THE INFLUENCES OF FUEL MOISTURE AND DIAMETER ON PYROGENIC CARBON PRODUCTION IN FINE WOODY DEBRIS FROM THREE BOREAL TREE SPECIES UNDER SIMULTED SURFACE FIRE CONDITIONS.

by

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ABSTRACT

Wildland fires burn millions of hectares annually, releasing a significant amount of carbon into the atmosphere. Wildland fires also produce pyrogenic carbon – thermally-altered biomass that is highly resistant to decay – which accumulates in fire-affected ecosystems over time. Large wildfires, common in the boreal forest, burn for extended periods and across wide areas; tree species, fuel loading, and fuel moisture are variable between and within these expansive wildfires. Identifying how the physical characteristics of forest fuels relate to the production of pyrogenic carbon is important to understanding how pyrogenic carbon production varies among wildfires. This thesis explores how tree species, stick-diameter, and fuel moisture content affect pyrogenic carbon production in fine woody debris through a laboratory burn study. In this experimental study, fine woody debris from 3 boreal tree species was separated into 5 stick-diameter size classes, conditioned to 3 fuel moisture contents, and burned under simulated surface fire conditions. The overall mean pyrogenic carbon production rate was 5.1% relative to pre-burn sample weight. Mean pyrogenic carbon production rates ranged from 3.9-7.9% among species, 1.3-9.4% among stick-diameter size classes, and 4.5-5.8% among fuel moisture contents. Trembling aspen (*Populus tremuloides* Michx.) produced significantly more pyrogenic carbon than black spruce (*Picea mariana* (Mill.); BSP) and jack pine (*Pinus banskiana* Lamb.); the mean pyrogenic carbon production rate for trembling aspen was 7.1%, while black spruce and jack pine had rates of 3.9% and 4.3% respectively. Smaller stick-diameters produced significantly more pyrogenic carbon than larger stick-diameters per unit mass; the mean pyrogenic carbon production rate ranged from 7.6-9.4% for 0-1cm diameter sticks, from 3.1-4.2% for 1.1-5cm diameter sticks, and was 1.3% for 5.1-7cm diameter sticks. Samples with 8% fuel moisture content produced significantly more pyrogenic carbon than those with 18% and 28% fuel moisture content; the mean pyrogenic carbon production rate was 5.8% for samples at 8% fuel moisture content, and ranged from 4.5-5.0 % for the two higher fuel moistures. The interaction between stick-diameter and fuel moisture content was also significant, with 5.1-7cm diameter sticks at 18% and 28% moisture content producing significantly less pyrogenic carbon than other samples. This research demonstrates variability in pyrogenic carbon production rates among individual forest stand components, highlighting a need to better understand the relationship between the physical characteristics of a forest and pyrogenic carbon production. With the national and global interest in the concept of carbon budgets, it becomes increasingly relevant in the field of wildland fire management to better understand the recalcitrant residues of wildland fire.

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CONTENTS

TABLES

FIGURES

1. INTRODUCTION

1.1. PREAMBLE

Wildfires are prevalent in Canadian forests, burning an average of 1.96 million hectares annually from 1959 to 2015, with naturally-occurring, large, lightning-caused fires accounting for 91% of area burned (Hanes *et al.* 2019). The annual average area burned in Canadian forests has increased significantly since 1959; in recent years, fire seasons are beginning earlier in the spring and ending later in the fall (Hanes *et al.* 2019). Climate change could continue to increase annual area burned in Canada (Wang *et al.* 2015, Wotton *et al.* 2017), causing shifts in vegetation communities and associated ecosystem carbon budgets (Bélanger and Pinno, 2008). A dominant natural disturbance force in Canadian and global forests, fire alters ecosystem processes and influences carbon cycling (Kurz *et al.* 2009). As forests are assessed for their potential to offset greenhouse gas emissions by sequestering carbon (Malhi *et al.* 2002; Kurz *et al.* 2009), forest disturbances—such as forest fires—must be considered now and under future climatic conditions. Carbon emissions from forest fires can be substantial (Harden *et al.* 2000, Randerson *et al.* 2006; de Groot *et al.* 2009; Sommers *et al.* 2014); emissions of CO_2 and other greenhouse gases from wildland fires contribute to climate warming, while subsequent deposition of pyrogenic carbon aerosols can contribute to atmospheric heating and surface melting by reducing the surface albedo on glaciers, snow, sea ice, and the Greenland ice sheet (Randerson *et al.* 2006). Concurrently, changes to ecosystem structure and species composition after a fire cause a decline in net radiation and sensible heat fluxes within the burned area, and an accumulation of carbon in organic soils and vegetation post-fire offset the pulse of carbon released during combustion (Randerson *et al.* 2006). Forest fires additionally produce a highly recalcitrant form of carbon that is often overlooked and/or underestimated (Preston and Schmidt 2006, Santín *et al.* 2015).

Pyrogenic carbon (PyrC) is a product of the partial combustion of organic materials, and is produced naturally during fire events (Scott *et al.* 2014). This thermally altered biomass can be incredibly stable in the environment, persisting in forest soils for hundreds and even thousands of years (DeLuca and Aplet 2008; Ohlson *et al.* 2009; Preston 2009). PyrC can also play important roles in forest soils, such as increasing nitrification rates (DeLuca *et al.* 2006; Hart 2013). PyrC must be included as part of the fire management equation when considering forests as potential carbon sinks (Preston and Schmidt 2006, Hart 2013, Flanagan *et al.* 2019). Despite its ecological importance, discrepancies exist in the literature regarding the amount of PyrC stored in the boreal forest (Amiro *et al.* 2001b, Preston *et al.* 2006, Santín *et al.* 2015). These discrepancies highlight a knowledge gap surrounding how much PyrC is produced during any single fire event. This thesis seeks to explore how tree species, stick-diameter, and fuel moisture content affect PyrC production in fine woody debris through a laboratory burn study.

1.2. CARBON DYNAMICS IN THE BOREAL FOREST

The Canadian boreal forest contains large, dynamic carbon reserves; carbon is constantly being transferred between forest carbon pools, and exchanged between forests and the atmosphere (Harden *et al.* 2000, Stinson *et al.* 2011; Figure 1). Forest carbon can be split into two broad pools: living biomass and dead organic matter (Kurz *et al.* 2009, Malhi *et al.* 2002). Living biomass consists of all live flora (e.g. live branches, foliage, and roots), while dead organic matter is woody debris, forest floor litter, and soil organic matter (Kurz *et al.* 2009, Malhi *et al.* 2002).

Dead organic matter makes up a substantial proportion of forest biomass. Kranabetter (2009) found that coarse woody debris and snags account for 9% of ecosystem carbon, on average, in southern boreal stands in British Columbia, Canada. Worldwide, down woody debris represents approximately 20% of total aboveground forest biomass (Bradford *et al.* 2009, Fraver *et al.* 2013). Dead woody debris loads vary depending on forest succession and disturbance (Hély *et al.* 2000). Hély *et al.* (2000) found that coarse woody debris levels in boreal mixedwood forests in Quebec, Canada generally increase with time following a fire disturbance. Additionally, different boreal tree species exhibit different trends in coarse woody debris loads; aspen log loads decreased with time, white birch remained high over the entire period, white spruce log loads were consistently the lowest, and white cedar log loads increased in stands older than 200 years (Hély *et al.* 2000). Coarse woody debris accumulation also differs with climate conditions, wetter climates are more favourable to decomposer fungi and thus exhibit lower coarse woody debris loads (Hély *et al*. 2000).

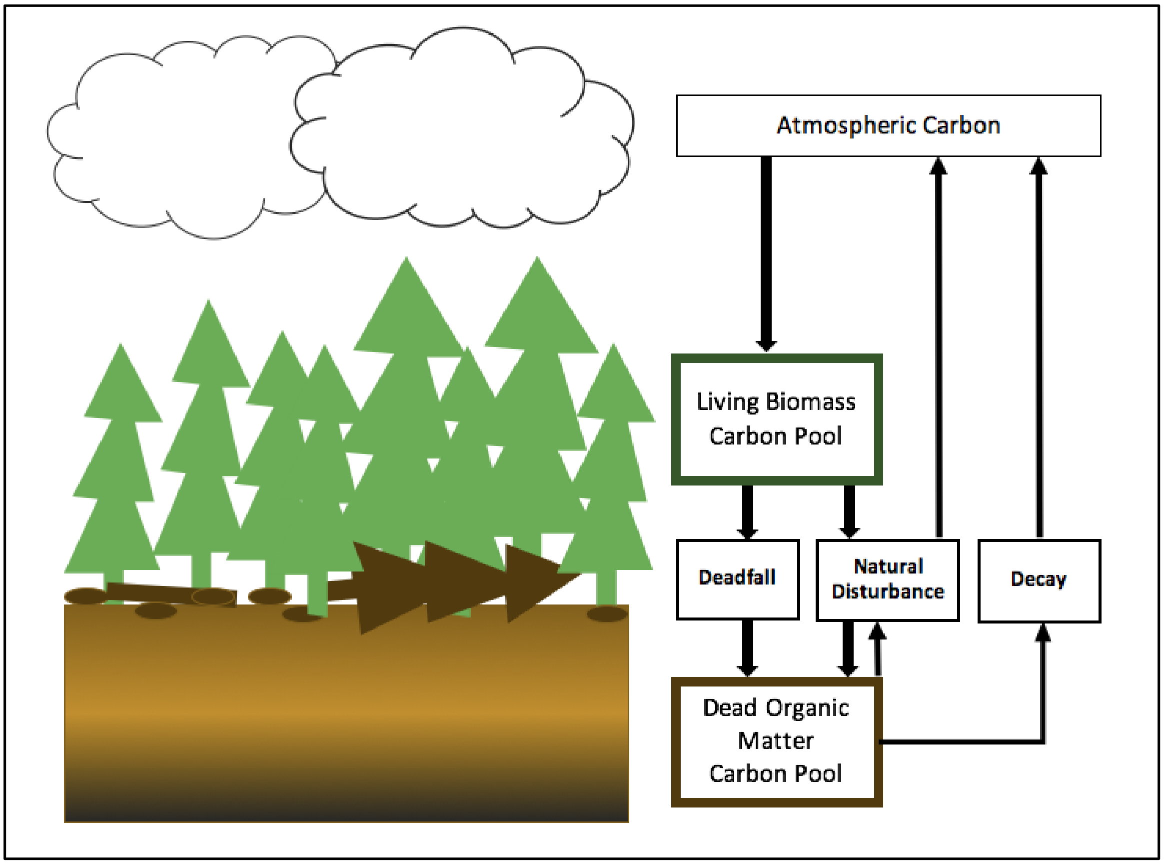

Figure 1. Forest carbon cycling.

The potential for carbon to be sequestered from or released into the atmosphere comes with any change to the amount of forest biomass (living or dead) (Malhi *et al.* 2002). Carbon can be released from the living biomass pool into the atmosphere directly and indirectly. Fire releases carbon directly through emissions of gasses and particulate matter in the smoke plume during combustion, and indirectly as it transfers carbon from living biomass to dead organic matter, where it is released slowly through decomposition (Malhi *et al.* 2002, Stinson *et al.* 2011, Scott *et al.* 2014). Other natural disturbances, such as forest insects and diseases, also release carbon in this indirect manner (Kurz *et al.* 2009, Malhi *et al.* 2002, Stinson *et al.* 2011).

