

Effect of particle aging on chemical characteristics, smoldering, and fire behavior in mixed-conifer masticated fuel



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ABSTRACT

Mastication is a silvicultural technique that grinds, shreds, or chops trees or shrubs into pieces and redistributes the biomass onto the forest floor to form a layer of woody debris. Unlike other fuel treatments that remove this biomass, masticated biomass often remains on site, which increases total fuel loading and causes concern over how the masticated particles may burn if exposed to prescribed fire or wildfire. Central to the question of how these particles may burn is how the time since mastication affects the decomposition of the wood particles comprising the fuels. We conducted controlled laboratory experiments to investigate how the particles changed chemically over the time since they were masticated and how those chemical changes affected fire behavior characteristics. The objectives were (1) to quantify the chemical differences of masticated materials from different climates and different decomposition stages, (2) determine whether chemical changes occurred similarly in all fuel particles, and (3) describe the fire behavior characteristics exhibited by these fuels. Masticated materials came from mixed-conifer forests at fifteen different sites throughout the Rocky Mountains. Paired stands from these sites were of similar vegetation and forest stage. They represented wet and dry climates, different stages of wood decomposition, and variable piece sizes based on the type of machine used to masticate the biomass.

Time since mastication and piece size affected the rate of chemical changes in the masticated particles. Fragmented particles had less heat value, N, and C than intact particles from the same site. C decreased and N increased with time since treatment. In most cases, cellulose decreased as decomposition occurred. Age of the particles, tree species, climate, and quantity of fuel load were all important factors influencing chemical change and burn characteristics. In the smoldering experiments, age was not a significant factor but soil substrate was. Soil surface temperatures in the smoldering tests differed significantly between dry sand and dry duff, and most of the smoldering burns in dry duff easily reached temperatures and durations at the surface between the fuel and the soil that would kill soil plants, microbes, and fauna and severely affect soil ecology. When planning prescribed burns in these treatments, managers need to consider not only the moisture of the fuels, air temperature, and wind, but also the dryness and type of soil, the amount of decomposition (time since mastication) of the fuel particles, fuel depths, fuel loads, and the spatial distribution of the fuel loads left by the masticator.

1. Introduction

Mastication is an important silvicultural technique in which trees and shrubs are ground, shredded, or chopped, thereby converting ladder fuels into surface fuels. This biomass is redistributed to form a layer of woody debris on the forest floor. Mastication is a popular fuel treatment because it (1) redistributes fuel from the tree canopy to the ground, changing canopy base height, reducing fire intensity, and

reducing crown fire potential in tree and shrub canopies (Battaglia et al., 2010); (2) affects the probability of fire occurrence across landscapes by changing spread rates (Cochrane et al., 2012; Kreye and Kobziar, 2015); and (3) may reduce detrimental effects from smoke on humans during prescribed burning (Naeher et al., 2006; Weinhold, 2011). It is also used to change or remove competing vegetation in areas requiring natural or artificial regeneration (Jain et al., 2012). Currently, mastication has become important in areas where using

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prescribed burning may pose danger to adjacent properties, such as in the wildland urban interface (WUI), or where thinning trees may be difficult and costly (Berry et al., 2006).

The physical, chemical, biological, and mechanical effects of mastication have been well studied since masticators were first developed to treat forest biomass (e.g., Ritter, 1950; Pokela, 1972; Busse et al., 2006; Kane et al., 2009). Although these studies have provided vital information for managers on implementing mastication treatments, previous research related to particle fragmentation and fire behavior in masticated fuelbeds is most relevant in this paper. A literature review to this effect, investigating studies related to fire behavior in masticated fuels, was completed by Kreye et al. (2014). It provided insights into a variety of factors that affect burn characteristics, including fuel characteristics (Kane et al., 2009) and relationships between particle size, fuel load and moisture content (e.g., Rothermel, 1972; Rothermel and Deeming, 1980). Important studies on the effects of particle fracturing and moisture content on fire behavior in masticated fuels have been conducted by Kreye et al. (2011), while the importance of fuel load has also been addressed by Battaglia et al. (2010). The impacts of prescribed burning on masticated fuels have been documented in field studies by Glitzenstein et al. (2006), Knapp et al. (2011), Wolk and Rocca (2009), Reiner et al. (2009), Kreye and Kobziar (2015) and Brennan and Keeley (2015). These studies have investigated fire behavior characteristics in a variety of ecosystems from forests to shrubs. Together the studies found that masticated materials produce low intensity, slow-moving fires; that fuel depth of the chips is important to burning; that flame length and height are much smaller in masticated materials than in wildland fires; and that these materials form novel fuel beds that defy easy classification in fuel models to describe their burn characteristics.

Several studies have also been done on the chemical changes that occur in wood during decomposition. Dobry et al. (1986), Boddy and Watkinson (1995), Creed et al. (2004), and Mattson and Swank (2014) all found that heat value and C generally decrease with longer decomposition times and N generally increases. N content has also been found to increase with progressive decomposition in several other studies (e.g., Kielak et al., 2016; Jurgensen et al., 2006). Kielak et al. (2016) and Larsen et al. (1978) hypothesized that increases in N content may relate to fungal and bacterial activities. For example, white-rot fungus *Hypholoma fasciculare* was recently shown to be able to translocate N into decomposing wood from soil under the colonized wood (Philpott et al., 2014). Similarly, Cowling and Merrill (1966) found that wood-inhabiting N-fixing bacteria were suggested to support fungi in fulfilling their N requirements (Hoppe et al., 2014). Increased N into the wood from either translocation or by active bacterial action is important because increased N accelerates decomposition of surface and buried wood (van der Wal et al., 2007). It also provides the N fungi need to increase their populations and breakdown wood cellulose during the decomposition process. Goldman et al. (1987) found that lignin decomposes more rapidly in soils when high amounts of easily degradable C and high concentrations of N are present because of an associated high metabolism and fast growth of microbial populations.

Heat value has been found to vary in response to lignin content and fungal activity (Demirbas, 2001). Dobry et al. (1986) found a difference in the combustion heat of wood depending on whether the wood samples were affected by white rot or brown rot. In samples affected by white rot, combustion heat ($Q_{\text{exp}} \times (\text{J gm}^{-1})$) remained virtually unchanged during decomposition and the relative portions of the main chemical wood components remained essentially the same. With brown rot, however, combustion heat was unchanged only in the initial stages of decomposition. After a weight loss of 30%, combustion heat and lignin content changed considerably (Dobry et al., 1986). The persistence of lignin and its role in the combustion heat of wood is well known to be determined by the type of fungal decay present (e.g., Kirk and Cowling, 1984; Dobry et al., 1986; Kielak et al., 2016). White-rot fungi are able to degrade lignin in order to get access to other

polysaccharides within woody material. They also usually destroy all wood components during decomposition. Alternately, brown-rot fungi are specialized in degradation of holocellulose and usually destroy cellulose early in the decay process without removing lignin (Kielak et al., 2016). In 2016, Venugopal found that fungal wood decay was affected by temperature, humidity, substrate quality and fungal diversity; but, wood quality and fungal assemblage composition can modify the influence of climatic factors on fungal decomposition rates.

Missing from the past studies on mastication and decomposition is how masticated particles change chemically as they lie on the ground during decomposition and, further, how these chemical changes may affect fire behavior characteristics if the masticated materials burn and how this burning in masticated fuels might affect soil. Therefore, the objective of this study was to determine how leaving masticated materials on the surface of the ground for varying lengths of time affects their chemical composition and fire behavior characteristics. Because decomposition is central to the aging process, four specific questions were addressed to explore the changes that may occur over time. Does the chemical composition of fragmented and intact particles of the same age differ? What chemical changes occur within the materials left on the ground during decomposition over time? What effect does time since mastication or chemical decomposition have on the smoldering and surface fire behavior characteristics of masticated fuel? And finally, which of the measured chemical properties and fire behavior characteristics are most influenced by time since mastication treatment?

2. Methods

2.1. Study area and sampling design

This study employed a spatial and chronological sequence sampling strategy where we sampled sites that had different times since masticated treatments. Within mixed-conifer forests across the western U.S., 15 sites were selected that represent masticated fuel treated 6 months to 10 years prior to sampling (Table 1). Within these sites, sample areas having the same forest ages, forest structural stages, vegetation composition, geographic area, and climatic conditions were paired based on their times since mastication to determine the extent of changes that had occurred during the time they laid on the ground. Often the paired sites were located in close proximity within the same experimental or national forest so their species composition was similar. All of the sites had merchantable timber removed, followed by masticating both the remaining overstory trees and understory. Shreds of understory vegetation were not a dominant component of the masticated material, and deciduous trees were rare at all sites.

Geographically, sites were located from Idaho to New Mexico in the US Rocky Mountains and to South Dakota in the Great Plains. Within this wide distribution, the sites varied from mesic to xeric based on their annual rainfall. Sites in northern Idaho had more than 40 cm annual average precipitation and were composed of a variety of tree species, including western redcedar (*Thuja plicata* Donn.), western white pine (*Pinus monticola* Dougl.), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and western larch (*Larix occidentalis* Nutt.). Sites in the remainder of the study area were drier and composed mainly of mixed ponderosa pine (*Pinus ponderosa* Dougl.) and Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco) stands. Prior to treatment, each site consisted of dense pole or mature stands that could experience increased fire behavior, including higher crown fire potential. Pre-treatment stand summaries were not available for many of the sites. All areas were treated using four general types of mastication equipment (Keane et al., 2017). These included a vertical rotating shaft cutting head with fixed teeth (6 sites), a horizontal drum head with fixed teeth (6 sites), a mowing horizontal shaft with swinging knives (2 sites); and a chipping head (1 site). All sites had a history of frequent fires prior to European settlement; but since the early 1900s, fires had been successfully suppressed creating dense canopies and heavy surface fuel

Table 1

Study sites sampled in the MASTIDON project arranged by climate and time since mastication (modified from Keane et al., 2017). Tree species include *Pinus ponderosa* (PP), *Pseudotsuga menziesii* (Douglas fir (DF)), *Tsuga heterophylla* (western hemlock (WH)), *Larix occidentalis* (western larch (WL)), *Pinus monticola* (western white pine (WWP)), and *Thuja plicata* (western redcedar (WRC)). Locations include six experimental forests (EF), one National Forest (NF), and a National Preserve (NP) with either PP or PP/DF stands (xeric) or the moist mixed species stands (mesic). Mastication method used these machines: horizontal shaft (HS) and Vertical shaft (VS) that either have fixed teeth (FT) or swinging knives (SK) and were boom mounted (BM) or front-end mounted (FEM) with or without a rotating head (RH).

