



Project Title: Masticated Fuels and Carbon Storage: Effects of Particle Size and Fuel Moisture on Black Carbon Production

Final Report: JFSP Project Number 11-3-1-30

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This research was sponsored in part by the Joint Fire Science Program. For further information go to www.firescience.gov.



I. Abstract

Forest managers are currently tasked to consider carbon retention as part of their management objectives at the stand level, including hazardous fuels reduction, which temporarily removes live-tree biomass carbon from a stand when prescribed fire follows the thinning treatment. Mastication, a cost-effective mechanical thinning treatment often followed by prescribed fire, is being increasingly utilized in many forests throughout the Western United States. As recently noted and tragically highlighted by the case of the North Fork Fire, CO, a thorough understanding of the fire behavior and subsequent effects of masticated fuel fires is lacking. To date, studies evaluating stand level carbon following such thin and burn procedures have not characterized the carbon remaining in the post-fire residues, often referred to as black carbon. Black carbon found in the charred post-fire residues is the byproduct of incomplete combustion. Due to structural changes brought about through the thermal alteration process, black carbon can have dramatically longer residence times (~100's to 1000's of years) in soils relative to unburnt soil organic matter (~10's to 100's of years). Due to its increased residence times, black carbon has received international attention as a potential avenue in which fire-affected forests may sequester carbon over extended time periods, as it is incorporated into forest soils and stored.

In order to better inform management decisions utilizing mastication, and in light of global efforts to use forests as long-term carbon sinks, we experimentally tested how black carbon was produced in masticated fuel beds. Specifically, we evaluated how (1) changes in fuel moisture influenced the black carbon produced, and (2) how particle size of the masticated woody material affected the amount of black carbon produced.

Major Findings:

- Black carbon production increased when burnt at higher fuel moistures,
- Higher quantities of black carbon were produced when masticated particles were small (i.e. < 1.3 cm in diameter).
- Radiant energy released from dry masticated fuel particles was several 100% greater per gram of fuel combusted than that released for wet masticated fuel particles. We observed similar differences per gram combusted for wet and dry pine needle and excelsior fuel beds.

II. Background and Purpose

Forested ecosystems have recently received attention for their potential role in sequestering carbon to help offset global greenhouse gas emissions from fossil fuel and biomass burning. As a result of this attention, policy and management efforts are currently being encouraged to include carbon inventories at the stand scale. A potential key contributor to long-term carbon storage in fire-affected ecosystems is the production of fire-altered charred residues remaining after a fire, commonly referred to as black carbon (BC; DeLuca and Aplet, 2008). BC has the potential to persist in terrestrial soils for thousands of years, thereby slowly increasing forest soil carbon stocks over time and multiple fire events. To provide more accurate accounting of stand-level carbon, future assessments should include some measure of the BC produced in fire events.

Throughout the forests of the Western United States, successful fire exclusion policies have led to large increases in biomass accumulation (Agee and Skinner, 2005). In many of these fire-affected forest systems, thinning and prescribed fires are commonly used to reduce excessive build-up of fuels. These management practices actively remove above-ground carbon in order to maintain ecosystem function and increase stand resilience to future disturbance, an increasingly important goal in the face of climate change and the potential increase of larger, more intense fires (Westerling et al., 2006). Mastication is an increasingly common forest thinning treatment in which a tracked or wheeled excavator mounted with a rotating head or drum grinds down smaller trees and shrubs, effectively reallocating aerial fuels to the forest floor (Battaglia et al., 2010). Oftentimes prescribed fire treatments are employed following mastication to reduce surface fuel loadings and to further reduce the threat of high-intensity wildfire.

The impact of fire in masticated fuels on the production of BC is largely unknown. Given the potential significance of BC, we think it is important to identify the mechanisms controlling BC in masticated fuels. However, effectively quantifying the highly resistant BC portion in the post-fire charred matter can be exceedingly difficult given the large variability in chemical structures that exist in these residues. Conceptually, fire-altered residues exist on a continuum, ranging from partially-charred plant material, with high O:C ratios, to re-condensed soot and BC, with low O:C ratios (Preston and Schmidt, 2006). Several factors control the chemical structure, and ultimately the soil residence times of the burnt materials. Two primary factors are 1) the pre-fire fuel composition and arrangement, 2) the fire intensity (e.g. fire temperature and duration; Czimczik and Masiello, 2007).