1.3. WHAT IS ‘PYROGENIC CARBON’?

The term ‘pyrogenic carbon’ has been used to describe a continuum (Figure 2) of thermally altered biomass – from partially charred plant materials, to charcoal, black carbon, and soot (Preston and Schmidt 2006). This thermally altered biomass is a result of the pyrolysis of plants in absence of oxygen; it is a product of incomplete combustion (Scott *et al.* 2014). During a wildland fire, rapid heating and high temperatures cause a breakdown of cellulose in plants (Pyne *et al.* 1996, Scott *et al.* 2014). As heat penetrates plant tissues, molecules are broken down with little to no oxygen present, producing flammable gasses, in a process called pyrolysis (Pyne *et al.* 1996, Scott *et al.* 2014). The gasses released during pyrolysis combust when mixed with oxygen in the air surrounding the plant, and the heat produced by the reaction perpetuates the fire (Pyne *et al.* 1996, Drysdale 2011). If the reaction stops before complete combustion occurs, the resultant solid residues are char, charcoal, and/or black carbon (Scott 2010, Schmidt and Noack 2000). Soot forms when small molecules released during pyrolysis re-condense into a highly graphitized product (Schmidt and Noack 2000).

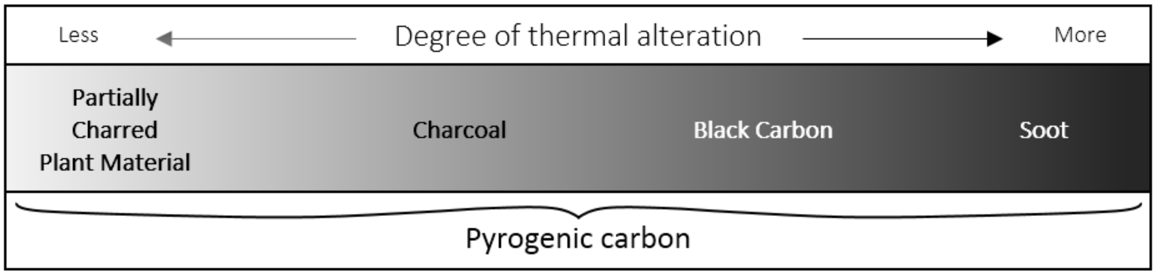

Figure 2. Pyrogenic carbon continuum. This figure was inspired by Hammes *et al.* (2007) and Hedges *et al.* (2000).

The PyrC continuum captures the sliding scale of thermal alteration that can result from different formation conditions during a wildfire such as fuel type, maximum temperature reached during combustion, abundance of oxygen, and duration of charring

(Hammes *et al.* 2007, Soucémarianadin *et al.* 2013). PyrC is understood to be highly resistant to degradation due to its thermally altered chemical structure, characterized by aromatic structures (Schmidt and Noack 2000, Preston and Schmidt 2006). Though, in the boreal forest, not all PyrC exhibits equal chemical recalcitrance; PyrC from low-severity, early-season fires has low rates of aromatic content when compared to the range of known values along the PyrC continuum, suggesting low potential for recalcitrance (Soucémarianadin *et al.* 2015). Belcher *et al.* (2018) found that PyrC formed in lower energy regimes are likely susceptible to greater post-fire degradation. These studies indicate that the degree of thermal alteration, and thus fire severity, may determine the degree of chemical recalcitrance of PyrC.

There are a variety of analytical techniques used to separate PyrC from other forms of carbon in soils: visual/microscopic techniques, laboratory oxidation techniques, and an approach based on the release of molecular markers called benzenepolycarboxylic acids (BCPAs; Preston and Schmidt 2006). Challenges exist with making comparisons of PyrC amounts across various research articles and publications because terms are not standardized or used consistently. Traditionally, when visual or microscopic analytical techniques are used to distinguish between blackened and unaltered plant particles, the results have been referred to 'charcoal'; it is unknown which proportion of these charred residues would exhibit the atomic H/C and O/C ratios that define the charcoal portion of the PyrC continuum as described by Schmidt and Noack (2000) and Preston and Schmidt (2006). The results of visual or microscopic analytical are perhaps better described as 'pyrogenic carbon' unless there are other indicators as to where they belong within the continuum. Literature shows 'black carbon' used interchangeably with 'pyrogenic carbon' to describe the whole continuum, but ‘black carbon’ is also commonly used to describe the part of the continuum that is resistant to laboratory oxidation or produces BCPAs (Preston and Schmidt 2006). For the purpose of this thesis ‘pyrogenic carbon’ (PyrC) will refer to the entire continuum; charcoal, black carbon, or soot will be used when a specific portion of the PyrC continuum is being referenced (Figure 2).

1.4. PYROGENIC CARBON, CARBON CYCLING, AND WILDLAND FIRE

Wildland fire alters forest ecosystems and influences carbon cycling, both in Canadian forests and on a global scale (Kurz *et al.* 2009). Fire contributes directly to the carbon dynamics of the boreal forest in a few ways: by releasing carbon into the atmosphere through combustion, by killing live vegetation (contributing to dead organic matter carbon pools), and by producing PyrC (Scott *et al.* 2014). Amiro *et al.* (2001b) estimated that Canadian forest fires produced an average of 27 ± 6 Tg of carbon per year in direct carbon emissions from 1959-1999. In addition to producing carbon emissions, forest fires also convert an estimated 1–9% of carbon from forest fuels (including both live and dead biomass) into PyrC (Preston and Schmidt 2006, Forbes *et al.* 2006). Approximately 40–270 Tg of black carbon is produced globally by vegetation fires each year (Kuhlbusch and Crutzen 1995); an estimated 7–17 Tg of PyrC is produced annually within boreal forest regions (Preston and Schmidt 2006), but these numbers may be grossly underestimated (Santín *et al.* 2015). Wildland fires emit carbon in their smoke plume, but also produce PyrC deposits; the recalcitrance of PyrC allows it to act as a countering sink to a fire’s carbon emissions.

In addition to acting as a carbon sink, PyrC stimulates microbial activity and nutrient cycling after fire, playing important roles in forest soils (Wardle *et al.* 1998, DeLuca *et al.*

2006, Pingree and DeLuca 2017). Increased nitrification, such that can be stimulated by PyrC, can facilitate increased forest productivity, thus potentially increasing the rate at which carbon is sequestered by a forest system following a fire (Wan *et al.* 2001). Amiro *et al.* (2001a) highlights the need for additional research to better explore the impact of fire on the forest carbon balance, especially with respect to post-fire carbon losses.

It is difficult to measure pre-fire fuel characteristics for a wildfire so that they might compare with PyrC amounts post-fire, this has prevented accurate accounts of PyrC production in the boreal forest (Preston and Schmidt 2006, Makoto *et al.* 2012, Santín *et al.* 2015). Experiments that measure these attributes are limited to laboratory trials or prescribed fires. The dynamic nature of wildland fire adds to these difficulties, since variables such as fire intensity, rate of spread, and even fuel types rarely remain constant across a wildfire. Quantifying the amount of PyrC produced by wildfires in the boreal forest and identifying the burning conditions conducive to differing production rates will help form a better understanding of how PyrC contributes to overall carbon cycling.

1.5. PYROGENIC CARBON PRODUCTION

PyrC production depends on the thermal alteration of woody biomass during a fire, which is primarily dependent on fire temperature, but heating duration plays a role at lower temperatures (Czimczik and Masiello 2007, Brewer 2012). Considering the dynamic nature of wildfire and the resulting variability in fire intensity and severity, it is likely that PyrC production rates and the degree of thermal alteration varies within the same fire. Though research on the formation of black carbon, specifically, has been conducted in laboratory settings, such research conducted in wildfire and prescribed fire settings is limited; there is very little available research into factors affecting the quantity and quality of PyrC production in the field, such as pre-fire fuel conditions and fire intensity measurements (Czimczik and Masiello 2007, Preston and Schmidt 2006, Santín *et al.* 2015). This knowledge gap prevents accurate modeling of PyrC production for wildfires in the present, and makes it difficult to consider how changing fire regimes might affect future PyrC production.

1.5.1. Combustion and flammability

Combustion is a rapid chemical oxidative reaction that generates heat, generates light, and produces a range of chemical products (Scott *et al.* 2014); one of these chemical products is PyrC. Martin *et al.* (1969) describes combustion in four stages. In the first stage, heat is transferred to the fuel by radiation, conduction and/or convection, causing the temperature and moisture content of the fuel to change and thus beginning the preheating phase (Martin *et al.* 1969). During the second stage, endothermic decomposition occurs, releasing flammable and non-flammable gasses (Martin *et al.* 1969). The third stage of combustion begins when decomposition becomes exothermic; at this point, the flammable gases being emitted become concentrated enough to exceed their lower critical flaming level and the flaming phase of combustion begins (Martin *et al.* 1969). During the fourth stage, the charred fuel continues to release energy through glowing combustion after the flames subside; depending on the condition of the fuel, some may remain in a charred condition whereas in hot/dry fuels only ash may remain (Martin *et al.* 1969). In more recent literature, ‘burning’ is sometimes used to describe the entire process described by Martin *et al.* (1969) and ‘combustion’ sometimes refers to only the oxidative portions of the process in stage 3 and 4 (Scott *et al.* 2014).

Flammability is important to combustion, and thus PyrC production, because it describes the likelihood that combustion can occur. Flammability is described as having three components: ignitability, sustainability and combustibility (Anderson 1970, Gill and Zylstra 2005). Ignitability is the ability of fuel to catch fire, often measured by the time it takes fuel to ignite when exposed to a heat source (ignition delay time); ignition delay time varies with differences in fuel density, specific heat, or size (Anderson 1970). Sustainability is described as a measure of how well a fire will continue to burn with or without a heat source (Anderson 1970), or how long a fire burns with a flame and by smoldering (Gill and Zylstra 2005). Combustibility is defined as a measure of how rapid a fire burns (Anderson 1970); combustibility can be expressed as the amount of weight lost during flaming combustion or the total weight of material burned divided by the length of time it burned, or it can be measured using a flame dimension (Gill and Zylstra 2005). Martin *et al.* (1994) added a fourth component of flammability; the fourth component, consumability, is defined as how much of the fuel will be consumed by the fire.

Many studies have linked fuel moisture content with forest fire ignition probability and thus flammability, with lower fuel moisture content contributing to higher flammability (Rothermel and Philpot 1973, Flannigan and Wotton 1991, Chuvieco *et al.* 2004, Larjavaara *et al.* 2004, Ganteaume *et al.* 2010). Fuel size and shape have been linked to the combustibility component of flammability, with fine round twigs <6mm in diameter and leaves being the most flammable in eucalyptus fuels (Burrows 2001). Flammability has also been found to differ between plant species; the causes of flammability are different among species and species of the same genus do not always exhibit the same flammability (Behm *et al.* 2004, van Altena *et al.* 2012). Understory plants in pine flatwoods show greater flammability than understory plants in hardwood hammocks, though measurements of consumability were similar between ecosystems (Behm *et al.* 2004).

