FINAL REPORT

Surface fuel characteristics, temporal dynamics, and fire behavior of masticated mixed-conifer fuelbeds of the U.S. southeast and Rocky Mountains

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Abstract

Mastication is a wildland fuel treatment technique that is rapidly becoming popular with fire managers for fire hazard reduction projects, especially in areas where reducing fuels with prescribed fire is particularly challenging. Mastication is the process of mechanically modifying the live and dead surface and canopy biomass by chopping and shredding vegetation to reduce canopy bulk density, raise canopy base height, lower surface fuelbed depth, and increase surface fuelbed bulk density, thereby reducing fire hazard. However, little is known about the properties of masticated fuelbeds as they age. In 2013, we began a comprehensive JFSP-funded study called MASTIDON (MASTIcated fuelbed Decomposition Operational Network) to measure the diverse characteristics of masticated fuelbeds at 15 treatment sites of different ages across the western U.S. Rocky Mountains. Our primary objective was to evaluate effects of aging of masticated fuelbeds on fire behavior, fuel moisture dynamics, soil heating, and smoldering combustion. The study consisted of five separate efforts (phases) that were integrated to produce a complex set of diverse deliverables. The Fuels Phase involved measuring a complex suite of fuelbed and particle physical and chemical characteristics to describe changes in masticated fuelbeds as they decomposed over time. In the Fire Phase, we created masticated fuelbeds and burned them in the burn chamber and measured a suite of fire behavior related variables that we then related to fuelbed age since treatment. In the Smoldering Phase, we created small fuelbeds that were ignited and the amount of heat pulsed through the soil via smoldering was recorded. And in the Drying Phase, we saturated three replicates of fuelbeds collected from the 15 sites with water and then measured their wet weight as they dried to develop drying curves for masticated fuelbeds and we then related the drying curve statistics to fuelbed age. And in the last Fuel Modeling phase, we evaluated the fire behavior and smoldering combustion results to determine if new fire behavior fuel models are needed. Each phase is summarized in this report and a synopsis of methods, results, and discussion is presented. We found little change in the physical and chemical characteristics of masticated fuel over the 10 years represented in this study, and this contributed to the fact that we found little change in fire behavior, drying rates, and smoldering combustion with masticated fuelbed age.

Keywords

Fuel particle; decomposition; mastication; ponderosa pine; chemical fuel properties; physical fuel properties; burn chamber; laboratory burns; moisture drying curve; soil heating; smoldering combustion.

Objectives

The original objective of the study was to determine how ignition, smoldering, and flaming are affected by the age of masticated fuels using a combined field and lab approach. The sub-objectives to achieve the primary objective were:

1. Determine effect of fuel depth and time since treatment on the moisture profile

in masticated fuel beds.
2. Describe fuelbed characteristics of aged fuels that are relevant to decomposition and smoldering potential including (a) fuel bed structural properties (thickness, moisture with depth, mineral content), (b) physical characteristics (particle size, bulk density, % rot), and (c) chemical composition (C:N ratio, cellulose content, lignin content).
3. Determine how age and characteristics of the masticated material affect the probability of ignition, smoldering, and mass loss.
4. Design custom fuel models for masticated fuels in mixed conifer forests that predict fire behavior.
5. Validate fire behavior predicted by the custom fuel model (developed in objective 4) on large fuel beds under controlled wind and humidity.

These objectives directly relate to several FON statements under task 5 "Masticated fuelbeds effects on combustion and fire behavior". The task statements that apply to our study include the following:

1. "Greater understanding of fuelbed characteristics and potential wild- and prescribed fire behavior in masticated fuels is necessary to analyze effectiveness of treatments and to anticipate changes in fire behavior and fire effects". We have fulfilled this goal by completing the most comprehensive analysis of masticated fuel particles ever accomplished.
2. "The Joint Fire Science Program (JFSP) is soliciting proposals that assess the effects of mastication fuels treatments on combustion and fire behavior". We have accomplished this by burning masticated fuelbeds in the burn chamber and measuring fire behavior and fuel conditions AND burning them in static fuelbeds to measure smoldering combustion heat pulse into soils.
3. "JFSP is particularly interested in proposals that collect new field data of masticated fuelbeds and fire behavior. Proposals that include modeled fire behavior must include independent field data sets to evaluate model predictions." This was accomplished by measuring the complete suite of fuel and fire characteristics need for fire behavior prediction.
4. We have specifically answered by following questions asked by the task through the objectives above:
    a. What are the effects of mastication treatments on fuelbeds?
    b. What are the effects of masticated fuel particle size and fuelbed depth on fuelbed moisture?
    c. How do changes in masticated fuel particle size, fuelbed depth, and fuelbed moisture influence combustion processes, fire intensity, and fire spread?
    d. How long does it take for masticated fuel beds to decompose, and how does this affect fire behavior? How are these results affected by depth of fuel bed, species, particle size, and geographic area?
5. "Effective fire behavior fuel models for masticated fuels are desired products. Resulting descriptions of masticated fuelbeds should provide enough detail to develop custom fuel models for use in fuel characteristics and fire behavior modeling systems". The final results of our study was to evaluate masticated

burns and determine which fuel model would apply.

6. "Research should be proposed in fuel types where mastication fuels treatments are common. Proposals should consider key variables that influence responses to the above questions, such as treatment type, intensity, and frequency; fuel type; geography; machine characteristics; or specific site conditions." Our research was done in the common and important Ponderosa pine cover type and these sites were treated using four common mastication treatments.

We completed all of our stated objectives except for the last – Field testing of the fire behavior fuel models – because none of our study sites were burned within the timeline of this study.

Background

Wildland fuel "mastication" has been used for some fire hazard reduction projects since the 1950s (Lambert and McCleese 1977; Pokela 1972; Ritter 1950), but only recently has it become the preferred method for fuel treatments in the United States. (Harrod et al. 2009; Stephens et al. 2012). Fuel mastication has been defined in several ways (Harrod et al. 2009; Rummer 2006). In this paper, we define mastication as the process of mechanically modifying live and dead surface and canopy biomass to reduce fire hazard by lowering fuelbed depth, increasing surface layer bulk density, and raising canopy base height (Kreye et al. 2014a). Today there are many methods and techniques for masticating fuels, including chipping, grinding, flailing, and cutting (Harrod et al. 2009; Jain et al. 2012; McKenzie and Makel 1991). This variety of methods and the low risk of harm to humans, make mastication a popular choice for a fuels treatment technique across many land management agencies and locations (Halbrook et al. 2006). In many areas of the wildland-urban interface, mastication may be the only alternative for reducing canopy fuels because prescribed burning treatments may pose greater threats to adjacent properties and commercial thinning may be a difficult and cost-prohibitive approach (Berry and Hesseln 2004).

Although research on this newly popular treatment is limited, there has been work on its implementation and effects. Halbrook et al. (2006) and Jain et al. (2012) reviewed available techniques, their application, and associated costs. The effects of mastication on fuel moisture dynamics were studied by Kreye and Varner (2007) and Kreye et al. (2012). Effects on soil properties were assessed by Busse et al. (2006). The effects of fire behavior (Bradley et al. 2006; Glitzenstein et al. 2006; Smith and Brewer 2011), soil heating (Busse et al. 2005), smoke production (Achtemeier et al. 2006; Naeher et al. 2006), and vegetation responses (Battaglia et al. 2006) were evaluated when masticated fuelbeds burned in the laboratory. Impacts of mastication on soil processes (Busse et al. 2006; Windell et al. 1986), vegetation development (Battaglia et al. 2006), and wildlife habitats (Moreno-Fernández et al. 2016) have been used to guide design of concurrent treatments for fuels management, ecosystem restoration, rehabilitation, or wildlife management. A major finding from many of these studies is that understanding effects of mastication on fuelbed characteristics and resultant fire behavior is critical to fire management because most adverse effects of mastication are from unplanned burning in wildfires (Smith and Brewer 2011). Given the diversity of mastication methods (Jain et al. 2012; Rummer 2006) and the high variability of fuel and microsite conditions within treated stands (Battaglia et al. 2010; Kane et al. 2006; Keane et al. 2012a), the impacts of mastication may be quite complex and highly variable.