In addition to the variability in chemical structure of the burnt material, several quantification techniques have been employed in the past to quantify BC (Hammes et al., 2007). Each method effectively isolates different portions of the BC continuum, making it difficult to interpret results across studies (Forbes 2006). This report will differentiate between:

- 1) *Post-fire residues*: the terms “charred residues” or “post-fire residues” simply refers to all of the charred organic material following a fire.
- 2) *Pyrogenic carbon (pyrC)*: refers to all of the fire-altered carbon within the post-fire residues, regardless of its resistance to future degradation mechanisms.
- 3) *Black carbon (BC)*: defined as the highly thermally resistant portion within the pyrC (see Study Description for exact quantification procedures).

In response to the growing needs of land managers to account for stand-level carbon, this work proposed to identify mechanisms influencing the production of BC in masticated fuels. Specifically, this research was developed in response to a 2010 call for a Graduate Research Innovation Award. It addresses the objective of fuel management effectiveness and effects on forest carbon balances.

This topic was addressed by designing two sets of experimental combustion studies using custom masticated fuel beds. The specific research objectives of this study were to:

- 1) Measure effects of fuel moisture on the carbon allocation in the post-fire residues when burning masticated fuel beds.

1b. Ancillary Objective: Evaluate effect of moisture content on radiant energy release in the masticated fuel beds, pine needle fuel beds and excelsior.

2) Objective: Quantify the effects of masticated particle chip size on the carbon remaining in the post-fire residues.

Fuel Bed Construction

An 8-ha mixed conifer stand, comprised of white pine (*Pinus monticola*) and Douglas-fir (*Pseudotsuga menziesii*) ingrown with lodgepole pine (*Pinus contorta*), on the Clearwater National Forest (Latitude 46.801 N, Longitude 119.47 W) in Idaho was masticated in June 2009. Mastication thinning was implemented in the stand to reduce canopy bulk density and wildfire risk as well as improve stand health for the remaining trees. Masticated particles were primarily chipped into smaller diameter (< 7.6 cm) particles, although large-diameter >7.6 cm particles and logs were also present. Fuel loading from this stand was established to ensure the laboratory-