Location, State	Name	Mixed Conifer Forest (Dominant species)	Time laid on ground after mastication (yrs)	Mastication method
<i>Mesic sites</i>				
Deception Creek EF, ID	DC1	WH, WWP, WL, <i>Linnaea borealis</i>	9	VS, FT, BM RH
Priest River EF, ID	PRCC1	WWP, WH, WL, <i>Clintonia uniflora</i>	6	VS, FT, BM RH
Priest River EF, ID	PR3	WRC, WH, WWP, WL	2	HS, FT, FEM
University of Idaho EF, ID	UI	PP, <i>Physocarpus malvaceus</i>	0	HS, FT, BM
<i>Xeric sites</i>				
Boise Basin EF, ID	Amber	PP	10	VS, FT, BM RH
Manitou EF, CO	MEFChip	PP, DF, <i>Symphoricarpos albus</i> , <i>Juniperus communis</i>	10	Chipped
Manitou EF, CO	MEFWS	PP, DF, <i>Arctostaphylos uva-ursi</i>	9	VS, FT, FEM RH
Santa Fe NF, NM	LG	PP, bunchgrass	8	HS, FT, FEM
Valles Caldera NP, NM	VC1	PP, sedge, bunchgrass	6	HS, FT, FEM
Boise Basin EF, ID	AmberNew	PP, DF <i>Purshia tridentata</i> , <i>Symphoricarpos albus</i>	4	VS, FT, BM RH
San Juan NF, CO	Skelton	PP, DF, <i>Artemisia tridentata</i>	3	VS, FT, FEM RH
Santa Fe NF, NM	PAL	PP, sedge	2	HS, FT, FEM
Valles Caldera NP NM	VC2	PP, bunchgrass, <i>Ribes</i> sp.	2	HS, FT, FEM
Black Hills EF, SD	BHMix	PP, <i>Arctostaphylos uva-ursi</i>	2	VS, SK, FEM (Mowed)
Black Hills EF, SD	BHMow	PP, <i>Arctostaphylos uva-ursi</i> , <i>Symphoricarpos albus</i>	2	VS, SK, FEM (Mowed)

loadings (Keane et al., 2017).

One macroplot 50 m × 30 m was established at each site. Six 10 m lines were installed along the macroplot length to create transect lines for measuring depths of fuel layers and for installing microplots to collect mastication fuels. 20 microplots (1 m × 1 m) were established along the transect lines. Within these microplots, additional depths were collected and masticated materials were sampled within a 0.5 m by 0.5 m portion of the microplot using methods described by Hood and Wu (2006). All material was collected down to bare soil and stored in paper or burlap bags for transport to the lab for sorting and various physical and chemical analyses (Keane et al., 2017). Materials were stored for 1–1½ years in a dry, heated warehouse, within their bags, until processing and burning. In the lab, 10 of the 20 microplots were used for lab analysis and 10 were used for experimental burns. In addition, the University of Idaho contributed newly masticated material to our study to run through the lab analyses adding to our total plots. A total of 151 (15 sites × 10 samples per site) microplots were used for the chemical tests. The remaining 150 microplots were used to conduct 45 experimental burns.

2.2. Wood chemistry and heat value

From the microplot samples, masticated materials were separated into 15 different shapes or groups using the entire fuel load. The wood pieces within these shapes were further separated into 1-h, 10-h, and 100-h size classes (see Keane et al. (2017) for details). Wood samples were randomly selected from the groups for further chemical and heat value tests. Four shape classes were tested from these groups for their chemistry: round, intact particles (i.e., cylinders); 3-sided particles (triangles); 4-sided particles (parallelograms); and small wood fragments < 3mm thick but > 6mm long. These four shape classes were subsequently subdivided into three size classes (1-h: 0–6 mm diameter; 10-h: 6–25 mm diameter; and 100-h: 25–76 mm diameter) (Brown et al., 1982). After the particles were sorted and separated, they were dried in an oven for at least 72 h at 90 °C before being crushed in a Wiley mill to fine powder. The powder was dried a second time before being subjected to further analysis. The same powdered samples were used for C, N, cellulose, lignin, and heat value tests. C and N were analyzed on 892 samples representing each of the different shape and size classes; cellulose and lignin were analyzed on 456 samples.

Keane et al. (2017) describe the complex set of measurements that were used to estimate the physical and chemical characteristics of the

masticated fuel particles. They evaluated correlations among more than 20 characteristics against time since treatment, finding few statistically significant relationships. However, they did find interesting correlations with some of the chemical variables measured in the masticated particles. Those chemical properties are explored in this paper to determine whether they had a relationship to smoldering or fire behavior.

2.2.1. C and N tests

Prior to running C or N tests, all powdered samples were redried in an oven at 65 °C for a minimum of one hour to remove any moisture and achieve an accurate mass measurement. For each C and N analysis, a mass of 0.0710–0.0719 g was compressed into a tin foil cup per the LECO EDTA standard method and placed into the sampling carousel. N and C samples were then analyzed using a LECO TruSpec Carbon Nitrogen Determinator (LECO, 2009). The TruSpec was utilized in accordance to the standard operating procedures outlined in TruSpec C N Determinator Instruction Manual. Each sample was run in duplicate. The reproducibility of the duplicates was assessed, and a third sample was analyzed if the variation was greater than 5%. Care was taken to avoid cross-contamination. Results from this analysis were recorded as percent on a mass basis but eventually converted to a volumetric basis.

2.2.2. Heat value, lignin and cellulose tests

Heat value measurements were conducted on fuel samples milled to pass a 20 mm sieve using a Wiley Mill. Sample mass ranging from 0.3 g to 0.5 g were put in a 0.9 mL gelatin capsules for analysis in an adiabatic calorimeter (Parr Instrument Company, Moline, IL). Gelatin capsules were utilized to improve combustion of the dried milled samples. This technique is used when pelletizing dry samples is ineffective and results in inconsistent combustion (Parr Instrument Company, Moline, IL).

Each sample capsule was placed in the calorimeter bomb unit, which was then placed in the sample bucket surrounded by deionized water within the calorimeter. Sample ignition was initiated a minimum 100 s after equilibration between the water temperature of external water jacket (21 °C) and the water temperature surrounding the bomb unit containing the sample. After ignition, temperature readings of the external water-jacket and water temperatures surrounding the bomb unit were taken every three seconds for 400 s. Heat content was then determined using the following equation:

$$Hg = (t \times W) \times (M)^{-1},$$

where H_g = heat content (MJ/kg); t = temperature rise ($^{\circ}\text{C}$); W = energy required to raise the temperature of the water surrounding the bomb unit one degree (2402 J/g); and M = sample mass or weight (g; corrected for weight of the gelatin capsule and energy). Results were recorded on a mass basis during this process but later converted to a volumetric basis.

The proportions (%) of lignin and holocellulose were calculated from the heat contents measured in the adiabatic calorimeter. The proportion of these two components was estimated using the following formula proposed by Tillman (1978), as cited by White (1987), to estimate the heating value of wood:

$$HV = (7527 \text{ btu lb}^{-1} \cdot C) + (11,479 \text{ btu/lb} \cdot (1-C)), \quad \text{where } C = \text{fraction holocellulose.}$$

In this case, the heating value (HV) of wood is a function of the proportion of holocellulose to lignin fractions (“C” and “C-1”, respectively) and average heating values of 7527 and 11,479 BTU/LB for holocellulose and lignin, respectively. Sample heating values were measured using a bomb calorimeter and the proportion of holocellulose (“C”) and the proportion of lignin (“1 – C”) were estimated mathematically using this formula.

Initial thermogravimetric analysis of samples from several sites showed that lignin, hemicellulose, and cellulose were the dominate components comprising the mass of the samples. There was no significant mass loss below 100 $^{\circ}\text{C}$, which is the temperature below which the more volatile compounds would be expected to thermally decompose. It was assumed that the lignin and holocellulose fractions dominated the heat output of the fuels and that Tillman’s (1978) formula would reasonably capture the major changes in fuel chemistry.

2.2.3. Chemical values

Chemical values for C, N, lignin, and cellulose (and heat value) used for this study are **volumetric** values rather than **mass**. A volumetric value for each chemical takes into account the density of the wood and the structural changes that these particles have undergone as they have lain on the ground and decomposed for different lengths of time. It was critical to capture the density differences as part of the wood character (Marcouiller and Anderson, 2003) to show whether the wood has changed since treatment, assuming that the materials have come from forests with the same ages, stages, vegetation, geographic area, and climatic conditions. Volumetric measures have been used for decades in studies on chemistry (Quintiere, 2006), duff (Varner III et al.), soil moisture content (Topp et al., 1980; Davidson et al., 2000), peat (Boelter, 1964), and combustion (Weise et al., 2005). They have only rarely been used in forestry or fuels studies. Volumetric values have been important, however, in creating fuel models for calculating surface fire rate of spread (Rothermel, 1972; Albini, 1976).

To compute a volumetric value from the chemical and heat value tests, the percent of chemical obtained from each test (described above) was multiplied by the average bulk density obtained for each of the shape and size classes at each sample site. Bulk density was derived for each particle using a two-fluid (kerosene and glycerin/water) displacement process that has been historically used to determine density in soils or duff (Williamson and Wiemann, 2010). The particle density (PD, g cm^{-3}) was computed using the following equation:

$$PD = W_{\text{sample}} \times (P_k - P_{\text{mix}}) \times (W_k - W_{\text{mix}})^{-1}$$

where W = particle dry weight (g), P_k and P_{MIX} = density (g cm^{-3}) of kerosene and glycerin/water mixture, respectively; and W_k and W_{MIX} = mass (g) of the particle in kerosene and glycerin/water mixture, respectively.

Particle volume was derived from the particle density measurements, and calculated as:

$$PV = W \cdot PD^{-1}$$

where PV = particle volume (cm^3). Both particle density and volume were averaged by particle shape and size (see Keane et al. (2017) for complete details).