1.5.2. Fire intensity and severity

In general, fire intensity is a measure of the energy released by a fire, while fire severity is a measure of the organic matter consumed (Scott *et al.* 2014). The head of a wildfire has a higher rate of spread and thus a higher rate of energy release than the back of a wildfire under the same fuel conditions (Martin *et al*. 1969). Carvalho *et al.* (2011) found backing fires produced almost twice as much charcoal as head fires in a Florida pine forest; presumably because of differences in residence times, oxygen availability, and fire intensity. Backing fires were found to convert approximately 1.5% of initial biomass to charcoal, while head fires only converted 0.4% of biomass to charcoal, with percentages of converted biomass for both head and back fires ranging between 0 and 6.2% (Carvalho *et al.* 2011). Brewer (2012) measured the amount of PyrC produced by burning masticated fuels (mulch) from Idaho mixed wood forests under three different fuel moisture regimes; the study used fuel moisture as a predictor of fire intensity and found that fire intensity decreased with increases in fuel moisture. There was no significant difference in production of PyrC production among the three moisture groups (4–8%, 10–12%, and 13–16%), but PyrC production generally increased with increasing fuel moisture (Brewer 2012). Brewer (2012) also measured the proportion of black carbon produced in their experiments, finding black carbon production also increased with increasing fuel moisture. These studies indicate that lower fire intensities produce greater amounts of PyrC.

Lower fire intensities and severities characteristic of early season boreal wildfires were found to produce PyrC with low chemical recalcitrance (i.e. partially charred plant material or charcoal; Figure 2) (Soucémarianadin *et al.* 2015). Results from an experimental crown fire showed that chemical characteristics of the PyrC layer in the forest floor were correlated with the temperature-time profiles at corresponding sampling points—higher maximum temperatures and associated prolonged heating durations increased degree of aromaticity, and thus recalcitrance, of the pyrogenic organic matter (Santín *et al.* 2016). An interaction between tree taxa and pyrolysis temperature has also been shown to affect the recalcitrance of resultant PyrC; gymnosperms were found to produce more recalcitrant PyrC at lower temperatures than angiosperms (Hatton *et al.* 2016). Fire intensity and severity therefore affect the amount of PyrC produced, and its degree of thermal alteration.

1.5.3. Chemical make-up of fuel

Aromatic components, such as lignin, and non-aromatic components, such as cellulose, both contribute to the quality of PyrC produced during burning (Shafizadeh 1984); fuels with high lignin-to-cellulose ratio have been found to produce greater amounts of black carbon (Keiluweit *et al.* 2010, Knicker 2010). Since lignin content in wood can vary considerably in different tree species (Sarkanen and Ludwig 1971), lignin content and/or lignin-to-cellulose ratios may also contribute to differences in PyrC projection rates between species.

1.6. PYROGENIC CARBON PRODUCTION IN THE BOREAL FOREST

Earlier studies used multiple methods to quantify PyrC production during and after wildland fires; many studies focused on PyrC production in one portion of a forest stand (e.g. soil organic matter), or else focused on one portion of the PyrC continuum, making studies difficult to compare. Ohlson and Tryterud (2000) used traps placed on the forest floor to quantify charcoal production and transport during experimental forest fires in the Scandinavian boreal forest. They estimated that experimental fires produced 235 kg ha^{-1} of charcoal on average, however the distribution was highly variable between fires as well as between different parts of individual fires (Ohlson and Tryterud 2000). Czimczik *et al.* (2003) quantified the conversion rate of soil organic matter to black carbon during a Scandinavian wildfire. The surface fire studied produced 5–72 g m^{-2} (50–720 kg ha^{-1}) of black carbon depending on the intensity and severity of the fire (Czimczik *et al.* 2003). Smaller amounts of black carbon were produced when less of the organic layer was consumed (Czimczik *et al.* 2003). It is difficult to compare PyrC levels between the Scandinavian studies because they quantified different parts of the PyrC continuum (Preston and Schmidt 2006).

Santín *et al.* (2015) sought to quantify the PyrC produced across the complete range of forest stand components immediately following a typical, high-intensity boreal crown fire. This study was one of the first to attempt this type of in-situ total account of PyrC production. Santín *et al.* (2015) found that 27.6% of the carbon affected by fire was retained in PyrC rather than emitted into the atmosphere, with a production rate of 4.8 ± 0.8 t ha^{-1} (4800 ± 800 kg ha^{-1}). This study showed substantially higher rates of PyrC production than many other studies, likely due to more comprehensive measurements being taken before any PyrC could be lost by leaching or erosion (Santín *et al.* 2015). Maestrini *et al.* (2017) found persistent PyrC stocks after initial post-fire erosion in a Californian mixed-conifer forest of 248 ± 30 g m^{-2} (2480 ± 300 kg ha^{-1}), which approaches the PyrC production rates measured by Santín *et al.* (2015). Maestrini *et al.* (2017) also found that total PyrC stocks remained constant across fire severity classes, but that distribution of PyrC across forest stand components changed with fire severity.

PyrC is very stable in the environment, persisting in forest soils for hundreds to thousands of years (DeLuca *et al.* 2006, Ohlson *et al.* 2009, Preston 2009, Pingree and DeLuca 2017). The stability of this thermally altered biomass creates the potential for stocks of PyrC to build slowly in fire-dominated ecosystems with successive fire events (DeLuca and Aplet 2008, Brewer 2012, Santín *et al.* 2013). In a scenario where fires become much more frequent on the landscape with climate warming, modeling indicates that production of new PyrC could out-pace climate-induced accelerated loss of residual PyrC (Landry and Matthews 2017). With the established residence times and the idea that PyrC will accumulate over time, Ohlson and Tryterud (2000) concluded that charcoal stocks in the boreal forest should be higher than observed. One theory is that some PyrC is consumed in subsequent fires (Ohlson and Tryterud 2000, Czimczik *et al.* 2005, Preston and Schmidt 2006). Brewer (2012) tested this theory with macro-charcoal particles (>6mm) in a laboratory, finding that an average of 41% of charred residues were lost in the first repeated burn event and 80% of charred material was lost after 4 repeated fires. In-stand coarse woody debris, unlike mulch, exhibited an increase in PyrC following a subsequent wildfire; coarse woody debris in once- and twice-burned upland mixed-conifer forest sites in Montana showed half the amount of PyrC on coarse woody debris in once-burned sites as compared to twice-burned (323kg ha^{-1} and 655 kg ha^{-1}, respectively) (Ward *et al.* 2017). Another study explored consumption of residual PyrC during an experimental fire and found substantially lower loss rates than Brewer *et al.* (2012) with 75% of 1–1.7cm-sized samples losing <15% and 75% of larger samples (2–4cm by 1–3cm) losing <25% of their mass (Santín *et al.* 2013).

Consumption rates of residual PyrC differ in wildfires of different intensities; Doerr *et al.* (2018) found that consumption of residual PyrC on the surface of the forest floor was greater in a high-intensity fire than in a low-intensity fire. PyrC from a jack pine burned in a slash pile experienced 64% and 17% loss under high- and low-intensity fires, respectively, while PyrC from jack pine burned in a wildfire experienced 84% and 50% loss in the same high- and low-intensity fires, respectively (Doerr *et al.* 2018). Consumption rates of residual PyrC could vary greatly depending on the location of the PyrC within the forest stand; if the residual PyrC is not exposed to a subsequent wildfire (for example, because it is protected within unburned soil or on a standing dead tree during a surface fire), then it cannot be consumed. As such, the loss rates reported by Doerr *et al.* (2018) likely represent an extreme upper end, since PyrC is not likely to remain exposed on the surface of the forest floor by the time the stand experiences a subsequent wildfire.

Recent interest in offsetting global greenhouse gas emissions has placed focus on forest ecosystems for their potential role in sequestering carbon (Malhi *et al.* 2002; Brewer 2012). Kurz *et al.* (2009) estimates that Canada's managed forests are a carbon source, taking into account the release of carbon due to forest fires and large insect outbreaks (such as mountain pine beetle and spruce budworm). This thesis works to further our understanding of the role wildland fire plays in sequestering carbon.

1.7. OBJECTIVES

This study focuses on quantifying the amount of PyrC produced by burning dead and down woody debris from three boreal tree species in a laboratory setting. This study also explores the effects of fuel moisture and diameter size class of fuels on the quantity of PyrC produced in laboratory burn trials. Separating fine woody debris samples by species, fuel moisture content, and diameter size class allows results from this study to be more easily applied to wildfires in the Canadian boreal forest, since land managers inventory dead and down woody debris in this manner (McRae *et al*. 1979, Alexander *et al.* 2004, ASRD 2009).

1.7.1. Research questions

1) Will trembling aspen (*Populus tremuloides* Michx.) is produce more PyrC than black spruce (*Picea mariana* (Mill.); BSP) and jack pine (*Pinus banskiana* Lamb.), as the sole deciduous species? Further, will black spruce and jack pine differ in PyrC production rates?
2) Will larger diameter samples produce more PyrC than smaller diameter samples?
3) Will higher moisture content samples exhibit higher rates of PyrC production than lower moisture contents?
4) Will there be any significant interactions between the three variables?

These questions were explored through laboratory burning under simulated surface fire conditions. This thesis details the experiment, results, and potential implications over the next 4 sections; Section 2 outlines the materials and methodology, Section 3 contains the results of the experiment, Section 4 discusses the significance of these results, and Section 5 summarizes the conclusions of the experiment. Details for all literature cited are found at the end of the document.

2. METHODS

2.1. SAMPLE COLLECTION

This study focuses on PyrC production through the combustion of dead and down woody debris from three boreal tree species in Alberta, Canada. Black spruce, jack pine, and trembling aspen were chosen because of their abundance in Alberta's boreal forest. These three species are also the dominant, over-story species in many of the benchmark fuel types defined by the Canadian Fire Behavior Prediction (FBP) System (Taylor *et al.* 1997); this system is used as a standard among wildland fire management organizations in Canada for estimating head fire rate of spread, fire intensity, type of fire, elliptical fire area, perimeter, and perimeter growth rate. Fine woody debris samples, of these representative species, were collected from three different sites; the black spruce dominant and jack pine dominant stands were located to the north of Edmonton, Alberta, while the trembling aspen dominated stand was located to the southwest of Edmonton, Alberta (Figure 7). Each forest stand was chosen for its visual match to the benchmark fuel type from the FBP system (Table 1).

The black spruce dominant stand, located at 55.068 N and -114.052 W, represents an example of the C-2 Boreal Spruce fuel type from the FBP system (Figure 3). 'C-2 Boreal Spruce' is defined by the FBP system as representing upland and lowland black spruce, white, and Engelmann spruce stands, but not spruce-sphagnum bogs (Taylor *et al.* 1997). This stand was made up of mature black spruce, with understory shrubs including Labrador tea (*Rhododendron groenlandicum* (Oeder) Kron & Judd) and wild rose species

(*Rosa* spp.); as depicted (Figure 3), the mature black spruce in this stand often had branching along their entire boles.