One major aspect of mastication that has not been well studied is the changes that occur as masticated fuelbeds age (Brennan and Keeley 2015; Kreye et al. 2014a, 2016). Newly masticated fuelbeds (less than 3 years) consist of amorphous chopped or crushed woody pieces that have sharp edges with higher surface area (Knapp et al. 2008). Initially, moisture contents of woody particles may be high, but subsequent drying increases the likelihood that these fuels will ignite easily and carry flames across a forest stand (Knapp et al. 2011). However, as masticated fuel particles age, the litter and fractured wood particles decompose, resulting in major changes in both particle and fuelbed characteristics, such as reductions in particle density, fuel loadings, and fuelbed depth (Keane 2015). Relatively little is known about how structural, physical, and chemical characteristics of masticated fuel particles change over time and how these changes affect fuelbed moisture dynamics and fire behavior. Kreye et al. (2016) explored the effects of aging on fire behavior and Battaglia et al. (2015) looked at changes in soil nitrogen and loading, but neither investigated changes in particle properties. Of special concern to fire managers is whether the properties of the masticated fuel change so much that new fire behavior fuel models are needed to simulate fire behavior (Knapp et al. 2008; Kreye et al. 2014a). Even more important is how temporal changes in masticated fuelbed properties will influence future fire effects if the masticated stand burns, such as smoke production, soil heating, and ecological responses to these novel fuel conditions (Busse et al. 2006).

In 2013, we initiated a comprehensive study called MASTIDON (MASTIcated fuelbed Decomposition Operational Network) to evaluate fire behavior, fuel moisture dynamics, soil heating, and smoldering combustion of different aged masticated fuelbeds. Critical to MASTIDON objectives was the measurement of the diverse physical and chemical characteristics of masticated particles, fuel layers, and fuelbeds to provide context for understanding changes in masticated fuelbed fire behavior and other important management considerations (Battaglia et al. 2006, 2015). Masticated fuelbed and particle properties measured in MASTIDON were then correlated with variables that represent fire behavior, moisture, and smoldering combustion dynamics (Sikkink et al. 2018[in prep]), and more importantly, the properties were used to evaluate fire behavior fuel models for application in masticated fuelbeds during operational fire management (Heinsch et al. 2018[in press]). Each of the five phases or efforts in the MASTIDON project is detailed in a separate publication. The MASTIDON phases and their citations are as follows:

1. Phase 1- **Fuel**. Describe masticated fuel particle and fuelbed characteristics and correlate with age (Keane et al. 2018[in press]).
2. Phase 2 - **Fire**. Burn masticated fuelbeds in the burn chamber and relate fire behavior to fuel characteristics, especially time since mastication (Sikkink et al. 2018[in prep])

3. Phase 3 - **Smoldering**. Burn masticated fuelbeds in the static burn bed under smoldering combustion and measure heat pulse in soils (Reardon et al. 2018[in prep])
4. Phase 4 - **Drying**. Measure moisture loss in saturated masticated fuelbeds (Smith et al. 2018[in prep])
5. Phase 5 – **Fuel Modeling**. Examine fire behavior and fuel characteristics to evaluate current fuel models and determine if new custom models are needed (Heinsch et al. 2018[in press]).

The following sections are summaries taken from the five of these efforts. Additional details are presented in the submitted publication.

Materials and Methods

Fuel Phase: Chemical and physical fuel characteristics

All field and lab methods and materials used in this study are presented in the Keane et al. (2018[in press]) RMRS General Technical Report. They are summarized next.

Field Sampling

We used a spatial chronosequence approach in this study to represent different fuel ages where we sampled 15 study sites in two types of mixed coniferous forests of the Rocky Mountains that represented seven "treatment" ages (years after treatment). Selection of sample sites was restricted to certain treatment areas because we needed a variety of: (1) treatment ages; (2) mastication methods; (3) mature, mixed-conifer stand types; and (4) geographic areas within the Rocky Mountains. Most of our sites (11) were composed of pure ponderosa pine (*Pinus ponderosa*) or mixed ponderosa pine and Douglas-fir (*Pseudotsuga menziesii*) stands; all were on relatively flat ground. Sites were spread from northern Idaho to New Mexico in the U.S. Rocky Mountains and to South Dakota in the Great Plains. Before treatment, all stands were dense, pole-size or mature stands with high fire hazard. We also had four treated areas in northern Idaho that represented more mesic sites with higher rainfall and cooler conditions.

All areas were treated using four general types of mastication equipment. A vertical shaft cutting head with fixed teeth was used on six sites, a horizontal shaft cutting head with fixed teeth was used on another six sites, two sites were treated with a horizontal shaft with swinging knives, and one site was chipped. All sites had a history of frequent fires before European settlement; but since the early 1900s, fires had been successfully suppressed, thereby creating dense canopies and heavy surface fuel loadings. Pretreatment stand summaries were not available for many of these sites.

Field sampling was conducted within a 30-m × 50-m macroplot located in an area within each study site that broadly represented the general conditions of the mastication treatment within the treatment unit. The 30-m sides of the rectangular macroplot were oriented up the slope and the 50-m sides were established perpendicular to the slope. We recorded the latitude and longitude at each corner of the macroplot, and at several points on a grid within the macroplot using a global positioning system. Within the macroplot, a duel subsampling design was employed that included both microplot and grid sampling. Most variables used to describe the masticated fuelbed were collected or sampled within 20 microplots that were established along two 30-m lengths within the macroplot using guidelines recommended by Hood and Wu (2006). We measured several fuelbed properties in situ within each of the 20 microplots. We then collected all of the material within microplot boundaries to measure additional physical and chemical characteristics of the fuel particles, layer, and fuelbed in the lab, and to use in other phases of the MASTIDON project, including the burning, smoldering, and drying experiments. We also sampled depths of five masticated fuelbed layers at 66 grid points within the macroplot to determine the spatial variation in fuelbed depth across the entire macroplot. It was impossible to establish enough microplots to accurately describe spatial properties, so we augmented the microplot data with this grid sampling. The grid and microplot depth measurements were used to compute spatial statistics that describe the spatial distribution of loading in the masticated fuelbed layers across the macroplot (Keane et al. 2012b).

The grid-point sampling consisted of taking depth measurements using a clear plastic ruler along six 30-m transect lines. These lines were established parallel to each other at 0, 10, 20, 30, 40, and 50 m from the bottom 50-m-long boundary of the macroplot. Along each line, starting at zero, masticated fuelbed depths were measured every 3 m to the nearest 0.5 cm for the five layers

Once grid sampling was completed, we established 20 microplots on the 10- and 40-m transects according to the Hood and Wu (2006) methods for sampling masticated materials. Depths of the five masticated fuelbed layers were measured at the corners of the microplot and at the corners of the quadrat using the same techniques as those described for the grid sampling. We did not collect live biomass from shrubs, herbs, or logs because they were rare and beyond the scope of this study. Logs were present within the microplots, but they were not measured in the MASTIDON project because of their rarity.

Laboratory tasks

Lab tasks consisted of the following five broad types of activities: (1) sorting field particles, (2) measuring and weighing a subsample of individual particles, (3) obtaining particle densities from subsamples, (4) analyzing fuels to estimate heat content and lignin and cellulose + hemicellulose fractions from subsamples, and (5) conducting chemical analysis on particles from subsamples for carbon and nitrogen concentrations. We randomly selected 10 of the 20 microplot collections to process for lab measurements. Material from the other 10 microplots was used in other efforts in the MASTIDON project. A total of 151 microplots were processed.