After chemical results were adjusted for volume, particle chemical characteristics were tested for the effect of the mastication process. These results were divided into chemical content for intact and fragmented particles, with no consideration of particle size. A weighted average was therefore calculated from the 1-h, 10-h, and 100-h results. The mean volumetric chemical content was then calculated for both intact and fragmented particles for each site for all particles. Intact particles are basically cylinders from whole branches that remained complete after mastication, while fragmented particles are shapes that were cut and mulched during the mastication process. These samples were tested in two ways. First, samples at each geographic location were analyzed to determine if structural integrity resulting from the mastication process affects particle chemistry (e.g., whether intact vs fragmented particles differ at a single site (i.e., Amber)). Second, sites were paired based on time since treatment, geographic location, and similar mastication method to examine the effect of time since treatment on particle chemistry (e.g., comparing each chemical between two sites, such as Amber and AmberNew).

2.3. Surface fire behavior

Experiments were conducted at the USDA Forest Service’s combustion facility at the Missoula Fire Sciences Laboratory (FSL). The combustion chamber does not include the ability to adjust wind speed, and the burns for this study were considered to be too intense to burn in the facility’s wind tunnel. Therefore, wind speed was not explicitly factored into the experiments. During the experiments, air temperature in the burn chamber was approximately 21 $^{\circ}\text{C}$. Relative humidity was not controlled and approximated that of the outside ambient air, which has a daily average of 62% for the months in which these fuels were burned. Full details on the setup and burning of the experimental fuel beds to calculate surface fire behavior can be found in Heinsch et al. (in press).

Three fuel beds were created to represent each site resulting in a total of 45 experimental burns. Each bed consisted of masticated materials from the 1-h, 10-h, and 100-h fuels; wood chips (wood < 3mm thick); wood ribbons; fresh litter; 1-h and 10-h bark; 100-h bark; and bark ribbons. No duff from the sample locations was used in the creation of the experimental burn beds because it is not a component of Rothermel’s fire spread model. The burn was, however, conducted on a RESCOR ceramic heat-resistant board (Cotronics Corp. Brooklyn, NY) that simulated conditions for burning on duff. Similarly, no 1000-h logs were used in the experimental burning because they were beyond the scope of the initial proposed study. To build the burn beds, we first examined the target fuel loads for each site by size class and fuel type. These were then averaged for a mean fuel loading to get the fuel load for each fuel bed in the experimental burn. Fuel beds were conditioned in an environmental chamber at 35 $^{\circ}\text{C}$ and 3% humidity for at least 36 h prior to burning to reduce moisture content as much as possible in all fuel categories.

Each fuel bed was created on a burn platform 2.7 m long and 0.86 m wide (Fig. 1A). The burn area for fuel bed was 0.8 m long and 0.86 m wide (Fig. 1 B), not including an excelsior and pine needle zone for starting the fire. The bed was inclined at either 12% (low) or 21% (moderate) slope. Three halogen work lights were focused on the material in an effort to emulate sunlight, preheat the air above the fuel, and facilitate burning. Graduated range poles were placed at 0.15, 0.30, and 0.60 m along the fuel bed. Weight scales were placed on each end of the fuel bed to measure fuel consumption during the burns.

All of the burn beds were ignited from a line of excelsior and pine needles (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

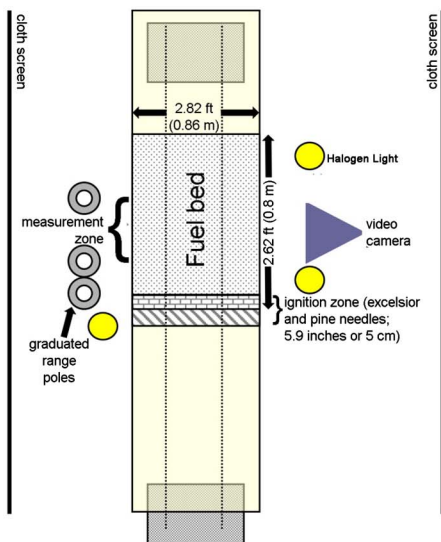


Fig. 1. Experimental bed setup including (a) diagrammatic of sections (from Heinsch et al., in press); and (b) photo of burn bed. In experimental setup, yellow circles represent the halogen lights; purple triangle is position of video camera; hatched zone represents ignition zone consisting of pine needles and excelsior; gray boxes on each end indicate the scales to measure mass loss. Gray rings are the stadia rods used to measure flame height and rate of spread. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of time it took the fire to travel the 0.3 m between the 2nd and 3rd graduated poles in the measurement zone (Fig. 1A and B). Flame height was recorded using the height measures on the graduated poles. Both minimum and maximum flame heights were recorded for each burn. All fire behavior values were evaluated both during the experimental burn and verified from viewing a high definition digital video of each burn after the burn was done. Data on rate of spread, minimum and maximum flame heights, flame duration, consumption, and radiant heat flux were obtained from these burns.

2.4. Smoldering fire behavior

Smoldering tests were performed under a fume hood at the FSL. The experimental burns were conducted in fire resistant boxes that were 18 cm wide $\times$ 28 cm long $\times$ 17 cm deep (Fig. 2A and B). Each box contained eight thermocouples placed at various depths in the fuel bed to record temperatures of the burns below the soil surface and within the masticated material itself.

Masticated biomass selected for the smoldering burns were from the same 15 sites that were used in the larger, experimental fuel-bed burns. As with the surface fire behavior experiment, the average total fuel load at the field site was used to create these fuel beds (Heinsch et al., in press). The fuel loads were then proportioned to the size needed for the smoldering boxes (497 cm²).

Both dry sand and dry duff were used in the smoldering tests. Duff was collected from each field site with thicknesses ranging from 2 to 6 cm. It was stored in a refrigerated unit for approximately two years before it was conditioned in an environmental chamber to < 10% moisture content prior to burning. The smoldering burn beds for the dry duff burns consisted of a substrate of sand overlain by a layer of duff then litter. For the dry sand smoldering burns, clean, dry sand was used as a base and masticated material and litter were placed on top of the bare sand substrate (Fig. 2A). Sand was used to eliminate the variation found soils found on the forest floor and make analysis of the resulting data cleaner.

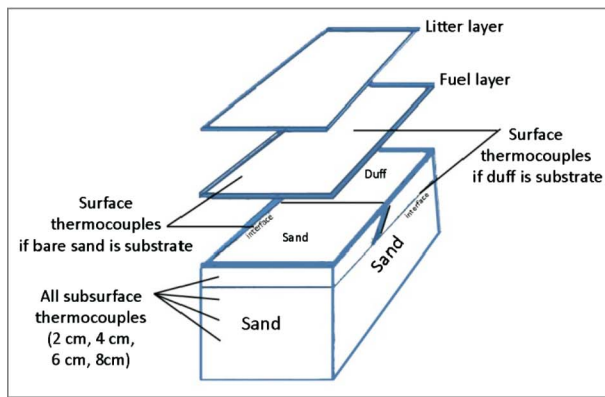
Two burn beds were designed for each test. Each burn box contained eight thermocouples spaced throughout the fuel bed (Fig. 2A). One box had two surface thermocouples and six thermocouples spaced

at 2 cm intervals from 0 cm to 10 cm deep (Fig. 2A). The other box had three surface thermocouples and five thermocouples spaced at 2 cm intervals from 0 cm to 8 cm deep (Fig. 2A and B). Burns were ignited with a propane torch and allowed to burn until they naturally extinguished (Fig. 2C). Temperature data were collected from each of the boxes every three seconds during the burn. Data obtained from each of the smoldering burns included maximum surface temperature and smoldering duration.

2.5. Statistical analyses

Statistical analyses were performed using the R statistics package (R CoreTeam, 2016). Tests for significant differences between chemicals in intact and fragmented particles were performed on paired plots of different ages using independent *t*-tests. Results were considered significant if $p < 0.05$. To determine the effects of structural integrity at each site on particle chemistry, the data were tested for normality, and then analyzed using one-way analysis of variance (ANOVA) when data was found to be distributed normally. Differences were considered significant if $\text{Pr}(F) < 0.05$.

Principal component analysis (PCA) was used to explore how masticated sites would group together based on several independent variables. It explored the relationships between time since treatment, chemical constituents (N, C, lignin, cellulose, C:N ratio, and heat value), surface fire behavior characteristics (radiant heat flux, surface rate of spread, flame length, flame duration, consumption), and smoldering characteristics (surface temperature and duration) in bare sand and dry duff. To explore these relationships, two PCA runs were conducted. The first run used smoldering results from burns done on the dry sand substrate; the second used results from burns done on the dry duff substrate. Missing data were imputed using techniques described in Josse and Husson (2013) and implemented in R function *imputPCA* in library *missMDA* (R CoreTeam, 2016). Correlation coefficients were used to create the cross-products matrix. Within the PCA, the sites that are most closely related using the test variables should plot more closely together on the PCA diagram; sites that are very different should plot further away from each other. The PCA uses vectors to show the correlations of the variables with the ordination space (i.e., how important



A.



B.



C.

Fig. 2. Smoldering test design. (A) Either dry sand or dry duff was placed on a sand base to use as the smoldering substrate. Masticated fuel, and their recent litter component, were placed over the substrate in the same proportions as the field fuel loads but adjusted to the small size of the burn bed. Single fuel bed is 18 cm wide $\times$ 28 cm long $\times$ 15 cm deep. (B) Burn arrangement showing the ceramic burn boxes, flaming fuel beds, thermocouple wires, and video camera. (C) Smoldering fuel bed during the burn.

some of the variables are to plotting the distribution of the sites in the graphs). Long vectors indicate strong relationships to the variable; short vectors indicate less relationship. The PCA axes are not labeled with actual variables; however, the variables that are important to site distribution along each axis within the PCA graphs can usually be discerned. Axis 1 of a PCA usually explains the most variation among the group of variables and axis 3 explains the least.

Data from the smoldering burn experiments were tested against time since treatment and substrate using SAS PROC GLIMMIX, Version 9.4 of the SAS System for Windows (SAS Institute Inc., 1989–2007). The dry sand and dry duff data were combined into one dataset, missing data were imputed, and the entire dataset was analyzed using substrate type, time since treatment, and the interaction of the two variables. Sample site was included as a random effect. A gamma distribution was used because responses were > 0 and the gamma distribution fit best according to the deviance.