The jack pine stand, located at 55.023 N and -113.973 W, represents an example of the C-3 Mature Jack or Lodgepole Pine fuel type from the FBP system (Figure 4). 'C-3 Mature Jack or Lodgepole Pine' is defined by the FBP system as representing fully stocked mature jack and lodgepole pine stands (Taylor *et al.* 1997). This stand was made up of mature jack pine with very few understory trees or shrubs. This closed-canopy stand had a crown-base height of approximately 5 m, likely as a result of self-pruning in the jack pine trees.

The trembling aspen stand, located at 55.928 N and -115.0265W, represents an example of the M-1/2 Boreal Mixedwood fuel type from the FBP system (Figure 5). 'M-1/2 Boreal Mixedwood' is defined by the FBP system as representing mixed stands of boreal species in the leafless (1) or green (2) stages and further defined by the percentages of coniferous and deciduous components (Taylor *et al.* 1997). This stand was made up of approximately 75% mature trembling aspen with white spruce (*Picea glauca* (Moench) Voss), white birch (*Betula papyrifera* Marsh.), and balsam fir (*Abies balsamea* (L.) Mill.) present. The understory was made up of balsam fir and various shrubs including beaked hazel (*Corylus cornuta* Marsh.), service berry (*Amelanchier* spp.), and wild rose species.

In addition to species, this study examines whether PyrC production rates differ between five diameter size classes within the fine woody debris samples; size classes are defined by a "go-no-go-gauge". The "go-no-go gauge", as seen in Figure 8, uses nested slots to categorize samples into the following diameter size classes: size class 1, <0.5cm; size class 2, 0.5cm to 1cm; size class 3, 1.1cm to 3cm; size class 4, 3.1cm to 5cm; size class 5, 5.1 to 7cm. The use of these size classes is common in Canada for the measurement of fine woody debris as wildland fire fuels (McRae *et al*. 1979, Alexander *et al.* 2004, ASRD 2009).

Table 1. A brief summary of Canadian Forest Fire Behavior Prediction System fuel type characteristics for C-2 Boreal Spruce, C-3 Mature Jack or Lodgepole Pine, and M-1/2 Boreal Mixedwood—Leafless/Green (summarized from Alexander *et al.* 1984, Table 1).

Fuel Type	**Forest Floor & Organic Layer**	**Surface & Ladder Fuels**	**Stand Structure & Composition**
C-2	Continuous feather moss and/or cladonia; deep, compact organic layer	Continuous shrub, e.g. Labrador tea common; low to moderate down woody fuels; tree crowns extended nearly to ground; arboreal lichens, flaky bark.	Moderately well-stocked black spruce stands on both upland and lowland sites; sphagnum bogs excluded
C-3	Continuous feather moss; moderately deep, compact organic layer.	Sparse conifer understory may be present; sparse down woody fuels; tree crowns separated from ground.	Fully-stocked jack or lodgepole pine stands; mature.
M-1 & M-2	Continuous leaf litter in deciduous portions of stands; discontinuous feather moss and needle litter in conifer portions of stands; organic layers shallow, uncompacted to moderately compacted.	Moderate shrub and continuous herb layers; low to moderate dead and down woody fuels; conifer crowns extend nearly to ground; scattered to moderate conifer understory.	Moderately well-stocked mixed stands of boreal conifers (black/white spruce, balsam/subalpine fir) and deciduous species (trembling aspen, white birch). Fuel types are differentiated by season and % conifer:%deciduous spp. composition.

Figure 3. FBP benchmark fuel type: C-2 Boreal Spruce (Taylor *et al.*1997).

Figure 4. FBP benchmark fuel type: C-3 Mature Jack or Lodgepole Pine (Taylor *et al.*1997).

Figure 5. FBP benchmark fueltype: (A) M-1 Boreal Mixedwood - leafless / (B) M-2 Boreal Mixedwood - green (Taylor *et al.*1997).

Finally, this study also explores the effect of fuel moisture on the amount of PyrC produced during combustion. The moisture content of dead fuels, such as fine woody debris on the forest floor, is determined by wetting and drying processes associated with weather conditions on an hourly, daily, and seasonal basis (Scott *et al.* 2014). Fuel moisture is used operationally as an indication of fuel ignitability (Scott *et al.* 2014). In Canada, fuel moisture content in fine fuels is approximated by the Fire Weather Index system, and represented by the Fine Fuel Moisture Code (FFMC) (Van Wagner 1987). FFMC values vary greatly throughout the spring, summer, and fall across Canadian forests; Figure 6 shows the seasonal variation in FFMC values across three sites from 2011-2015. Three moisture prescriptions were examined: 8% fuel moisture, 18% fuel moisture, and 28% fuel moisture; these moisture contents roughly correspond with FFMC values of 93, 83, and 73, respectively.

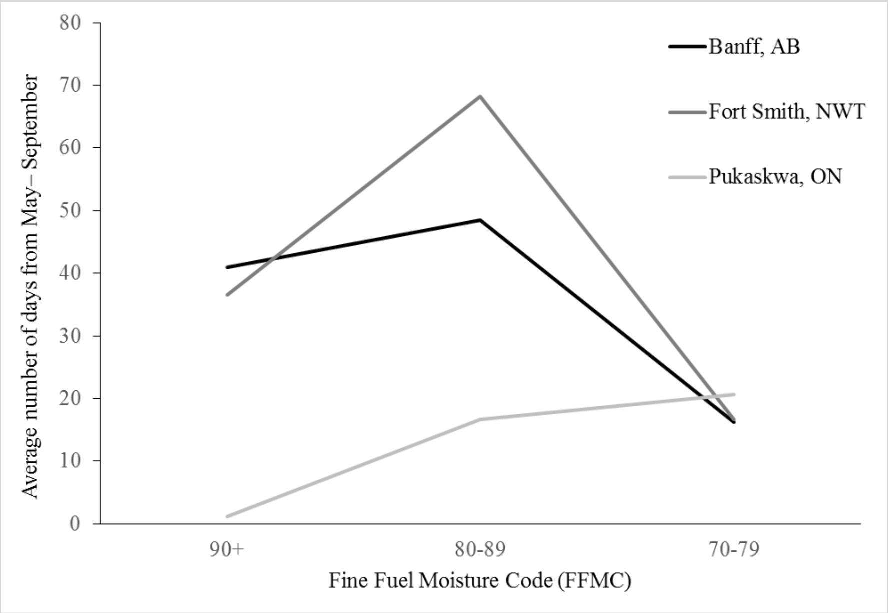

Figure 6. Average number of days (from May-September, annually) with FFMC values >70 across three Canadian sites.

Three replicates of each fuel moisture prescription were assigned randomly to tag numbers belonging to each species and size class. All samples were dried at 90˚C overnight to obtain oven-dry weights, then soaked in water for 24 hours. The wet weights needed to achieve each fuel moisture prescription were calculated for each sample and samples were allowed to air dry until they reached their prescribed moisture content. Fuel moisture was calculated as a proportion of dry weight (Equation 1).

$$Fuel\ moisture\ \% = \frac{wet\ weight - dry\ weight}{dry\ weight} * 100$$

Equation 1. Fuel moisture as a proportion of the dry weight of the sample.

2.2. LABORATORY BURNING

Laboratory burn trials were conducted to simulate a surface fire passing over the fine woody debris samples. Samples were assigned numbered metal tags to maintain their unique identities throughout laboratory testing. Using the burn table at the Canadian Forest Service's Northern Forestry Centre in Edmonton, Alberta, each sample was placed in a fine (0.5mm), stainless-steel-wire-mesh basket and held above a propane burner for three minutes (Figure 9). The burn order was determined by randomly selecting from those samples that had dried enough to reach their pre-determined target moisture content. The heating duration of three minutes was based on a literature review of residence times in surface fires (Santín *et al.* 2015, Scott *et al.* 2014, Hartford and Frandsen 1993). Two temperature data loggers were attached to each sample prior to burning to record the heat of combustion, and times of flaming combustion (if applicable) were observed and recorded. After three minutes, the propane burner was turned off and each sample was allowed to burn to self-extinguishment. Once cooled, burned samples were placed in bags and labelled with their tag number.

2.2.1. Pre-burn measurements and preparation

Prior to burning, the diameters of each sample were recorded; diameter measurements were six centimeters from each end of the sample. Comments about the physical condition of each sample were recorded, including decay, presence and condition of bark, cones, and any other distinguishing features.

2.2.2. Post-burn processing and measurements

PyrC was separated from unburned biomass on each sample by hand-scraping the thermally-altered biomass back into its sample bag. Handling and scraping each sample over the sample bag prevented small pieces from being lost during processing. After scraping, the unburned portion of the sample was placed in an aluminum tray labelled with the sample's tag number. The PyrC was rinsed out of its sample bag onto a filter paper, using water. Once the water had drained through the filter paper, the filter paper and PyrC were placed in another aluminum tray labelled with the sample's tag number. All unburned and thermally-altered sample components were dried at 90˚C overnight to obtain oven-dry weights. PyrC production was expressed as a proportion of the pre-burned sample weight (Equation 2).

$$PyrC\ \% = \frac{PyrC\ dry\ weight}{sample\ dry\ weight} * 100$$

Equation 2. Pyrogenic carbon production as a proportion of sample weight.

2.3. STATISTICAL ANALYSIS

All statistical analyses were completed using SAS Studio University Edition using an alpha value of 0.05 to determine significance. PyrC production (%) measurements were subject to a 3 (species) x 3 (moisture contents) x 5 (diameter size class) three-way analysis of variance (ANOVA) in order to test the relationship between species, diameter size class, and fuel moisture content on PyrC production. The data was transformed by natural logarithm so that it met the assumptions of ANOVA, exhibiting experimental errors that are normally distributed and have equal variance. Least Significant Difference (LSD) tests were completed to further explore the relationships of each significant independent variable on the production of PyrC and to further analyze the significant interaction. A subset of the LSD pairwise comparisons were chosen for further analysis, to prevent Type 1 errors. Pairwise comparisons were only examined for levels of variables determined to be significant to the interaction, and only for interactions that shared a common variable. A Bonferroni correction of alpha was used to further reduce the chance of Type 1 error during pairwise comparisons.

A subset of the data was re-analysed, containing only samples that had experienced at least some charring (as detailed in Section 3, there were 13 samples that did not burn). Since the subset of data was unbalanced, the Type III sum of squares results were used during the three-way ANOVA. Tukey-Kramer tests were completed to further explore the relationship of a significant independent variable on the production of PyrC and to further analyse the significant interaction in this unbalanced dataset. Additionally, a one-way ANOVA was used on this same subset of data to compare PyrC production among samples that experienced visible flaming combustion against samples that did not (i.e. samples that only smouldered).

