ_1 and τ_2 occurred late in desorption where 80 percent or more of the evaporable moisture has been lost. The increase in response time in the later stage of desorption indicates a decrease in the rate of desorption during later stages of drying. Fuelbeds on the other hand desorbed moisture at a higher rate during the later stage of drying as indicated by the increase in response time in the second timelag section (τ_2).

Pine dowels and masticated manzanita dried faster at the individual particle level (experiment 1) as compared to any of fuels at the fuelbed level (experiment 2) during the first timelag section (τ_1). Although initial response time of masticated manzanita was shorter than pine dowels at the individual level, 12 hours versus 13 hours, respectively, they appear to have desorbed moisture fairly similarly. The transition from timelag section τ_1 to τ_2 both occur at 51 hours. Response time τ_2 of pine dowels was shorter than that of masticated manzanita at the individual level.

All fuels initially (τ_1) desorbed moisture more quickly than do fuelbeds (fig. 7). After 4 days fuelbed desorption appeared to increase, as shown by the shift of response time from 71 to 43 hours (table 2), which differs from all other fuel types. Desorption rates decreased during later stages (τ_2) in all other fuel types. Of all fuel types, maple dowels had the longest initial response time (τ_1) of 36 hours. Pine dowels, intact manzanita, and masticated manzanita had similar initial response time of 20, 19, and 20 hours, respectively. Later stages of desorption (τ_2) are fairly similar between all four fuel types (maple dowels, pine dowels, intact manzanita, masticated manzanita) with response times of 74, 68, 71, and 66 hours respectively, although the transition (J) from timelag section τ_1 to τ_2 was later in maple dowels (table 2). Transition times (J) are similar between pine dowels, intact manzanita, and masticated manzanita occurring at 36, 39, and 36 hours, respectively.

The times at which 63 percent of evaporable moisture was actually lost (T) during desorption were similar to response times calculated for the initial timelag sections τ_1 (table 2) for all fuels in both experiments including the fuelbed.

Discussion

Analyzing moisture dynamics in masticated fuels is important in attempting to understand observed fire behavior and fire effects within masticated fuels treatments. Desorption of moisture within fuels addressed here occurs differently at the individual level as compared with those fuels drying at the fuelbed level. Also while diameter affects moisture dynamics within forest fuels, the effect of particle density is shown to affect moisture dynamics.

Comparing relative moisture content over time as well as calculating response times under the timelag concept reveals no substantial differences in the way that masticated manzanita desorbs moisture as compared with intact manzanita or ponderosa pine dowels. The similarity of desorption rates between manzanita and pine dowels and the difference between manzanita and maple dowels suggests density and species differences having a role in moisture dynamics. Because intact manzanita and masticated manzanita do not appear to differ in desorption rates, the similarity of masticated manzanita in experiment 1 with that of pine dowels may not necessarily be explained by

the idea that surface area to volume ratio and density are working against each other. Although it may be that physical and chemical properties of manzanita versus ponderosa pine at the species level may be significant in moisture dynamics, the fact that the manzanita had weathered for 2 years on site before moisture experiments had been conducted may be a factor in these results. Discrepancies in modeling fire behavior in masticated fuels do not lie in an inability of predicting fuel moisture based on surface area to volume ratios being altered by the mastication process. It should be noted though that the effect of surface area to volume (SA:V) ratio in fire danger rating systems has been in regard to the effect on the heating of fuels ahead of the flaming front during combustion as moisture is evaporated and the interior portions of fuel particles increase in temperature to the point of combustion. The differences in SA:V ratio between masticated and intact fuels may play a role in the combustion process and should not be disregarded altogether in terms of modeling discrepancies in fire behavior prediction in masticated fuels.

The role of density, as analyzed through specific gravity here, plays a role in desorption rates in these fuels. The role of density in the timelag concept was addressed by Byram (1963), but the extent of its role might not be fully understood. While timelag categories have been developed based on fuel diameter, specific gravity appears to be positively correlated with diameter and plays a similar role in moisture dynamics. Both increases in diameter and increases in fuel density result in slower desorption rates. The degree of effect between diameter and density on moisture dynamics in fuels analyzed here appears to change temporally whereby diameter and density shift in their dominance in controlling desorption. Diameter appears to have more control in early stages of desorption while density becomes more dominant during later stages. While the preliminary analysis of these data suggests an insignificant role in the mastication of fuels in regards to moisture dynamics, these results are from a single site conducted with one species. Future analysis of experiments with masticated fuels from other sites, different species, and various times since treatment should increase our understanding of the role that mastication has on influencing moisture dynamics in these fuels.

The response times and their respective linear portions described here are from desorption of fuels from initial fuel moisture contents much higher than fiber saturation, through soaking, to that of equilibrium moisture contents in an environment of approximately 25 °C and 30 percent RH. Previous studies referenced here have conducted moisture dynamics experiments under standard conditions of 26.7 °C while shifting relative humidity from 90 to 20 percent and then from 20 to 90 percent for desorption and adsorption, respectively, allowing fuels to come to equilibrium at each stage. Differences in timelag sections developed here and that of previous studies may be a result of the scale at which desorption is being analyzed. The use of developing response times for certain portions of desorption curves by partitioning may be useful in attempting to describe desorption or adsorption rates in general, but these curves appear to be curvilinear following logarithmic transformation and more precise modeling may be useful in further understanding how various factors affect moisture dynamics in forest fuels. Further research regarding other particle and fuelbed characteristics of masticated fuels is needed to explore the questions regarding the inability of current fire modeling systems to accurately predict fire behavior and fire effects in these types of treatments.

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