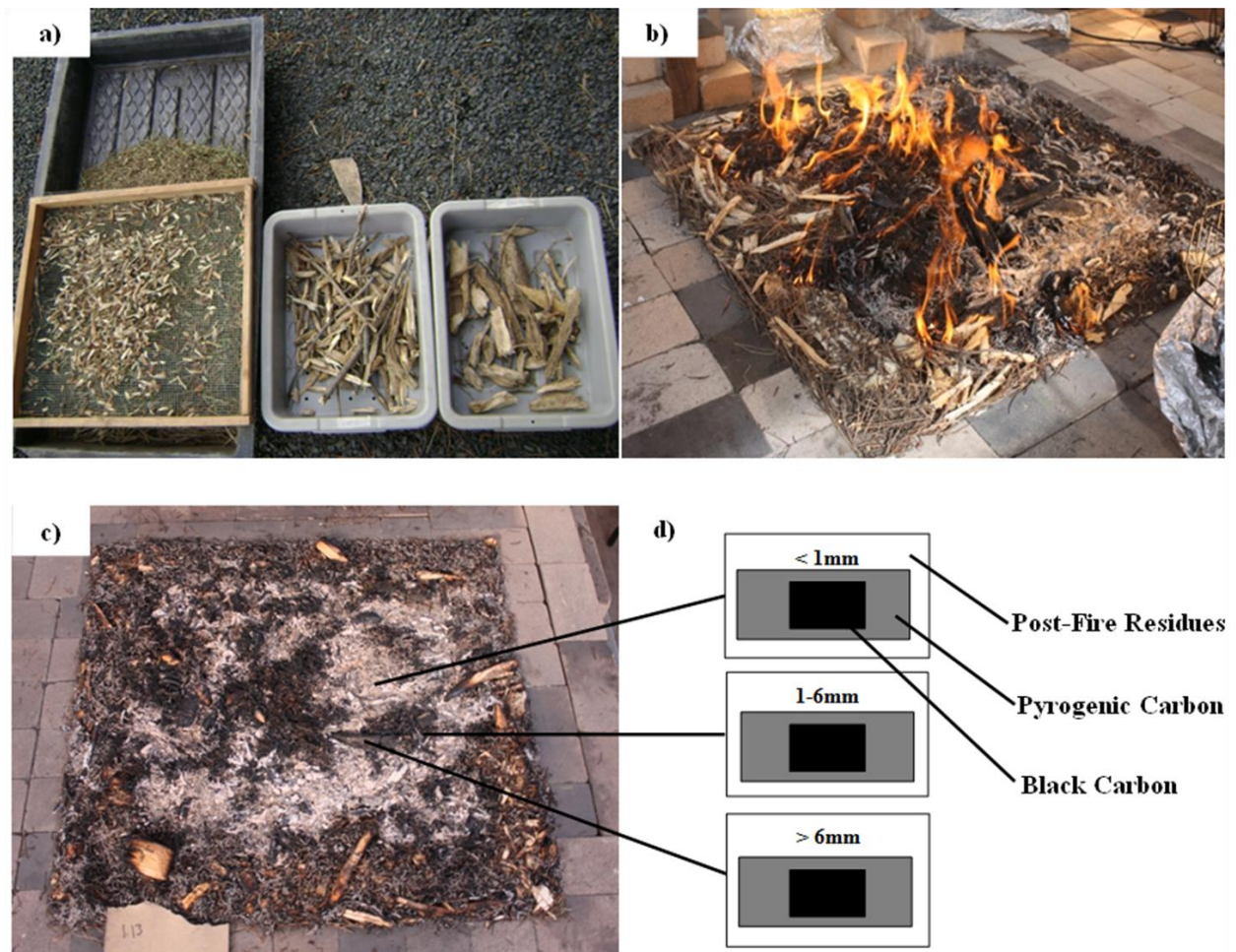


Figure 1: Images of: a) fuel bed construction of the individual size classes, b) a masticated fuel bed during combustion, c) post-fire residues, and d) a conceptual diagram of the carbon components associated with the residues after sieving.

created fuel beds closely resembled conditions in the field. The stand was sampled for fuel loading using square frame methods adapted from Hood and Wu (2006). Using a random start location within the stand, a quadrat (0.37 m^2) was placed at distances of 5, 10, 15, 20, and 25 m from the starting point in the four cardinal directions for a total of 20 plots. Fuel bed height measurements were taken at the four corners of the quadrat and once in the center; and fuel bed bulk density was determined by dividing the dry weight of fuel within the quadrat by the volume of the fuel bed. Fuels within the quadrat were removed to mineral soil, placed in a bag, and transported back to the University of Idaho's Fire Laboratory. Due to their high degree of spatial variability, fuels $>7.6 \text{ cm}$ in diameter were excluded from the experiments. Fuels from each of the 20 plots were then individually sorted into five separate size classes ($7.6 - 2.5 \text{ cm}$, $2.5 - 1.3 \text{ cm}$, $1.3 - 0.6 \text{ cm}$, and $0.6 - 0.3 \text{ cm}$, and needles), dried at 100°C until weights remained constant, and weighed. Fuel loadings for these fuel beds averaged 58.35 Mg ha^{-1} , which were slightly lower than to masticated fuel loadings in mixed conifer stands measured in Colorado (Battaglia et al., 2010). In addition to the 20 samples taken for fuel loading determination, masticated fuels

