Forest Ecology and Management 369 (2016) 59–65

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Fuel size impacts on carbon residuals and combustion dynamics in masticated woody debris

D.K. Thompson [a,*], T.J. Schiks [b], B.M. Wotton [b,c]

[a] Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta T6H 3S5, Canada
[b] Faculty of Forestry, University of Toronto, Toronto, Ontario M5S 3B3, Canada
[c] Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre, Sault Ste. Marie, Ontario P6A 2E5, Canada

ARTICLE INFO

Article history:
Received 9 November 2015
Received in revised form 10 March 2016
Accepted 12 March 2016
Available online 21 March 2016

Keywords:
Fuel management
Mastication
Mulch
Smouldering
Black carbon
Pyrogenic carbon

ABSTRACT

Mastication of standing trees to reduce crown fuel loading is an increasingly popular method of reducing wildfire hazard in the wildland–urban interface of Canada. Previous research has shown that masticated fuel beds can leave considerable pyrogenic and black carbon residuals after burning, though the impact of fuel particle size and the influence of combustion dynamics such as the rate of combustion are not understood. Replicated fuel beds of masticated boreal conifer woody debris were experimentally combusted under two moisture content levels and with and without coarser fuel particles (1–3 cm diameter). Pyrogenic carbon production in fragments greater than 1 mm was doubled with the inclusion of coarse fuel particles, and carbon content of the pyrogenic carbon increased to 80%. Conversely, combustion dynamics such as the duration and mean mass loss rates during flaming and smouldering phases were controlled exclusively by moisture content, with no effect of particle size. Pyrogenic carbon production in fragments <1 mm in size was independent of moisture or size treatment, but related to two metrics of combustion dynamics: maximum conductive heat flux and the duration of combustion. Prescribed burning of masticated fuel beds undertaken with both coarser fuel particles while under moderate moisture conditions will achieve both a higher yield of residual carbon owing to the particle size effect, as well as limiting the intensity of combustion due to the moisture content effect.

1. Introduction

Wildfire is an important disturbance and driver of ecological processes across numerous terrestrial ecosystems. In many fire-prone landscapes, land management agencies attempt to align the ecological requirement for this disturbance with the need to protect public safety, property and natural resources (Martell, 2015). One objective of fire management is to reduce the risk of wildfire spreading from unoccupied lands into human development, the intersection termed the wildland–urban interface (WUI). Predicted increases in the frequency and severity of wildfire (Flannigan et al., 2013), coupled with increasing rural development, suggest that efforts to protect communities and other values is a growing concern. The Canadian wildfire regime is dominated by crown fires (de Groot et al., 2013), with spotting from high-intensity crown fires being the utmost threat to communities, as shown in the 2011 Slave Lake fires in Alberta that caused $700 million CDN in damages and destroyed 375 homes (Flat Top Complex Review Committee, 2012). Key to understanding crown fire regimes is a better understanding of the surface fuels that drive fires which ultimately spread into the crown (Van Wagner, 1977).

Many Canadian communities undertake crown fire mitigation measures following the FireSmart programme, which encourages fuels modification efforts in forest stands near communities at risk of wildfire (Partners in Protection, 2003). One of the most popular methods of fuel modification is mechanical mastication, in which whole live trees are chipped into smaller pieces and spread evenly on the ground surface (Keane, 2015); mulching can take place between large trees or in geometric strips or chequerboard (Mooney, 2010). In the continental United States, this treatment is most widely applied to the understory of small trees and shrubs, with the effects of mastication treatments on fire behavior (Knapp et al., 2011), ecology (Potts and Stephens, 2009), and soil thermal processes (Busse et al., 2005) being of particular research interest. In contrast to the situation in the United States, mulching in Canada primarily takes place in remote, low-volume stands on whole trees where the timber is not commercially viable (Mooney, 2010). This translocation of fuels from the canopy to the ground surface has been shown to cause a decrease in fireline

* Corresponding author.
E-mail address: daniel.thompson@canada.ca (D.K. Thompson).

http://dx.doi.org/10.1016/j.foreco.2016.03.029
0378-1127/

intensity, and a shift toward an increasing proportion of smouldering consumption (Kreye et al., 2014).

DeLuca and Aplet (2008) suggested that fire-altered charred residues are an important consideration for long-term C-storage in the context of fuel management, because they can reside in soils for thousands of years. Global production of pyrogenic carbon (PyrC) from incomplete combustion during wildfire is estimated to be on the order of 100 Tg C yr^{-1} (Santín et al., 2015). Black carbon (BC) is differentiated from the larger pool of partially charred PyrC by the higher temperature conditions (>400 °C) required for its formation (Keiluweit et al., 2010), and is an important atmospheric factor behind a fire's net radiative forcing (Randerson et al., 2006). Laboratory-based experimental burning suggests higher moisture content fuels leads to an increase in PyrC and BC in mulched shrub fuels (Brewer et al., 2013). However, over 90% of the BC produced during a fire remains on the ground (Kuhlbusch et al., 1996). In contrast to masticated shrubs fuels which are limited in diameter, the mulching of entire tree stems (as is the case in boreal Canada) allows for the possibility of utilizing larger diameter fuel particles, which has been shown to contribute to changes in fire behavior in coarse woody debris (Hyde et al., 2011) and wood crib fires (Rothermel, 1972). Currently, the impact of these larger fuel particles on mulch combustion dynamics and carbon emissions is not known.