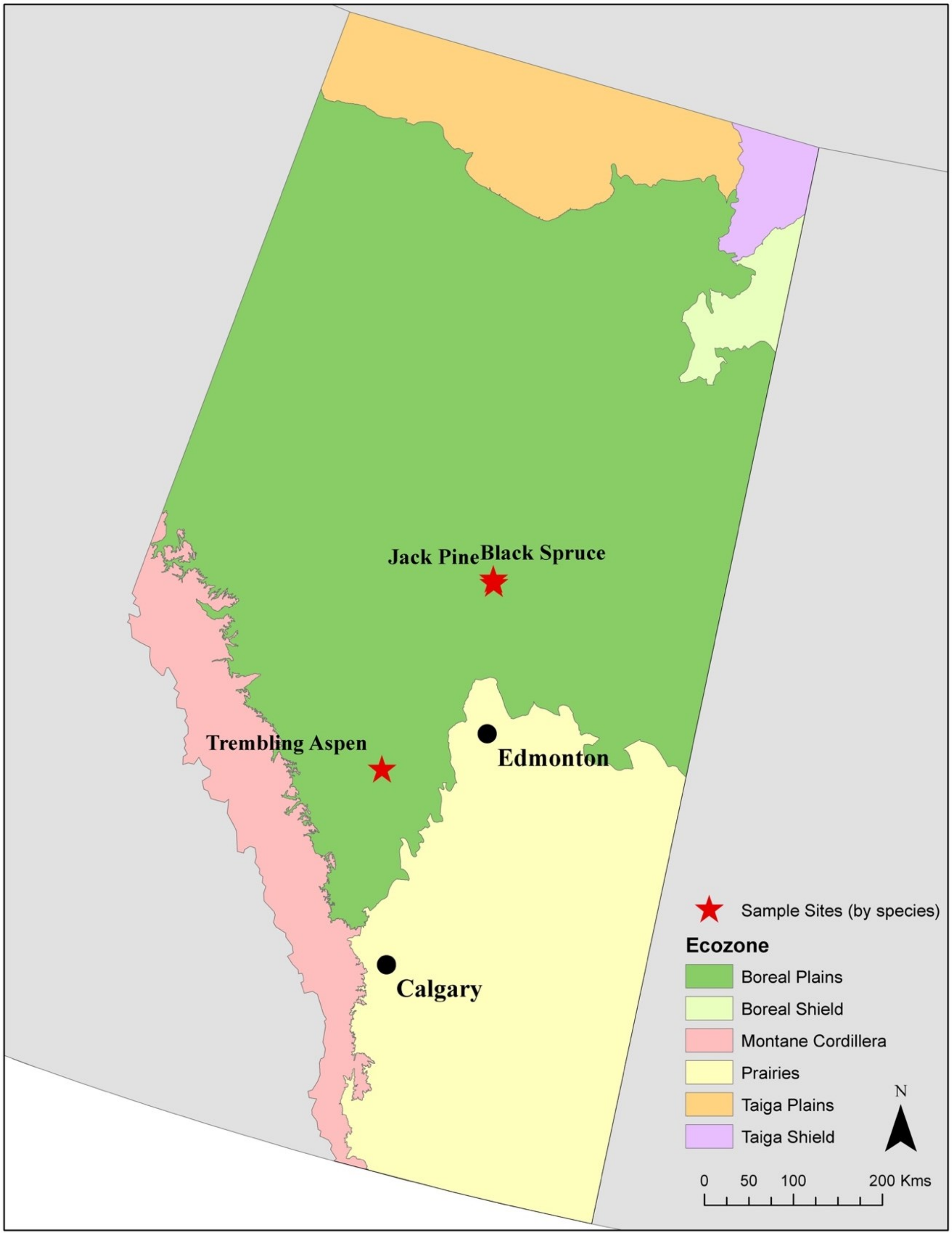

Figure 7. Sample sites in relation to the Boreal Plains Ecozone in Alberta, Canada.

Figure 8. Go-no-go gauge; sample showing size class 2, 0.5 to 1cm.

Figure 9. Sample being burned under simulated surface fire conditions in the lab.

3. RESULTS

3.1. OBSERVATIONS DURING LABORATORY BURNING

Of the 135 samples exposed to simulated surface fire conditions during the laboratory burn trials, 13 samples exhibited no charring, and thus produced no PyrC (0% PyrC production). All 13 of the unburned samples were of the largest diameter size class (5.1–7cm) and of the two highest moisture contents (7 at 18% moisture and 6 at 28% moisture). All three species were represented fairly evenly among the unburned samples (5 jack pine, 4 trembling aspen, and 4 black spruce). Each of the remaining 122 samples exhibited at least some charring. None of the samples were completely consumed by burning, but 16 samples had only thermally altered biomass left after burning. The PyrC produced by these 16 samples ranged from 0.02–1.15g, though most were <0.30g.

Of the 122 charred samples, 35 samples experienced flaming combustion; flaming durations ranged from 3 seconds to nearly 10 minutes. The average flaming duration among those 35 samples was 92 seconds. Black spruce samples experienced flaming combustion more often than jack pine or trembling aspen samples (17, 10, and 8 samples with flaming combustion, respectively). Lower moisture content samples experienced flaming combustion more frequently than higher moisture content samples; 17, 10, and 8 samples with flaming combustion for 8%, 18%, and 28% moisture content, respectively. Finally, smaller diameter samples experienced flaming combustion more often than larger diameter samples; 22 size class-1 and -2 samples experienced flaming combustion, while 13 size class-3, -4, and -5 samples experienced flaming combustion.

3.2. ANALYSIS OF VARIANCE (ANOVA)

Mean PyrC production for all samples was 5.1% (5.7% when unburned samples were excluded). Mean PyrC production across species ranged from 3.9–7.1%, across sample diameters ranged from 1.3–9.4%, and across moisture contents ranged from 4.5–5.8%.

3.2.1. Unburned samples included

The ANOVA indicated that at least one species (*F*=4.09, *P*=0.020), at least one diameter size class (*F*=29.97, *P*<0.000), and at least one moisture content (*F*=6.51, *P*=0.002) had a significantly different mean PyrC production. There was also a significant interaction between diameter size class and moisture content (*F*=4.08, *P*=0.000) in terms of their effect on the population mean PyrC production. The interactions between species and diameter size class (*F*=1.27, *P*=0.270), species and moisture content (*F*=0.46, *P*=0.764), or among species, diameter size class, and moisture content (*F*=1.20, *P*=0.281) were not significant on the mean PyrC production.

3.2.2. Unburned samples excluded

The ANOVA indicated that at least one diameter size class (*F*=12.39, *P*<0.000) had a significantly different mean PyrC production. Species (*F*=1.71, *P*=0.187) and moisture content (*F*=2.78, *P*=0.068) were not found be significantly different with respect to mean PyrC production. There was a significant interaction between diameter size class and moisture content (*F*=2.14, *P*=0.041) in terms of their effect on the population mean PyrC production. The interactions between species and diameter size class (*F*=1.36 *P*=0.228), species and moisture content (*F*=0.59, *P*=0.668), or among species, diameter size class, and moisture content (*F*=1.18, *P*=0.306) were not significant on the population mean PyrC production.

3.2.3. Flaming vs. non-flaming combustion

There was no significant difference in charcoal production between burned samples that experienced flaming combustion and samples that did not (*F*=0.32, *P*=0.571).

3.3. POST-HOC TESTS

3.3.1. Unburned samples included

Among species, mean PyrC production in trembling aspen differed significantly from that in jack pine and black spruce (Figure 10); the deciduous species exhibited higher rates of PyrC production than the two coniferous species. Among sample diameters, post-hoc testing revealed 3 significant groupings; mean PyrC production differed significantly between sample diameters 0–1cm, 1.1–5cm, and 5.1–7cm (Figure 11). The larger diameter samples exhibited lower rates of PyrC production than the smaller diameter samples. Mean PyrC production differed significantly for 8% moisture content compared to the 18% and 28% moisture treatments (Figure 12). The samples with higher moisture contents produced less PyrC under simulated surface fire conditions than those with a lower moisture content.

Moisture content had a significant effect on mean PyrC production for samples from the 3 largest diameter size classes (diameters 1.1–7cm; size class 3, *F*=3.75, *P*=0.027; size class 4, *F*=3.15, *P*=0.047; and size class 5, *F*=13.85, *P*<0.000), but not for samples from the 2 smallest diameter size classes (size class 1, *F*=0.80, *P*=0.454; and size class 2, *F*=1.28, *P*=0.2838). Samples with diameters of 0–1cm were found to produce similar amounts of PyrC regardless of moisture content. The sample's diameter had a significant effect on mean PyrC production for samples with 18% (*F*=19.07, *P*<0.000) and 28%

(*F*=17.56, *P*<0.000) moisture content, but not for samples with 8% moisture content (*F*=1.49, *P*=0.2113). The drier samples produced similar amounts of PyrC regardless of their diameter.

Pairwise comparisons were completed for combinations of interactions between the three largest diameter size classes and two highest moisture contents. Alpha was adjusted to reduce the chance of type 1 error during these 9 pairwise comparisons; alpha = 0.0056 was used to determine significance for pairwise comparisons.

Table 2 shows the P-values for the 9 pairwise comparisons. These pairwise comparisons indicated that the largest diameter samples (5.1–7cm diameter) from the two highest moisture contents (18% and 28% moisture) produced significantly less PyrC than other samples (Figure 13).

In addition to producing less PyrC, samples from the two largest diameter size classes (3.1–7cm diameter) at the two highest moisture contents (18% and 28% moisture) had the highest rates of residual, post-test unburned biomass (Figure 14). When PyrC production is expressed as a percentage of consumed biomass (Equation 3), trends in PyrC production appear to follow trends in residual unburned biomass (Figure 15).

$$PyrC\ \% = \frac{PyrC\ dry\ weight}{sample\ dry\ weight - (dry\ weight\ postburn\ biomass\ and\ PyrC)} * 100$$

Equation 3. Pyrogenic carbon production as a proportion of sample weight.

Table 2. Least squares difference (LSD) pairwise comparisons for the significant interaction between sample diameter and sample moisture content.