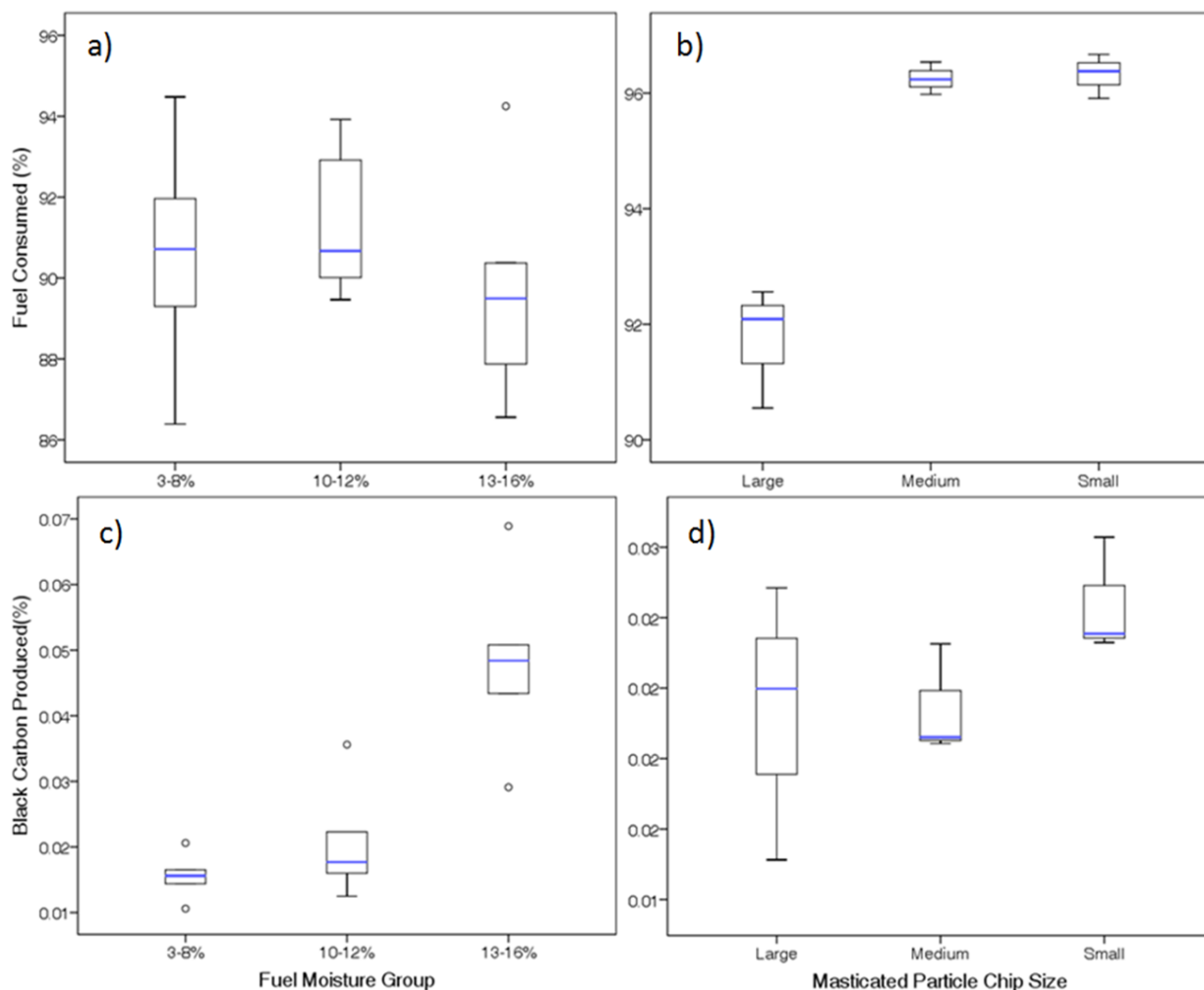


Figure 2 Consumption (%), and BC produced (%) as a function of fuel moisture (panels a and c) and masticated particle size (panels b and d).

were collected *en masse* from the site and also sorted in a similar manner for the construction of the experimental fuel beds (see figure 1a).

For the fuel moisture experiment a total of 15 fuel beds were assembled by recombining the sorted particles, using estimates of average dry weights of each size class. Replicates of five fuel beds were designated to one of three pre-determined moisture levels of 3-8%, 10-12%, and 13-16%; fuel moisture was measured as a proportion of the dry weight. The pre-constructed fuel beds were stored in a chamber with average fuel moistures ranging from 10-12%. The five fuel beds to be dried to 3-8% were taken from the control chamber the day of the burn trial and were dried in a convection oven for 4 hours at 37.5 °C, to simulate the temperature conditions similar to those of a hot summer day in the Northern Rockies when a wildfire might occur. The five fuel beds to be burnt at the 13-16% level were exposed to ambient conditions during the spring months of March and April to simulate conditions which might exist during prescribed fire settings. Prior to ignition for each burn, fuel moisture samples were taken from a small bin of excess fuel particles allowed to condition similar to the fuel beds ($n = 10$ for each size class of the fuel bed).