The first step in the processing of a masticated sample for physical description was to sort collected material into the major components of the masticated fuelbed. Fresh litter was processed just as it was collected in the field without sorting or sizing. Masticated wood and bark were sorted into 15 shape categories according to the criteria in table 5, and into three size categories (1-, 10-, 100-hr fuels). The duff collected in the field was cleaned of all fresh litter, bark, and wood particles that belonged in the other categories. The only remaining materials in the duff bag were pieces of debris less than 6 mm (0.25 inch).

After sorting the particles collected from each quadrat sample, we oven-dried the particles at 90 ^{o}C for 2 days and then weighed them to compute total load in each shape, size, and layer class. We then randomly selected a subset of particles from each shape and size class to measure their individual dimensions and obtain their particle dry weight (PW). We tried to select at least 5 percent of the total number of particles for the subsample to conduct the finer scale measurements and weights on individual particles. However, in many cases, there were fewer than 10 particles available, so we could select only 1 or 2 particles for the subsample. In some cases, there were more than 200 particles, such as 1-hr parallelograms (table 5), so we selected a maximum of 10 particles for the subsample. For the fresh litter, bark pieces, wood chips, and duff, a standard 20 percent of the field bag by total bag weight (not individual material pieces) was measured to create the subsample for weight and moisture content measurements. Length (mm), width (mm), and height (mm) were measured on each woody particle to the nearest 0.1 mm using a caliper connected to a computer to capture measurements. Other dimensional measurements were taken for each particle depending on the shape because we needed to compute volume and surface area for each particle (table 5). A second subsample included a random collection of particles of four shape types—cylinder (circular cross-section), pyramid (triangular cross-section), parallelepiped (multi-sided polygon cross-section), and wood chips—and the three size-class categories on which to conduct chemical analyses. These shapes were selected because most particles were classified into these four shapes. A third subsample was taken from the duff component only. Small samples of duff were placed in a crucible for drying. This subsample was used to determine mineral content at the microplot.

The particle densities (PDs) were estimated using a two-fluid displacement process that has historically been used to determine density in soils or duff (Williamson and Wiemann 2010). The method consisted of slowly submerging particles in a large cylindrical tube containing a combination of two fluids. The upper fluid was 100 percent kerosene; the lower fluid was a solution of 50 percent glycerin and 50 percent water. Both fluids were approximately 20 cm deep to allow enough room for submersion of large particles; the cylinder sat on a lift so that it can be raised and lowered as needed during the submersion process. The particle was attached to plastic line that had a large lead weight at the end to keep it submerged. The line with the lead weight and the particle was attached to a scale. The lead weight and line were tared by submerging them in each fluid without a particle attached and recording a weight in each fluid from the scale. Densities for each fluid were taken from the literature for inputs in the formulas that follow.

In the displacement method, the balance was first tared to zero with the particle, line, and lead weight all connected but outside of the fluids. Then the particle was slowly lowered into the kerosene until it was about 1 cm above the kerosene-glycerin boundary, and it was left at that depth for 3 minutes (fig. 7). After 3 minutes, the weight on the balance was recorded. The particle was then lowered into the glycerin-water layer to within 1.25 cm of the boundary between the two fluids and left to equilibrate and displace glycerin. After 3 minutes, the weight of the particle in the glycerin-water layer was recorded. The PD was computed using the following equation (Sarli et al. 2001):

$$\mathrm{PD} = \mathrm{PW}\frac{(P_k - P_{mix})}{(W_k - W_{mix})}$$

where PD is the particle density (g cm^{-3}), PW is the particle dry weight (g), P_k and P_{mix} are the densities of the kerosene and the glycerin-water mixture, respectively (g cm^{-3}); and W_k and W_{mix} are the weights (g) of the particle in the kerosene and glycerin-water mixture layers, respectively.

We calculated surface area (SA) by solving for particle volume (PV) from the PD measurement discussed in section 2.3.2.1 and then calculating a new length from generalized volume equations for each shape (table 4). The new length was put in generalized surface area equations.
First, PV was calculated as follows:

$$\mathrm{PV} = \frac{\mathrm{PW}}{\mathrm{PD}}$$

where PV is the particle volume (cm^3), PW is the particle dry weight (g), and PD is the particle density (g cm^{-3}) as obtained in the process described in section 2.3.2.1. Using PV from the particle density, we solved for a new length using the standardized shape-volume equations taken from the literature (Math.com, n.d.); we then applied the new length to standard formulas used to compute surface area for the individual particle shapes.

We measured the ratios of carbon to nitrogen and cellulose to lignin of the masticated fuels to represent the degree of decomposition. We did this by measuring carbon, nitrogen, lignin, and cellulose + hemicellulose (both cellulose and hemicellulose) fractions in each masticated wood particle. We measured carbon and nitrogen fractions with a machine that uses a combination of flow-through carrier gas and individual, highly selective infrared and thermal conductivity detectors, and we estimated lignin and cellulose + hemicellulose fractions from heat content. Carbon and nitrogen contents (percent) were estimated using a TruSpec® carbon nitrogen analyzer (LECO Corp., St. Joseph, MI). The particles used for this analysis came from the second set of subsamples described in section 2.3.2. Particles from four shapes and three size classes were randomly selected from each microplot for each subsample, oven dried, prepared using a Wiley® mill (Thomas Scientific, Swedesboro, NJ), and then analyzed for carbon and nitrogen percentages in triplicate. This resulted in 892 chemical samples from all 151 microplots.

Lignin (percent) and cellulose + hemicellulose (percent) fractions were estimated using heat contents measured with an adiabatic calorimeter and the average heat content of cellulose + hemicellulose (18.2 MJ kg^{-1}) and lignin (24 MJ kg^{-1}). The samples were from

the second set of subsamples (see sections 2.3.2 and 2.3.3.1) that were oven dried and prepared for analysis using a Wiley mill.
Estimates of lignin fractions (percent) were calculated using the measured heat content (HC) of the sample and the HCs of lignin and cellulose + hemicellulose. This calculation (using the following equation) assumes fuel HC reflects a mixture of the dominant materials present in wood: lignin and cellulose + hemicellulose.

$$\mathrm{HC} = \mathrm{HC_c}(100 - \mathrm{LIG}) + \mathrm{HC_l}(\mathrm{LIG})$$

where HC is the heat content of the sample (MJ kg^{-1}), HC_c is the heat content of cellulose + hemicellulose (18.2 MJ kg^{-1}), LIG is the lignin fraction (percent), and HC_l is the heat content of lignin (24 MJ kg^{-1}). The cellulose percentage was estimated as 100 — LIG.

Mineral content (MC) was measured only for the duff samples. The duff bag was first shaken and mixed well to combine fine duff particles and mineral soil. Three small crucibles were then half filled with materials from the shaken duff bag. The crucibles were weighed and then placed in a drying oven for at least 72 hr at 90 °C to drive off any water. They were weighed again after drying and then placed in a muffle furnace at 550 °C for 24 hr. The crucibles were weighed for the last time and the mineral content was computed as a percentage based on the ratio of the remaining weight to dry weight minus the weight of the crucible.

Fire Phase: Burning measurements

The burning measurements are presented in detail in the Heinsch et al. (2018[in press]) and Sikkink et al. (2018[in prep]) reports.