Pairwise Comparison					
1st Interaction			**2nd Interaction**		***P*-value**
Interaction	Mean PyrC production		Interaction	Mean PyrC production	
size class 3 at 18%	3.32%	vs.	size class 3 at 28%	2.90%	0.4229
size class 4 at 18%	2.04%	vs.	size class 4 at 28%	1.95%	0.8275
size class 5 at 18%	0.09%	vs.	size class 5 at 28%	0.45%	0.4992
size class 3 at 18%	3.32%	vs.	size class 4 at 18%	2.04%	0.2474
size class 3 at 18%	3.32%	vs.	size class 5 at 18%	0.09%	<0.0001
size class 4 at 18%	2.04%	vs.	size class 5 at 18%	0.09%	0.0002
size class 3 at 28%	2.90%	vs.	size class 4 at 28%	1.95%	0.5651
size class 3 at 28%	2.90%	vs.	size class 5 at 28%	0.45%	0.0007
size class 4 at 28%	1.95%	vs.	size class 5 at 28%	0.45%	0.0044

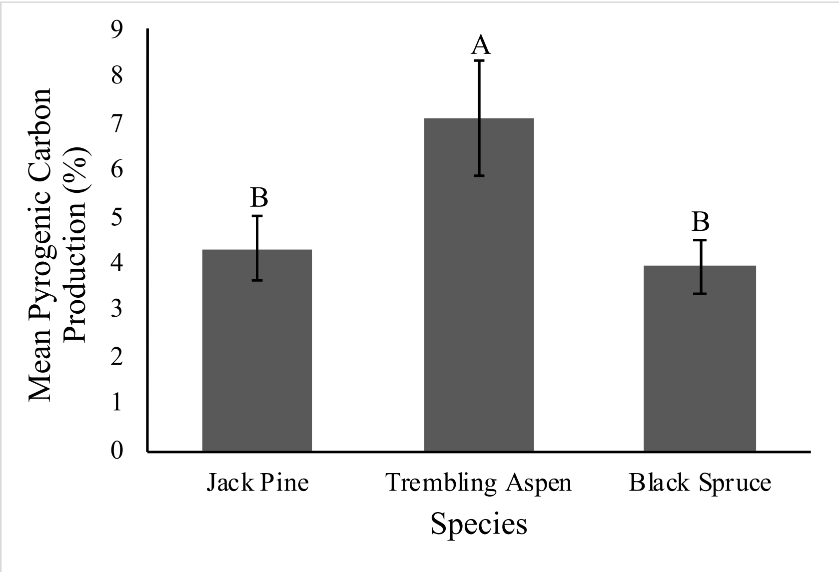

Figure 10. Mean pyrogenic carbon production (%) among species for the dataset including unburned samples; standard errors of each mean are denoted by whiskers, and species with different letters were significantly different.

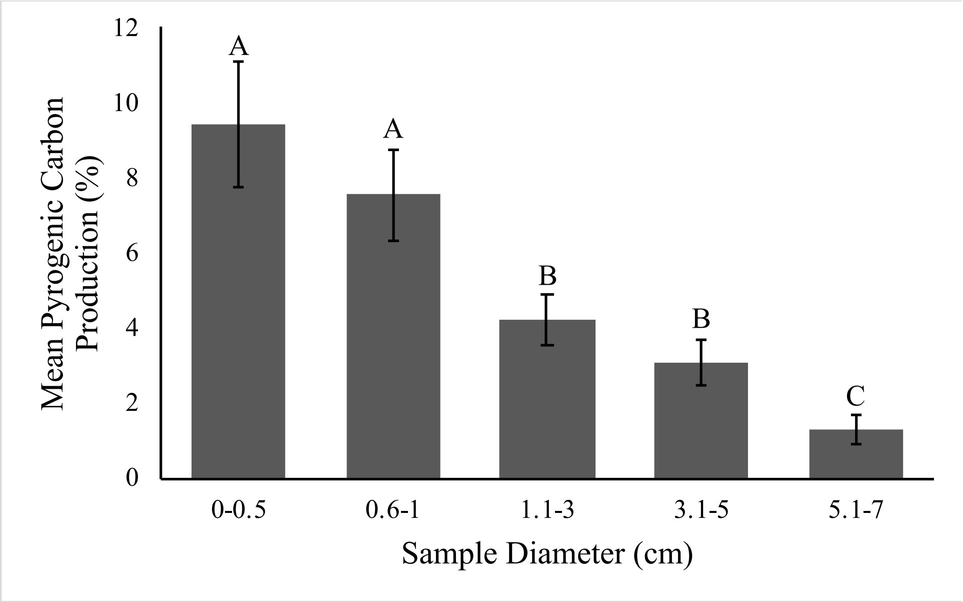

Figure 11. Mean pyrogenic carbon production (%) among sample diameters for the dataset including unburned samples; standard errors of each mean are denoted by whiskers, and sample diameters with different letters were significantly different.

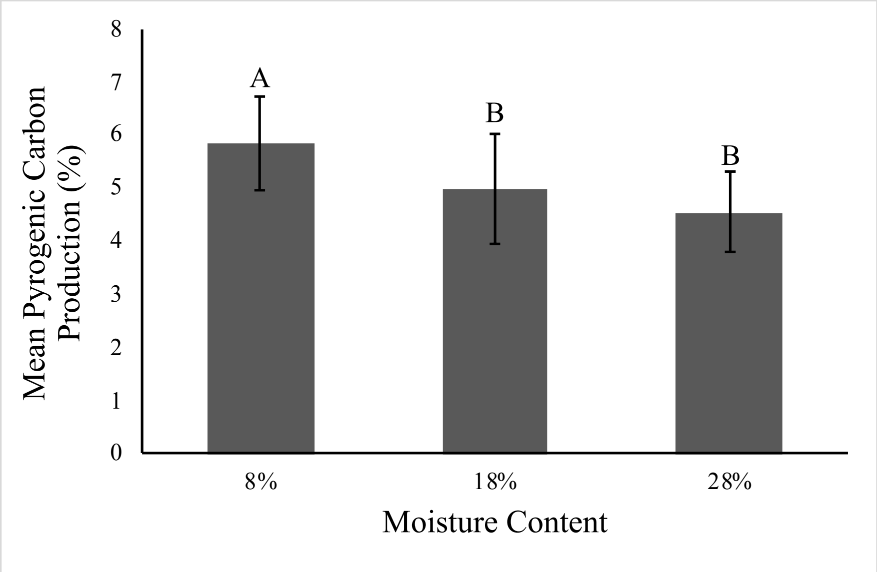

Figure 12. Mean pyrogenic carbon production (%) among moisture contents for the dataset including unburned samples; standard errors of each mean are denoted by whiskers, and moisture contents with different letters were significantly different.

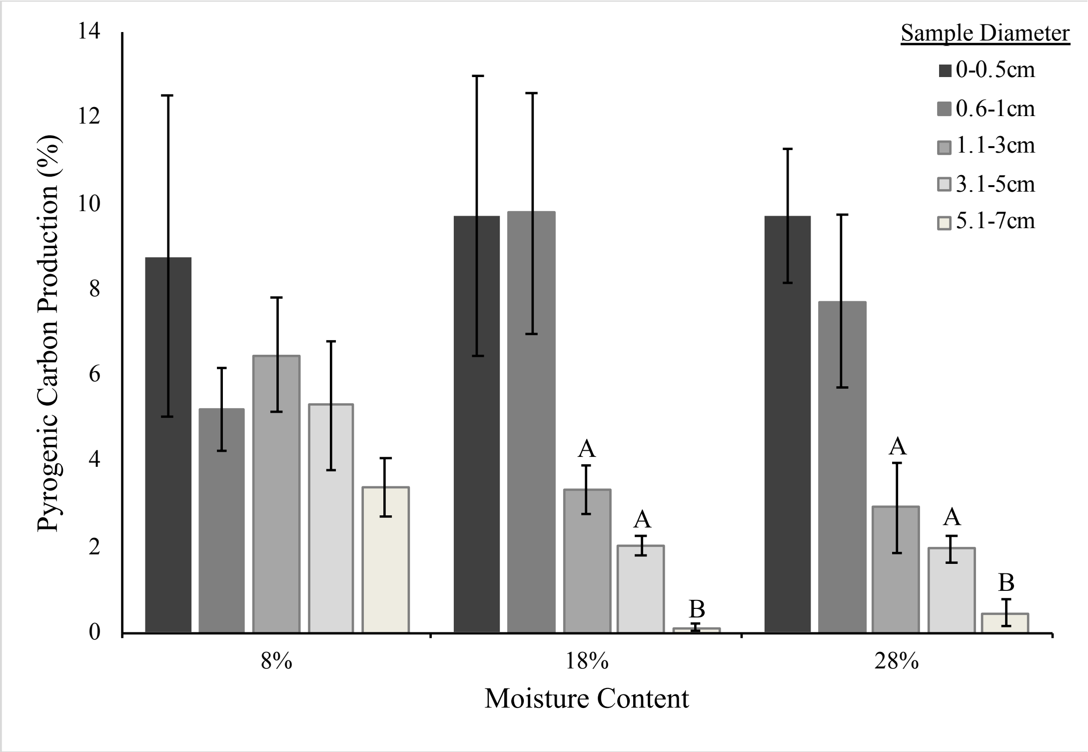

Figure 13. Mean pyrogenic carbon production for samples of different diameters at different moisture contents for the dataset including unburned samples; standard errors of each mean are denoted by whiskers, and different letters indicated pairwise comparisons that were significantly different.

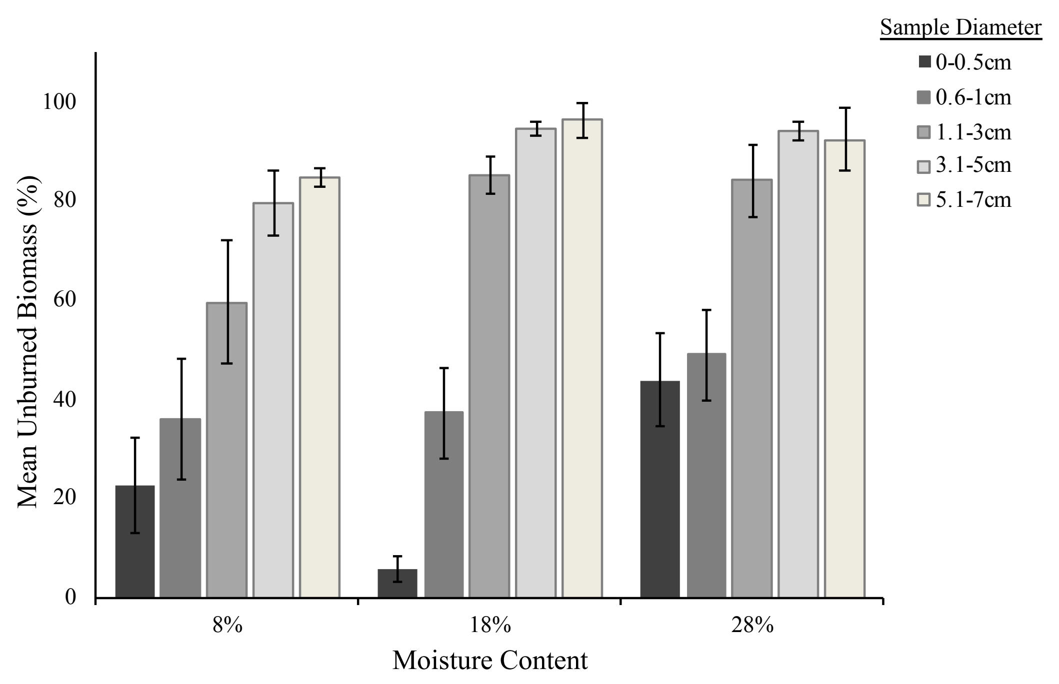

Figure 14. Mean post-test unburned biomass for samples of different diameters at different moisture contents for the dataset including unburned samples; standard errors of each mean are denoted by whiskers.