For the particle size experiment a total of 9 fuel beds were constructed and burnt. Three woody size classes (7.6 – 2.5 cm, 2.5 – 1.3 cm, and 1.3 – 0.3 cm), comparable to 1, 10, and 100 - hr fuels were set to evaluate the effects that fuel particle size had on BC production. Each size class contained three replicates for a total of 9 experimental trials. Dry weight of the fuel bed was held constant, and bulk densities of the fuel beds varied slightly as a function of the size of the masticated particles.

Fire Measurements

The fuel bed was thoroughly mixed in a large bin for one minute, spread onto the burn table over the 0.37 m² area, and compressed to achieve the average bulk density observed in the field (see figure 1b). A dual band spectrometer was placed over the fuel bed and fire radiative power (FRP, W m⁻²) was logged at five second intervals throughout the burn trial. FRP measurements were integrated over the time of the burn trial to calculate Fire Radiative Energy (FRE). Temperature and relative humidity readings were recorded every five minutes throughout the trial with a Kestrel[®] 3000 pocket weather meter to validate that ambient conditions were not responsible for differences in fire behavior. The fuel beds were burnt on a Sartorius EB Series scale (Goettingen, Germany) to log mass loss throughout the burn period. The burn trial was considered complete when mass was no longer lost.

Post-fire Carbon Analysis

For both sets of experiments, post-fire residue mass (g) was first established by weighing post-fire materials immediately following the burn trial (see figure 1c). Remains of the fuel beds were then dry sieved into 3 size classes (< 1mm, 1 - 6mm, and > 6mm) and weighed, as the composition of each size class was likely to vary as a function of parent materials [Nocentini *et al.*, 2010]. Two samples were then taken from each size class for further analysis, one for pyrC and the other for BC analysis (see figure 1d).

For pyrC, the concentrations of organic C and nitrogen (N) in all samples were measured via high temperature combustion (ECS 4010, Costech Analytical, Valencia, CA). Carbon to Nitrogen (C:N) ratios were calculated by molar ratio. PyrC concentration (%C) of the residue was then multiplied by the mass (g m^{-2}) of the post-fire residue to calculate pyrC production for each of the fuel beds.

The second sample was analyzed for BC using an adapted thermo-chemical method outlined in (Gustafsson et al., 1997; Hatten and Zabowski, 2009). Samples were dried at 100°C , weighed, spread evenly across the bottom of a 35-mm ceramic crucible, and placed in a pre-heated muffle furnace at 375°C for 20 hours to remove any organic, non-recalcitrant carbon. Care was taken to maintain a sample thickness of $< 1\text{ mm}$ to prevent additional pyrolysis from occurring in the muffle furnace. Samples were then treated with 6N HCl to remove any carbonates from the sample. Following the thermo-chemical treatment, the samples were elementally analyzed, using the same methods as described above for pyrC. BC production (g m^{-2}) was then calculated by multiplying the proportion of the sample resistant to thermal oxidation by the proportion resistant to chemical oxidation, and then by the mass of the post-fire residue. To determine pyrC and BC production rates, BC and pyrC values were normalized by pre-fire organic carbon content

Statistical Analysis

One-way ANOVA was used to statistically detect differences in production between groups for both experiments ($\alpha=0.05$). Tukeys post-hoc analysis was used to identify homogenous subsets. All statistical analysis was conducted using IBM SPSS statistical software, version 19.

IV. Key Findings

The findings discussed here evaluate both the entire fuel bed, as well as the individual size classes of post-fire residues. Total fuel bed consumption (pre-fire dry weight – post-fire dry weight) provides an initial evaluation of the mass of the fuel bed remaining. PyrC and BC production are the primary variables of interest, and are controlled by the consumption. The BC:pyrC ratio was used as a proxy for the relative recalcitrance of the fire-altered C produced, with higher ratios indicating greater recalcitrance. Both BC and pyrC were quantified in each individual size class of the post-fire fuel bed ($> 6\text{ mm}$ residues, $1-6\text{ mm}$ residues, and $<1\text{ mm}$ residues) in order to better determine the composition and carbon allocation in the post-fire residues. For more in depth findings and discussion please refer to the peer-reviewed journal articles currently in review available through the JFSP website.