Each fuel bed was created on a burn platform consisting of an aluminum frame with wire mesh and removable heat-resistant 0.5 inch (1.27 cm) Thermal Ceramics Kaowool M Board. Experimental fuel beds were created using the relative proportions of 1-hr, 10-hr, and 100-hr woody fuels; wood chips (wood < 3mm thick); wood ribbons; litter; 1-hr and 10-hr bark; 100-hr bark; and bark ribbons from each masticated site (Keane et al. 2018in press). Because duff load does not contribute substantially to fire behavior at the flaming front, no duff from the sample locations was used in the experimental burn beds. The masticated material from the 10 sample plots was combined, and three fuel beds were created as representations of each study site. The amount of material selected in each fuel category was typically based on the mean of each fuel category from the field site. Occasionally, this mean seemed unreasonably high because of the variability in fuel deposition resulting from the mastication process itself, which resulted in uneven distribution of fuel across the site. In these rare cases, either the 50th or 90th percentile fuel load was used to more accurately represent the fuel load across the entire treatment site.

Additionally, the fuel moisture content decreased during long-term storage at the lab. When weighing out fuels to create the burn beds, we adjusted fuel loading by size class accordingly. Fuel beds were conditioned in an environmental chamber at 95 ºF (35 ºC) and 3% humidity for at least 36 hours prior to burning to reduce moisture content as much as possible in all fuel categories. At the time of ignition, samples of 1-hr, 10-hr, and 100-hr fuels were collected and placed in a drying oven set to 212 ºF (100 ºC) for 72 hours. These fuel moisture measurements were used to determine the moisture content of each fuel category, as well as the oven-dry weight for the fuel load needed in fire behavior modeling.

Experiments were conducted at the U.S. Forest Service's combustion facility at the Missoula Fire Sciences Laboratory. The combustion facility is a large environmentally controlled chamber. Additional information on the combustion facility may be found in the paper by Christian et al. (2004). During the experiments, air temperature in the burn chamber was approximately 69.8 □F (21 □C). Relative humidity was not controlled and approximated that of the outside ambient air. The burn chamber does not include the ability to adjust wind speed and the burns had the potential to be too intense to burn in the wind tunnel. Therefore, wind speed was not explicitly factored into the experiments.

The fuel bed was inclined at either 11.75 (low) or 21.25 (moderate) percent slope. Graduated range poles were placed at 0.5, 1.0, and 2.0 ft (0.15, 0.30, 0.61 m) along the fuel bed. Each burn was filmed using a GoPro Hero 3+ Silver Edition HD video camera. Cloth screens were set up on each side of the burn platform to block air flow during the experimental burn. The screens also aided in blocking any light from interfering with the video. Two halogen work lights on either side of the video camera tripod were focused on the material in an effort to preheat the air above the fuel and facilitate burning to simulate solar heating. A third light was placed on the opposite side of the fuel bed over the excelsior layer. This third light was turned off at the time of ignition since it interfered with the video recording. All of the fires were ignited from a line of excelsior and pine needles (5.9 inches; 15 cm wide) at the beginning of the fuel bed. The material was ignited with a single pass at the bottom edge of the excelsior mix using a handheld butane torch. Rate of spread was calculated as the amount of time it took the fire to travel the 1 ft distance between the 2nd and 3rd graduated poles in the measurement zone. Flame height was recorded using the height measures on the graduated poles. Both minimum and maximum flame heights were recorded for each burn. Consistency of the flaming front was first measured visually and later verified using the video from each burn.

Smoldering Phase: Soil heating experiments

The smoldering phase methods can be found in the Reardon et al. (2018[in prep]) manuscript.

Common western wild fire and fall prescribed fire conditions were replicated during laboratory burning using air dried fuels (RH 20 to 30 %) and soil with a moisture content of less than 10%. The average fuel loading determined for each site and was burned on the surface of a surrogate soil monolith. Laboratory burning was done using litter, 1 hour, 10 hour and 100 hours fuels and the shape classes found on each site.

The effects of soil type differences were eliminated by using sifted quartz sand in place of native soil. The soil was contained within a ceramic box (LxWxH) constructed of 2.45 cm thick high purity refractory board which limited heat loss from the soil. Burns were conducted in a chemical fume hood with a wind speed of 1 mph at the fuel surface. A 500 watt quart lamp 45 cm above the fuel surface was used to stabilize ambient temperature conditions in the hood during burning.

The soils/burns were instrumented with K type thermocouples made from 28 gauge wire. Flaming combustion temperatures were captured using two thermocouples placed within the fuel. Additional temperatures were measured at 0, 2, 4, and 8 cm soil depths in the center of the burn box. The temperature data was recorded at 3 seconds intervals during the burning and cool down of each burn using a standard laboratory data acquisition system.

Three laboratory burn treatments were designed to compare soil heating that results from burning with a consistent masticated fuel layer and little or no duff with soil heating that results from burning with a consistent masticated fuel and duff layer. In the first instance, burning fuel loads on the mineral soil surface simulated soil heating resulting from the combustion of only surface fuels. In the second instance, burning fuel loads on the dry duff surface on top of mineral soil simulated soil heating resulting from the consumption of the surface fuels and duff. The third instance, burning dry fuels on the wet duff, simulated the transfer of heat from burning surface fuel through the wet duff into the mineral soil.

The last burning treatment was also used to evaluate the existing duff consumption models under masticated fuel conditions and the ability of the wet duff to insulate the soil from the burning of masticate surface fuels.. Based on the work by Brown et al (1985) and Frandsen (1987) the moisture content of these duff samples were conditioned to moistures estimated to have low consumption rates and intermediate probabilities of sustained smoldering respectively. Frandsen (1987) reported that smoldering combustion in forest duff was constrained by moisture and duff inorganic content. The forest duff moisture content that would support smoldering combustion at a 50% probability level is expressed as a linear relationship between moisture content and inorganic content from 0 to 100%. Brown et al (1985) developed a number of numerical models for the prediction of duff consumption for use under a range of conditions in slash and non slash fuels from several cover types. These models integrate one or two independent variables; moisture content and preborn duff thickness. The model applied in this study is used for predicting percent duff reduction (DR %) from the average duff moisture content and is commonly used in the in the Interior West and Pacific West. In this instance, duff reduction (%) is expressed as a liner function of moisture content.

Duf Reduction (%)= 83.7 - 0.426*duff moisture (%)

Moisture contents of the wet duff samples used in this portion of the analysis were between 61 and 178%. This moisture content range covers the transition between lower moisture where duff consumption is influenced by the consumption of surface fuel and higher moisture content where surface fuels have little influence on duff consumption (Sandberg 1980), Artley et al. 1978, Norum 1977, and Shearer 1975).

Samples used in treatment 3 (wet duff) portion of the laboratory burning were conditioned to target moisture contents using a microwave oven. Duff samples were initially saturated and then allowed to drain. Samples were then dried in a microwave at 50% power for 3 minute intervals. The number of drying intervals was determined using the initial dry sample weight and the moisture loss at the end of each drying interval to estimate moisture content. The number of drying intervals need to bring the samples within the desired moisture treatment range from 3 to 6.

Actual pre-burn moisture and inorganic contents of each duff sample were determined from three 5 to 10 gram subsamples from each duff sample. The subsamples were oven dried at 90 c for 48 hours and then placed in a muffle furnace at 450°C for 24 hours to determine moisture and inorganic contents respectively. Evaluation of the two existing duff consumption models was conducted using estimated fuel moisture limits and percent duff reduction calculated using above equations. These estimates were compared with the observed results of laboratory burning. For each burn a simple metric of heat input into the soil was calculated using the maximum temperature at the soil surface and the time for the soil surface to reach this maximum. These variables were combined to calculate a rate of temperature increase at the soil surface in degrees per minute. Comparisons were made between burning treatments.

Soil heating effects were characterized by the maximum temperature, median temperature and duration of heating within the soil profile of each burn. The potential effects were generalized into three broad temperature ranges which were derived from Hungerford and Ryan (2001). These groups were delineated by three temperature range; 60 to 120 c, 121 to 300 c and greater than 300.