3. Results

3.1. Chemistry and heat value

3.1.1. Effects of the mastication process on particle chemistry

Sample sites were paired sites using several criteria, such as geographic proximity and climate, similar forest cover and understory vegetation, and similar forest age and structural stage to test for the effect of mastication on particle chemistry by comparing the chemical content of intact and fragmented wood particles. The South Dakota sites (BHMow and BHMix) were not tested because there were too few samples. The differences in chemical values and heat value between

intact and fragmented wood particles are shown in Fig. 3. Generally, intact particles had greater heat value, N, and C than fragmented or masticated particles when adjusted for volume (Table 2; Fig. 3A–C), whether the materials were young or old. Fragmentation of particles had the most effect on N, with six of seven paired locations showing a significantly greater amount of N between the fragmented and intact particles (Table 2). Heat value and C were also affected by particle type, with four locations showing a significant difference between intact and fragmented particles. Xeric sites all showed higher lignin in intact particles, which was statistically significant (Fig. 3). Mesic sites showed higher lignin in the fragmented particles, which were not significant (Table 2). The mesic sites and xeric sites at Colorado had higher cellulose in the intact particles (Fig. 3). Of these, the mesic sites had statistically significant differences (Table 2). All other xeric sites had higher cellulose in fragmented particles, of which only the MEFChip and Skelton differences were significant. Even though N and C values were both significant at more than half of the locations, the C:N ratio was not significantly different between the intact and fragmented particles at any location. In 1995, Entry and Backman proposed that a cellulose:lignin:N ratio may be a more accurate predictor of decomposition rates on some sites. However, because cellulose was not isolated from holocellulose and other associated chemicals for this study, we could not use this ratio with our current data.

3.1.2. Chemistry and heat value compared in old and young paired plots

Time since treatment did not have as great an impact on chemical characteristics as particle type (i.e., fractured or intact). Paired sites were used as a proxy for a chronosequence (e.g., Amber (10 years old) and AmberNew (4 years old)). The “older” sites (> 5 years since

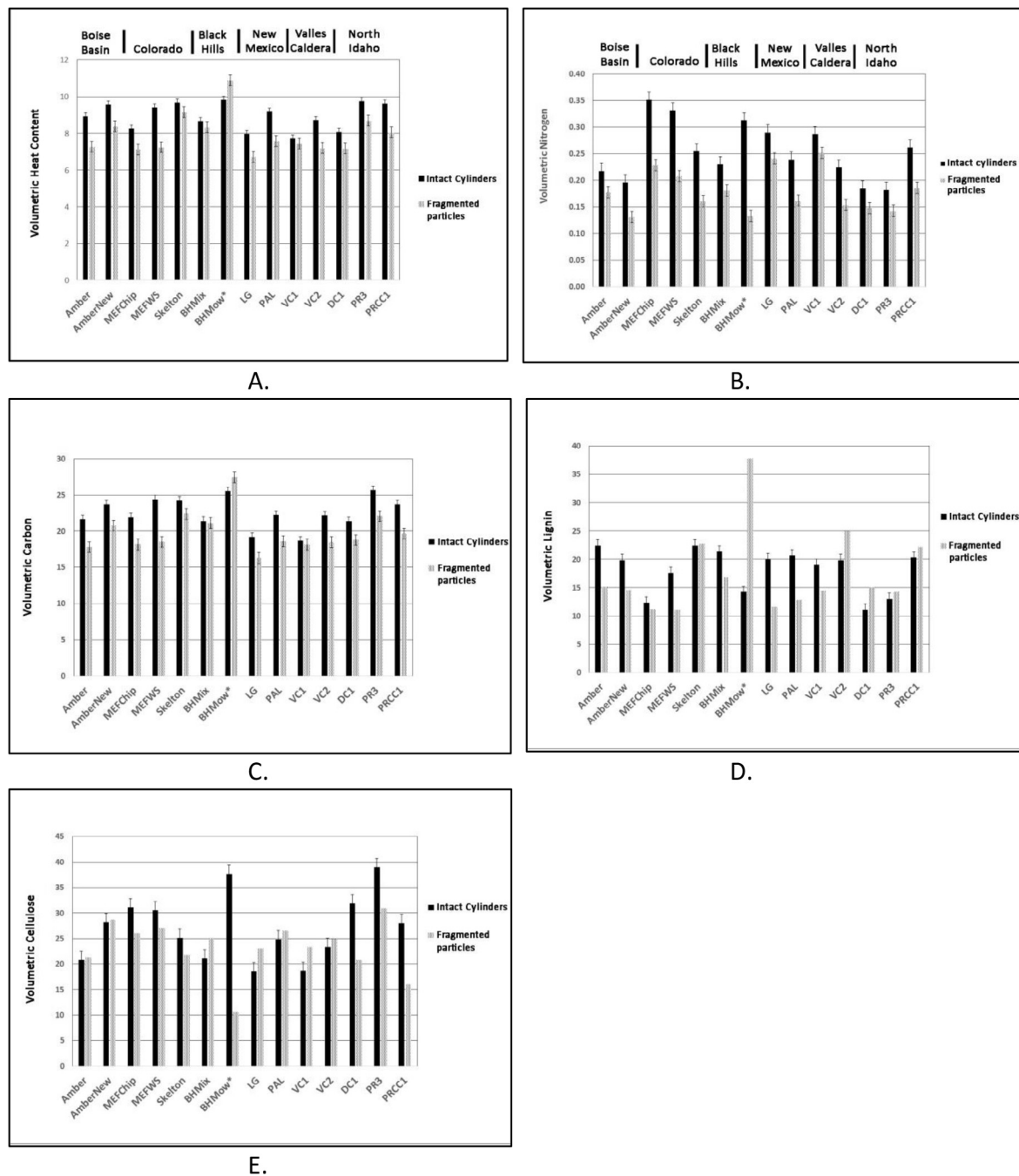


Fig. 3. Relationship between intact particles (cylinders) and fragmented particles for (A) heat value; (B) N content; (C) C content; (D) lignin content and (E) cellulose content. Site name and time since treatment is provided in Table 1. Volumetric heat value calculated as heat value (MJ kg^{-1}) $\times$ particle density (g cm^{-3}). Volumetric N = $\text{N\%} \times$ particle density (g cm^{-3}). Error bars show standard error. Sites are arranged geographically in each graph to show site proximity to each other.

mastication) ranged from 6 to 10 years since treatment, while the “younger sites” (< 5 years since mastication) ranged from 2 to 4 years since treatment, with average difference in time since treatment of 5.7 years. Generally, younger sites had higher heat value and more C, although these values are not significant at most sites (Table 3, heat value p -values = 0.003–0.798; C p -values = 0.054–0.996). In contrast, N content was generally higher in the older sites. Exceptions were found in mesic sites, where, for example, PRCC1 had less N than the nearby PR3. In addition, there was no significant difference with time since treatment for lignin, or cellulose, and values varied between the young and old sites (Table 3; Fig. 4). For example, lignin content was greater in older materials (such as Amber (10 years old), younger materials (Skelton (3 years old), VC2 (2 years old)), or showed no difference

between old and new materials (LG, DC1). Time since treatment did affect the C:N ratio significantly for all seven paired sites (Table 3, p -values = 5.15×10^{-10} –0.030). In six of the seven pairs, younger sites had much higher C:N ratios than the older sites with only Amber:AmberNew not significant. The average decrease in the C:N ratio with time was 32% (Table 3). Time since treatment had a significant impact on N content at four of seven pairs (MEFChip:Skelton, VC1:VC2, LG:PAL, and PRCC1:PR3), with N decreasing with time at three sites (Table 3) but increasing at the fourth paired site (PRCC1 and PR3).

N was usually greater in older pairs of the paired site comparisons, such as between MEFChip and Skelton (Fig. 4). In contrast, C and heat value were usually greater in younger materials (see Amber and Amber New, Fig. 4). Lignin content was more varied in the materials

Table 2

One-way ANOVA results from tests for significant differences in chemical constituents of fragmented and intact particles at similar sites having different years since treatment. All chemical values are volumetric (i.e., chemical value $\times$ particle density). Time since treatment and mastication method are given in Table 1. Decomp = difference in the number of years that particles have lain on the ground between each pair of sites. $\text{Pr}(> F)$ values of < 0.05 are considered significant and are marked with *.

Paired plots	Decomp Yrs	Volumetric heat value		Volumetric N		Volumetric C		Volumetric lignin		Volumetric cellulose		C:N ratio	
		F-value	$\text{Pr}(> F)$	F-value	$\text{Pr}(> F)$	F-value	$\text{Pr}(> F)$	F-value	$\text{Pr}(> F)$	F-value	$\text{Pr}(> F)$	F	$\text{Pr}(> F)$
Amber-AmberNew	6	3.59	0.060	5.45	*0.022	3.50	0.070	8.68	*0.004	0.68	0.413	1.89	0.173
MEFChip-Skelton	7	3.06	0.088	13.19	*0.001	4.64	*0.038	0.38	0.539	4.05	*0.050	1.96	0.169
MEFWS-Skelton	6	0.02	0.881	0.06	0.803	0.00	0.996	0.02	0.895	0.13	0.722	2.23	0.141
VC1-VC2	4	4.21	*0.044	4.94	*0.029	3.76	0.057	9.01	*0.004	1.78	0.187	1.13	0.291
LG-PAL	6	28.23	*0.000	15.41	*0.000	27.98	*0.000	47.78	*0.000	2.82	0.096	0.54	0.464
DC1-PR3	7	12.9	*0.001	9.98	*0.002	15.34	*0.000	0.80	0.375	42.41	*0.000	0.42	0.518
PRCC1-PR3	4	7.095	*0.010	4.32	*0.042	9.82	*0.003	0.70	0.407	27.92	*0.000	0.19	0.667

* $\text{Pr}(> F)$ values of < 0.05 are considered significant.

Table 3

Paired comparisons of chemical means for masticated sites with different times since treatment using independent *t*-tests. Chemistry adjusted for volume using chemical value $\times$ particle density. HC = Heat value; C:N = C:N ratio. Values obtained from *t*-test and *p* values given for each chemical tested. *P*-values of < 0.05 considered significant in the *t*-tests and are marked with *.