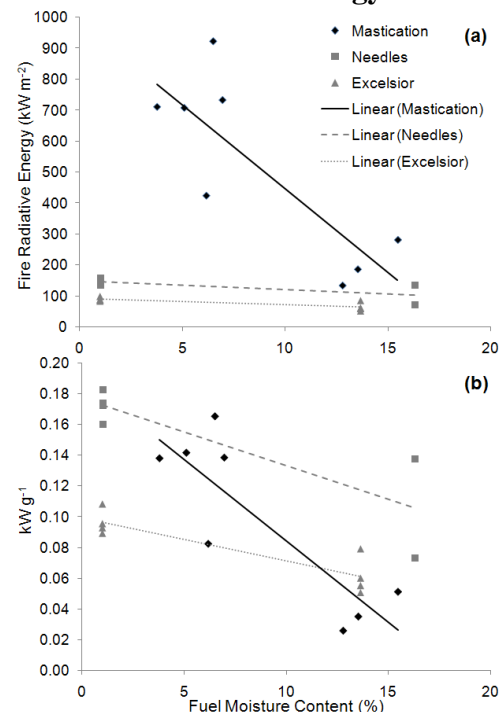
1. Objective: Measure effects of fuel moisture on the carbon allocation in the post-fire residues when burning masticated fuel beds.

- Fuel bed consumption in the masticated fuels ranged from 90 to 91% across all burns regardless of fuel moisture (see fig 2a, $p = 0.622$).
- Total pyrC produced did not vary as a function of fuel moisture; and pyrC production rates ranged from 7-9% (normalized by the pre-fire organic C, $p = 0.638$).

- Total BC production ranged from 0.02 to 0.05% of pre-fire organic C, with production rates in the 13-16% fuel moisture group significantly higher than the two drier moisture groups ($p < 0.000$, see fig 2c). This converts to 4.4, 5.8, and 14.2 kg ha⁻¹ for the 3-8%, 10-12%, and 13-16% fuel moisture groups respectively.
- The BC:pyrC ratio for the entire fuel bed was also significantly higher (5.59×10^{-3}) in the 13-16% moisture group, indicating that a greater proportion of the post-fire carbon was converted to BC when burnt at fuel moistures $> 13\%$ ($p = 0.019$).
- Allocation of the pyrC and BC within the separate size classes of the residues provide valuable insight into the combustion mechanisms responsible for BC production. The greatest proportion of black carbon was allocated in the smallest $< 1\text{ mm}$ sized residues (ranging from 0.27 to 0.90 g m⁻²). This suggests that these residues likely contained recondensed soot and highly recalcitrant BC.
- Larger woody charred residues $> 6\text{ mm}$ contained the smallest amounts of BC (1.88×10^{-3} to 6.59×10^{-3} g m⁻²), indicating that the interior of these particles likely did not reach sufficient temperatures to convert the unburnt organic C to BC.
- The $> 6\text{ mm}$ charred residues contained the highest amounts of pyrC relative to the smaller residues (200.63 to 253.32 g m⁻² in the $> 6\text{ mm}$ charred residues vs. 31.31 – 39.65 g m⁻² in the $< 1\text{ mm}$ residues). Mean residence times in soils associated both pyrC and BC as defined here are difficult to obtain, but given the thermo-chemical treatment procedures the BC was subjected to it may be likely this highly thermally resistant portion of the residues will persist longer in soils.

1b. Ancillary Objective: Evaluate effect of moisture content on radiant energy release in masticated fuel beds.

A comparison of Fire Radiative Energy released by 3 fuel bed types and burnt at 2 fuel moisture levels ($n=8, 8, 6$) is shown in Figure 3 (right). (a) shows total energy released through fuel bed combustion, and (b) FRE normalized by mass consumed. The discrepancy in both total energy released and the normalized energy released between the moisture levels is clear and when contrasting the 3 fuel types it is apparent that the smaller the surface area to volume ratio, the greater the contrast between the moisture levels (Porterie et al., 2007; Knapp et al., 2011). Linear lines of best fit are presented only to show trends. Lower than expected FRE values ($\sim 10\%$) were due to a systematic sensor calibration error.