Drying Phase: Drying curves for masticated fuels

The Drying Phase methods and results are found in the Smith et al. (2018[in prep]) manuscript. This report is NOT finished and the analysis in this study is still ongoing.

We used the material from 10 microplots to estimate all the physical and chemical properties of the sampled masticated fuelbeds (Keane et al. 2017); the material from the other 10 microplots was used to create various masticated fuelbeds used in the MASTIDON project (see Keane et al. 2017). That material was used to create the fuelbeds used in the drying experiment.

In this MASTIDON sub-project, we created 30 cm by 30 cm by 12 cm wire cages within which we built a masticated fuelbed that represented the conditions found at each of the 13 masticated sites (fig 2). The cage was created from hardware cloth that formed five of the six sides in the desired fuelbed volume; the sixth side was the top and it was left open. On the bottom, we placed a muslin fabric that would contain the fine materials so they wouldn't fall through the hardware cloth. We then created three replicates of masticated fuelbeds from 13 of the 15 sites based on the various measurements taken in the Keane et al. (2017). Two of the sites used in the Keane et al. (2017) analysis did not have enough collected material to make a fuel drying fuelbed.

We then conditioned the 39 replicate fuel cages (13 sites and 3 replicates) for five days inside a fuel warehouse at 25oC and approximately 30% relative humidity, and weighed each of these cages to approximate a starting dry weight. The conditioned fuel cages were then taken outside where they were placed under a set of water misters and then soaked with water over a 25 hour period (fig 2). We assumed that most fuel particles in the fuelbeds attained water saturation during this soaking period. The cages were then weighted and placed in an environmental chamber that was set at 26.6^{o}C and 30% relative humidity. We then weighted these cages every 24 hours thereafter or until the cages reached their pre-wetting weight or they reached an equilibrium (weight did not change within 1% of previous measurement).

We also completed the same experiment as above, but this time we placed the wetted cages outside in the direct sun and measured the loss in moisture but at different time intervals. The daily maximum temperatures during this time were 30oC and minimum temperatures were around 10oC with relative humidities ranging from 90% to 20% (fig. 4). We measured weights of all cages every 2 hours for the first 12 hours and then every 24 hours thereafter. The measurements for chamber and sunlit drying conditions were entered into a spreadsheet.

The calculations of the physical characteristics of the masticated fuelbeds are detailed in Keane et al. (2017). The measured weights of each cage replicate were plotted over time to present the drying curves. We then fit a regression line through each replicate drying curve using a negative exponential transformation to create mathematical models that approximate the drying curve. From the drying curve equations, we estimated several variables that we thought represented the unique aspects of the drying curve (table 2). We selected the beginning weight of the fuelbed minus the dry weight of the fuelbed (i.e., water weight) as an indication of the amount of voids available for water saturation. We felt that the coefficient of the exponent provided an index of how fast the material dried, and the time (hr) it took to reach equilibrium was a good index of the density of the fuelbed and its particles.

We then correlated the set of variables to the fuelbed age using the standard parametric statistics of person's correlation. We also performed regression analysis on the data in an attempt to create a statistical model.

Fuel Modeling Phase: Evaluating existing fuel models

The fuel modleling analysis methods and results are presented in detail in the Heinsch et al. (2018[in press]) report.

Surface fire behavior was estimated using BehavePlus version 5.0.5. Predicted surface fire rate of spread was obtained using Rothermel's fire spread model (Albini 1976; Rothermel 1972), while flame length was estimated using Byram's (1959) equation. Moisture values were calculated from samples collected and oven-dried at the start of each burn. Surface fire behavior rate of spread and flame length from our experimental burns were compared to three standard and five custom fuel models (Anderson 1982; Glitzenstein et al. 2006; Knapp et al. 2011; Scott and Burgan 2005). The three standard fuel models were 11 (light logging slash), SB1 (low load activity fuel) and SB2 (moderate load activity or low load blowdown) (Anderson 1982; Scott and Burgan 2005). These three fuel models were the most representative of the 53 standard fuel models given the fuel loads measured for the experimental sites. Custom fuel models for masticated fuel have been developed by Knapp et al. (2011) for California chaparral and by Glitzenstein et al. (2006) for pine forests in the southern U.S. These fuel models were also compared to the experimental burns since they were designed specifically for masticated fuel.

We compared the results of the modeling effort to observed values from the experimental burns. While we recorded measured values of flame height and modeled estimates of flame length, the two are quite similar in this instance. Since the experiment did not include wind, and the slopes were relatively low, the resulting flame were nearly vertical, so that flame height could be used as a proxy of flame length in these experiments.

Results and Discussion

Results and discussion are summarized by phase below. Additional detail are provided in the appropriate MASTIDON citations. In general, our results can be summarized by the following bullet statements:

1. We found few changes in masticated fuel particles over the 10 year time span sampled in this study.
2. The high across-site variability introduced by using a chronosequence approach (space-for-time substitution) probably masked some, but not all, changes in fuel characteristics
3. Because of the lack of a decomposition signal, we found little differences over time since treatment with all burning, smoldering, and moisture treatments.
4. The data collected and summarized in this study has great use in many fuels and fire modeling efforts as they were collected over a diverse array of fuelbeds over 10 years in time.
5. Existing fuel models in the standard 13 or new 40 fire behavior fuel models are sufficient to predict fire behavior in the masticated fuels collected in this study. No new FBFMs are needed.

Fuel Phase

Our analysis found few changes in most of the measured masticated fuelbed properties over the 10 years represented in our sample. Woody fuel decomposition was expected to alter important physical characteristics, such as particle density, surface area, and bulk density, and the critical chemical properties, primarily nitrogen, lignin, and cellulose + hemicellulose fractions, of masticated fuels (Keane 2015), yet we found few significant changes. The few changes that we observed in our study, such as decreases in nitrogen and cellulose concentrations and increases in bulk density, were minor and highly variable.

There are probably several reasons that we found little change in fuel properties over a decade. First, most of the sites sampled (11 of 15) were warm, dry ponderosa pine sites with low precipitation and high temperatures where decomposition was slow. Previous studies in woody fuel decomposition indicated that these warm, dry sites had the lowest decomposition rates of most sites in the Northern Rocky Mountains (Keane 2008a,b). Second, deposition of post-treatment fuels, such as litter and woody debris from surviving trees, may have added newer fuel to aging fuelbeds, thereby influencing physical and chemical characteristics. The study sites also did not have the same silvicultural prescription for cutting trees; the resulting disparate post-treatment tree densities influenced accumulation of woody debris since mastication. Our data were not normally distributed, so we were required to use nonparametric statistics, which have little power and limited ability to detect significant relationships (Boddy and Smith 2009).

Another source contributing to high variability is the great differences among mastication techniques. We had to include four mastication methods in the study because it was logistically difficult to get enough sites of different ages by holding mastication method constant. Again, in our pairwise comparison when mastication method is the same across the pair, there were subtle differences with age. The interaction of mastication method with climate also compounds variability. Techniques that produce smaller, amorphous particles may have decomposed faster, especially on mesic sites.

However, we feel that the great differences in biophysical conditions across the different aged sites added the most variation in our substitute-space-for-time empirical approach. The dry, warm ponderosa pine sites were scattered over Idaho, Montana, South Dakota, and New Mexico, while the mesic sites were from different stands in a small area of northern Idaho. Combining these two site types also increased variance and made it difficult to get statistically significant relationships with age. When we excluded mesic sites from the analysis, our correlations increased but only marginally. However, when we held site and mastication method constant in our paired site comparison, we found that there were indeed the anticipated changes occurring over time.

Fire Phase

Both standard and custom fuel models were compared with the fuel beds that could be modeled for fire behavior in this study. Modeled fire behavior was minimal, with rates of spread less than 2 ft/min (0.6 m/min) and flame lengths less than 4 ft (1.2 m). Most estimates of flame length were less than 2.5 ft. (0.8 m). In general, all of the fuel models overestimated both observed rate of spread and minimum flame length, with SB2 generating the highest estimates. The fuel models more accurately modeled observed maximum flame length values.