Paired-site names	Age years	Volumetric heat value $\text{MJ kg}^{-1} \times \text{g cm}^{-3}$	t (p value)	Volumetric N $\% \times \text{g cm}^{-3}$	t (p value)	Volumetric C $\% \times \text{g cm}^{-3}$	t (p value)	Volumetric lignin $\% \times \text{g cm}^{-3}$	t (p value)	Volumetric Cellulose $\% \times \text{g cm}^{-3}$	t (p value)	C:N Ratio	t (p value)
Amber	10	8.07	−1.62 (0.109)	0.20	1.26 (0.210)	19.61	−1.96 (0.054)	19.37	0.01 (0.316)	20.14*	−4.20 (0.000)	114.73*	−2.59 (0.011)
Amber New	4	8.92		0.17		22.05		17.49		27.78*		140.13*	
MEFChip	10	6.78*	−3.16 (0.003)	0.26*	2.06 (0.048)	17.51*	−2.75 (0.010)	10.23*	−4.15 (0.0003)	25.43	0.99 (0.32)	75.17*	−4.14 (0.000)
Skelton	3	9.24*		0.19*		22.83*		22.57*		22.51		136.05*	
MEFWS	9	9.33	0.04 (0.968)	0.31	1.49 (0.144)	22.87	0.01 (0.996)	15.70	−1.50 (0.139)	32.70	1.38 (0.17)	83.64*	−3.70 (0.001)
Skelton	3	9.24		0.19		22.84		22.57		22.51		136.05*	
VC1	6	7.53	0.26 (0.798)	0.27*	4.67 (0.000)	18.31	−0.50 (0.617)	15.91	1.00 (0.322)	21.83	−1.09 (0.28)	72.25*	−6.15 (0.000)
VC2	2	7.39		0.17*		18.93		13.67		24.26		116.35*	
LG	8	7.15	−1.52 (0.134)	0.26*	4.98 (0.000)	17.29	−1.71 (0.092)	14.64	−0.45 (0.656)	21.39*	−3.18 (0.002)	68.63*	−7.82 (0.000)
Pal	2	7.76		0.19*		18.93		15.30		25.25*		112.39*	
DC1	9	7.10	−1.44 (0.158)	0.15	0.27 (0.785)	18.65	−1.37 (0.177)	13.53	1.38 (0.172)	23.16*	−5.61 (0.000)	128.99*	−2.19 (0.034)
PR3	2	8.11		0.14		21.12		11.29		35.56*		155.10*	
PRCC1	6	8.11	−0.846 (0.402)	0.15*	−3.14 (0.003)	21.12	−0.15 (0.884)	11.29*	−5.86 (0.000)	21.19*	6.13 (0.000)	155.10*	3.10 (0.003)
PR3	2	8.73		0.22*		21.40		21.38*		35.56*		113.95*	

* *P*-values of < 0.05 considered significant in the *t*-tests.

depending on the climatic setting. In dry climates, fragmented particles usually had lower lignin content than intact particles; but the overall comparisons of the time materials laid on the ground had no consistent result for whether older sites had more lignin content than younger (Fig. 4). In mesic sites (PR3, PRCC1 and DC1), intact particles always had less lignin content than fragmented particles, but the oldest site and youngest site were basically equal in lignin content (see DC1 vs. PR3 in Fig. 4).

3.2. Surface fire behavior

Fire behavior varied both between (Table 4) and within (Fig. 5) sites. Time since treatment did not appear to have a significant effect on rate of spread, maximum flame height, flame duration, or consumption. Minimum flame height was the only fire behavior characteristic measured in this study on which particle age had a significant effect ($K_t = -0.251$, $p = 0.034$; Table 4). Forty percent of the burns exhibited heading fire behavior, which could be measured. Sixty percent

of the burns either failed to burn across the entire measurement zone or exhibited flanking fire behavior, for which we could not obtain reliable estimates of surface rate of spread. Heinsch et al. (in press) conducted these burns to determine the burn characteristics of these masticated fuels and whether building custom fuel models was needed to describe these characteristics. Full details on these burns can be found in that publication (Heinsch et al., in press). Fire behavior was minimal in all burns with rates of spread (when they could be measured) of less than 0.3 m/min and flame heights ranging from 0.08 to 0.91 m (Table 4, Fig. 5). Consumption was measured until the fire naturally extinguished or after one hour. Fuel bed consumption ranged from 2.5 to 94.2%, with an average consumption of 61.6%. It was not significantly related to fuel load or time since mastication (statistical results not shown).

3.3. Smoldering fire behavior

We evaluated only surface temperature and smoldering duration in the smoldering tests. There was no statistically significant relationship

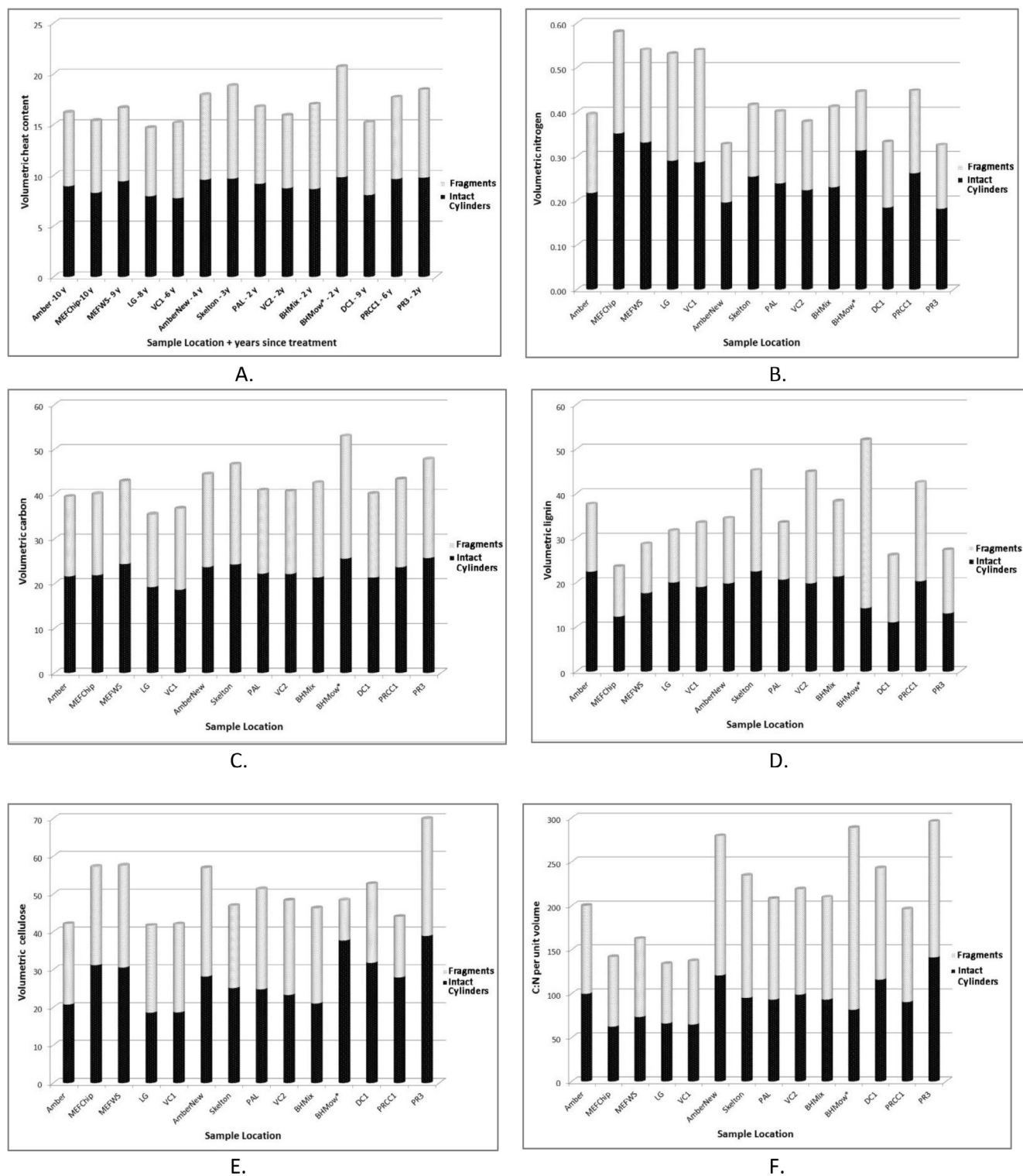


Fig. 4. Relationship of time since treatment to (A) heat value; (B) n; (C) c; (D) lignin; (E) cellulose; and (F) C:N ratio. Stacked graphs compare contribution of each value across categories of fragmented and intact cylinder particles. Graphs are arranged by time since treatment with xeric sites on left and mesic sites as the last three sites on the right. Years since treatment are given with each location in (A).

between time since treatment and smoldering fire behavior. Generally, the maximum temperature and duration of smoldering both increased with fuel load. Neither maximum temperature nor duration of smoldering was significantly correlated with time since mastication when burned on dry duff as opposed to bare sand. Masticated material overlaying dry duff burned at least twice as long and was at least 50% hotter than the bare sand burns (Table 5). Samples on dry duff

smoldered for an average of 105.6 min (range 10.7–192.5 min), with an average maximum temperature of 298.5 °C (range: 88.1–388.3 °C). Materials on bare sand, on the other hand, smoldered for an average of 24.5 min (range: 6.0–60.7 min) at a temperature of 185.6 °C (range: 67.7–291.6 °C). Statistically, however, duration of smoldering was only significantly related to fuel substrate ($F = 8.14$, $Pr > F = 0.01$).

Table 4

Fire behavior characteristics summarized from 45 experimental burns. The characteristics were averaged for three replicates at each site. Detailed results for each burn can be found in Heinsch et al. (in press). RH = Rotating head; HD = Horizontal drum; Mow = mower; Chip = chipper. ND = no data available.

Burn name	Time since mastication years	Mast. method head type	Ave. fuel load (field) ¹ kg m ⁻²	Ave depth mast layer (field) cm	Ave rate of spread ^{2,3} m min ⁻¹	Min flame height m	Max flame height m	Ave flame duration ⁴ min:sec	Ave consumption percent
<i>Mesic Sites</i>									
DC1	9	RH	6.0	9.8	0.13	0.13	0.80	26:15	86.0
PRCC1	6	RH	5.2	10.5	0.01	0.15	0.46	27:30	77.7
PR3	2	HD	7.6	11.7	0.07	0.15	0.50	21:30	89.6
UI	0	HD	6.3	ND	0.17	0.31	0.46	27:10	ND
<i>Xeric sites</i>									
Amber	10	RH	4.0	7.6	0.09	0.16	0.40	22:50	76.0
MEFChip	10	Chip	8.7	8.7	ND	0.08	0.25	21:20	39.7
MEFWS	9	RH	3.0	3.5	0.10	0.11	0.17	20:20	68.5
LG	8	HD	8.7	8.7	0.09	0.20	0.20	30:00	91.7
VC1	6	HD	9.7	10.2	0.03	0.08	0.23	39:00	89.5
AmberNew	4	RH	4.7	8.5	ND	0.20	0.33	32:30	29.4
Skelton	3	RH	4.5	6.0	0.10	0.10	0.38	18:25	50.0
PAL	2	HD	7.5	7.5	0.02	0.05	0.20	40:50	76.6
VC2	2	HD	6.4	7.6	ND	0.08	0.30	29:30	83.6
BHMix	2	Mow	4.1	5.6	ND	0.10	0.30	19:50	35.5
BHMow	2	Mow	2.6	4.7	ND	0.05	0.20	5:45	19.4

¹ Fuel loads are the field measures. Proportions of 1-h, 10-h, 100-h, wood chips, litter and bark comprising this total were adjusted for the size of the burn bed.