2. Objective: Quantify the effects of masticated particle chip size on the carbon remaining in the post-fire residues

- Particle size of the masticated chips influenced the amount of post-fire residues present following the burn trials, and overall consumption of the fuel bed varied as a function of particle size, with 91% consumption occurring in the large (7.6 – 2.5cm) size class and 96% consumption in both the medium (2.5 – 1.3cm) and small (1.3 – 0.3cm) size classes (fig 2b, $p < 0.000$).
- PyrC production was also the greatest for fuel beds comprised of large woody particles due to the presence of more large charred material. PyrC production rates ranged from 1% in the small size class to 10% in the large particle size class ($p < 0.000$).
- BC production rates were slightly higher when the fuel beds comprised were comprised of the smallest masticated woody particles (1.3 – 0.3 cm), but results were not significantly different (fig 2d, $p = 0.335$).
- Similar to the fuel moisture experiments, the greatest amount of BC was allocated in the $< 1\text{mm}$ post-fire residues. As consumption increased more of the biomass was converted to ash residue, which contained the majority of the BC produced.
- BC:pyrC ratios were the largest in the small woody masticated fuel beds ($p = 0.015$). These results are particularly interesting in that despite there being greater overall consumption in the small sized fuel beds, BC:pyrC ratios were highest in these fuel beds. However, the increase in BC:pyrC ratio is not necessarily due to increased BC formation, rather the ratio increases due to the lack of pyrC in the remaining residues.

V. Management Implications

Less than 0.1% of the fuel bed organic C was converted to BC in masticated fuels regardless of fuel moisture or masticated particle size. When evaluating the effects of a single fire on a stand's C budget the BC production can never offset the losses in C associated with above ground biomass removal. However, it is important to begin incorporating BC production rates when evaluating stand-level C over time through multiple fire events as residence times associated with this fire altered carbon can be orders of magnitude longer than unburnt soil organic matter (DeLuca and Aplet 2008).

The results of these experiments suggest that burning at fuel moistures $> 13\%$ will maximize BC production and maintain the highest BC:pyrC ratios. Our results align well with Busse et al. (2009) results comparing lethal soil temperatures of burning wet or dry masticated fuels. They found that burning at increased soil moisture reduced the risk of prolonged soil heating. Burning at wetter fuel moistures not only maximizes BC production, but also decrease mortality associated with soil heating.

Particle size of the masticated fuels had relatively little effect on BC production, although the small chipped fuel beds produced slightly higher amounts of BC. To the extent to which masticated particle chip size can be controlled is likely dependent on fuel type and equipment

used. From these results, however, managers should consider using mastication machinery that produces smaller chip sizes to maximize BC production in masticated fuels when mastication is followed by prescribed fire.

VI. Relationship to other recent findings and ongoing work

This research provided a rigorous experimental approach to quantifying pyrC and BC production in masticated fuels burnt in a simulated fire environment. Previous BC studies have utilized muffle furnaces to produce charred samples, which may not accurately capture the dynamic nature associated of wildland fire (Baldock and Smernik, 2002). Unlike Hatten and Zabowski (2009), who also used experimental fires to produce BC, our masticated fuel beds contained woody material and not just pine needles which likely influenced overall BC production and BC:pyrC ratios (which can be considered a proxy for degradation, where lower BC:pyrC ratios likely lead to faster degradation). Results of the fuel moisture experiment are somewhat contradictory to existing models of BC formation (Hatten and Zabowski, 2009; Keiluweit et al., 2010). Previous studies found that biologic degradation, measured via soil incubation, of BC was highest when burnt at low temperatures or severity (Baldock and Smernik, 2002; Hatten and Zabowski, 2009). However, this research found that BC production and BC:pyrC ratios were maximized when fires burnt with lower intensities (i.e. higher fuel moistures). Our results suggest that when masticated fuels are burnt at lower fuel moistures the lignin-based precursors to BC are indiscriminately consumed relative to the combustion that occurred when burnt at fuel moistures >13%.

Fuel type has been identified as a major factor in controlling how much BC is present in soil organic matter (Czimczik 2007). The present work provides a crucial link between pre-fire biomass characteristics (particle size in this case) to direct BC production. In a slash and burn study Eckmeier 2007 found charred residue production to be 4.8% based on pre-fire dry biomass weight, which is similar to the charred residues produced in this study (4-10%). However, simply using residue weight may not provide the necessary accuracy to calculate post-fire C budgets given the pyrC and BC production differences observed in this work. Future research should attempt to use more stringent methods to define post-fire C in the remaining charred residues.