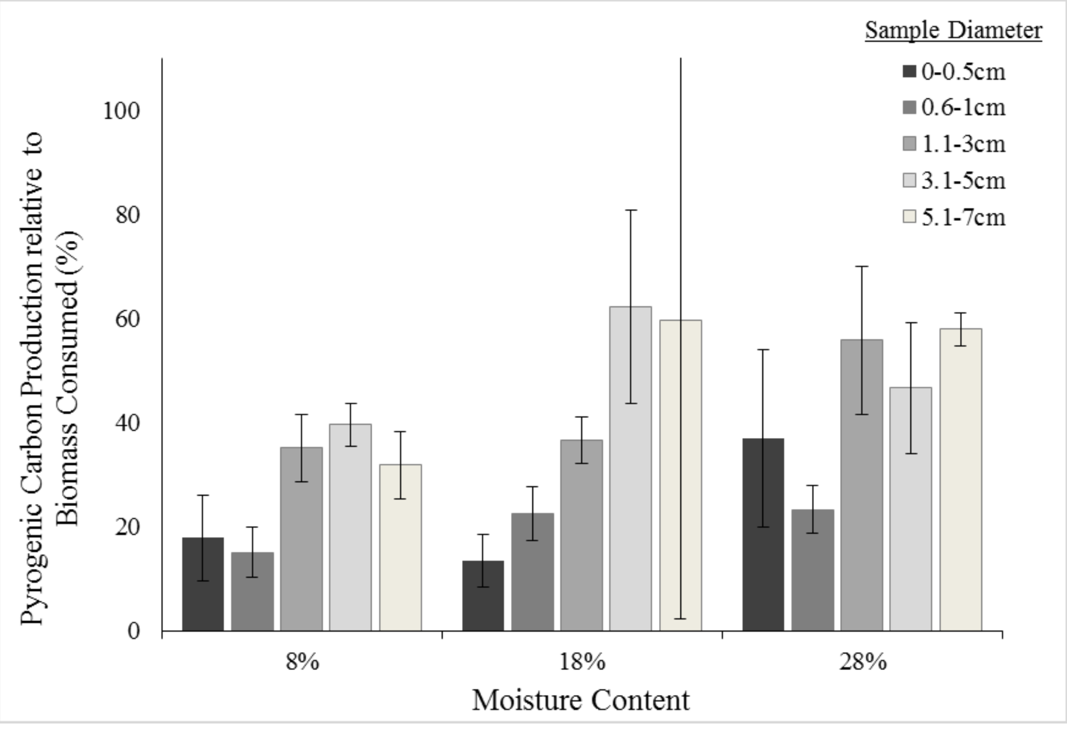

Figure 15. Mean pyrogenic carbon production relative to consumed biomass for samples of different diameters at different moisture contents; standard errors of each mean are denoted by whiskers.

3.3.2. Unburned samples excluded

Like before, post-hoc testing revealed 3 significant groupings among sample diameters, though there were not enough replicates of 5.1–7cm diameter samples for the Tukey-Kramer test to include it. Each sample diameter produced similar amounts of PyrC to the next closest sample diameter(s), but produced significantly different amounts of PyrC than all other sample diameters (Figure 16); sample diameters 0–0.5cm had a significantly different mean PyrC production than sample diameters 1.1–5cm; sample diameters 0.6–1cm had a significantly different mean PyrC production sample diameters 3.1–5cm; sample diameters 1.1–3cm had a significantly different mean PyrC production sample diameters 0–0.5cm; and sample diameters 3.1–5cm had a significantly different mean PyrC production sample diameters 0–1cm. The larger diameter samples exhibited lower rates of PyrC production than the smaller diameter samples (Figure 16).

Multiple comparisons were completed to examine the significant interaction between moisture content and sample diameter; comparisons completed using the Tukey-Kramer used alpha=0.05. Though the Tukey-Kramer test produces comparisons for all potential pairwise combinations, only those that shared a common variable were compared. This post hoc test showed that the lowest moisture content still had no effect on mean PyrC production at any sample diameter, even after removing unburned samples from the dataset (Figure 17). Additionally, there were no significant differences in mean PyrC production for common diameter size classes at different moisture contents (ex. diameters 0.6–1cm at 18% moisture vs. diameters 0.6–1cm at 28% moisture). At 18% moisture content, two diameter size classes (0.5–1cm and 3.1–5cm) were significantly different with respect to mean PyrC production (*P*=0.026); 5.1–7cm diameter samples at 18% moisture content did not have enough replicates to be include by the Tukey-Kramer test (Figure 17). At 28% moisture content, the smallest diameter size class was significantly different than the three largest diameter size classes with respect to mean PyrC production (*P*=0.015, *P*=0.002, *P*=0.017) (Figure 17). Overall, larger diameter samples showed lower mean PyrC production than smaller diameter samples when fuel moisture was 18% or greater.

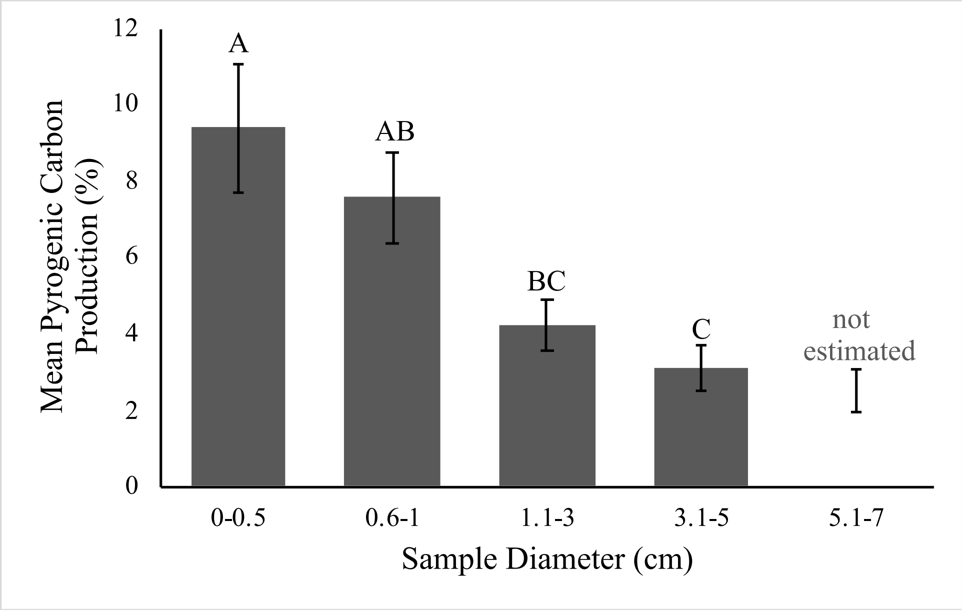

Figure 16. Mean pyrogenic carbon production (%) among sample diameters for the dataset excluding unburned samples; standard errors of each mean are denoted by whiskers, and sample diameters with different letters were significantly different.

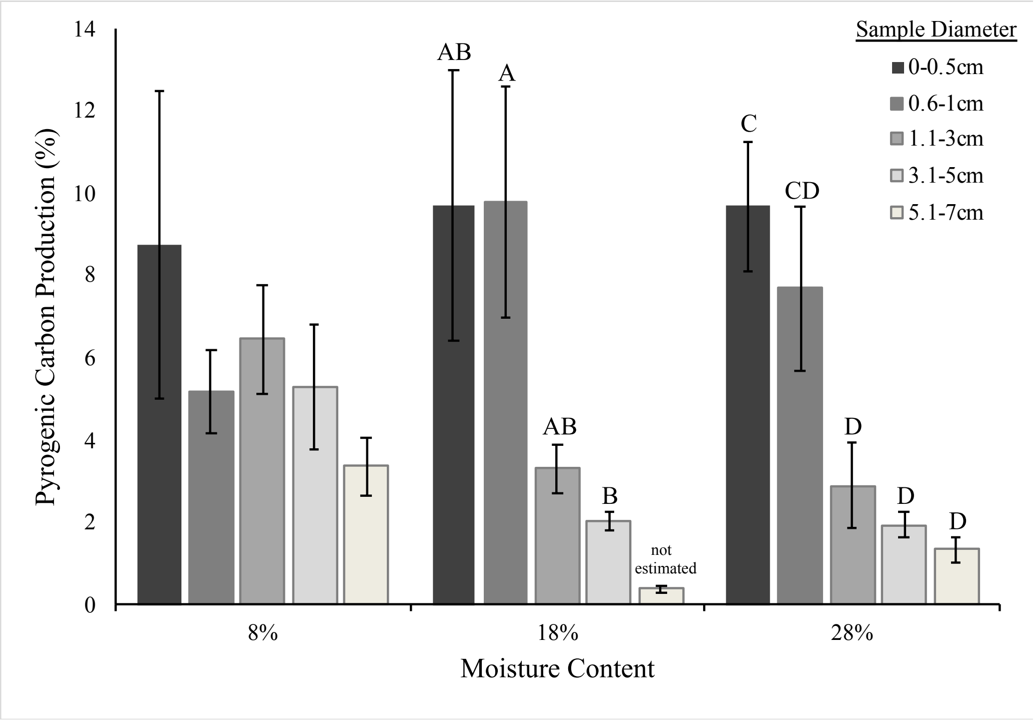

Figure 17. Mean pyrogenic carbon production (%) for samples of different diameters at different moisture contents for the dataset excluding unburned samples; standard errors of each mean are denoted by whiskers. Pairwise comparisons between similar diameters across moisture contents showed no significant differences; different letters indicate significant differences between sample diameters of the same moisture content.

4. DISCUSSION

4.1. EFFECT OF SPECIES ON PYROGENIC CARBON PRODUCTION

Trembling aspen, the only deciduous species in this study, exhibited a significantly higher mean PyrC production than jack pine and black spruce; this result supports the first hypothesis outlined in section 1.7.1. Differences in PyrC production could be a result of differing physical and/or chemical properties between species. Fire behavior in trembling aspen slash has been observed to be substantially less than that of jack pine slash under similar environmental conditions, with spread rates of 2.5 m min^{-1} as compared to 36.6 m min^{-1} (Alexander 1982). Alexander (1982) indicated that aspen slash was light and discontinuous when compared to jack pine slash, but did not indicate if the differences in fuel loading and arrangement accounted for the entire difference in fire behavior. In general, coniferous species have a higher cellulose content, higher lignin content, and lower pentosane content as compared to deciduous species (Rowell *et al.* 2005). Wood density also commonly varies between tree species; a study of Canadian tree species, including the three boreal species studied here, found that black spruce typically had a higher density than trembling aspen and jack pine (Singh 1986).

Lower densities, along with lower volumetric heat content, higher lignin content, and higher gravimetric heat content have been associated with increased consumption of coarse woody debris in various states of decay during laboratory fires (Hyde *et al.* 2012). Additionally, differences in chemical make-up, such as lignin to cellulose ratios, have also been linked to differences in pyrolysis and combustion in natural, non-wood fibres (Dorez *et al.* 2014, Gani and Naruse 2007). It has been postulated that materials richer in lignin, such as wood from pine trees, may face relatively smaller losses of mass due to charring

(Santín *et al.* 2015, Cornwell *et al.* 2009). Differences in fuel loading or arrangement cannot be used to explain differences in PyrC production in this study, since samples were burned individually. The difference in PyrC production among species could be linked to differences in combinations of chemical make-up and wood density among species; this should be explored further in future studies.