² Fire behavior characteristics are averaged for three burns. Two of the burns were on beds with a slope of 21%; one was on bed with slope of 12%.

³ All fuels for the burns were conditioned to 3–5% moisture in an environmental chamber.

⁴ Flame duration is the amount of time in minutes and seconds that the experimental bed exhibited visible flames.

3.4. Multivariate distribution of sample sites in 3-D space

When multivariate ordination analysis (PCA) was used to group sites with similar chemical composition, fire behavior characteristics, smoldering temperatures and durations, and time since treatment, the length of time the masticated material spent on the ground was not a significant factor in the groupings. Young sites (< 5 years old) and old sites (> 5 years old) were intermixed together in the PCA biplots on all axes of each run.

In the PCA run using dry sand, the factors that were most important to how the sites were distributed in 3-D space were explained by axis 1. They included fuel load, N content, percent consumed during burning, maximum flame height, and smolder duration (Fig. 6). The importance of fuel load as a fire behavior factor was also evident during the experimental burns when small fuel loads resulted in creeping burns with very small flames that extinguished rapidly. Burns from sites comprised of light fuels plotted in their own particular space on the PCA biplot (i.e., the low end of axis 1) indicating that they were quite different than the other fuels in this study. Interestingly, the PCA highlighted the importance of fuel loading even though it was not a direct entry into the data set used for the PCA. Axis 2 of the dry sand substrate burns plotted sites in 3-D space based on flame duration in both the experimental and smoldering burns. Axis 3 was driven by the rate of fire spread and minimum flame height. The dry sand run explained a total of 73.95% of the variation in the data, with 35.58% of the variation explained by axis 1.

In contrast to the PCA dry sand distributions, the dry duff substrate was more complex with different variables contributing to grouping the sites on each axis. Flame duration, smoldering temperature, and smoldering duration appeared most important to position of the sites along axis 1 (Fig. 7). Variables important to distribution along axis 2 included N and lignin, consumption, heat value, and flame height; while locations along axis 3 were driven by rate of fire spread, radiant heat flux, and minimum flame height. Consumption had the shortest vector of this set of variables, indicating it was of less importance to plotting site distributions. The dry duff run explained a total of 75.55% of the variation in the data with 33.44% of the variation explained by axis 1.

The fire behavior vectors in these runs are all fairly short, indicating

fire behavior had limited importance compared to other variables. In contrast, the chemical vectors were longer than the fire behavior vectors and N was important to distribution of the sites in 3-D space in both runs. Lignin and N vectors align toward old sites in the dry duff run (Fig. 7), as did N in the dry sand run.

4. Discussion

4.1. Time-since-treatment effects

The most obvious effect of time since treatment on masticated materials was found in the chemical content of the wood particles. Even though most of the materials were treated less than 10 years ago, chemical changes in heat value, N, C, and lignin were evident (Fig. 3). The changes are similar to those found in other decomposition studies, in that C decreases during the decomposition process (Boddy and Watkinson, 1995) while N increased with time (Dobry et al., 1986; Boddy and Watkinson, 1995; Creed et al., 2004; Mattson and Swank, 2014; Finer et al., 2016), which could indicate that decomposing fungi were probably retaining these nutrients at least passively in the decaying wood, thereby acting as a slow-release fertilizer in the forest (Mattson and Swank, 2014). These changes in C and N are reflected in the strong relationship between time since treatment and the C:N ratio. As expected, cellulose decreased with age across most sites as decomposition occurred. Cellulose is easily decomposed, leading to rapid decreases in C as microbial fauna digest the wood particles respiring C.

In contrast to cellulose, lignin is a complex polymer of phenylpropane units that is difficult to characterize biochemically and difficult for microbes to degrade (Ruiz-Duenas and Martinez, 2009). This makes lignin one of the most slowly decomposing components of dead vegetation (Rahman et al., 2013). Thevenot et al. (2010) explain that lignin exists as different complex polymers. They found that decomposition rates were different in each of these polymers and that the variability in decomposition rate observed under forest conditions could be explained by a higher heterogeneity of vegetation and land-use, soil properties (e.g., mineral composition and pH) and climate (e.g., temperature and water content). They also found that gymnosperms (i.e., our conifers) took longer to decompose than other types of vegetation. Ruiz-Duenas and Martinez (2009) explain how the molecular structure and

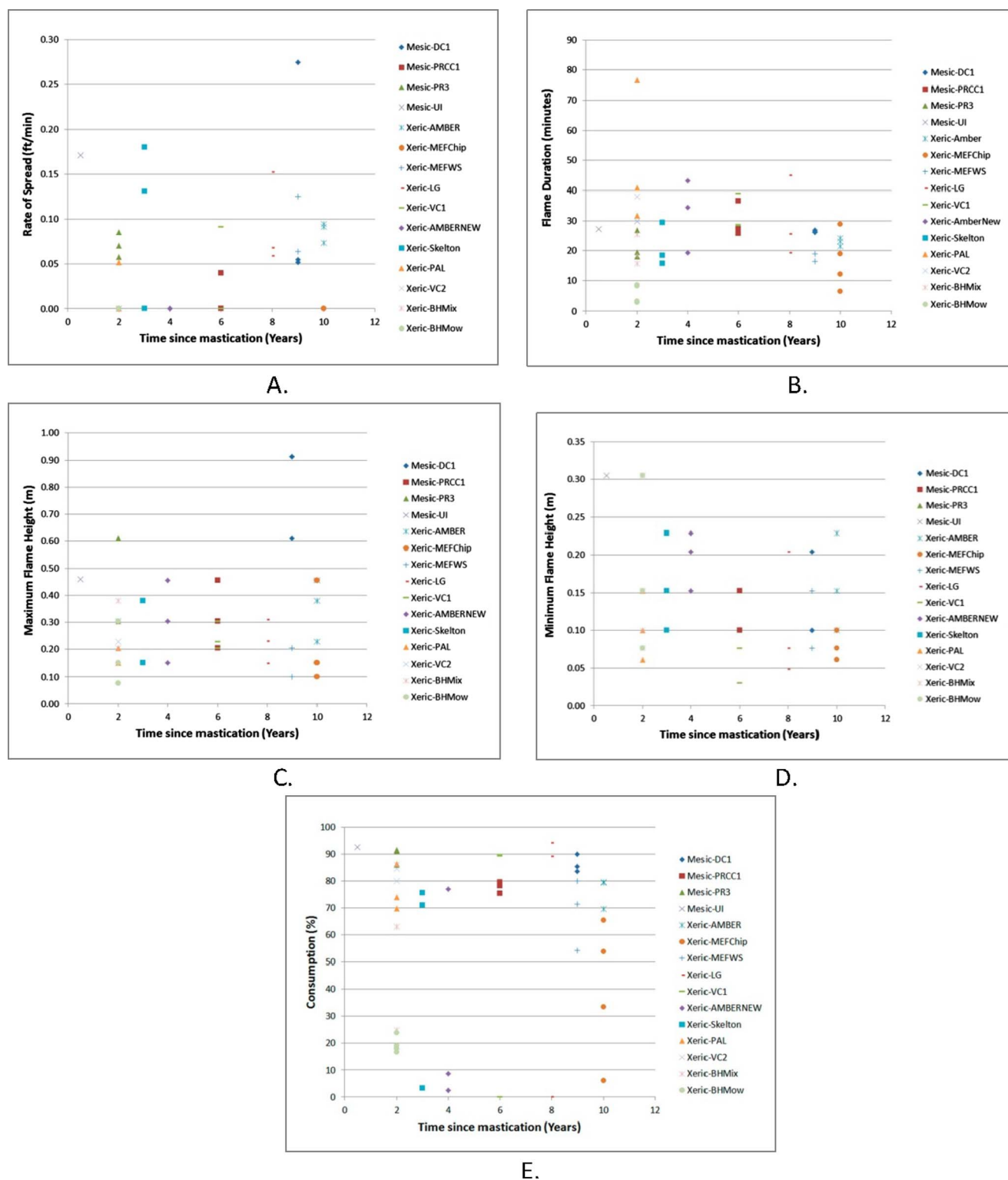


Fig. 5. Fire behavior characteristics by time since treatment shown for the experimental burns on materials from each sample site. Characteristics include (A) rate of spread, (B) flame duration, (C) maximum flame height, (D) minimum flame height, and (E) percent consumption for each fuel bed. For information on each individual burn, see Heinsch et al. (in press). All site names are defined and described in Table 1.

complexity of these polymers make it hard for bacterial and fungal colonies to invade the wood, which makes decomposition much more difficult; but Larsen et al. (1978) pointed out that common fungi are able to adequately fixate nitrogen and decompose Douglas-fir and western hemlock found in the Rocky Mountains and that the fungi coexist in the woody substrates to fix appreciable amounts of nitrogen. In our study, soils and climate conditions varied from north to south at

the sample sites and the lignin content investigated was in wood particles not soil. Lignin in the masticated wood particles did not appear to change significantly in the 10 years examined in this study, as can be common with recalcitrant lignin. Because lignin increased at some sites and decreased at others, the use of paired sites in the study as opposed to a true chronosequence could also affect the results. Other factors, not studied here but highlighted by Thevenot et al. (2010), that could

Table 5

Mean values for smoldering characteristics. TSM = Time since mastication (i.e., time lying on ground); BS = Bare soil substrate; DD = Dry duff substrate. – indicates insufficient duff available for burning. Missing values were imputed for analysis in the PCA. Smolder duration is the time of burning without visible flames. Max temp is the maximum temperature achieved at the interface between the sand and the fuel bed during the smoldering.