The presence of BC in soil organic matter is not simply the accumulation of BC produced from previous fire events (Ohlson et al., 2009). The fate of BC in soils is also a function of ecosystem properties and the complex interactions of BC degradation mechanisms (Schmidt et al., 2011). Incorporation into mineral soils physically protects BC from degradation and transport off site. For example, fire is required to produce thermally altered BC. However, if a subsequent fire returns to the site before the remaining “old” BC is incorporated, it is susceptible to loss in the new fire. This work was funded through a continuing research grant, where the initial study experimentally quantified BC loss rates associated with repeated burning. Worst-case scenario results (which assumes none of the “old” BC was incorporated into the soil) from this research indicate that 40% of the BC created from an initial fire event may be lost in the subsequent fire. Over 4 repeated burns 99% of the BC created in the original fire is lost through repeated burning. This research suggests that subsequent fires may be a significant mechanism of BC loss, especially in high fire frequency forests where the “old” BC may not have enough time to successfully integrate into the soil matrix.

VII. Future Work Needed

Several questions still exist regarding the influence of fuels management on the long-term “sink” capacity of fire-affected forests. A full accounting of C budgets, which include BC, is necessary in order to make better informed management decisions. Further research is warranted to address the following topics:

- Field validation of the experimental results produced in this study. Did these experimental studies provide an accurate representation of BC production in masticated fuels?
- Also, what are the effects of time on the masticated materials, and will this influence BC production? For example, the bulk density of the fuel bed may increase over time as fuels become more compact. Weathering will likely also influence the fuel particle densities.
- What is the influence of coarse woody debris on BC production? The present study only accounted for fuel particles smaller than 7.6 cm in diameter. Given the differences observed in BC production across the size classes tested here, we would expect CWD alter the BC produced in masticated stands.
- What are the incorporation rates of BC into soils? And what are the primary factors control vertical transport of newly created BC?
- What are the residence times associated with pyrC and BC as defined by methods used in this study?

VIII. Deliverables

Deliverable Type	Description	Delivery Dates
Conference talk/poster	Talk or poster of findings at a related conference: "Effects of Repeated Burning and Fuel Moisture on Black Carbon Production in Masticated Fuelbeds", Brewer, N., Smith, A.M.S., Higuera, P.E., Hatten, J.A., Hudak, A.T. and Ottmar, R.D., Abstract B31F-0379, presented at 2011 Fall Meeting, AGU, San Francisco, Calif., 5-9 Dec	Dec 2011
Masters Thesis	Thesis Defense at the University of Idaho	April 2012
Refereed Publication	The following publications resulted in whole or in part due to the GRIN funding: (1)Brewer, N.W., Smith, A.M.S., Higuera, P.E., Hatten, J.A., Hudak, A.T., Ottmar, R.D. and Kremens, R.L. Fuel Moisture Influences on Fire-altered Carbon in Masticated Fuels: An Experimental Study, <i>Journal of Geophysical Research - Biogeosciences</i> . (2)Brewer, N.W., Smith, A.M.S., Hatten, J.A., Ottmar, R.D. and Tinkham, W.T., Effects of particle size on black carbon production in masticated fuels, <i>International Journal of Wildland Fire, to be submitted summer 2012</i> (3)Brewer, N.W., Smith, A.M.S., Higuera, P.E., Kremens, R.L., Tinkham, W.T., Hudak, A.T., Falkowski, M.J. and Roy, D.P., Controls of moisture on fire radiative energy, <i>Geophysical Research Letters, to be submitted summer 2012</i> (4)Brewer, N.W., Smith, A.M.S., Higuera, P.E., Hatten, J.A., Hudak, A.T., Ottmar, R.D. and Tinkham, W.T., Quantifying the response of fire-altered residue to repeated burning, <i>Nature - Geosciences, to be submitted summer 2012</i>	(1) In review (2) In progress (3) In progress (4) In progress
Training Session	Results incorporated in FOR 450 Fire Behavior Lecture.	March 2012, and ongoing.

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