The aim of this research was to observe residual carbon production and energy release associated with the burning of masticated fuels. Our objectives are to: (1) examine the impacts of particle size and fuel moisture content on the quality and quantity of carbon residuals in boreal woody masticated fuels; and (2) investigate the influence of combustion dynamics (both flaming and smouldering) on carbon residuals. The outcomes of this study provide guidelines for the mulch size and moisture conditions that maximize beneficial residual carbon in the forest floor.

2. Methods

2.1. Masticated fuel beds

Masticated wood fuel particles were collected from the Horse Creek Research Site (54.0°N, 117.8°W), located in the Upper Foothills natural subregion of west-central Alberta, Canada. The stand was composed of mature lodgepole pine (*Pinus contorta* var. *latifolia* Dougl.) and black spruce (*Picea mariana* (Mill.) B.S.P.), with a pre-treatment basal area of 45 m^2 ha^{-1} and stem density of 7100 stems ha^{-1}. All stems within a 50 × 100 m clearing were masticated. For a full description of the study site, refer to Schiks et al. (2015). Fuel particles were sorted by size class into the following diameter size classes (SC): <0.5 (SC 1), 0.5–1.0 (SC 2), 1.0–3.0 cm (SC 3), following McRae et al. (1979); larger fuel particles were excluded, though they were present in the fuel beds at the study site. The diameter of each masticated particle was defined as the minimum thickness spanning >50% of the particle length following Kane et al. (2009).

The experiment consisted of a 2 × 2 factorial design, with factors of moisture content and size class mixtures. The two levels of moisture content were: (i) 9% and; (ii) 18% (gravimetric moisture content). The two size class mixtures were: (i) 50% particles (by weight) with diameter <0.5 cm and 50% from 0.5 to 1.0 cm, and; (ii) 33% from each of the particle size classes. Four fuel beds were constructed at each factor level combination resulting in 16 tests in total. Mulch beds 30 × 20.5 cm in area were constructed to a depth of approximately 6.5 cm and between 317 and 372 g in total mulch dry mass. The average bulk density of the fuel beds was 100 kg m^{-3}, which was lower than the 153 kg m^{-3} observed within the treatments at the Horse Creek Research Site (Schiks and Wotton, 2015a) where the mulch was sourced, but was similar to California mixed conifer stands (105 kg m^{-3}) as reported by Kreye et al. (2014).

The lower moisture content treatment (9%) was achieved by allowing fuels to equilibrate to ambient laboratory conditions (20 °C and 30–40% humidity). The 18% moisture content was achieved by allowing the fuel beds equilibrate to conditions inside a walk-in refrigerator at a 3 °C and 80–85% humidity. Consistent moisture manipulation was confirmed by destructively sampling additional fuel particles placed in each of the aforementioned environmental conditions. Prior to the initiation of each burn test, the fuel beds were removed from the drying environment, thoroughly mixed and placed into the burning container for ignition 10–15 min following removal from the refrigerator, which allowed fuel particles to warm but with minimal moisture loss.

2.2. Laboratory apparatus

Laboratory burning experiments took place in August 2014 at the Burn Lab at the Northern Forestry Centre, Canadian Forest Service (Edmonton, Alberta). Samples were contained in 1.3 cm thick ceramic fibreboard rated to 1000 °C (Cotronics Corp., Brooklyn, NY) with interior dimensions of 27 × 27 × 6.5 cm (L × W × H). Ignition was achieved using a 15 × 2 cm electric heating coil operating at 100 W. The coil was placed on top of the mulch at the centre of the fuel bed until flaming ignition was achieved, typically less than 30 s in total. Mass loss of the samples were recorded every 1 s and aggregated to 30 s intervals on the dataloggers (Campbell Scientific CR1000) using an electronic balance (Omega Corp LSC7000) rated to 10 kg with an accuracy of 2 g. Two 20 gauge, E-type, Nextel sheathed (rated to 1200 °C) thermocouples were placed at the fuel bed surface, and two within the fuel bed, approximately 3–5 cm below surface. A custom made heat flux sensor with the same construction as the sensor described in Sullivan and McDonald (2014), but made of a silicate mineral of known thermal conductivity (0.97 W m^{-1} K^{-1}) rather than aluminum, and placed directly below the ceramic fibreboard underneath the centre of the sample. Conductive heat flux was calculated using the temperature gradient within the sensor following Fick's first law, similar to the technique used to measure the meteorological soil heat flux (Foken, 2008). Since the conduction observations were made with a layer of ceramic fibreboard between the sensor and the combusting sample, the conduction values do not represent the true conductive flux at the bottom of the combusting area, but rather a relative index of conductive heat flux amongst trials. Data collection rates varied between 1 and 30 s depending on the instrument, but all data were aggregated to the 30 s time steps. Flaming combustion duration was measured from the first visible flame caused by the ignition, and ended when visible flaming ceased. Smouldering combustion duration was measured from when flaming combustion ceased to when the mass loss had plateaued.

2.3. Post-fire residues

Post-fire residue mass was obtained immediately following each burn trial. Fuel consumption was calculated as the pre-fire mass minus the post-fire residue mass (including ash). All residues were removed from the burning container, divided into two size categories using a 1 mm dry sieve, and weights recorded. Most of the post-fire residues were <1 mm in size, though some larger particles were obtained which exhibited uncharred cores. Two subsamples were obtained from each of the size categories, one of which was analyzed for PyrC and the other for BC. Post-fire PyrC concentration was determined via infrared gas analysis (TruSpec CN Analyzer, LECO Corp., St. Josheph, Michgan, USA; method: 'Dumas'). BC concentration was determined using a procedure of