SITE	TSM years	Total fuel load g cm ⁻²	Substrate Type	Smolder Duration min	Smolder Max temp °C	Substrate Type	Smolder Duration min	Smolder Max temp °C
<i>Mesic Sites</i>								
DC1	9	260.70	BS	35.0	225.0	DD	44.7	296.0
PRCC1	6	282.38	BS	–	–	DD	–	–
PR3	2	125.66	BS	12.9	226.7	DD	–	–
PR3	2	125.66	BS	27.4	225.8	DD	–	–
UI	0	415.55	BS	–	–	DD	–	–
<i>Xeric Sites</i>								
Amber	10	129.20	BS	60.5	204.9	DD	91.6	219.6
MEF-Chipped	10	95.60	BS	7.6	67.7	DD	–	–
MEF-Chipped	10	95.60	BS	6	109.3	DD	–	–
MEF-WS	9	74.80	BS	6.3	127.8	DD	–	–
MEF-WS	9	74.80	BS	6.3	153.2	DD	–	–
LG	8	192.73	BS	17.5	233.5	DD	192.5	362.8
VC1	6	289.89	BS	60.7	291.6	DD	100.9	348.5
Amber New	4	242.80	BS	37.7	285.5	DD	52.1	316.6
Skelton	3	137.80	BS	14.8	113.9	DD	–	–
Skelton	3	137.80	BS	17.0	182.4	DD	–	–
PAL	2	192.40	BS	43.3	276.5	DD	170.8	388.3
VC2	2	165.81	BS	32.7	231.9	DD	136.3	311.5
BHMix	2	124.27	BS	19.7	112.3	DD	150.9	354.8
BHMow	2	72.79	BS	10.7	88.1	DD	10.7	88.1
Average				24.5	185.7		105.6	298.5

contribute to the differences in lignin contents found in this study, include climate, soil conditions, site temperatures, microbial fauna, and fungal diversity (Jurgensen et al., 2003; Fissore et al., 2016) (Fig. 8).

Complicating the interpretation of our chemical results is the fact that changes happened differently in fragmented particles than in intact particles (Table 2). It was evident that decomposition occurred in both types of particles over time because the C:N ratio did not vary between the two types. However, C and N content responded differently at different locations. Differences in lignin were more apparent at xeric sites, while cellulose differed between intact and fragmented particles at mesic sites, which may indicate that changes in climate, and therefore microbial fauna, also plays a strong role in the decomposition of these wood particles. Hattenschwiler and Gasser (2005) found that litter species richness and soil fauna interactively determine rates of decomposition in a deciduous temperate forest, indicating a range of controls on litter diversity that effects ecosystem C and nutrient cycling. Edmonds also discusses how climate, fauna, litter, and organic matter

interact to influence decomposition rates at https://forest.moscowfs.wsu.edu/smp/solo/documents/GTRs/INT_280/Edmonds_INT-280.php.

He suggests that N can be tied up for long periods of time in coarse woody debris like these masticated particles. In our study, lignin and cellulose did not exhibit the same responses as C. This may be a function of mastication. Intact particles retain full structure and were usually protected by bark. Fragmented materials, on the other hand, are more exposed at the soil surface, allowing chemical changes to occur more quickly.

Only three factors known to be important to decomposition were examined in this study (Fig. 8), and their effects were not examined comprehensively. Keane et al. (2017) examined wood quality and structure in individual particles, including particle bulk density across a variety of species typically found in mixed-conifer forests. Both the size and shape of the materials themselves (Keane et al., 2017) and the type of particle (fragmented or intact) were important to decomposition rates. However, particle density was included in each chemical value

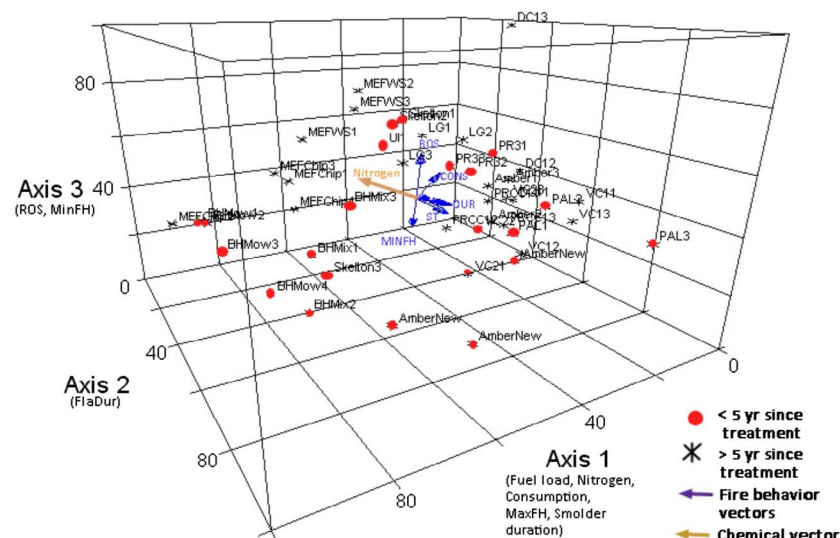


Fig. 6. Principle component analysis (PCA) correlation biplot of masticated sites using all chemistry, fire behavior, and smoldering variables for a burn on **bare soil**. Each experimental burn (black stars) is shown with a name and burn replicate number. Abbreviations are as follows: DUR = Flame and smoldering duration dry sand (minutes); ST = Smoldering maximum temperature bare sand (°C); Min FH = Minimum flame height; MaxFH = Maximum flame height; CON = Consumption; FlaDur = Flame duration in experimental burns; ROS = Rate of spread. Angles and lengths of vector lines indicate direction and strength of relationships of the fire behavior and chemical variables with the ordination scores. Variation explained in this ordination by axis 1 = 35.58%; axis 2 = 26.85%; and axis 3 = 11.52%.

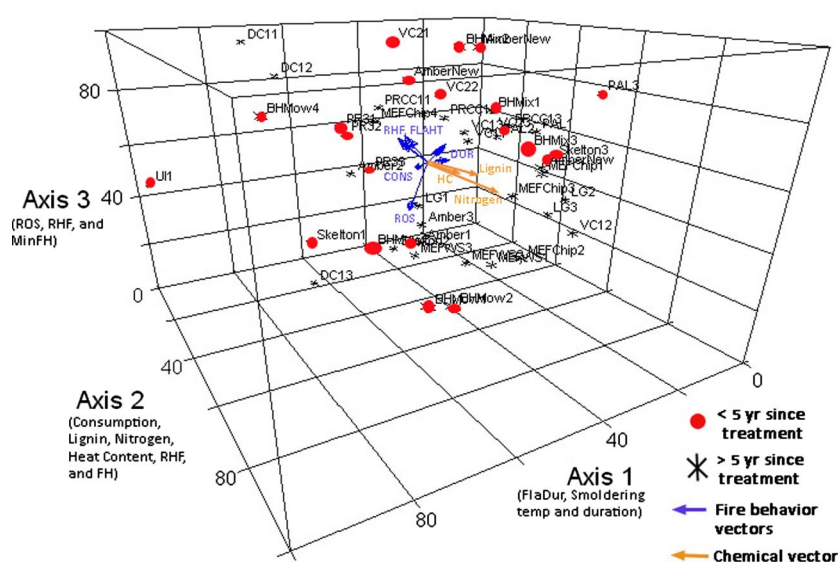


Fig. 7. Principle component analysis (PCA) correlation biplot of masticated sites using all chemistry, fire behavior, and smoldering variables for a burn on dry duff. Each experimental burn (black stars) is shown with a name and burn replicate number. Abbreviations are as follows: DUR = Flame duration and smoldering duration on dry duff (minutes); FlaDur = Flame duration in environmental burns; FLAHT = Flame height; MinFH = Minimum flame height; RHF = Radiant heat flux; CONS = Consumption; ROS = Rate of spread. Angles and lengths of vector lines indicate direction and strength of relationships of the fire behavior and chemical variables with the ordination scores. Variation explained in this ordination by axis 1 = 33.44%; axis 2 = 30.85%; and axis 3 = 11.26%.

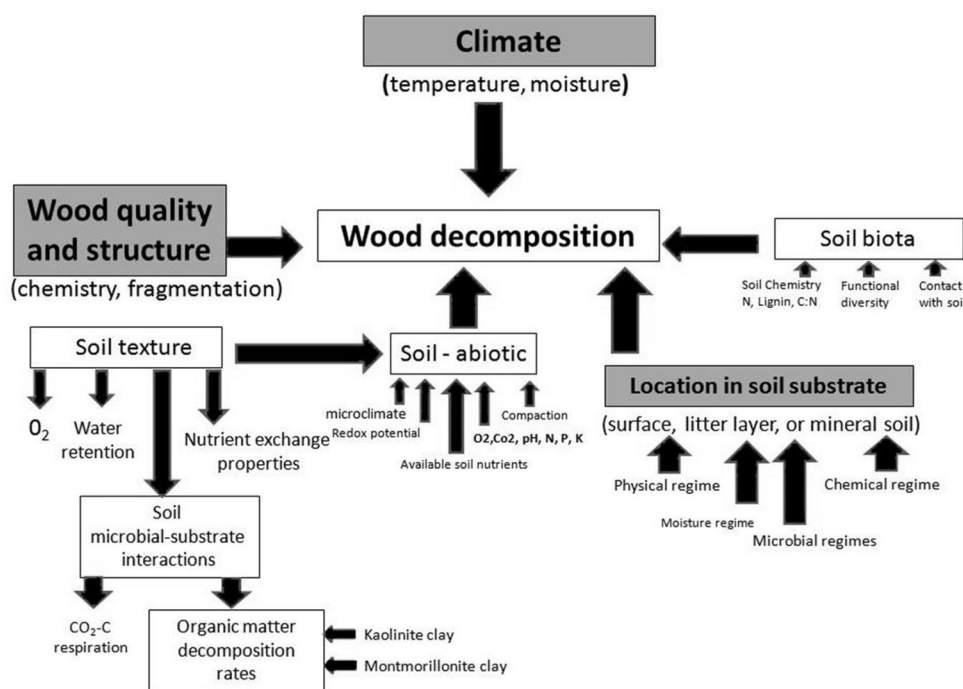


Fig. 8. Factors affecting wood decomposition (summarized from [Finer et al., 2016](#); [Jurgensen et al., 2006](#); [Laiho and Prescott, 2004](#); [Moroni et al., 2015](#); [Palviainen and Finer, 2015](#); [Silver and Miya, 2001](#); [Fissore et al., 2016](#); [Seely et al., 2010](#); [Yatskov et al., 2003](#); [van der Wal et al., 2007](#); [Larsen et al., 1978](#)). Only wood quality, moisture, and depth and bulk density of the masticated layers in relation to the litter layer and mineral soil substrate during deposition were examined in this study (highlighted in gray).

when it was converted to a volumetric value for analyses in this paper so it may not appear obvious that the analyses already included these factors. Climate was examined by collecting masticated particles from a large geographic region of the western U.S. Separating sites into mesic and xeric sites from this area allowed for examination of the effects of climate moisture; however, the effects of temperature were beyond the scope of this study. Finally, the mastication process itself affects decomposition in an important way. Masticated materials are most often deposited on the soil surface and covered with new litter or they were slightly embedded in the duff horizon. In a companion paper, we examine the effects of how the machinery creates particles, deposits them on the soil surface, and compresses them into the soil, possibly increasing soil contact and, therefore decomposition ([Jain et al., in preparation](#)). The mastication treatment method itself can strongly affect the size, surface position, and environment where these particles are laid down to undergo decomposition.