4.2. EFFECT OF SAMPLE DIAMETER ON PYROGENIC CARBON PRODUCTION

The mean PyrC production percentage decreased as sample diameter increased; there were three significantly different groupings of diameter size classes. The trend of decreasing PyrC production as sample diameter increased was consistent through all diameter size classes, and remained when the 13 unburned samples were removed from the dataset. These results do not support hypothesis 2 (section 1.7.1) and are difficult to compare with other studies, since pre-burn biomass has not often been classified by size for comparison to post-burn residues.

Brewer (2012) quantified PyrC production in masticated fuels of less than 7cm diameter, but the study burned the masticated fuels in mixed fuel beds and did not explore differences in PyrC production by the size of masticated pieces. Santín *et al.* (2015) compared the pre-burned mass of forest stand components to the post-burn pyrogenic organic matter for the same stand components following a crown fire in a jack pine stand; forest biomass components were separated into forest floor, down wood, overstory bark, and overstory needles. The down wood component accounted for all of the fine woody debris of diameters 0.6–7cm that would be comparable to this study, while 0–0.5cm diameter fine woody debris was combined with forest floor fuels (Santín *et al.* 2015).

Santín *et al.* (2015) found that the conversion rate to PyrC was lowest for overstory jack pine needles, but highest for overstory bark followed shortly by down wood. Santín *et al.* (2015) measured charring depth on down wood components, observing that the smallest diameter pieces were most affected by fire; these results are consisted with non-quantitative observations from this study—many of the samples from smaller size classes had very little unburned wood left after combustion.

The ratio of surface area to volume may affect combustion completeness, and thus conversion of biomass to PyrC (Santín *et al.* 2015). Comparing this study to Santín *et al.* (2015), it seems as though there may be an optimal surface area to volume ratio for PyrC production that lies somewhere between that of a jack pine needle and that of 5.1–7cm diameter down woody debris.

4.3. EFFECT OF MOISTURE CONTENT ON PYROGENIC CARBON PRODUCTION

PyrC production decreased as moisture content increased. This result does not support an initial hypothesis of this study (section 1.7.1) and is inconsistent with a similar study by Brewer (2012), which explored PyrC production across three fuel moisture ranges (4–8%, 10–12%, and 13–16% fuel moisture) in masticated fuels. In the masticated fuels, the fuels with the highest moisture contents were found to produce the highest amounts of PyrC, but this production rate was not found to be significantly different than the other moisture contents (Brewer 2012). Inconsistencies between Brewer (2012) and this study may be as a result of different fuel moisture treatments among samples; only one moisture content treatment used in this study overlapped with those used by Brewer (2012). Additionally, there were 13 samples that did not burn (and thus produced no PyrC) in this study; all unburned samples had received one of the two highest moisture content treatments (18% and 28% fuel moisture).

Babrauskas (2006) found that the effective heat of combustion in wildfires is strongly dependent on moisture content for all vegetation. It is possible that moisture content has a greater effect on the ability of fine woody debris samples to ignite than it does on PyrC production; this should be explored further in future research.

4.4. THE INTERACTION BETWEEN DIAMETER SIZE CLASS AND MOISTURE CONTENT IN PYROGENIC CARBON PRODUCTION

Larger diameter woody debris often retains moisture longer than woody debris of smaller diameters (Scott *et al.* 2014). Wood dries from the outside in, as water in wood moves from zones of higher moisture content to zones of lower moisture content; the surface of the wood must be drier than the interior of the wood if moisture is to be removed (Simpson 2001). The drying rate is affected by the thickness of the wood, with rates increasing by three or four times if thickness is doubled (Simpson 2001). Moisture content expressed as a percentage of dry weight effectively provides the average moisture content for the entire sample and does not describe the moisture gradient that exists from the exterior to interior of especially the larger diameter samples. During this study, samples were saturated and allowed to air-dry to target moisture content treatments. Though each whole sample met its moisture content treatment, it is likely that there were portions of biomass in each sample with higher and lower moisture contents; for example, 5.1–7cm samples at 28% fuel moisture were likely to have interior moisture contents that were higher and surface moisture contents that were lower than 28%. Since fuel moisture content determines fuel ignitability, rate of combustion, and the amount of fuel consumed (Scott *et* *al.* 2014), it makes sense that this interaction is significant with respect to PyrC production. A lower overall loss of mass occurred as sample diameter and moisture content increased (Figure 14); this is indicative of the reduced ignitability, combustion and consumption in the larger diameter, higher moisture content samples.

The largest diameter size class (5.1–7cm diameter) and the two highest moisture contents were found to have a significant effect on this interaction, producing lower mean PyrC percentages than the other pairwise comparisons; these are also the same treatments that yielded all of the samples that failed to ignite during laboratory burning. When data was reanalysed excluding the unburned samples, there was still a significant effect of sample diameter on mean PyrC production for the two highest moisture contents. These results support the forth hypothesis outlined in section 1.7.1. It is possible that the combination of diameter size class and moisture content may be affecting fuel ignitability and ability of ignited fuels to sustain combustion. In New Zealand shrubland, dead fuels failed to ignite at fuel moistures above 36%, and ignition only resulted in spreading fire below 19% moisture (Anderson and Anderson 2010). Chuvieco *et al.* (2004) summarizes that the threshold moisture content above which fire cannot be sustained varies between 12% and 40% for dead fuels, but for some very fine fuels (such as conifer needles) this threshold is much higher. This range of moisture contents also coincides with the fibre saturation point for most species (Simpson 2001). The fibre saturation point is defined as the moisture content at which the cell walls are saturated but no free water remains in the cell cavities within the wood; the fibre saturation point for most species is about 30% moisture content (Simpson 2001). This study suggests that the threshold moisture content at which fire cannot be sustained for 5.1–7cm diameter down woody debris of the three species studied may coincide with the fibre saturation point.

It is difficult to compare this result to other studies, since fuel diameters and moisture contents have not been examined for their relationship to PyrC production in the same manner. Other similar studies did not appear to have issues with lack of ignition (Brewer 2012, Santín *et al.* 2015); this suggests that there is likely an ideal range of burning conditions in dead fuels where maximum PyrC production occurs, and this ideal range occurs somewhere between conditions that allow for complete combustion and conditions that limit ignition potential.

4.5. OTHER POTENTIAL INFLUENCES ON PYROGENIC CARBON PRODUCTION

Though samples were separated by species and diameter size class, there is inherent variety between fine woody debris samples of the same species and size class. For example, some samples were older than others with less bark and more decay while other samples had cones attached. Very fine fuels, such as flakey bark or needles, are easier to ignite and burn more completely than more coarse fuels (Santín *et al.* 2015, Scott *et al.* 2014). The presence/absence of bark on samples in this study may have affected the ignitability of a sample, and thus the sample's ability to produce PyrC by combusting. Another study showed that backing fires produced more PyrC than head fires (Carvalho *et al.* 2011), supporting the notion that factors affecting fire intensity such as the presence/absence of very fine fuels and wood density are likely to have an effect on PyrC production.

The apparent effects of moisture content on the ability of a sample to ignite and sustain combustion (and thus the ability to production of PyrC) during this study suggests that other factors affecting the ignitability and the ability of ignited fuels to sustain combustion might also affect PyrC production. Hyde *et al.* (2012) found that decayed coarse woody debris (>7cm diameter) was likely to be consumed completely under low fuel moisture conditions, while sound wood was less likely to be consumed completely under the same conditions. Differing stages of decay between samples, and thus variability in wood density and chemical make-up, may have had an effect on fuel consumption during combustion and therefore on PyrC production. The presence/absence of flakey bark and the degree of decay present in samples were outside of the scope of this study, but should be evaluated with respect to their effects on PyrC production in future studies.

In this study, there was no significant difference in mean PyrC production between samples that experienced flaming combustion and samples that only smouldered. Brewer (2012) observed longer flaming durations in masticated fuels with 13–16% moisture content which also produced generally more PyrC and a higher proportion of black carbon as compared to lower moisture content treatments; there was no significant difference in PyrC production between moisture content treatments in their study, but there was significantly more black carbon produced by the 13–16% moisture content treatment. Soucémarianadin *et al.* (2015) and Belcher *et al.* (2018) found that PyrC produced under lower-severity fires/lower-energy conditions (conditions consistent with a low-intensity, smouldering fire) exhibited lower chemical recalcitrance. Though there was no significant difference in PyrC production between samples that experienced flaming combustion and those that did not in this study, it is likely that the PyrC produced without a flaming phase of combustion would fall into the less thermally altered end of the PyrC continuum.

5. CONCLUSIONS

The experimental approach of this study allowed for different diameters and species of fine woody debris to be examined in isolation of other surface fuels that would exist in a forest stand. This lab-based approach also provided opportunities to control fuel moisture and burn replicates of each combination of independent variables. Mean PyrC production decreased as stick diameter and moisture content increased. Trembling aspen exhibited higher mean PyrC production than both conifer species. Though some samples experienced a flaming combustion phase while others did not, there was no significant difference in mean PyrC production between these two groups. A significant interaction between moisture content and diameter size class indicated that the largest diameter samples produced significantly less PyrC at 18% and 28% moisture content, suggesting that moisture content approaching the fiber saturation point may be a limiting factor in PyrC production. The differing rates of PyrC production across the variables in this study highlights the importance of considering forest stand dynamics, such as species composition and quantity of woody debris per diameter size class, when seeking to comprehensively quantify PyrC production during wildland fire.

Wildland fire management strategies seeking to maximize carbon retention could consider timing prescribed fires or allowing for extensive management of wildfires during stand conditions that are optimal for PyrC production. Flanagan *et al.* (2019) suggest that prescribed fire regimes in some environments may even approach a carbon neutral state in carbon emissions and sequestration if PyrC production and influences are factored into modeling. Fuel moisture is an easily-measured and commonly estimated forest-fuels variable. When managing for carbon retention, burning when fuel moistures are optimal for

PyrC production should be considered; this study suggests that burning with 8% fuel moisture produces more PyrC than at 18% or 28% fuel moisture, while Brewer (2012) suggests 13–16% fuel moisture is optimal. Target fuel moisture ranges for optimal PyrC production also depend on fuel diameter—stands with abundant larger-diameter forest fuels should be targeted at lower moisture contents than stands with higher proportions of smaller-diameter fuels. Future research should focus on further refining the ideal moisture content, by fuel size, for PyrC production.

Future work should also focus on identifying PyrC production rates for key components in forest stands under various fire behaviour conditions so that PyrC production might be modelled post-fire based on forest resource inventory data and fire intensity/severity metrics. With the national and global interest in the concept of carbon budgets, it becomes increasingly relevant in the field of wildland fire management to better understand the recalcitrant residues of wildland fire. As climate change and anthropogenic influences further alter wildland fire regimes, better comprehension of PyrC production as a component of forest carbon dynamics will assist in understanding how these changes may further affect the environment. As noted, there is a knowledge gap with respect to how specific fuel properties and fire behaviour influence PyrC production. The experimental approach employed in this study was useful for comparing PyrC production of specific forest stand components in a controlled manner.

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