Within the masticated fuels that could be modelled for fire behavior, several important aspects of burning were observed, none of which can be predicted using current fire behavior models.

1. Once ignited, fuel beds from sites with larger fuel typically burned longer.
2. The smaller fuel facilitated fire spread, while the large fuel continued burning after the flaming front had passed. Once the flames died out, many beds continued to smolder for at least an hour.
3. Rate of spread and flame height tended to increase as the bed burned, which is an indication that the fires did not reach steady state conditions.
4. Mastication method appeared to have some impact on burning. As stated earlier, none of the fuel beds from sites treated with a chipper or mower burned the complete length of the fuel bed, and we were unable to estimate the fire behavior.
5. Often, larger pieces of fuel acted as a barrier to fire spread. Flames burned around or under the larger fuel. These larger fuels tended to light after the flaming front had past, a result of residual burning and heat generation during the smoldering phase.

We did not find a relationship between time since mastication and fire behavior. All of the sites were treated no more than 10 years prior, and most of the wood was quite sound. Decomposition was not readily apparent and would likely not have been great enough to affect fire behavior. Sites with masticated fuel older than 10 years or in which decomposition was readily apparent (e.g., “punky” or soft, rotted wood) would be expected to show different fire behavior than the ones included in this study.

Mastication method appeared to have some impact on burning. As stated earlier, none of the fuel beds from sites treated with a chipper or mower burned the complete length of the fuel bed, and we were unable to estimate the fire behavior. We hypothesize that the fuel beds that exhibited smoldering fire behavior were too shallow and dense to provide the necessary air flow to ignite the fuel without the assistance of wind. These results are similar to those of Glitzenstein et al. (2006), who measured slow rates of spread and identified large patches of unburned fuel in their prescribed burn experiments in field conditions that were composed of shallow fuel beds. There did not appear to be a clear relationship between mastication type and fire behavior for the sites where a rotating head or horizontal drum head was used. Some of the fuel beds with these mastication methods were able to be used in analysis; others were not.

There are two possible reasons why fuel beds did not burn homogeneously. First, our fuel beds were relatively narrow and the edges of the fuel bed had an effect on the fuel as mentioned previously. Second, the halogen lights also affected fire behavior in unpredictable ways. In many cases, the side of the fuel bed with the halogen light burned faster than the side on which the halogen light was removed. There were also experimental burns in which the side without the halogen light burned faster. These edge effects were not consistent among sites, or even within a site, making it difficult to determine exactly what caused the fire behavior observed in these 11 burns.

Given that all of our burns occurred at low moisture levels, we were unable to distinguish between fire behavior at moist and dry sites. However, we were unable to get any of the fuel beds to burn at higher moisture contents, such as those typically found in areas like the Priest River Experimental Forest in northern Idaho (data not shown). Our sites had very little litter to carry the fire or provide the energy necessary to ignite the larger fuels. This limits the utility of our experiments in determining the importance of such factors on observed fire behavior.

Smoldering Phase

Soil Surface Heating

The maximum temperatures measured within the surface fuel and duff combustion zones for all treatments ranged from 318.6 °C to 708.9 °C, 314.3 °C to 565.2 °C and 345 °C to 561.1 °C respectively. Average heating durations of heating in the combustion zone were 220.4 and 462.9 and 613.0 minutes respectively.

Treatment 1 mean soil surface temperature and heating duration under surface fuels was 181 oC and 115 minutes. Higher treatment 2 mean temperature and duration were observed on the soil surface (0 cm) under surface fuels and dry duff, 304 oC and 27 minutes respectively. The calculated mean rate of temperature increase at the soil surface, which combined temperature and duration, was higher for treatment 1, 10.8oC/minute than treatment 2, 3.7 °C/minute.

Within treatment 1, the surface temperature and duration of heating were positively correlated with masticated fuel loading (r^2=0.80, p <.001). In contrast, there was no relationship between surface temperature and loading for treatment 2 burns. The treatment 3 samples with high duff moisture and limited consumption, (masticated fuel/wet duff) class showed no soil surface heating (n=12). In contrast, wet duff samples (n=6) that were consumed showed a surface heating range of 157.2 °C to 409.7 °C with an average duration of 187.6 minutes. The mean rate of temperature increase of the burned treatment 3 samples was 1.6 °C /minute.
Heating effects

Results show potential heating effects from laboratory burning were influenced by burn treatment and depth. Treatment 1 burns showed the potential for effects in the low (60 to 120oC) and moderate (120 to 300 °C) effect classes. The low temperature class burns had an average burn duration of 164 minutes and the average maximum temperature decreased from 77 oC at 2 cm to 62 oC at 8 cm. Moderate effect burns in treatment 1 had an average duration of 479 minutes and average maximum temperatures of 148 oC at 2 cm and showed a decrease to low temperature effects of 65 oC at 8 cm.

Temperatures in 7 of 9 treatment 2 burns showed potential effects in the moderate class. The burns had average heating duration of 622 minutes with a maximum temperature 181 °C at 2 cm which decreased to 104 oC at 6 cm. The remaining treatment 2 burns were classified as low and high temperature classes. Average maximum temperatures of the low class temperatures were 70 and 65 °C at 2 and 8 cm while temperatures of 400 and 171 °C at 2 and 104 °C at 8 cm were found for the high temperature burn.

Model Evaluation

Two duff samples from nine sites were burned in treatment 3 for duff model evaluation (n=18). Surface fuels were conditioned to low moisture contents while duff fuels were conditioned to moisture contents ranging from 58 to 201%. The average duff mineral contents of these sites ranged from 27 to 88 %. Of the 18 samples tested in this treatment, 6 samples had duff consumption rates of approximately 90 % or greater while 12 samples had consumption rates of approximately 10 % or less.

Fuel Moisture Limit 50 estimates, which are dependent on duff mineral content, were calculated using Eq 1. The estimated moisture limit of sustained smoldering averaged 20.92% and a range of 0 to 75.6 % for all treatment 3 samples. Analysis of duff moisture conducted using a post hoc classification of burned and unburned samples shows the average moisture contents of the burned and unburned duff samples was 101.7 and 144.6 % respectively. There was overlap in the burned and unburned sample moisture content ranges; 58.6 to 139.3% and 138.8 and 201.7% respectively.

Duff reduction estimates, which are dependent on duff moisture content, were calculated using Eq 2. Reduction estimates averaged 30 % with a range of 7 to 57 % for all treatment 3 samples. Estimates limited to samples with burned surface fuel and high duff consumption show an average of 39.5 % with a sample range of 23 to 57 %. Estimates calculated for the burned samples under-estimated the observed consumption by an average of 64 %. In comparison, estimates restricted to samples with burned surface fuel and no duff consumption show an average of 25.2% with a sample range of 7 to 34 %. Estimates calculated with these samples over-estimated the observed consumption by an average of 29.8 %.

Drying Phase

These data are still being analyzed and the final publication will hopefully be ready by December of 2017.

Fuel Modeling Phase

With the exception of fuel model SB2, the predicted values of rate of spread and flame length from the fuel models included in this report are reasonably close to observed values of fire behavior in this study. Observed rates of spread in the fairly dry conditions were minimal at less than 1.0 ft/min (0.3 m/min) and flame lengths less than 3.0 ft (0.9 m), which agree with other studies of fire behavior in masticated fuel (Glitzenstein et al. 2006; Knapp et al. 2011). The fuel model with the shallow fuel bed from Glitzenstein et al. (2006; figure 9, Mast_TrSh_SC) modeled zero rate of spread and flame length for our fuel beds. Those authors found similar results when developing the fuel model. They hypothesized that the fuel bed included in the fuel model was too shallow for the Rothermel (1972) fire spread model to calculate a rate of spread or flame length. We have included it in the graphs for completeness, but it has been removed from further discussion. These results, however, support our hypothesis for patchy burning in the shallow fuel beds from our laboratory experiments.