4.2. Relating time since treatment to fire behavior characteristics

Attempts to relate age of particles directly to our fire behavior were not successful. Surface fire behavior in all masticated fuel beds can be characterized as low in several key characteristics, including flame dimensions, rate of spread and energy release, which made it difficult to associate the observed fire behavior directly with time since treatment. Consumption in experimental fuel beds varied greatly as a result of variation in fire behavior. Many fires burned primarily under flanking fire, which is less intense than heading fire ([Byram, 1959](#); [Albini, 1976](#); [Wade and Lunsford, 1988](#); [Pyne et al., 1996](#)). Some fuel beds were unable to burn because the fuel load was likely too small to carry the fire. Finally, fires were extinguished after an hour if they did not extinguish naturally, which reduced the amount of consumption that could be recorded. In this study, we also found that the substrate beneath the masticated fuel plays a significant role in consumption. Temperature and duration of burn are much more intense above dry

duff than above dry sand. The presence of duff, then, increases the heat value, thereby increasing consumption. Given the minimal fire behavior observed in this and other studies (e.g., Glitzenstein et al., 2006; Kreye et al., 2011; Kreye and Kobziar, 2015), resistance to control as a result of glowing combustion is likely to be of greater concern than consumption. Masticated fuels can burn for a very long time (Kreye et al., 2014). In both laboratory and field fires, residual flaming masticated woody fuels sustained glowing combustion for up to an hour after the initial flaming front had passed (Knapp et al., 2011; Busse et al., 2006; Brewer et al., 2013; Kreye et al., 2014). When residual heat remains, a change in the weather could cause transition to flaming in these surface fuels, leading to issues related to resistance to control (Bass et al., 2012). In addition, the smoldering tests used in this study demonstrate that masticated materials may burn hot enough and long enough to affect vegetation and soil microbes, which would have effects on regeneration at treated sites. However, Hartford and Frandsen (1992) found that high temperatures at the surface do not automatically mean high temperatures in the subsurface. In their study, surface temperatures could become as high as 690 °C, but moisture and mineral content in the duff could prevent high temperatures from progressing downward into the soil (Hartford and Frandsen, 1992). Small variations in species could also vary fire behavior characteristics (van Wagtenonk et al., 1998; Beyler et al., 2014). This study focused on mixed-conifer forests; but conflicting results have occurred from studies in shrublands with different species. In these studies, their heat transfer to soil varies because fuels loads are smaller and shrubs have different resistances to burning.

4.3. The multivariate view

Attempts to relate time since treatment to fire behavior characteristics in this study with PCA were unsuccessful. Young sites were intermixed with old sites in both sand and dry duff runs across all axes in the PCA. Therefore, the process of aging and decomposition in these materials is much more complex than simply determining how long they have been on the ground. The fire behavior characteristics were also not strongly correlated with the sites, which is evident from the short vectors in the PCA biplot. As previously mentioned, surface fire in these burns was minimal and, as a result, consumption varied greatly in the experimental burns so strong correlations would not be expected. Glitzenstein et al. (2006) and Kreye et al. (2011) found the same slow rates of spread and short flame heights as we did in their burns of masticated materials in South Carolina and in laboratory burns of *Arctostaphylos manzanita* Parry and *Ceanothus velutinus* Dougl., respectively, so our burn characteristics were not unique.

The differences between burning on dry sand and dry duff, however, gave quite different perspectives on what is important in burning masticated materials on different soil substrates. On dry sand, fuel load is most important to the fire behavior characteristics even though it was not directly used as a variable in the PCA inputs. Rate of fire spread and flame duration also correlate with these older materials. Minimum flame height, however, correlates with materials from the young sites. Nitrogen content, either in the form of chemicals in the wood or lignin in the particles, is also important. Nitrogen correlates in PCA space with sites that were treated nine to 10 years ago, thereby leaving more time for decomposition to take place. A different perspective is given in the PCA run with dry duff. Most important to the distribution of these sites in 3-D space is the duration of flaming and smoldering, which explains over 33% of the variation in the data. Secondary to burn duration is chemical content and consumption. Nitrogen, lignin, and heat value are all strong vectors that correlate in space with materials from sites that have lain on the ground for more than five years. As opposed to the dry sand run, both young and old sites in the dry duff run correlate with rate of spread and consumption. The most important observation from the multivariate analyses is that the soil substrate can make quite a difference in the duration and temperatures of burns in masticated fuels

that will need to be planned for in treatment prescriptions.

5. Management implications

This study examined the effects of time since treatment on fire behavior characteristics. Only by using multivariate analyses could any correlations with particle age be found with the variables and these differed depending on the type of soil substrate tested. The PCA showed that, as materials age, chemicals become important to grouping the mastication sites. Fire behavior characteristics are less important than the chemical changes judging by the length of fire behavior and chemical vectors in the PCA. This study showed several considerations, based on fuels, soils, and fire behavior, that managers will need to take into account when deciding whether or not to use mastication to treat biomass in forests or shrublands. These include the following:

- Chemical changes occur with time since treatment. In this study, fragmented particles have higher heat value, which will affect fire behavior. C and N content are key to all fuels, regardless of age. Cellulose C shows some changes in both mesic and xeric sites with the 10 years of this study. Changes in lignin (N) content changes within the particles, however, do not show clearly defined trends. Changes in chemical composition have occurred over four to 10 years, and they were accelerated by fracturing the particles in mastication. In the PCA, they appear to have a negative correlation with burning characteristics in that the vectors of these two types of variables point in opposite ways. Finally, even after 10 years, obvious changes in lignin or cellulose content are not clearly evident between the mesic and xeric sites.
- Soil subsurface will affect the burn characteristics more than the time that material has lain on the ground. A subsurface of dry duff will affect burn characteristics differently than a subsurface dominated by dry sand. When burning on a dry sand substrate, fuel load is probably the most important consideration. On a dry duff substrate, however, the most important consideration will be the duration and temperature of the burns. In the experimental burns conducted within this study, surface fire behavior was minimal. However, high possible temperatures from glowing combustion must be considered as a strong fire behavior characteristic - especially if duff is present.
- Moisture in the subsurface soil matters to smoldering characteristics. In this study, very dry conditions were used to determine worst-case scenarios because long-term drought has been prevalent in the western U.S. Heat was only measured on the surface but, if pulsed into the soil at high enough temperatures and long enough duration, it could kill roots, seeds, soil biota, and microbes in smoldering burns (Albini, 1976). If prescribed burns are to be conducted to completely remove surface fuels after mastication, managers will have to consider timing in the context of season to minimize the effect on soil for revegetation, recovery, or restoration (Harvey et al., 2000). Burning the same year as mastication may be difficult to get desired removal of the fuels when they are still wet but soil recovery may be optimum (Byram, 1959; Albini, 1976; Harvey et al., 2000). Waiting until the masticated fuels have dried will require considerations of higher temperatures and durations than if soil moisture is high. However, age (over the range explored here) was not significant when these smoldering burns were tested so managers may be able to wait for better soil moisture conditions.
- Fuel loads matter (Fig. 6). In both the experimental and smoldering burns, sites with high fuel loads, such as DC1 and AMBER, carried the fire better than those with small fuel loads, such as at the mowed sites in the Black Hills. Fuel load contributed to the PCA results even though it was not a direct input into the PCA runs. The contribution of fuel loads to burn characteristics has also been observed by many others (Reiner et al., 2009; Battaglia et al., 2010; Kreye et al., 2014; Harvey et al., 2000).

- Mastication alters fire behavior in the fuel bed. As has been found in other studies, slow fires with glowing combustion were common. Even in beds with higher loads, consistent flaming fronts with flames higher than 1 m were not obtained in all replicates from the same site (Fig. 4). The burn characteristics from these fires were partially correlated with time since treatment/decomposition only when examined as part of a multivariate framework.
- Fuel loads and piece size can be manipulated during mastication (Jain et al., in preparation). This study comprised only 1-h to 100-h fuels, but many mastication treatments also focus on leaving large 1000-h logs for wildlife habitat. Large logs that smolder for long lengths of time will certainly alter burn characteristics from those observed in this study. This leads to issues of resistance to control of smoldering fires in masticated fuels, which may be a more important consideration than fire behavior characteristics during an active fire. Anecdotal evidence indicates that masticated fuel burns much longer than other fuel types (Bass et al., 2012). Masticated fuel is rarely spread evenly across an area, and pockets of high fuel concentrations have been known to smolder for long periods of time (Kreye et al., 2014). When residual heat remains, a change in the weather could cause transition to flaming in surface fuels, leading to issues related to resistance to control (Bass et al., 2012). Given the minimal fire behavior observed in this and other studies, resistance to control, as a result of glowing combustion, is likely to be of great concern.

6. Conclusion

Decomposition of wood particles happens slowly in the Rocky Mountains but chemical changes have certainly occurred within these sites during the 2–10 years that their particles have lain on the ground. Time since treatment does not specifically correlate with the burn or smoldering characteristics. Soil substrate, however, is important to both. Mastication has accelerated the decomposition process, but the roles of several other factors that are normally associated with decomposition were not addressed. Studies on how these additional factors, such as relationships of soil biota, soil texture, or soil microbial-substrate interactions (Fig. 8), affect masticated wood could clarify how decomposition progresses in these unique fuel particles.

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