Conclusions and Management Implications

We have some simple and succinct conclusions that have great management implications. The primary implication of this study's findings is that masticated fuelbeds, especially in dry environments, may take at least 10 years for ecological processes to change fuel characteristics enough for adverse fire effects to be mitigated. The most harmful impact of mastication occurs when the fuelbed burns in a wildfire because the often prolonged and intense post-frontal combustion period results in deep soil heating and lingering surface heat intensity that tends to kill plants, especially living trees left after mastication (Bradley et al. 2006; Busse et al. 2005; Reiner et al. 2009). Fire managers often hope that masticated fuels will decompose quickly to reduce the adverse effects of prolonged combustion. But this may not be the case for some ponderosa pine stands, such as the ones in this study, as there were few changes in fuel characteristics with time since treatment for most of our sampled sites. Furthermore, when masticated fuelbeds are burned in wildfires, the subsequent fire effects, such as soil hydrophobicity and plant mortality, may possibly be much greater than if the area had never been masticated.

Our smoldering study has found that there is a great deal of heat that is pulsed into the soil and that this could cause major mortality to belowground systems. This supports the notion that the greatest ecological damage from mastication is when the fuelbed is burned during a fire. And our fuel moisture study showed that nearly all of the masticated fuelbeds dried to equilibrium in less than 7 days. This means that even though masticated fuelbeds are mostly wood, the amorphous particle shapes and sizes dry quickly and the fuelbed can be readily susceptible to smoldering combustion after only 5-7 days of drying.

And last, our fuel modeling effort found that the existing fuel models evaluated, except for SB2, were good at representing expected fire behavior. The three standard fuel models were 11 (light logging slash), SB1 (low load activity fuel) and SB2 (moderate load activity or low load blowdown) (Anderson 1982; Scott and Burgan 2005). These three fuel models were the most representative of the 53 standard fuel models given the fuel loads measured for the experimental sites. Custom fuel models for masticated fuel were developed by Knapp et al. (2011) for California chaparral and by Glitzenstein et al. (2006) for pine forests in the southern U.S.

The data summaries generated from this MASTIDON project should have great value to fuel and fire managers. First, many of our measured fuel properties are useful inputs to fire behavior and fire effects models (Andrews 1986; Reinhardt and Keane 1998) and provide the data for developing other fire behavior fuel models (Burgan and Rothermal 1984). Fire managers can use the data to initialize fire models and to parameterize fuel inputs (Knapp et al. 2008). The measured and calculated fuel properties can also be used as inputs to ecosystem models to simulate future decomposition (Keane 2008a). The data may also provide information that is useful for wildlife habitat description (Pilliod et al. 2006; Ucitel et al. 2003), erosion control (Kokaly et al. 2007; Robichaud et al. 2007), and site productivity longevity (Harvey et al. 1989). The fire behavior and fuel moisture results can be used by managers to estimate fire hazard and risk.

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Sikkink, Pamela G.; Jain, Theresa B; Heinsch, Faith Ann; Reardon, James; Keane, Robert E.; Butler, Bret. 2018[in prep]. Effect of aging on US Rocky Mountain masticated fuel particles based on changes in fire behavior and fuel particle characteristics. Forest Ecology and Management.
Smith, Helen Y.; Keane, Robert E.; Sikkink, Pamela G. 2018. Drying rates for saturated masticated fuelbeds from mixed-conifer stands of the U.S. Rocky Mountains. Research Paper RMRS-RP-xxx. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.
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Appendix A – Contact Information

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Appendix B – Science Delivery Products

Here are the deliverables that were promised in the original proposal:

Deliverable Type (see proposal instructions)	Description
Non-refereed publication	Effects of time on masticated fuels (Ecology and Environment, Nature, Science, or equivalent)
Non-refereed publication	Technical Note: Designing and validating custom fuel models for the BehavePlus fire modeling program
Non-refereed publication	Jain: General Technical Report on parameters for implementation and prescription burning of masticated fuels
Training session	Heinsch: Workshop: *Predicting fire behavior in masticated fuels using BehavePlus* at Missoula Fire Sciences Laboratory
Training session	Heinsch/Sikkink: Workshop on BehavePlus at national AFE conference highlighting custom fuel models created for masticated mixed-conifer fuels
Tech transfer	Sikkink: On-line presentation at Landscape Conservation Cooperative or equivalent seminar (focused on appropriate LCC's in Rocky Mountains and southeast US)
Refereed publication	The moisture properties of degraded masticated fuels
Refereed publication	Controls on fire behavior in aged masticated fuels
Refereed publication	Mixed-conifer masticated fuel particles: their changing physical and chemical properties with time
Web site: (MASTIDON) MASTIcation Decomposition and Operative Network	Sikkink: revamp and rename existing I-MAST web site to refocus on mixed-conifer mastication materials, publications, and issues that are pertinent to fuels treatment and prescriptions for managers

The following table presents the list of deliverables that were generated from the MASTIDON project. We have or will produce 4 data archives, 1 journal publication, 5 Forest Service publications (peer-reviewed), 2 symposium proceedings, 4 online publications, 2 workshops, 1 field trip, and 11 presentations for a total of 28 deliverables. We did NOT deliver one of the journal papers (refereed publications) above because we thought it more appropriate for a General Technical Report, but we generated all other promised deliverables and much more. We do recognize, however, that some of these deliverables are in the preparation stage and have not yet been accepted. All of the manuscripts below have been submitted as finished products and we will see them through to publication. Moreover, we are sure that there will be at least 2 more publications from this effort that we have not yet started but we are sure that we will create them after all other manuscripts are finished.

Deliverable	Type	Status
Sikkink, Pamela G. 2017. Characteristics of masticated particles in mixed-conifer forests of the western United States: Shape, particle, and fuel load characteristics. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2017-0012	Data Archive	Done
Sikkink, Pamela G. in review. Characteristics of masticated particles in mixed-conifer forests of the western United States: Chemistry, heat content, and mineral percentage results. Fort Collins, CO: Forest Service Research Data Archive.	Data Archive	In review
Sikkink, Pamela G. in review. Characteristics of masticated particles in mixed-conifer forests of the western United States: Experimental burns and smoldering tests. Fort Collins, CO: Forest Service Research Data Archive.	Data Archive	In review
Sikkink, Pamela G. in review. Characteristics of masticated particles in mixed-conifer forests of the western United States: Field data. Fort Collins, CO: Forest Service Research Data Archive.	Data Archive	In review
Sikkink, Pamela G.; Jain, Theresa B; Heinsch, Faith Ann; Reardon, James; Keane, Robert E.; Butler, Bret. 2018[in prep]. Effect of aging on US Rocky Mountain masticated fuel particles based on changes in fire behavior and fuel particle characteristics. Forest Ecology and Management.	Refereed Journal	In prep
Reardon, Jim. 2018[in prep]. Soil heating resulting from the flaming and smoldering combustion of masticated fuels in the Rocky Mountain West. International Journal of Wildland Fire submission expected May 30, 2017.	Refereed Journal	In prep
Keane, RE; Sikkink, P; Jain, T. 2017[in press]. Physical and chemical characteristics of surface fuels in masticated mixed-conifer stands of the US Rocky Mountains. Gen. Tech. Rep. RMRS-GTR-xxx. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.	RMRS GTR	In press
Heinsch, Faith Ann; Pamela G. Sikkink, Helen Y. Smith, and Molly L. Retzlaff. 2018[in press]. Characterizing fire behavior from laboratory burns of multi-aged, mixed-conifer masticated fuels in the western United States. Research Paper RMRS-RP-xxx. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 26 pages.	RMRS Research Paper	In press
Jain, Theresa, Pamela Sikkink, Robert Keefe, John Byrne. 2018[In prep]. To Masticate or not: Useful tips for treating forest, woodland and shrubland vegetation. U.S. Department of Agriculture Forest Service Forestry Sciences Laboratory, Moscow, ID. RMRS-GTR-XXX. XX p.	RMRS GTR	In prep
Smith, Helen Y.; Keane, Robert E.; Sikkink, Pamela G. 2018. Drying rates for saturated masticated fuelbeds from mixed-conifer stands of the U.S. Rocky Mountains. Research Paper RMRS-RP-xxx. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.	RMRS Research Paper	In prep
Morgan, Penny; Sikkink, Pamela; Heinsch, Faith Ann; Andreu, Anne; Ottmar, Roger; Jain, Terrie; Tomayko, Anjeleeca;; Lyon, Zach. In progress. Guide for Quantifying Masticated Fuels in Mixed Conifer Forests. U. S. Department of Agriculture, Forest Service, Pacific Northwest. ##p.	PNW GTR	In prep
Keane, Robert E. 2016. New frontiers in fuel sampling: Techniques for measuring surface fuel loadings for fire management in the US. Pages 127-134 in the Proceedings for the 5th International Fire Behavior and Fuels Conference. April 11-15, 2016, Portland, Oregon, USA. International Association of Wildland Fire, Missoula, Montana, USA	Symposium Proceedings	Done
Sikkink, P.; Keane, Robert E.; Jain, T.; Heinsch, F.A.; Reardon, J.; Butler, B. 2016. Changes in Masticated Fuelbed Properties over Time in the Western U.S.	Symposium Proceedings	Done

Pages 29-34 in the Proceedings for the 5th International Fire Behavior and Fuels Conference. April 11-15, 2016, Portland, Oregon, USA. International Association of Wildland Fire, Missoula, Montana, USA.		
Sikkink, P.G. 2016. Aging masticated fuels - How do they change over time? Northern Rockies Fire Science Network Research Brief No. 2 (published on NRFSN website 2/2/17)	Online Publication	Done
Sikkink, Pamela G. 2016. Drupel project spotlight on Firelab.org describing mastication project, personnel, and highlights. https://www.firelab.org/project/mastidon	Online Publication	Done
Sikkink, video interview on mastication project posted at Z:\Resources\multimedia\ScienceDelivery\Videos\Overview_Videos (submitted for final on line editing 12/2016).	Online Publication	Done
Sikkink, Pamela G.; Heinsch, Faith Ann. 2018. Story map on mastication project for web site. https://www.firelab.org/project/mastidon	Online Publicaton	In prep
Heinsch, Faith Ann; Sikkink, Pamela G. 2015. Fire behavior fuel modeling for masticated fuels from forests. Workshop for creating fire behavior models at the University of Idaho, Moscow, ID. November 4-6, 2015. (we presented information on the UI and RMRS mastication projects then spent a couple of days training students on custom fuel models and summarizing data from both projects to apply FCCS, Consume, and Behave to.)	Workshop	Done
Heinsch, Faith Ann. 2016. BehavePlus and Prescribed Fire Planning, October 2016. In a series of four workshops across the Southeastern U.S., we discussed the use of BehavePlus in prescribed fire planning, which included a brief discussion of modeling fire behavior masticated fuels based on results from this research.	Workshop	Done
Keane, Bob; Sikkink, Pam. 2016. Presentation on JFSP mastication project to University of Montana students on 4/22/16, morning.	Field Trip	Done
Keane, Robert; Sikkink, Pam; Jain, Terrie; 2015. "Physical and chemical characteristics of surface fuels in masticated mixed-conifer stands of the western United States." Sixth Fire Ecology Congress: advancing ecology in fire management. San Antonio, TX. November. 18, 2015.	Presentation	Done
Keane, Robert. 2016. Physical and chemical characteristics of different aged fuelbeds. Proceedings for the 5th International Fire Behavior and Fuels Conference, April 11-15, 2016. Portland, OR. Missoula, MT: International Association of Wildland Fire.	Presentation	Done
Sikkink, P.G.; Keane, R.; Jain, Theresa; Heinsch, Faith Ann; Reardon, Jim; Butler, Bret. 2016. "Changes in masticated fuelbed properties over time in the western U.S." in Proceedings for the 5th International Fire Behavior and Fuels Conference, April 11-15, 2016. Portland, OR. Missoula, MT: International Association of Wildland Fire, 6 p.	Presentation	Done
Sikkink, Pamela; Morgan, Penny. 2016. Presentation to MT/ID Airshed group 2016 Annual North Idaho Burners' Meeting. February 10th, 2016. Best Western Coeur d'Alene Inn, Coeur d'Alene, ID. Talk presented with Penny Morgan, University of Idaho. Talk entitled: Fire Behavior in Masticated Fuels.	Presentation	Done
Jain, Theresa B, Sikkink, Pamela, Keane, Robert. 2015. Mastication: Can we alter	Presentation	Done

post-treatment outcomes? Sixth Fire Ecology Congress: advancing ecology in fire management. San Antonio, TX. November. 18, 2015.		
Jain, Theresa B. 2014. Regeneration to tending opening size thresholds for early-seral species. Video teleconference. Forest Service, Region 1 reforestation workshop. Missoula, MT. February 20, 2014.	Presentation	Done
Jain, Theresa, Battaglia, Michael, Graham, Russell. 2015. Moist forest restoration: Evaluating irregular selection regeneration methods. National Silviculture Workshop. Baton Rouge, LA. November 4-6, 2015	Presentation	Done
Jain, Theresa. 2016. Abridged dialog on recent silvicultural research activities. Region 1. Reforestation workshop. February 16-18, 2016.	Presentation	Done
Jain, Theresa. 2016. Abridged dialog on recent silvicultural research activities. Region 1. Reforestation workshop. February 16-18, 2016.	Presentation	Done
Jain, Theresa, Graham, Russell T. Graham, Battaglia, Michael. 2016. Irregular selection: An uneven-aged management alternative that links science concepts to integrated restoration management. 10th International IUFRO Workshop on Uneven-aged Silviculture. Little Rock, Arkansas, May 30-June 2, 2016.	Presentation	Done
Jain, Theresa B., Graham, Russell T. Ecology and management of moist forests in the northern Rocky Mountains. Tour given to Region 1 Silviculture and Wildlife. October 3-8, 2016.	Presentation	Done
Jain, Theresa B., Graham, Russell T. Ecology and management of moist forests in the northern Rocky Mountains. Tour given to Foresters who work for Monticola Forest Ltd. BC. Canada. June 10, 2016.	Presentation	Done

Appendix C – Metadata

All data and metadata descriptions are presented in the following five data archives.

Deliverable	Type	Status
Sikkink, Pamela G. 2017. Characteristics of masticated particles in mixed-conifer forests of the western United States: Shape, particle, and fuel load characteristics. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2017-0012	Data Archive	Done
Sikkink, Pamela G. in review. Characteristics of masticated particles in mixed-conifer forests of the western United States: Chemistry, heat content, and mineral percentage results. Fort Collins, CO: Forest Service Research Data Archive.	Data Archive	In review
Sikkink, Pamela G. in review. Characteristics of masticated particles in mixed-conifer forests of the western United States: Experimental burns and smoldering tests. Fort Collins, CO: Forest Service Research Data Archive.	Data Archive	In review
Sikkink, Pamela G. in review. Characteristics of masticated particles in mixed-conifer forests of the western United States: Field data. Fort Collins, CO: Forest Service Research Data Archive.	Data Archive	In review